Land-cover fragmentation and configuration of ownership parcels in an exurban landscape

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Abstract The rate of low-density development beyond the urban and suburban periphery, known as exurban areas, has occurred at a rate faster than both urban and population growth and has the potential to affect water quality, carbon storage, and habitat availability. This paper is aimed at understanding the relationships between the heterogeneity of the human and natural components of the land system and their interactions, through assessment of residential land-cover characteristics and ownership parcels in these poorly understood exurban lands. New data are presented that describe the distribution of land-cover quantities and their degree of fragmentation in three townships in Southeastern Michigan. Analysis of land-cover data, collected from aerial photographs from 1950–2000 and digitized with a 10 m minimum mapping unit, provide an empirical link between lot-size and vegetation. Results show, among other findings, 1) the quantity and pattern of land-cover types significantly differ with parcel size, 2) the degree of difference was greatest between small parcels and all other sizes and least among large parcels, and 3) of five landscape metrics used to evaluate the quantity and fragmentation of land-cover types in residential parcels, the percent of parcel area provided the strongest delineation of differences in land cover among parcel sizes. Capturing quantities and patterns of land-cover at different sizes of land (parcel) ownership provide new data that can be coupled to ecosystem literature and models to link the outcomes of residential land-cover processes with simple ecosystem functions (e.g. carbon storage, albedo). Understanding how residential land-use and management processes collectively create regional land-cover patterns can provide insight into how residential lands might be managed to mitigate the effects of land change on climate.

Keywords Exurban · Residential land-use · Parcel size · Land-cover · Landscape metrics

Introduction

Anthropogenic drivers of land-use and land-cover change (LUCC) have altered over 30% of the Earth's surface (Houghton 1994; Vitousek et al. 1997). The effects of these changes

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are to alter biogeophysical (e.g. albedo, evaporation, and heat flux), biogeochemical (e.g. carbon and nutrient cycling), and biogeographical (e.g. location and movement of species) processes that in turn affect local and global climate (Stohlgren et al. 1998; Kalnay and Cai 2003). Estimates are that LUCC has contributed about 30% of the total historical anthropogenic CO_2 efflux to the atmosphere, which makes it the second largest contributor after fossil fuel burning (Sarmiento and Sundquist 1992; Sundquist 1993). Because of the profound effect of LUCC on CO_2 emissions to the atmosphere, extensive research has focused on quantifying and mapping LUCC at coarse resolutions and global scales (e.g. Hansen et al. 2000).

Understanding the relationship between LUCC and global climate becomes difficult because LUCC is driven by local complexities and feedbacks in human behavior that are non-stationary across space and time (Foley et al. 2005). Similarly, heterogeneity in human characteristics and behaviors, biophysical characteristics of the landscape (e.g. soils or topography), and climate exist and have differential impacts on LUCC outcomes and trajectories. Incorporating micro-level heterogeneity into our understanding requires a bottom-up approach to LUCC research that focuses on 1) the composition and quantity of different land-cover types, 2) the pattern and fragmentation of land-cover patches, 3) the influence of spatial and network effects on (1) and (2), and 4) how government policies and other factors influence 1–3.

Because it is one of the more prominent land-use changes in recent decades, urban growth has been a focus of many modeling, theory building, and predicting activities in LUCC. As of 2000, 47% of human population lived within urban areas, which is estimated to increase to 68% by 2050 (UN 2009). The United States is also expected to experience substantial urban growth. In 2000 79% of the US population lived within urban areas and this is estimated to increase to 90% by 2050 (UN 2010).

While the rate of global urbanization is alarming, perhaps just as striking is the rate of low-density development in developed countries like the United States (Brown et al. 2005). Classified as exurban areas, and defined by Theobald (2005) as having between 0.68 and 16.18 ha per housing unit, these areas grew at a rate approximately 25% greater than population between 1980 and 2000 in the conterminous United States. In year 2000 the extent of exurban residential land use consumed 11.8% of the land area within the conterminous United States while urban and suburban residential land use accounted for only 1.6% (Theobald 2005). The dispersion of human population around and beyond the urban/suburban periphery is often overlooked, and the complex land-cover composition of exurban residential parcels complicates generalizations about the ecological effects of these land-use conversions.

This paper sets out to test the degree to which the quantity and fragmentation of land-cover types are significantly influenced by parcel size and the effect exurban growth can have on land-cover change at local and regional scales. Parcel size is an important determinant of land-cover because 1) the parcel is a legal administrative unit within which the environment is managed by the land owner, 2) parcel size is often influenced by minimum lot-size zoning policies (Drzyzga and Brown 2002) imposed to achieve some socio-ecological outcome, 3) in the case of subdivision or parcelization the parcel identifies a unit of land change, 4) parcel size is a dominant factor affecting land value (Thorsnes and McMillen 1998), and 5) the parcel is the preferred unit for monitoring land-use and land-cover change (Moudon and Hubner 2000).

Geographical information systems (GIS) is combined with aerial imagery to analyze the extent of land-cover fragmentation in relation to the size and configuration of ownership parcels in exurban environment. Through the analysis of spatial land-cover data this paper

addresses the following question: How are land-cover types distributed and patterned relative to residential parcel sizes in the exurban landscape of Southeastern Michigan? In order to address this question the following pattern metrics are used: total land cover, number of patches, mean patch size, edge density, and area weighted mean shape index. The analysis is focused on residential land parcels that have been identified as single family residential parcels (or "lots"), and where the property is not connected to urban infrastructure, such as a sewer system.

The presented data and analysis fill a gap in regional science, urban ecology, and exurban literature where land-cover analyses at resolutions finer than the county or urban area are lacking (Irwin and Bockstael 2007). Furthermore, when used in combination with ecosystem process models or bookkeeping approaches to carbon accounting, these data may be used to estimate the ecosystem impact of settlement patterns and lot-size zoning policies in highly fragmented and human dominated environments.

Methods

Study area

The analysis is focused on three townships, Pittsfield, Ray, and Scio Townships, in Southeastern Michigan (Fig. 1). Collectively the townships represent a mixture of population growth rates and land-use and land-cover types (Fig. 2). While each township was primarily agrarian in 1950, Ray Township had a small population of 1671 individuals and grew slowly over time to remain predominately rural in 2000. Unlike Ray Township, both Pittsfield and Scio Township border the city of Ann Arbor, which has experienced higher levels of growth. To the south of Ann Arbor the already well populated Pittsfield Township grew exponentially and experienced substantial changes in land use and land cover. The same population and land-use and land-cover change trends occurred to a lesser degree in Scio Township, located just west of Ann Arbor.

