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RESEARCH ARTICLE

The impact of urban sprawl on forest landscapes in Southeast Michigan, 1985–2015

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Abstract
Context Urban sprawl typically consists of low-density urban development dominated by single-family housing and automobile-oriented land use patterns. Sprawl impacts landscape structure and composition, especially along the urban periphery. However, few studies have simultaneously examined sprawl at the building level and by building type (e.g. single family, multi-family) and its relationship to forest landscapes within an urbanizing region.
Objectives (1) To map and quantify 30-years of sprawl and assess its impacts on forest landscapes in southeast Michigan, a seven-county region centered on the City of Detroit (2) to investigate how different building types, densities, and distances affect forest structure.
Methods We used the Random Forests algorithm to analyze high resolution remote-sensing imagery and computed three landscape metrics of forest fragmentation and cohesion, incorporating data on built types and densities. Finally, we investigated the relationship between single-family housing sprawl and forest landscape functionality.
Results The built-up expansion was correlated with an increase in overall tree canopy in the region. However, multilevel analysis revealed these same forest landscapes became less cohesive and more fragmented over time as a result of urban sprawl. Additional correlation tests revealed an increase in patch density and decrease in effective mesh size (meff) and patch cohesion in areas proximate to low-density single-family housing.
Conclusions The analysis documents how urban sprawl negatively impacts forested landscapes. Single-family housing in particular had a detrimental impact on the functionality of adjacent forested landscapes. High thematic resolution enables policy-makers and planners to identify specific policies and interventions to increase landscape functionality.

Keywords Forests · Fragmentation · Urban sprawl · Single-family housing · Landscape metrics · Remote sensing

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Introduction

An estimated 80% of the US population currently resides in urban areas (United Nations 2018). Since World War II, low-density, automobile-oriented forms of development have typified growth of American cities and surrounding regions. Lifestyle preferences, expanding auto ownership, freeway construction, and federal policies promoting single-family home ownership are factors shaping this trajectory (Nelson 2013). This type of development, often composed of car-dependent, low-density, single-family housing, has expanded into former forests, farmland, and other categories of rural land use—a phenomenon dubbed "urban sprawl." Although the concept has been operationalized in different ways, we define urban sprawl as development composed primarily of low-density, single-family housing, a common dimension within multiple definitions (Galster et al. 2001; Peiser 2001; Jaeger et al. 2010).

Simultaneous with the phenomenon of urban sprawl, forests across metropolitan landscapes have undergone their own evolution. Forest fragmentation is a form of habitat degradation that has been well documented in the literature (Andren 1994; Hanski et al. 2013; Haddad et al. 2015). Studies have documented the impact of fragmentation on plant and animal species distribution (e.g., Crooks et al. 2017), populations (e.g., Hepinstall et al. 2008), and genetic diversity (e.g., Gibbs 2001). Numerous approaches exist to analyze fragmentation patterns, but they have limitations if used in isolation (McGarigal et al. 2002). Critics of pattern-based indices cite their lack of ecological meaning and limited relevance for audiences beyond those in ecology (Costanza et al. 2019). Fragmentation is complex, and depending on the magnitude, impacts will vary by ecosystem type and species (e.g., Debinski and Holt 2000; Ewers and Didham 2006; Thornton et al. 2011; Ibáñez et al. 2014). Species response to habitat fragmentation is also influenced by their movement ability (Tischendorf and Fahrig 2000) and the spatial configuration of the landscape. Moreover, one significant aspect of remnant-fragmented forest patches and habitat quality is time, since the effects of fragmentation may intensify for decades after urbanization (Brooks et al. 1999; Hansen et al. 2005).

Sprawl has also been shown to fragment habitat, especially forests (Marzluff et al. 2001; Irwin and Bockstael 2007; Radeloff et al. 2010). Numerous studies show the correlation between housing development and decline in species richness (Hansen et al. 2002; Pidgeon et al. 2007; Piano et al. 2019), vegetation structure (Borgmann and Rodewald 2004), habitat quality (Theobald et al. 1997; McKinney 2002), and ecological functionality and connectivity (Dupras et al. 2016). Nonetheless, these more specific studies investigate particular relationships rather than the evolution of landscapes across an entire region. It is therefore particularly useful to create baseline knowledge about landscape changes over time and at scales that go beyond geographically-limited case studies, and to link the findings with universal processes such as fragmentation and its drivers.

Within this regional context, there has been renewed interest in understanding urban tree coverage. Many cities have embarked on ambitious tree-planting initiatives to boost quality of life, address air and water pollution, and increase adaptive capacity to climate change. In addition, tree canopies may be maturing in older neighborhoods or expanding in urban neighborhoods where vacant land is prevalent. Standard national land cover datasets typically categorize entire metropolitan areas as urban, making it impossible for researchers to understand fine-grain forest habitats located within urban areas. A further problem is that different types of buildings as well as different building densities have different ecological effects. For the US, among others, Robinson et al. (2005) documented 25 years of land cover change in Seattle, Washington, and found single-family housing expansion to be the primary cause for sharp decreases in core forest areas, which, in turn, increased fragmentation. Kim and Zhou (2012) found that single-family housing contributes to a more fragmented landscape in Morgantown, West Virginia. Lee et al. (2017) detected changes in single-family neighborhoods in Los Angeles, California, and found sharp decreases of forests and green space in those areas. In southeast Michigan, only a few studies of a similar nature have been carried out (Brown et al. 2008; An et al. 2011; Pijanowski and Robinson 2011; Wilson and Brown 2015).

What sets this study apart is that we measure urban sprawl at the building and road level on a regional scale (comprising seven counties ~ 12,000 km^2) while accounting for specific types of buildings as well as building densities. Analyses at the individual building level and per specific type of building is the ideal unit to actually inform and to steer policy-makers and urban planners (Galster et al. 2001). Second, we use very high-resolution (1 m) ortho-photos to map and quantify land cover changes. This enables us to map these changes at the scale of the individual building (as well as the broader configurations it is part of), as well as smaller patches of street trees. Studies at coarser resolutions (> 10 m) tend to underestimate patterns occurring in smaller patches (Gounaridis et al. 2019; Wickham and Riitters 2019), including low-density residential development in non-urban areas (Irwin and Bockstael 2007). One benefit of more detailed analysis is that it fosters the crafting of planning and policy measures at various jurisdictional levels. Third, we use this detailed change analysis to calculate a series of landscape metrics of the spatial composition and configuration of forests (Gustafson 1998; McGarigal et al. 2002). Landscape metrics are often calculated as a single numerical value for the entire landscape or a fraction of it, but for many applications, this is less informative. In addition, studies often calculate metrics at the administrative boundary scale, but this practice is prone to producing biased estimates, since patches do not coincide with boundaries of administrative and planning units and may well extend beyond them. To overcome this issue, we create spatially-explicit illustrations in tandem with statistics at multiple levels. These landscape metrics are far more meaningful when visualized in a spatially explicit way, which is especially useful for guiding decision-makers as they decide which measurements to prioritize and which areas are most problematic and should be targeted.

Within this stream of research, this paper contributes new findings on the relationship between forests and urban sprawl. The objectives of this paper are threefold: (1) to document and quantify changes in the built-up land and the tree canopy in southeast Michigan over a 30-year period (1985–2015); (2) to detect and quantify urban sprawl and changes in density through analysis at the individual building level; (3) to spatially illustrate changes in structure, composition, and functionality of forests and street trees as a result of development.

Our results indicate that built-up land expanded significantly during the 1985–2015 period, especially at the urban periphery of Detroit, and that the vast majority of this expansion involved low-density, single-family housing. Along with this expansion, we also observe an increase in forest coverage. However, our analysis of landscape metrics reveals that these forests are also more fragmented and less cohesive in areas proximate to urban sprawl. We also show that low-density, single-family housing significantly shaped the landscape over the years. We argue that nuanced views on specific types of buildings allow for comprehensive understanding of patterns, processes, and phenomena, as well as amplifying evidence of associations with specific policies, choices, and preferences. Additionally, given that sprawl does not equal expansion and that sprawl is a complex, multidimensional process, it is meaningful to spatially demarcate its various aspects.

Overview of the study region

This study site is in southeast Michigan, USA (Fig. 1), and consists of seven counties. In addition to the City of Detroit and its suburbs, the region contains a large exurban area characterized by low-density residential development and agricultural land uses. Our case study region encompasses the Detroit metropolitan area, which has witnessed a steady exodus from the urban core to the periphery. As such, it typifies the decline of center cities and the flight to suburbs that so many metropolitan regions in the US have undergone (Alig et al. 2004; Auch et al. 2004). In addition to the urban core of Detroit, important urban centers in this region include Monroe (Monroe County), Pontiac (Oakland County), Ann Arbor (Washtenaw County), and Sarnia (St. Clair County).

Home to the US auto industry, Detroit grew rapidly in the twentieth century, experiencing rapid suburbanization beginning in the postwar period. This is due to a well-documented constellation of factors: freeway construction, dispersion of manufacturing facilities and employment, public policies subsidizing suburban homes, urban disinvestment, and racism against African Americans. As a result of this ongoing process, despite slow overall population growth in recent years, the City of Detroit has continued to experience population declines while land development continues at the urban fringe. After decades of economic decline and restructuring (Allard et al. 2017; Camprag 2018), some areas of Detroit are experiencing a renewal (Reese et al. 2017), although the

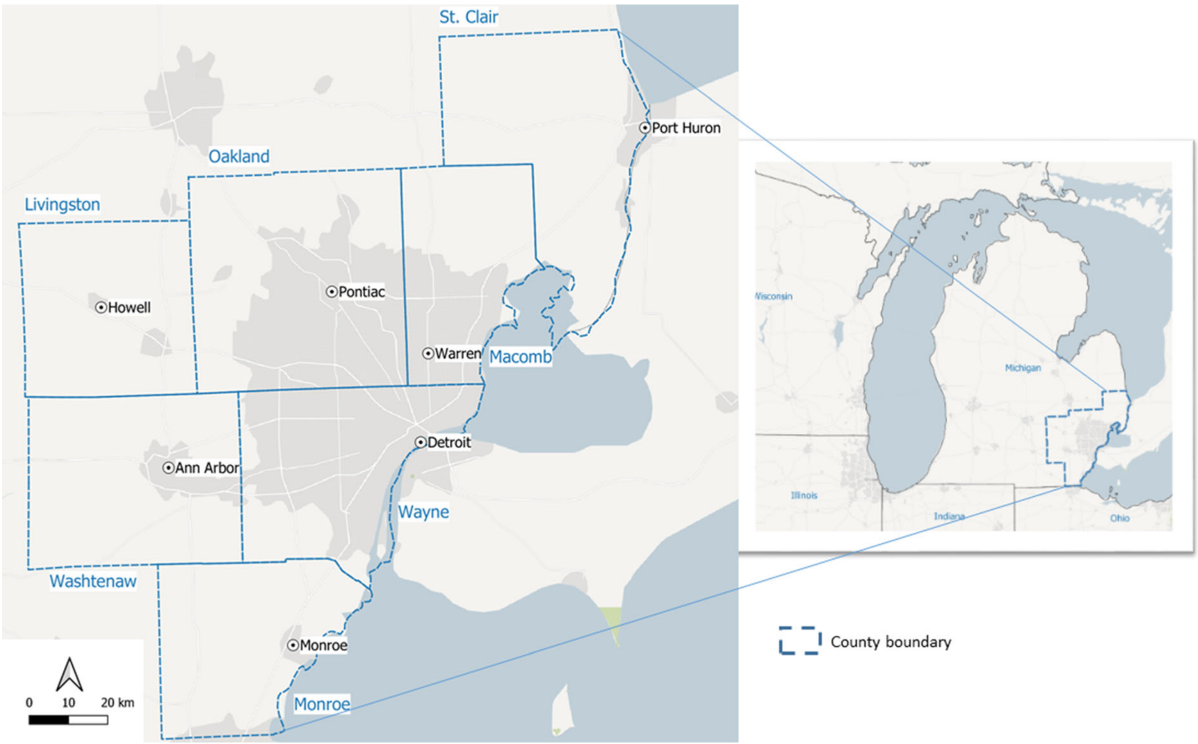


Fig. 1 Seven county study area in southeast Michigan, USA

population continues to decline (Endsley et al. 2018; Sampson et al. 2019) and the city continues to suffer from high land vacancy (Wilson and Brown 2015).