Typical land-use and land-cover transitions in Southeastern Michigan, and across the Upper Midwest (Brown 2003), from 1950 to 2000 involved the transition from agriculture to residential use and farm abandonment followed by forest regrowth. It is expected that forest regrowth in the Midwest will slow or level off as it did earlier in New England (Foster 1992); however, the rate of the transition from agriculture to residential and farm abandonment to forest has been and will likely continue to be slower in the Midwest than New England, which experienced a strong and rapid decline in agriculture due to poor soil quality and the ability to acquire agricultural products from the Midwest (Simpson et al. 1994).

Land-cover data

Land-cover data were manually digitized from aerial photograph interpretation at multiple dates for each township. Aerial photographs from 1950–2000 used were acquired from the DNR, FSA, AIA, and SEMCOG.[1] On-screen digitizing was performed at a scale of 1:3000 with a linear minimum mapping unit (MMU) of 10 m. The MMU was used for all

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[1] Department of Natural Resources, Farm Service Agency (FSA) and Aerial Photography Field Office (APFO), Aerial Imagery Archive (AIA)—Michigan State University, and the SouthEastern Michigan Council of Governments (SEMCOG).
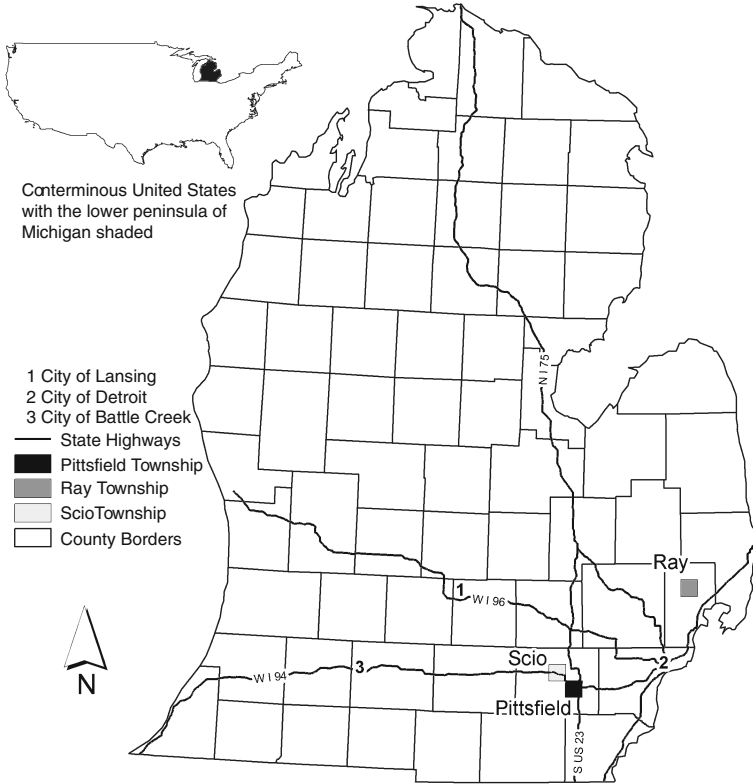
Fig. 1 Scio, Pittsfield, and Ray Township are located in the southeastern corner of the lower peninsula of Michigan, USA. In addition to the plotted cities, the city of Ann Arbor infringes on the eastern border of Scio Township and the northern border of Pittsfield Township
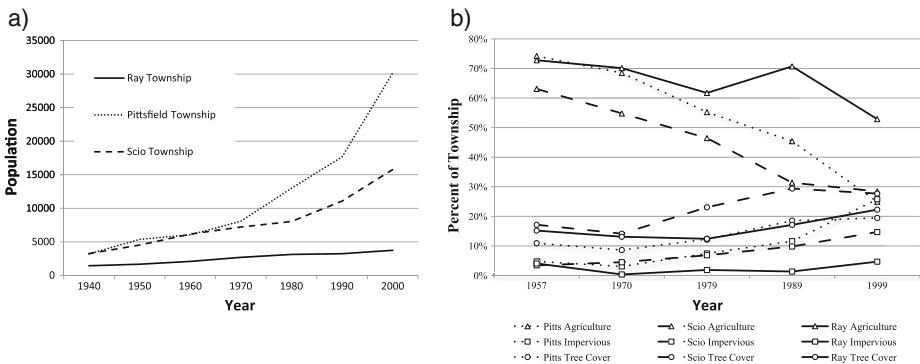
Fig. 2 Trends in **a** population and **b** land-cover types for the three study townships. Population data obtained from U.S. Bureau of Census (1950, 1970, 2000). Open natural areas such as grassland landscapes are not shown, but follow a very similar trend to that of tree cover. Land-cover data were derived from aerial photograph interpretation at the University of Michigan

landscape features (e.g. tree cover, water, and other natural patches) with the following exception. Strong linear features with a high perimeter-to-edge ratio such as impervious surfaces (e.g. roadways) and tree cover (e.g. tree row along property lines) that were <10 m in width but >10 m in length were digitized because of their prevalence and identifiability.

Altogether, seven land-cover classes were digitized. Tree cover consisted of forest patches and individual trees of any species that exceeded the MMU. Open fields that did not show cropping striations or a park-like appearance were classified as open natural areas (e.g. prairie and pasture lands). Maintained lawn consisted of manicured areas adjacent to commercial, industrial, and residential structures as well as golf courses and other managed areas (e.g. recreation fields). Impervious lands consisted of 1) impervious structures (e.g.. building footprints and driveways) and 2) impervious transportation features (e.g. roads). Saturated areas that were not open water, wooded wetlands, or the result of recent precipitation events were classified as wetlands. Open water consisted of ponds, lakes, rivers and other permanent hydrologic features. Cropland consisted of row crops and land-cover types that appeared to be of an agrarian nature (e.g., fallow fields). It was rare that cropland was found in residential parcels. However, cropland did occur 1) when errors associated with parcel-boundary overlay with neighboring cropland occurred, or 2) when parcels boundaries were accurate but adjacent land uses spilled over beyond property boundary lines. Furthermore, in some cases residential parcels created out of farmland and not part of a subdivision had continued agriculture on the back part of the property. Further investigation into when and why residential parcels have agricultural lands within their boundary need to be conducted, but is beyond the scope of this paper.

In a limited number of cases land cover was in transition, usually to development. In these cases if new road or structure outlines were visible the land was classified as residential and otherwise it was classified as the prior land cover type.