According to the Köppen–Geiger climate classification (Peel et al. 2007) the State of Michigan has a continental climate with warm summers and humid continental winters (Köppen codes: *Dfb;Dfa*). The forests are predominantly temperate deciduous, with the most common species being maples, ash trees, oaks and birch. Throughout the state, there are numerous native plant and animal species, including birds, mammals, amphibians, and reptiles. The US Fish and Wildlife Service lists more than 25 of those native species as endangered or threatened, and many of these are forest species that require unimpaired habitat, meaning their remaining populations can be impacted by land cover changes (US Fish and Wildlife Service 2018).

Methods

Our analysis approach proceeded in four steps, as summarized in Fig. 2. First, we used very high-resolution (1 m) ortho-photos for 1985, 2005, and 2015 along with the Random Forests modeling framework to map and quantify land cover changes over a 30-year period, specifically focusing on changes in buildings and roads (referred to hereafter as built-up) and forests along with tree patches within the urban area (referred to hereafter as forests). Second, we computed and spatially illustrated changes in forest patch density, patch cohesion, and effective mesh size (meff) to delineate spatial patterns across urban, rural, and natural gradients. Third, the classified built-up areas were further analyzed using data on building footprints and land use to classify building types and density. Fourth, we investigated the relationship between built-up areas and the functionality of forests through the landscape metrics and the proximity to sprawling buildings.

Data processing and landscape change model implementation

Very high-resolution (1 m) ortho-imagery for three periods (1985, 2005, 2015) was provided by the Southeast Michigan Council of Governments

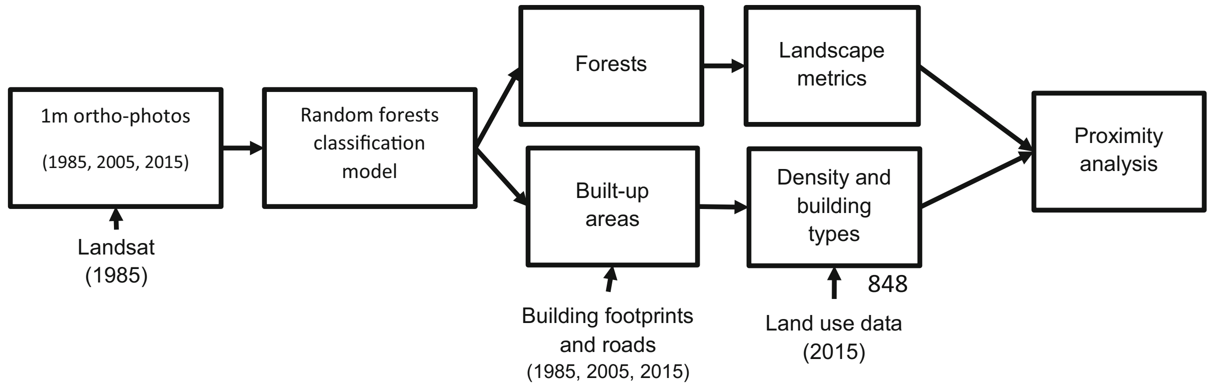


Fig. 2 Overview of methodological workflow of the study

(SEMCOG) (Table 1 in Supplemental Material (SM)). The 2015 and 2005 imagery had a spectral resolution of three bands (R:G:B), while the 1985 image had a single band. For each year, we applied histogram matching to normalize the images and to balance the colors before mosaicking. The images were then mosaicked and processed at the county level for computational convenience. To overcome the limited spectral resolution of the 1985 image, we fused it with Landsat data (Table 1 in SM), using the pan-sharpening HPF-resolution merge function (Chavez et al. 1991). Since Landsat imagery was not available during 1985, we acquired data from the Landsat Thematic Mapper (TM) Mosaics dataset which was the closest year available (1986). Prior to pan sharpening, we clipped and mosaicked the Landsat images at the county scale and used the dark-object subtraction (DOS) method to radiometrically normalize them (Chavez 1996). Fusion techniques enable the use of heterogenous data (Vrabel 1996) and thus, through this process, we were able to generate a multispectral 1985 image with very high spatial resolution and three bands.

To detect forested areas throughout the region, we used the non-parametric Random Forests (RF) algorithm (Breiman 2001). RF is able to incorporate inputs from multiple sources (Gounaridis and Koukoulas 2016) and is relatively insensitive to outliers and noise (Gislason et al. 2006). It also performs well when dealing with heterogeneous classes, such as urban areas and forests (Gounaridis et al. 2016, 2018) and can handle large datasets, being computationally faster than other classifiers (Belgiu and Dragut 2016). Before processing, lakes and other water bodies were masked out by using a lakes and rivers layer provided by SEMCOG (Table 1 in SM). Training samples were collected with visual inspection for each year (1985, 2005, 2015) against the corresponding ortho-imagery. Two land cover categories were identified and assigned different values ("forest" and "non-forest"). For each year, approximately equal-sized training samples were collected for each category, resulting in an average of 5000 samples per category and per county. During the training process, special attention was paid to take only clear samples (with no fuzziness) for each category; thus, we eliminated or relocated any samples near the boundaries of adjacent categories (Gounaridis et al. 2016). As a last step, to minimize any sources of confusion to the model, we plotted the samples per category along with the spectral values from the three bands and removed outliers from the training.

We ran 21 models (years 1985, 2005, 2015 for seven counties) using the *RandomForest* package in R (Liaw and Wiener 2002). The three spectral bands available for each image served as predictors. The number of decision trees was set to 700 for each run, while the value of predictor variables for each tree split was set to be three. Since the scope of our analysis was not to capture isolated trees but rather forests and smaller patches of urban trees, the final step was to eliminate all isolated patches in the resulting layers because isolated patches are often noise and misclassified pixels. To do this, we applied a moving window technique centered to only isolated patches that were less than 5 pixels in size and replaced their value with the mode class value of the window (Gounaridis et al. 2016, 2018). Accuracy of results was assessed independently from the training process by allocating 500 random samples per year and per county (3500 per year). Values denoting “forest” or “non-forest” were assigned after visually interpreting each point against the corresponding image. To assess the accuracy of the resulting maps, we collected the land cover value for the location of each validation sample and compared the agreement. Overall accuracy for 1985 is 91.05%, 92.1% for 2005, and 92.71% for 2015 (Table 2 in SM).

To detect built-up areas, we used the building footprint data per county (Table 1 in SM). These data capture individual buildings for 2015, with full coverage for the southeast Michigan region. For the road network, we used the TIGER/Line dataset (2016 version). Both data were collated in a GIS environment and organized per county. To detect changes for 2005 and 1985, we visually inspected built-up changes per county using the 2005 and 1985 ortho-imagery as background. Buildings and roads not present in the years 1985 or 2005 respectively were manually discarded. This process allowed us to create building and road level data for 1985, 2005, and 2015. A large number of structures have been demolished in the City of Detroit over this time period. Since it is beyond the scope of our project, we did not focus on detecting these structures. Since we begin with a 2015 building footprint layer, our analysis does not include any structure that existed but was demolished before 2015.

After obtaining land cover results, we conducted supplementary analysis of the proportion of ownership and protection of forests. To do so, we used a polygon layer (Table 1 in SM) that includes protected land at various jurisdictional levels. Specifically, this layer indicates areas owned by federal, municipal, metro, state, and county entities as well as nature reserves and forests preserved for research. Forested pixels not falling within any of these designated areas were considered to be privately owned.

Forest landscape metric analysis

For this step, we focused on the forest class, our objective being to compute metrics on landscape composition and functionality for 1985 and 2015 and then to map the changes as a means of visualizing the magnitude of effects of built-up expansion. The goal was to compute metrics for a specific area as well as the landscape as a whole and to spatially illustrate those metrics. Therefore, the landscape metrics were calculated at a 1 × 1 km scale. To do so, we created a 1x1 km grid for the study area and assigned each grid cell a unique id value. Although we anticipated that maximum values of the three metrics would be restricted by the grid-cell size, our goal here was to generate continuous surfaces visually reflecting the actual forest patterns per metric. The resulting land cover maps for 1985 and 2015 were masked per grid cell, splitting the image into 12,633 1 × 1 km pieces for each year. These smaller land cover maps were loaded into FRAGSTATS (McGarigal et al. 2002) and treated as unique landscape maps. Since forests were the primary focus for the landscape metrics analysis, the “non-forest” class was assigned as background and excluded from further analysis. To assess changes in the forest landscape, we calculated the following metrics:

(1) Effective mesh size (meff) indicates the probability of two randomly chosen locations within a landscape being connected without dissection. Higher fragmentation patterns in the landscape are reflected in a decreased value of meff, and conversely, higher meff values indicate homogeneity and compactness of the focal class. Meff is frequently used to assess habitat fragmentation and is suitable to measure landscapes with differing extents and/or proportions of the focal patches (Almenar et al. 2019; Jaeger 2000). An advantage of meff over other indices is that it also implies connectivity; most importantly, it takes into account both within-patch and between-patch connectivity (Spanowicz and Jaeger 2019).

(2) Patch cohesion measures the spatial cohesiveness of patches. This index reflects the degree of aggregation and physical connectedness of the corresponding patch type and is a favored consistent measure of landscape structure and configuration (Opdam et al. 2003). Patch cohesion is used to characterize the physical connectedness of a patch type and low values indicate that the focal class is subdivided and unconnected. It is used to characterize habitat connectivity and is useful for evaluating less heavily forested landscapes (Opdam et al. 2003; Neel et al. 2004).

(3) Patch density is the number of patches of the focal land category in a given area. It is

conceptually the simplest and most frequently used metric to inform on landscape structure (Tinker et al. 1998; Zhou et al. 2011; Gounaridis et al. 2014) and has been particularly useful in indicating fragmentation (McGarigal and Marks 1995; Wang et al. 2014).

Results generated by FRAGSTATS were joined back to the grid (with "unique id" as a common field). To smooth the edge effect of using gridded polygon maps with unique values and to construct smooth continuous surface layers, we extracted the centroids and applied a multilevel B-spline interpolation for each metric (Lee et al. 1997). Finally, we created a 30-year change map by subtracting the resulting rasters of 1985 from 2015.

Analysis of building use and density

To classify buildings per type, we used polygon land use data for 2015 created by SEMCOG. This dataset delineates areas of different land use types of developed land, using a very high thematic resolution. For instance, it classifies residential use as multi- or single-family housing, attached condominiums, mobile homes, and agricultural housing. Industrial, retail, and institutional areas are also classified separately. Since we sought to show the built-up expansion in this region throughout the 30-year period, we extracted the differences between 2015 and 1985. We used this classification system to overlay with the buildings developed throughout the 30-year period and assigned values to each building from the land use data using a spatial join.

Besides categorizing the land use associated with each building footprint, we also sought to take density into account, given that not all urbanization is sprawl (Galster et al. 2001). Many metrics that distinguish sprawl have been proposed in the literature (Wilson and Chakraborty 2013), but density is widely accepted as an essential dimension (Theobald 2005). Therefore, we opted to calculate the number of buildings per 0.04 km^2 (10 acres) across the region. In doing so, we extracted polygon centroids from the building polygons, created a 0.04 × 0.04 km^2 (10 × 10 acre) grid, and used the count points in polygon function to calculate building density for the seven-county region.

Quantifying impact of single-family housing on forest functionality

To further examine the impact of sprawling single-family housing to changes in regional forest fragmentation and cohesion we calculated the correlation between the distance to newly developed single-family housing and the three metrics: effective mesh size, patch cohesion, and patch density. Physical distance to newly developed single-family homes was calculated using the Euclidean distance function. At the location of 245,000 random samples we calculated bivariate Spearman's correlation to establish a baseline picture of associations between each metric individually and the distance to single-family homes. Correlations were calculated at 95% confidence interval at both the regional southeast Michigan and county scales.