The above land-cover classes were digitized at decadal time steps from 1950 to 2000. While coregistration of a series of images taken at different dates can minimize location errors for land-cover change detection, at the fine resolution used in air photo interpretation and the presented analysis, this was not possible due to splicing and mosiacking issues in the air photos. Instead the 2000 digitized land-cover data was used as a template for previous land-cover interpretation dates. The use of a template effectively fixed the location of land-cover features, such that one could delineate an area (i.e. parcel) and obtain an accurate temporal description of land-cover change for that area. This digitization procedure required that, on occasion, earlier aerial photo data be shifted to correct for spatial misregistration and match the earlier photo with the original 2000 year data. Parcel data from all dates were lumped together to increase the size of the sample used to derive representative generalizations of land-cover by parcel size.

Since on-screen digitizing was labor intensive, several individuals were employed to perform the digitizing process. Each digitizer was asked to digitize land cover from the 1969 aerial photograph of Pittsfield Township, which was the most difficult photo to discern land-cover types from. The mean standard deviation of land-cover type by proportion of parcel area for 65 residential parcels, by three individuals, was as follows: 2.5% crop, 4.6% tree cover, 2.0% impervious surface, 17.5% maintained lawn, 13.8% open natural areas, and 0.2% for water. The main source of confusion occurred in the classification between maintained lawn and open natural areas. Arguably, at a minimum mapping unit of 10 m, the digitized data used in this analysis provides a more accurate representation of land cover and land-cover change (Kunapo et al. 2005) at a finer resolution than that available from other sources (e.g. 30 m NLCD, Homer et al. 2007).

Data on parcels and built structures

Contemporary (2003) parcel data for Scio and Pittsfield Townships were obtained from the Washtenaw County Metropolitan Planning Commission, and for Ray Township (2003) from the Macomb County Planning and Economic Development Department. All parcels classified as single family residential were selected from these data and used. While the Washtenaw County data contained a land-use designation, Ray Township land-use types were determined by aerial photograph interpretation.

To remedy the lack of archived historical residential parcel data, the locations (as point features) of built structures were digitized from aerial photographs from approximately 1950 to 2000. All of the year 2003 parcel polygons that "completely contained" built structures identified from 1990 aerial photographs were then selected to obtain a set of residential parcels that did not change in size or land-use status over the time from 1990–2003. This process was repeated for each earlier decade to obtain a set of residential parcels for which to record land-cover characteristics by parcel. Note, it was assumed that each parcel was uniquely owned.

The analysis assumed that residential land-use parcels in 2003 that had residential structures going back to 1950 did not change their size or shape during that period. It is possible that at some earlier time, a 2003 residential parcel was part of a much larger parcel that was subdivided to create the one found in 2003. It may also have been the case that a parcel from 2003 was formed by the combination of several smaller parcels at an earlier date. Using photo interpretations and the interpreted structures, I removed any parcels where these issues occurred.

Residential properties were selected from among parcels identified as residential and grouped by size. However, several parcels were included in the analysis that were in the range of 20 to 26 hectares (50 to 65 acres) in size. The classification of such large parcels solely as residential begs the question at what size can we continue to describe a property as only residential in land-use type? While this paper assumes that the entire parcel is used solely for residential purposes, it is worth noting that because exurban lands are situated at the transition zone in an urban-rural gradient it becomes more likely that as lot sizes increase individual landowners may implement multiple land uses or land-management behaviors. Similar problems associated with the definition and identification of exurban sprawl exist (Ban and Ahlqvist 2009), but the range of land-use definitions used have not been discussed at scales as fine as individual residential properties. To accommodate the weakness of using larger parcels as the unit of land-use change, parcels are stratified by parcel size as described in the next section.

Analysis

The presented land-cover analysis is stratified by parcel size. A frequency distribution of the parcel data illustrated natural breaks in parcel size (ps) at 0.405 ha, 0.81 ha, 1.22 ha, 2.03 ha, 4.05 ha, and 8.1 ha[2] (Fig. 3). The natural breaks coincide with historical land policies that defined the constraints on the subdivision of large surveyed land units in the United States at areas of 64.7, 32.4, and 16.2 ha (160, 80, and 40 acres, respectively) into small farm and residential parcels. Based on these natural breaks the following bins were used (in ha): 0.000 – 0.404, 0.405–0.809, 0.810–1.219, 1.220–1.619, 1.620–2.429, 2.430–3.649, 3.650–4.459, 4.460–8.099, and 8.1+,[3] where lower bound < ps ≤ upper bound. The

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[2] 0.405 ha=1 acre
[3] Bins in acres are approximately 0–0.99, 1–1.9, 2–2.9, 3–3.9, 4–5.9, 6–8.9, 9–10.9, 11–19.9, 20+
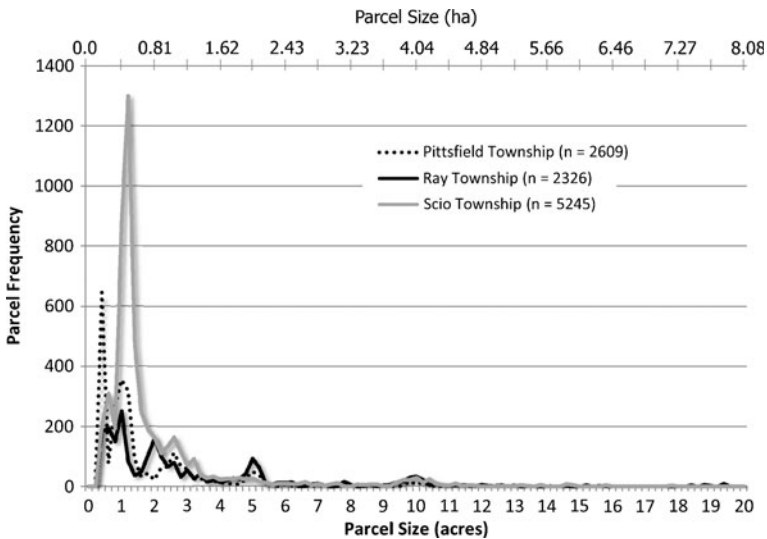
Fig. 3 Distribution of parcel sizes by township. Due to the low number of parcels >20 acres (27 parcels in total), the figure is truncated. All figure legends are listed in the vertical order that coincides with the data series order at 0.4–7.9 ha

use of other bin arrangements may lead to different conclusions; however, because exurban parcels are typically sold in whole acre amounts at 1, 2, 3, 5, 10, and sometimes 20, the selected bin categories are most representative of parcel sizes across the Midwest and arguably the majority of the United States (e.g. Northwest exurban parcel sizes are often 5, 10, or 20 acres, Nelson 1988).