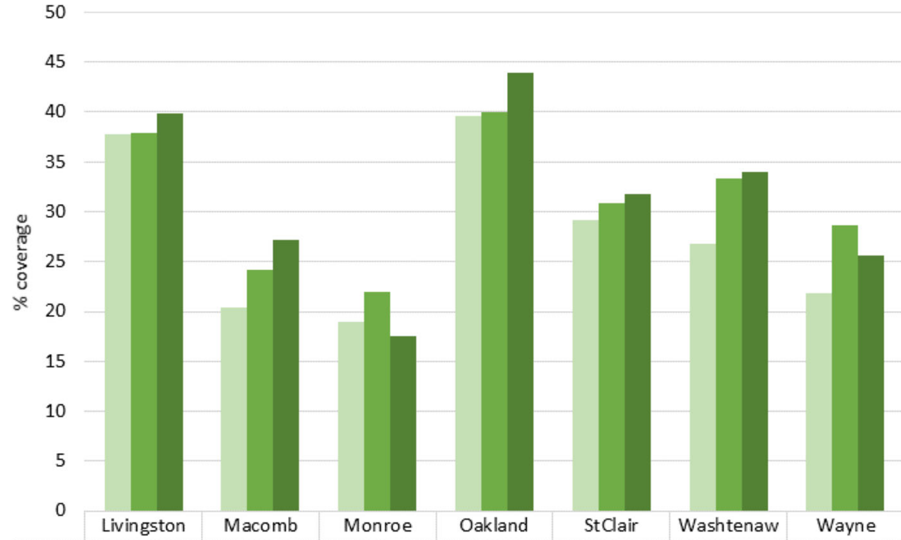
Other regional land use transitions

As a final step, at the regional scale, we used a supplementary type of analysis to benchmark our results to a widely used national product, to explore the effect of spatial resolution, and finally to get an overview of land cover transitions between other categories (e.g. cropland). We used the NOAA C-CAP Regional Land Cover and Change dataset, because its information for Michigan includes the dates of our analysis at 30 m spatial resolution (Table 1 in SM). We used the 1985, 2006, and 2016 layers of this database, clipped to the boundaries of the southeast Michigan region. To simplify the analysis, we aggregated classes focusing only on forests, developed land, cropland, grass/scrubland, wetlands, and other, and presented the land use transitions as a Sankey diagram using R and the *network D3* library (Fig. 2 in SM).

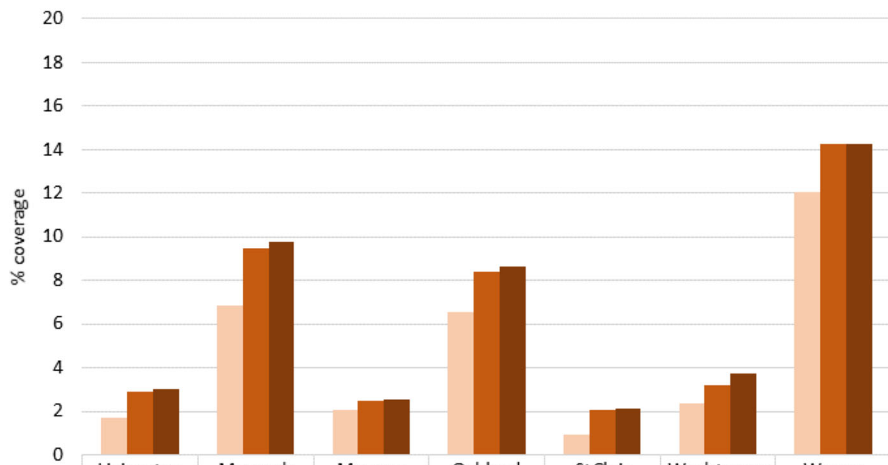
Results

Overview of landscape change in southeast Michigan (1985–2015)

Based on our classification results, we found that forests in the study area increased over the 30-year period, with the largest increase seen in Washtenaw (+ 7%), Macomb (+ 6.5%), and Oakland (+ 4.5%) counties (Fig. 3). Wayne showed an increase during



	Livingston	Macomb	Monroe	Oakland	StClair	Washtenaw	Wayne
1985	37.78	20.38	19.02	39.64	29.21	26.79	21.82
2005	37.86	24.25	21.9	40.02	30.81	33.31	28.69
2015	39.8	27.17	17.58	43.92	31.78	34	25.62



	Livingston	Macomb	Monroe	Oakland	StClair	Washtenaw	Wayne
1985	1.73	6.86	2.07	6.53	0.93	2.34	12.01
2005	2.89	9.46	2.49	8.41	2.04	3.19	14.24
2015	3.04	9.75	2.55	8.64	2.13	3.73	14.27

Fig. 3 Changes in forests and built-up areas in southeast Michigan, 1985–2015, by county

the first two decades (1985–2005) (+ 6%), followed by a decrease (− 2%) during the 2005–2015 period. A similar pattern was observed for Monroe County, while in Livingston and St. Clair counties, forest coverage remained relatively unchanged. In terms of the protected status of the forests, one-quarter of them are under no form of protection, while the remaining three-quarters are protected as state parks (38% of the total), regional parks (called Metroparks) (11%), municipal parks (11%), nature preserves (7%), and county parks (7%). The unprotected forests are probably mostly privately owned, except for street trees along public right-of-ways.

Over the 30-year period (1985–2015), the built-up land expanded by 336 km^2 (+ 12%) in the seven-county study area (Fig. 3 and Fig. 1 in SM). This represents the addition of 335,000 new buildings, of which 75% are single-family houses while another

16% are other types of housing (multi-family housing, attached condominium housing, mobile homes). The remaining building types included industrial/commercial, service, or institutional buildings (9%). Almost two-thirds (64%) of newly developed single-family housing is low density (1–4 houses per 4000 m^2), 19% is medium density (5–10 houses per 4000 m^2), and 17% is high density (> 10 houses per 4000 m^2) (Fig. 4).

The rate of built-up expansion over the 30-year period varied among counties (Fig. 3). In Livingston and Washtenaw counties, the pace of change was relatively low (+ 1.3% and + 1.2%, respectively), with the lowest occurring in Monroe County (+ 0.48%). In contrast, expansion was much more rapid in Oakland (2.1%), Macomb (2.9%), and Wayne (2.3%) counties, all of which contain the urban periphery of the Detroit metropolitan region. A closer focus of two areas exhibiting rapid expansion in Macomb and Oakland counties (Fig. 5), illustrates the spatial configuration of this building expansion (with a total of 65,000 buildings in Macomb, of which 80% are single-family houses, and a total of 42,000 buildings in Oakland, of which 73% are single-family houses). In terms of density, 35% of newly developed single-family housing in Macomb is low density, 22% is medium density, and 43% is high density. Oakland presents a slightly different configuration, where 48% of single-family housing is low density, 27% is medium density, and 25% is high density.

Forest landscape metric analysis

Results for landscape metrics at the county scale diverge from the aggregate findings, which show increased forest coverage and urban trees in almost all counties (Fig. 3).

Over the southeast MI region as a whole, the mean meff decreased by 50,181 m^2, the mean patch density increased by 100 forest patches per 10^6 m^2, and the mean patch cohesion remained relatively stable (mean cohesion increased by 0.16) over the 30-year period. Breaking these figures down into protected versus unprotected status, meff increased by 19,830 m^2 in protected areas and decreased by 70,011 m^2 in unprotected ones. Patch cohesion increased slightly by 0.15 in protected areas and decreased by 0.17 in unprotected. Over the same period, patch density also decreased in protected and increased in unprotected areas.

Fig. 4 Single-family housing per density in southeast Michigan, 1985–2015. Examples of different density classes: **a** low density (1–4 houses); **b** medium density (5–10 houses); **c** high density (> 10 houses)

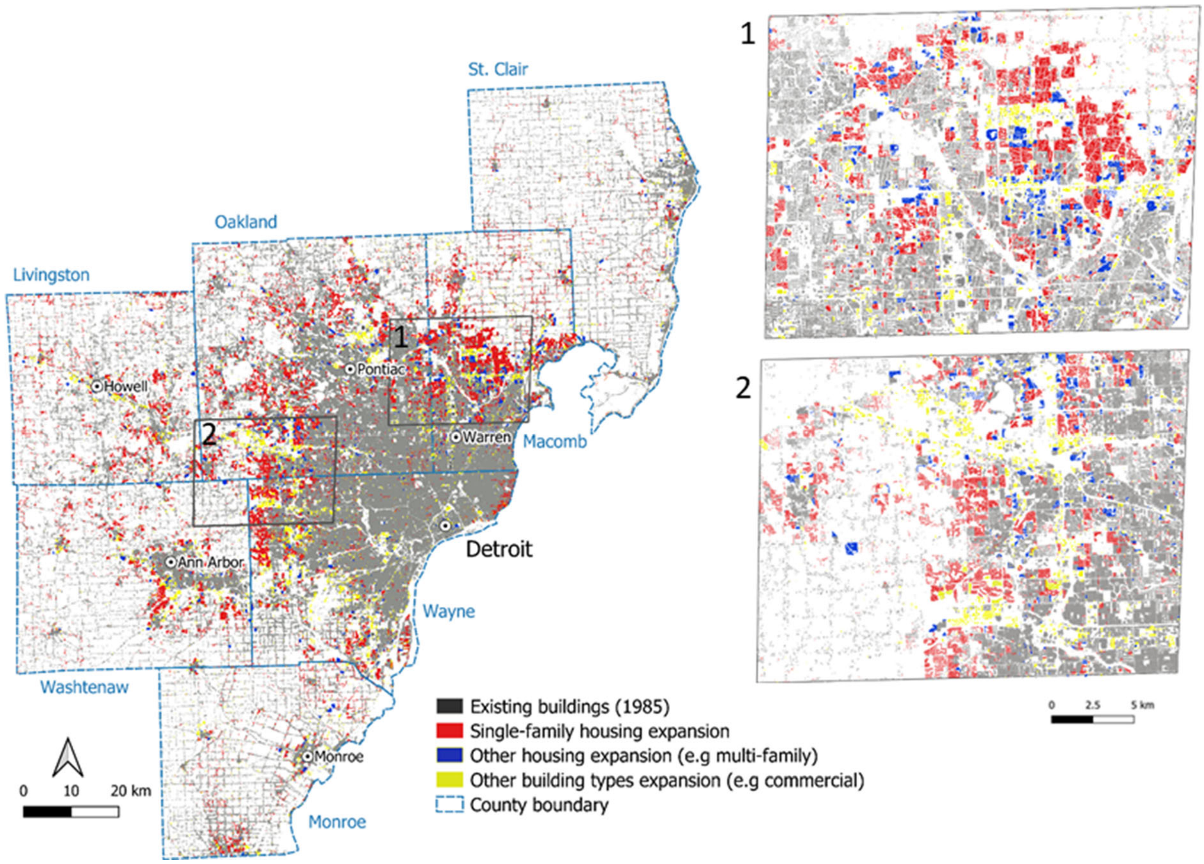


Fig. 5 The expansion of urban sprawl in southeast Michigan, 1985–2015, by building type. Selected fast-growing swaths in the urban periphery of Detroit: (1) Macomb, (2) Oakland

Effective mesh size (meff)

Analysis of mean meff by county reveals a decrease in Washtenaw (− 106,028 m^2), Macomb (− 64,154 m^2), St. Clair (− 78,914 m^2) and Oakland (− 33,184 m^2). Wayne and Monroe had a modest decrease (< − 20,000 m^2) while Livingston was the only county with a modest increase (+ 29,946 m^2). The larger clusters of decrease in meff appear in the northern part of Oakland County, in eastern St. Clair, and along the boundary between Livingston and Washtenaw (Fig. 6). There was also a notable decrease in the suburban areas west of Detroit. Focusing on Macomb and Oakland, we see that the patterns of encroachment of newly developed buildings and, in particular, single-family housing align with a decrease in meff (Fig. 7). Based on our calculations, we see a difference based on building types. In Macomb, the mean meff decreased in areas proximate to single-family housing (− 103,600 m^2), other housing types (− 44,111 m^2), and other building types (− 24,686 m^2). In Oakland, the mean meff decreased near single-family housing (− 75,676 m^2), other types of housing (− 35,612 m^2), and other types of buildings (− 43,706 m^2).

Patch cohesion

In terms of patch cohesion (Fig. 7), the most notable decrease was shown in Macomb (− 0.6), followed by St. Clair (− 0.2). Patch cohesion in Oakland, Washtenaw and Livingston remained unchanged during the years and, surprisingly, increased in Wayne. The largest decrease happened in the eastern part of St. Clair, in Macomb, and in southern Washtenaw. The urban fringe appears to play a role in these patterns. For instance, in Macomb, we see that existing buildings appear to have a positive