In addition to parcel size, another determinant of land cover is how the land is used by the land owner. Analysis of the proportion of different land-cover types by land use provides a rough representation of land-owner behavior with respect to land cover. Because there is variability in land-owner behavior, the degree of variation in addition to the quantity of land cover types was calculated. Using a map overlay procedure to acquire land cover within each sampled parcel, the number, type, proportion, and pattern of land cover within each residential parcel was calculated, which provided a summary of the land-cover characteristics associated with residential parcels.

Ecological characteristics associated with land-cover types are determined to some degree by the spatial configuration and fragmentation of land-cover patches (Li et al. 1993). Therefore, in addition to describing land-cover proportions, I use landscape metrics that examine the edge characteristics (edge density), degree of fragmentation (number of patches and mean patch size), and shape (area weighted mean shape index) of land-cover patterns within each parcel (McGarigal et al. 2002). Two fragmentation indices were used because knowledge of both the number of patches and mean patch size are necessary to accurately describe, and replicate, land-cover patterns in a landscape. For example, a high number of patches and low mean patch size provide evidence of a high degree of fragmentation. Conversely a low number of patches and a large mean patch size provide evidence of lower fragmentation.

Edges can affect the functioning of ecosystems (Robinson et al. 2009). Edge density, calculated as the total edge of a land-cover type divided by the total area of analysis (i.e. parcel), further facilitates measurement of fragmentation. For the purposes of this study, we assume that parcels with high edge density (ED) exhibit more fragmented patterns, while

those with lower values are less fragmented. Similarly, the shape of a patch influences the amount of edge and interior patch area. In addition to ED, the area weighted mean shape index (AWMSI) is used to describe the mean patch shape within residential parcels. The AWMSI has a value of one when the patch is most compact (i.e. a circle for vector analyses or a square for raster calculations; Rempel et al. 1999; McGarigal et al. 2002). The AWMSI value increases with increasing distortion from these two geometric shapes.

To account for the variation across all parcel sizes a one-way analysis of variance (ANOVA) was performed for each landscape metrics and land cover type (Table 1). The values acquired for the parcel-based landscape metrics are bounded by zero, typically right skewed, and are non-normally distributed resulting in some variance levels (e.g. standard deviation) being larger than the mean. Because the land-cover metric outcomes are non-normally distributed, the non-parametric Mann-Whitney U statistic was used to test if the average difference among metrics at different parcel sizes is significant (Table 2). The Mann-Whitney statistic is the non-parametric equivalent to the student t-test, which assumes normality and homogeneity of variance. Because the mean and standard deviation are used by modelers to create distributions, with resampling when values are beyond specified boundaries, the mean and standard deviations are presented in Table 3 and boxplots are used to visualize results.

Results

An ANOVA was conducted to determine if significant difference in landscape metric values existed across the nine parcel-size classes for each of the reported land-cover types (Table 1). Results showed significant differences ($\alpha=0.01$) and warranted further investigation, which was done using multiple pair-wise comparisons using the Mann-Whitney U statistic as described above (Table 2). Reported values are rounded to two decimal places for presentation purposes, but no two sample means were equal, which suggests little chance of a Type I error occurring due to multiple comparisons. Based on the suggestion of Saville (1990), no corrections for multiple comparisons have been made and all mean and standard deviation values are provided to the reader (Table 3). The following sections break the results down by the distribution of land-cover in parcels and the types of metrics.

Distribution of land-cover in residential parcels

The relationship between parcel size and quantity of land cover differed by land-cover type over the range of lot sizes examined (Fig. 4). Results show the difficulty in characterizing the distribution of land-cover types in highly fragmented and human dominated environments.

Table 1 Analysis of variance f-values. All values are significant ($\alpha=0.01$) and were acquired using R for statistical computing (RDCT 2008)

	Tree cover	Maintained lawn	Impervious	Other natural area
Percent of area	48.98	125.38	763.39	203.61
Number of patches	229.91	15.81	36.68	421.65
Mean patch size	525.16	304.28	309.77	613.18
Edge density	35.16	749.25	766.90	36.76
Area weighted mean shape index	218.47	9.49	228.66	226.72

Table 2 Pair-wise comparison p-values among parcel sizes for tree cover, maintained lawn, impervious, and open natural areas. Boxed numbers show insignificant results while bold numbers show significant differences in results among parcel size classes. P-values were acquired using Mann-Whitney U tests performed with R for statistical computing (RDCT 2008)

Column bins (ha) per land-cover group: c1 = 0.405–0.809, c2 = 0.810–1.219, c3 = 1.220–1.619, c4 = 1.620–2.429, c5 = 2.430–3.649, c6 = 3.650–4.459, c7 = 4.460–8.099, c8 = 8.1+

Tree Cover

Metric	Parcel Size (ha)	c1	c2	c3	c4	c5	c6	c7	c8
Percent of Area	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.01	0.73	0.23	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.06	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.35	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.00	0.00	0.00	0.00
	2.430 – 3.649						0.17	0.00	0.00
	3.650 – 4.459							0.11	0.03
	4.460 – 8.099								0.09
Number of Patches	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.28	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.00	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.00	0.00	0.00	0.00
	2.430 – 3.649						0.60	0.00	0.00
	3.650 – 4.459							0.09	0.00
	4.460 – 8.099								0.01
Mean Patch Size	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.27	0.04	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.53	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.00	0.00	0.00	0.00
	2.430 – 3.649						0.60	0.00	0.00
	3.650 – 4.459							0.00	0.00
	4.460 – 8.099								0.09
Edge Density	0 – 0.404	0.00	0.00	0.83	0.27	0.90	0.40	0.86	0.85
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.02	0.74	0.03	0.23	0.40	
	1.220 – 1.619				0.11	0.83	0.67	0.92	
	1.620 – 2.429					0.02	0.10	0.14	
	2.430 – 3.649						0.58	0.69	
	3.650 – 4.459							0.35	
Area Weighted Mean Shape Index	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.24	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.03	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.01	0.00	0.00	0.00
	2.430 – 3.649						0.53	0.13	0.12
	3.650 – 4.459							0.01	0.04
	4.460 – 8.099								0.32