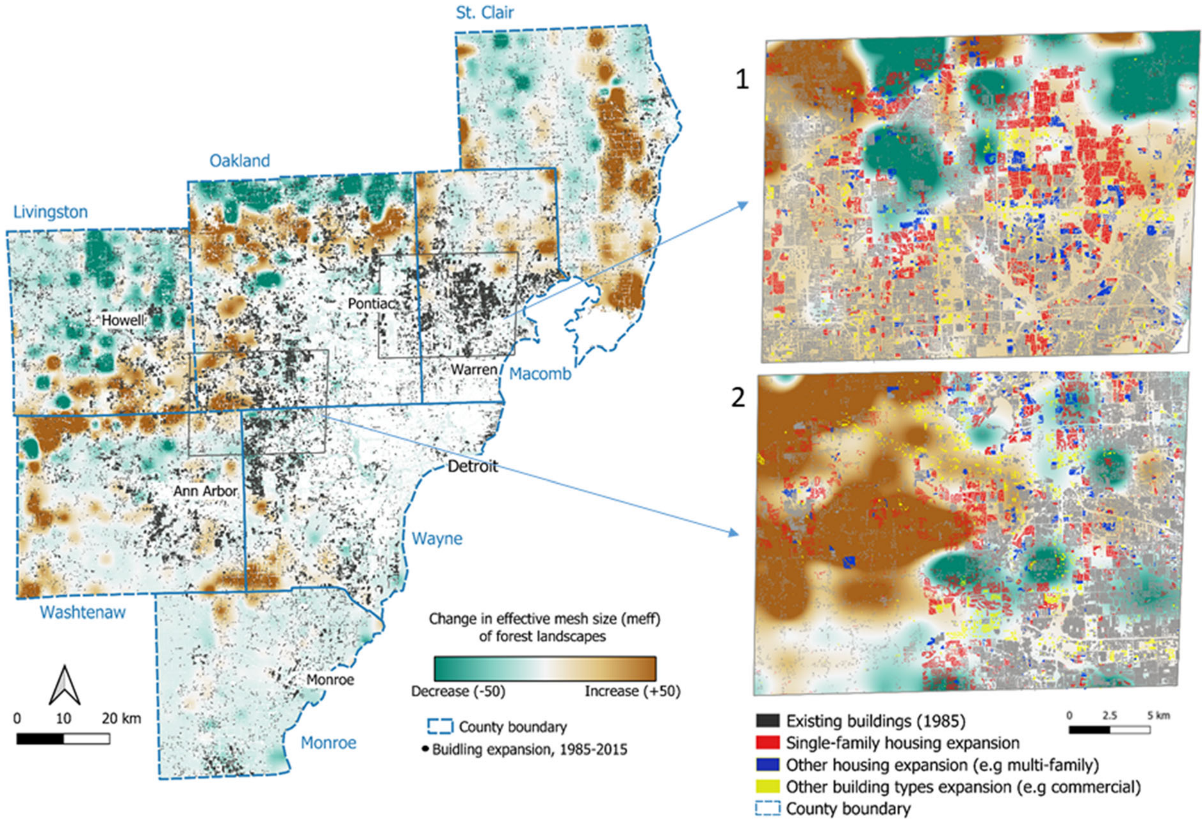


Fig. 6 Change in effective mesh size (meff) of forest landscapes, in southeast MI, 1985–2015 and the role of specific building types. Selected fast growing swaths in the urban periphery of Detroit: (1) Macomb, (2) Oakland

influence in patch cohesion while newly developed single-family housing had the opposite effect. In Oakland, the existing buildings showed no impact on patch cohesion. Instead, encroachment of single-family housing as well as of other building types (retail, industrial, institutional, offices) decreased patch cohesion. Focusing on the two swaths of Macomb and Oakland and distinguishing buildings by their type, we see a mean decrease in single-family housing (− 1.09) but a slight decrease in other housing types (− 0.09) and other building types (− 0.24) in Macomb. In Oakland, we see a slight decrease in single-family housing (− 0.37) and, at the same time, an increase in other housing types (+ 0.18) and other building types (+ 0.57).

Patch density

Patch density increased significantly in Macomb, St. Clair, Oakland, and Washtenaw counties while Monroe, Livingston, and Wayne showed a less pronounced decrease (Fig. 8). Notable increases were in the northern and western suburbs of Detroit, in Wayne, Oakland, and Macomb counties, and south of Ann Arbor in Washtenaw County. Dispersed, low-density, discontinuous building clusters do not seem to cause fragmentation in these areas; rather, patch density showed a decrease over the years. Finally, patch density appears to be affected by the presence of buildings in general. In both Macomb and Oakland, we see that, regardless of whether the buildings are pre-existing or newly developed, and regardless of building type the landscape became more fragmented over the years.

Quantifying impact of single-family housing on forest functionality

Figure 9 presents the results of bivariate analyses using heat map colouring to indicate correlation