Maintained Lawn

Metric	Parcel Size (ha)	c1	c2	c3	c4	c5	c6	c7	c8
Percent of Area	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.57	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.00	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.00	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.00	0.00	0.00	0.00
	2.430 – 3.649						0.18	0.00	0.00
	3.650 – 4.459							0.00	0.00
	4.460 – 8.099								0.07
Number of Patches	0 – 0.404	0.02	0.04	0.00	0.00	0.68	0.00	0.00	0.02
	0.405 – 0.809		0.76	0.02	0.00	0.76	0.00	0.00	0.04
	0.810 – 1.219			0.04	0.00	0.71	0.00	0.00	0.05
	1.220 – 1.619				0.12	0.11	0.03	0.15	0.18
	1.620 – 2.429					0.00	0.27	0.43	0.32
	2.430 – 3.649						0.02	0.06	0.24
	3.650 – 4.459							0.94	0.55
	4.460 – 8.099								0.53
Mean Patch Size	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.06
	0.405 – 0.809		0.00	0.00	0.00	0.04	0.02	0.22	0.19
	0.810 – 1.219			0.68	0.61	0.79	0.02	0.07	
	1.220 – 1.619				0.98	0.95	0.01	0.05	
	1.620 – 2.429					0.87	0.05	0.11	
	2.430 – 3.649						0.02	0.06	
	3.650 – 4.459							0.57	
Edge Density	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.00	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.00	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.00	0.00	0.00	0.00
	2.430 – 3.649						0.00	0.00	0.00
	3.650 – 4.459							0.00	0.00
	4.460 – 8.099								0.03
Area Weighted Mean Shape Index	0 – 0.404	0.48	0.00	0.00	0.00	0.00	0.00	0.01	0.04
	0.405 – 0.809		0.36	0.00	0.00	0.56	0.00	0.03	0.04
	0.810 – 1.219			0.00	0.02	0.82	0.13	0.26	
	1.220 – 1.619				0.82	0.00	0.53	0.95	
	1.620 – 2.429					0.01	0.72	0.04	
	2.430 – 3.649						0.14	0.22	
	3.650 – 4.459							0.78	

Impervious

Metric	Parcel Size (ha)	c1	c2	c3	c4	c5	c6	c7	c8
Percent of Area	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.00	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.00	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.00	0.00	0.00	0.00
	2.430 – 3.649						0.00	0.00	0.00
	3.650 – 4.459							0.00	0.00
	4.460 – 8.099								0.00
Number of Patches	0 – 0.404	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.05	0.00	0.98	0.01	0.94	0.15	
	0.810 – 1.219			0.12	0.23	0.57	0.25	0.39	
	1.220 – 1.619				0.01	0.37	0.03	0.79	
	1.620 – 2.429					0.10	0.95	0.21	
	2.430 – 3.649						0.14	0.50	
	3.650 – 4.459							0.22	
	4.460 – 8.099								0.10
Mean Patch Size	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.03
	0.810 – 1.219			0.03	0.02	0.00	0.00	0.00	0.27
	1.220 – 1.619				0.99	0.02	0.00	0.00	0.58
	1.620 – 2.429					0.02	0.00	0.00	0.59
	2.430 – 3.649						0.33	0.01	0.92
	3.650 – 4.459							0.08	0.65
	4.460 – 8.099								0.29
Edge Density	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.00	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.00	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.00	0.00	0.00	0.00
	2.430 – 3.649						0.00	0.00	0.00
	3.650 – 4.459							0.00	0.00
	4.460 – 8.099								0.03
Area Weighted Mean Shape Index	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.05
	0.810 – 1.219			0.03	0.00	0.00	0.00	0.00	0.11
	1.220 – 1.619				0.07	0.00	0.00	0.00	0.11
	1.620 – 2.429					0.09	0.00	0.00	0.43
	2.430 – 3.649						0.05	0.02	0.82
	3.650 – 4.459							0.65	

Other Natural Areas

Metric	Parcel Size (ha)	c1	c2	c3	c4	c5	c6	c7	c8
Percent of Area	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.01	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.00	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.30	0.00	0.00	0.00
	2.430 – 3.649						0.14	0.00	0.00
	3.650 – 4.459							0.00	0.01
	4.460 – 8.099								0.48
Number of Patches	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.18	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.00	0.00	0.00	0.00	0.00
	1.620 – 2.429					0.00	0.00	0.00	0.00
	2.430 – 3.649						0.10	0.00	0.00
	3.650 – 4.459							0.00	0.00
	4.460 – 8.099								0.10
Mean Patch Size	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.810 – 1.219			0.00	0.00	0.00	0.00	0.00	0.03
	1.220 – 1.619				0.00	0.00	0.00	0.03	0.00
	1.620 – 2.429					0.03	0.00	0.00	
	2.430 – 3.649						0.01	0.00	0.00
	3.650 – 4.459							0.00	0.00
	4.460 – 8.099								0.04
Edge Density	0 – 0.404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	0.405 – 0.809		0.00	0.00	0.00	0.00	0.00	0.00	0.01
	0.810 – 1.219			0.13	0.00	0.00	0.00	0.00	0.00
	1.220 – 1.619				0.03	0.03	0.01	0.00	0.07
	1.620 – 2.429					0.80	0.95	0.03	0.53
	2.430 – 3.649						0.88	0.02	0.39
	3.650 – 4.459							0.01	0.33
	4.460 – 8.099								0.57
Area Weighted Mean Shape Index	0 – 0.404	0.59	0.06	0.01	0.00	0.00	0.00	0.00	0.01
	0.405 – 0.809		0.01	0.00	0.00	0.00	0.00	0.00	0.01
	0.810 – 1.219			0.12	0.00	0.00	0.00	0.00	0.07
	1.220 – 1.619				0.32	0.20	0.53	0.01	0.16
	1.620 – 2.429					0.50	0.80	0.02	0.23
	2.430 – 3.649						0.44	0.19	0.37
	3.650 – 4.459							0.03	0.22
	4.460 – 8.099								0.77

Parcel Size (acres): 1–1.99, 2–2.99, 3–3.99, 4–5.99, 6–8.99, 9–10.99, 11–19.99, 20+

Values are bounded by zero and the distributions are typically right skewed, but they also cover the entire range from 0–100% of the parcel area for tree cover, impervious, and in some cases they come close to 100% for maintained lawn and other natural areas. However, Fig. 4 shows that the proportion of the parcel area in tree cover and other natural area increases with increasing parcel size. In contrast, the proportion of the parcel in maintained lawn and impervious decreases with increasing parcel size (Table 2, Fig. 4).

Variance in the proportion of parcels in impervious was small relative to other land cover types, suggesting that housing footprints and housing distance from roadways are not likely to change substantially relative to parcel size. Nearly all land-cover proportions were significantly different ($\alpha = 0.05$, Table 1) among parcel sizes. Proportions of land-cover that were not significant between parcels sizes were typically in adjacent bins.

Land-cover patterns

The distribution of the number of land-cover patches by parcel size shows that impervious and maintained lawn typically formed fewer than two patches regardless of parcel size (Table 2). Impervious had very little variation in patch number, which is due to most residential properties consisting of only a driveway leading to a home. While, in some cases there may be overlaying errors with adjacent street networks or larger properties may have additional structural features (e.g. sheds), there was typically little difference in the number of impervious patches among parcels sized greater than 0.810 ha (2.99 acres, Table 1).

A consistent level in the number of patches of maintained lawn was found such that 75% of the parcels less than 8.1 ha (20 acres) in size had less than two patches. While the number of patches significantly differed at small parcel sizes (e.g. 0–1.219 ha) they were not significantly different among larger parcel sizes. The number of patches classified as

Table 3 Mean and standard deviation values for percent parcel area, number of patches per parcel, mean patch size (ha), edge density, and area weighted mean shape index (AWMSI) for each land cover type by parcel size

| Percent size (ha)		0–0.404		0.405–0.809		0.810–1.219		1.220–1.619		1.620–2.429		2.430–3.649		3.650–4.459		4.460–8.099		8.1+	
Percent size (acres)		0–0.99		1–1.99		2–2.99		3–3.99		4–5.99		6–8.99		9–10.99		11–19.99		20+	
		n=3537		n=3481		n=1324		n=433		n=666		n=218		n=338		n=156		n=27	
		mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Tree cover	Percent parcel area	19.62	26.00	27.91	28.96	29.64	29.52	26.23	28.78	25.65	29.38	35.80	31.85	38.59	29.22	42.62	25.75	51.12	25.08
	Number of patches	1.00	1.07	1.48	1.23	1.87	1.45	1.97	1.56	2.36	1.80	2.82	2.12	2.96	2.30	3.22	2.24	4.67	3.22
	Mean patch size (ha)	0.04	0.06	0.11	0.15	0.21	0.27	0.25	0.37	0.31	0.50	0.63	0.84	0.90	1.07	1.21	1.33	2.46	3.27
	Edge density	0.04	0.05	0.05	0.03	0.04	0.03	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.01	0.03	0.01	0.03	0.01
	AWMSI	0.69	0.47	1.82	0.56	1.94	0.61	1.99	0.61	2.12	0.77	2.25	0.72	2.21	0.74	2.36	0.73	2.56	0.92
Maintained lawn	Percent parcel area	56.41	27.81	51.64	31.24	45.65	32.20	44.66	32.01	36.32	31.11	27.89	28.72	23.26	25.60	15.30	19.01	7.87	12.16
	Number of patches	1.32	0.79	1.38	0.89	1.38	0.89	1.51	1.03	1.57	0.98	1.37	0.96	1.71	1.26	1.70	1.42	1.81	1.21
	Mean patch size (ha)	0.12	0.10	0.22	0.17	0.37	0.32	0.47	0.43	0.53	0.57	0.64	0.78	0.68	0.94	0.49	0.69	0.36	0.51
	Edge density	0.11	0.05	0.07	0.03	0.05	0.03	0.04	0.02	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
	AWMSI	1.85	0.36	1.86	0.39	1.94	0.46	1.98	0.62	2.11	0.60	2.08	0.55	1.96	0.49	2.05	0.55	2.10	0.57
Impervious	Percent parcel area	19.54	9.85	12.51	5.83	8.49	4.67	7.11	4.55	5.36	3.31	3.74	2.26	3.05	1.87	2.53	1.83	1.40	1.03
	Number of patches	1.09	0.51	1.10	0.50	1.23	0.64	1.32	0.75	1.40	0.91	1.23	0.70	1.32	0.76	1.23	0.65	1.56	1.22
	Mean patch size (ha)	0.04	0.02	0.06	0.03	0.07	0.05	0.09	0.06	0.09	0.06	0.09	0.06	0.10	0.07	0.12	0.10	0.11	0.11
	Edge density	0.06	0.03	0.03	0.02	0.03	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
	AWMSI	1.70	0.44	1.94	0.57	2.31	0.88	2.41	1.12	2.47	0.85	2.64	1.02	2.78	1.00	3.00	1.14	2.95	1.41
Other natural areas	Percent parcel area	3.82	12.99	6.78	16.75	13.21	21.72	18.18	26.26	24.18	29.17	23.46	27.45	25.82	27.10	33.15	24.46	36.37	23.69
	Number of patches	0.21	0.47	0.39	0.64	0.73	0.83	0.81	0.92	0.99	1.02	1.51	1.45	1.67	1.44	2.31	1.73	2.96	2.05
	Mean patch size (ha)	0.01	0.04	0.04	0.09	0.11	0.20	0.22	0.35	0.40	0.54	0.50	0.73	0.74	0.98	1.15	1.25	1.95	2.00
	Edge density	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.01
	AWMSI	1.93	0.85	1.87	0.82	1.94	0.78	2.11	1.05	2.11	1.09	2.06	0.69	2.06	0.99	2.12	0.67	2.21	0.76
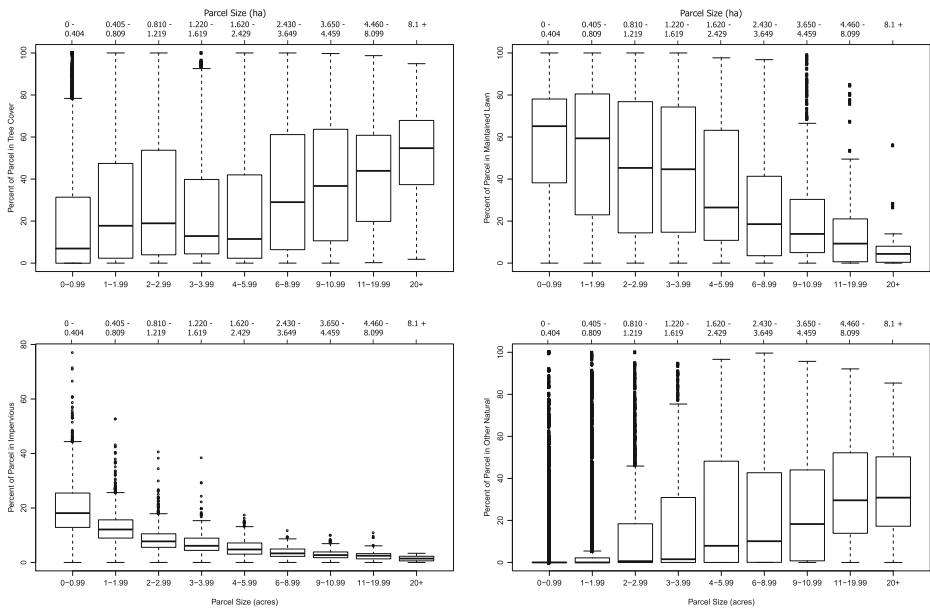
Fig. 4 Box plots of the percent proportion of parcel for tree cover, maintained lawn, impervious, and open natural area by parcel size class

open natural area increased slightly with parcel size, but typically remained less than three in total. The variation in the number of open natural area patches increased with increasing parcel size. Variation in the number of tree cover patches was high regardless of parcel size, however, tree cover, like open natural areas, experienced an increase in the number of patches with increasing parcel size. The number of tree cover patches increased from (on average) fewer than 2 for small parcels (0.000–0.809 ha) to 4 or more for parcels greater than 8.1 ha. All but 3 of the pair-wise comparisons among parcel sizes showed significant differences for both tree cover and other natural areas (Table 1).

All land-cover types (except impervious) experienced an increase in mean patch size (MPS) with increasing parcel size (Fig. 5). The mean patch size of tree cover and open natural areas increased exponentially with increasing parcel size ($R^2=0.98$ and $R^2=0.91$, respectively), while the MPS of maintained lawn and impervious areas increased initially then decreased at larger sizes. Variation in MPS was highest for maintained lawn and impervious land-cover types. Open natural areas and tree cover MPS were significantly different among parcel sizes (Table 1).

Edge density (ED) decreased with increasing parcel size for most land-cover types (Fig. 6). Tree cover experienced the highest edge density values, signaling that tree cover was more fragmented than the other land-cover types. While the ED of tree cover decreased strongly with increasing parcel size up to 1.620–2.429 ha (4–6 acre) parcels, further increases in parcel size had less of an effect. The ED of open natural areas initially increased slightly with larger parcel sizes, due to an increase in the number of patches of that land-cover type. While it is unusual to describe the ED of maintained lawn and impervious surfaces for ecological purposes, which both decreased significantly with increasing parcel size (Table 1, Fig. 6), the metric provides a description of the shape of these land-cover types within parcels that may be referenced and used in subsequent modeling analyses. With the reduction in ED with increasing parcel size for maintained
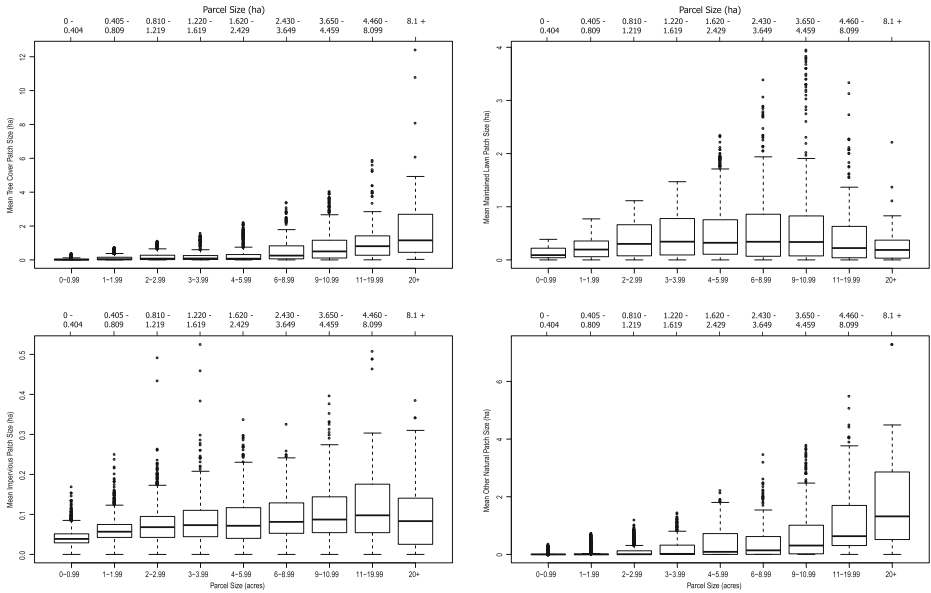
Fig. 5 Box plots of mean patch size of tree cover, maintained lawn, impervious, and open natural area by parcel size

lawn and impervious surfaces was a corresponding reduction in the variation in ED values. All pair-wise comparisons among parcel sizes were significant for maintained lawn and
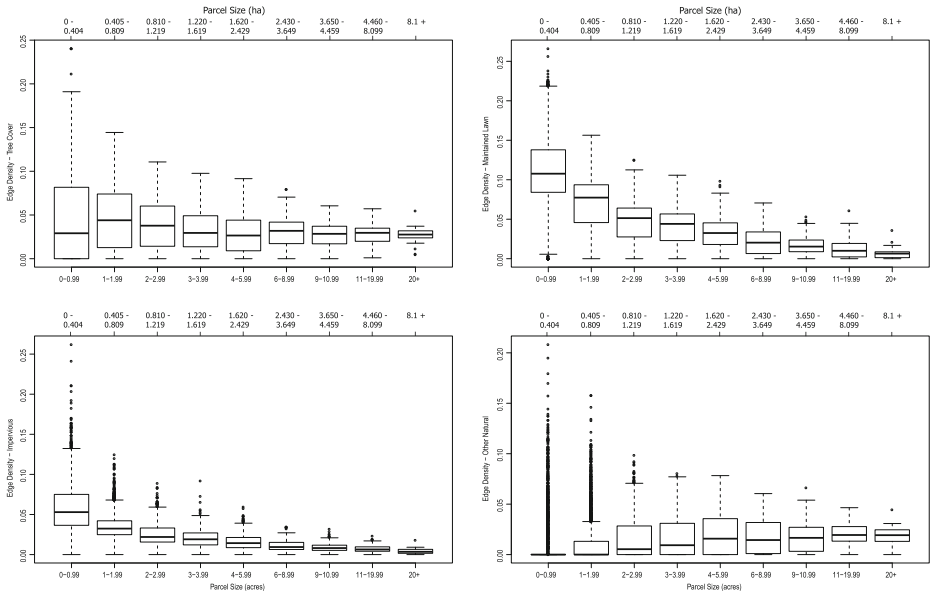

Fig. 6 Box plots of edge density of tree cover, maintained lawn, impervious, and open natural area by parcel size

impervious surfaces, while differences among ED were not significant at larger parcels sizes for tree cover and other natural areas.

All land-cover types became less compact (i.e. increasing area weighted mean shape index—AWMSI) with increasing parcel size. Open natural areas and maintained lawn both changed little, had the lowest amount of variation in AWMSI values, and held the most compact shape with increasing parcel size. While tree cover had a high degree of variation in AWMSI values across all parcel sizes, nearly all AWMSI values were significantly different among all parcel sizes (Table 1). For most parcel sizes, impervious surface had the highest deviation, which also increased with increasing parcel size. The obvious result of impervious surface AWMSI values is due to the rectangular nature of long narrow driveways that extend with increasing parcel size but add little area in proportion to the overall parcel area.

Discussion and conclusions

The paper describes new data analyzed using five landscape metrics to determine if the quantity and fragmentation of land-cover types differ among a range of exurban parcel sizes in Southeastern Michigan. While specific outcomes by land-cover type and landscape metric are unique, the aforementioned results demonstrate that 80% of the 720 pair-wise comparisons among parcel-size classes yield significant differences in landscape metric values (Table 1). The degree to which the quantity and fragmentation of land-cover types differ was greatest at smaller parcel sizes. Ninety-one percent of the 420 pair-wise metric comparisons among smaller parcels (i.e. <4.46 ha) were significant. In contrast, only 52% of the 120 pair-wise comparisons among parcels ≥2.43 ha showed significant differences. These tabulations (Table 1) provide evidence that the differences in land-cover proportions and patterns tend to decrease with increasing parcel size.

With respect to tree cover, the proportion of the parcel in tree cover increased as did the number and size of tree-cover patches (on average) along with the amount of tree-cover edge with increasing parcel size. Collectively these patterns create less confined or compact tree-cover patches within residential land-use parcels as evidenced in higher AWMSI values. While these results may not be generalized to other geographic locations without additional research in those areas, they do provide a descriptive context for exurban residential land-cover outcomes in the Midwest, US. The next step to realize the full potential of these data would be to combine them with values and relationships between land-cover and ecosystem function in peer-reviewed literature (e.g. albedo, Oke 1987; carbon storage, Robinson et al. 2009) to estimate simple ecosystem function values in exurban landscapes. Alternatively, these land-cover data could be used as input into ecosystem process models that estimate corresponding ecosystem function outputs based on land cover, meteorological, and site characteristics (e.g. Robinson et al. 2010). Either approach may provide insight into the provision of ecosystem services in exurban areas.

Results for impervious surface differed in important ways from the tree-cover results. Specifically, impervious surface area increased little with increasing lot size so that the proportion of the parcel in impervious decreased, the pattern remained relatively consistent among lot sizes, and the shape of impervious patches were not compact, on average having a larger ratio of edge to area than other land-cover types. These results provide needed data on the extent of impervious surfaces in exurban residential properties that could be used to evaluate the possible effects of policies aimed at reducing impervious surface and surface-water runoff (e.g. incentives for using porous paving). Further research describing target

values for impervious surfaces at varying parcel sizes may provide additional use to policy makers. While research within ecological boundaries (e.g. watershed) denote broadly that declines in ecosystem health occur when 10% of the watershed is in impervious cover and at 30% impervious ecosystem health is severely impaired (Stone 2004), it is not known how these results transfer to the legal property boundaries and functioning of ecosystems within residential parcels.

If one was to directly follow the aforementioned impervious surface guidelines, then the presented data would suggest that a focus on reducing impervious surface and surface-water runoff on small parcels is important since small parcels are more likely to exceed the 10% threshold, but an approach such as this clearly does not contextualize small lots within the larger landscape matrix. Lastly, this research describes land cover within residential parcels and not land cover beyond the parcel boundary. Therefore, while the impervious surface results corroborate other research (e.g. Stone 2004), the presented work does not include road frontage or associated road networks, both of which contribute to the negative ecological effects of exurban impervious surfaces.

The proportions of parcels in maintained lawn decreased substantially as parcel size increased. One may expect this to be the case since lawn maintenance can be both capital (e.g. irrigation and fertilizer; UW 2001; Robbins et al. 2001) and labor intensive (Dannenberg et al. 1989; Bittman et al. 2004). The measurement of the distribution and variance of maintained lawn are particularly relevant since it is estimated that maintained lawn now occupies more land area in the United States than major food crops such as barley, cotton, and rice (Robbins and Birkenholtz 2003). Understanding the patterns of maintained lawn can shed light on the positive and negative ecological effects of lawn in residential areas and with the reported data one can model the ecological effects of lawn using the same approach as Milesi et al. (2005).

Given the context set by Theobald (2005), that the rate of exurban growth is 25% greater than population growth, and Ellis and Ramankutty (2008), who demonstrated that anthropogenic biomes cover more than three quarters of the Earth's ice-free land, additional empirical knowledge of anthropogenic landscapes at high resolution is needed. The presented analysis was conducted at the parcel level because little if any literature or empirical work exists that describes land-cover patterns within exurban residential land parcels. The value of linking human structures (e.g. parcels) with biophysical features (e.g. land cover) within this paper is that it provides some insight into where (what types of parcels) and how much (the distribution and pattern) land-cover types exist within the exurban residential landscape. While the results do not provide direct insight into other land-use science challenges (Rindfuss et al. 2004) such as the why and how these land-cover outcomes came to be, the data and presented results demonstrate that a key indicator in the human system (i.e. parcel size and changes in parcel size), which is driven by socio-economic processes as well as policy, has direct implications for indicators in the natural system. It is within this context of coupled natural-human systems of land use that the presented data, and the link between parcel size and land cover, may aid coupled models of land use, land management, and ecosystem function to address the ecosystem impacts of land-use and land-cover change in highly fragmented and human dominated landscapes. The presented data are currently being used to empirically inform distributions of land-cover types created by virtual residential agents representing real-world actors in agent-based models of residential settlement and development (e.g. Brown et al. 2008; Robinson and Brown 2009, Robinson et al. 2010).

The presented analysis focused on the parcel as the level at which land-cover decisions and outcomes are made; however, one must acknowledge that the biophysical world is not

always constrained by human systems. Therefore the descriptions of land cover types within groups of parcels, subdivisions, townships, and counties may differ slightly. Furthermore, land-cover types often do not directly map to ecological zones, whereby an ecological zone may account for a specific combination of plant functional types and/or homogeneity in ecosystem process rather than the observable land-cover type(s). For example, a closed canopy can hide many underlying human and natural features such that a parcel is interpreted as 100% tree cover. The issue of ecological-zone (e.g. tree cover with maintained lawn beneath, or savanna) versus land-cover classifications is difficult to untangle and adequately account for when using remotely sensed products.

Lastly, it should be noted that if any of the aforementioned results suggest to the reader that it may be possible to obtain ecologically beneficial outcomes through increased parcel size, the reader must evaluate these benefits against the human activities and behaviors associated with larger parcel size developments that consume resources and influence human well-being such as increases in vehicle miles travelled, energy consumption and air pollution, and greater infrastructure and public service costs.

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