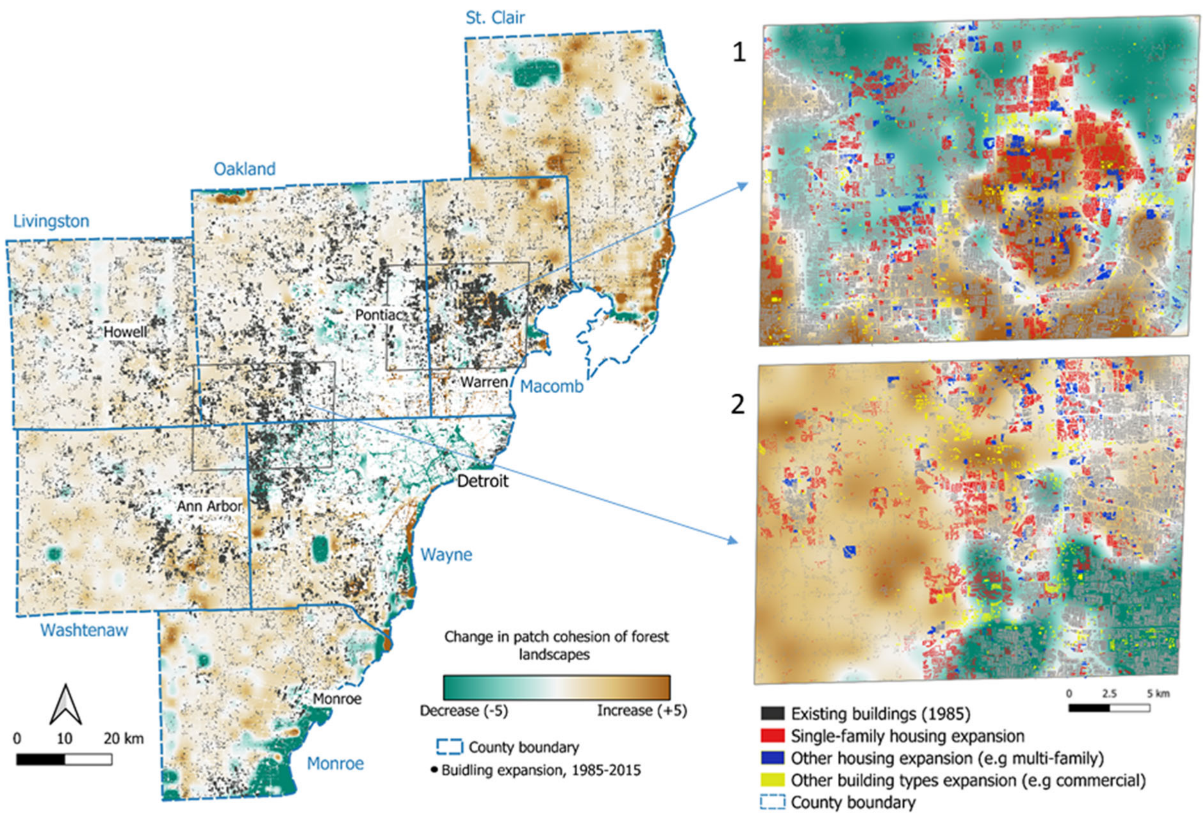


Fig. 7 Change in patch cohesion of forest landscapes, in southeast MI, 1985–2015 and the role of specific building types. Selected fast growing swaths in the urban periphery of Detroit: (1) Macomb, (2) Oakland

strength. We found evidence that across the region, proximity to sprawling single-family housing had an impact on forest functionality. Specifically, forest patch density increased while patch cohesion along with the effective mesh size decreased during the 30-year period. At the county level, the patterns remain unchanged but the correlations are not consistent across counties. Macomb, followed by Oakland, the two counties exhibiting the most single-family sprawl, show the highest positive correlation between forest patch density and distance to sprawling new houses. At the same time, correlation scores indicate that in those two counties, effective mesh size and patch cohesion tends to decrease as the distance to sprawling single-family houses is reduced.

Other regional land use transitions

Analysis of the land cover changes based on the the NOAA C-cap product provides insight into the impacts of the development on the region's forests and cropland. Land for development came primarily at the expense of "cultivated land" (i.e., farmland), which resulted in a 4% decrease over the 30-year period. This loss was especially pronounced from 1985 to 2005. Forestland, as recorded in the NOAA C-cap data, was relatively stable during the study period and this finding is consistent with our results that did not show forest loss in the region. In addition, this finding further supports our assertion that the increases in forests we observe are occurring in urban areas and underlines the significance of spatial resolution. The NOAA C-cap product is available at coarser spatial resolution (30 m) and does not capture patterns occurring at spatial resolution bellow this threshold.

Discussion

Our remote sensing analysis showed increasing built-up expansion, largely driven by the construction of

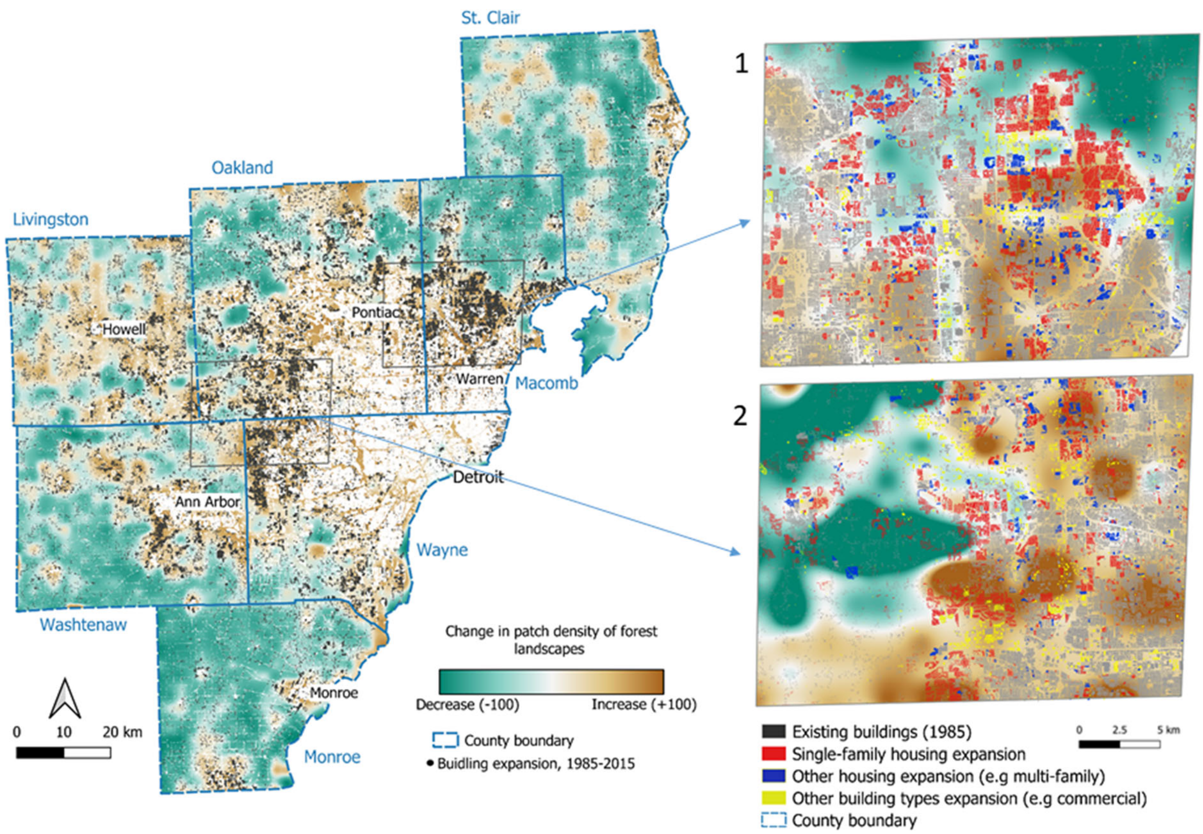


Fig. 8 Change in patch density of forest landscapes, in southeast MI, 1985–2015 and the role of specific building types. Selected fast growing swaths in the urban periphery of Detroit: (1) Macomb, (2) Oakland

	Patch density	Effective mesh size	Patch cohesion
Southeast Michigan	0.25	-0.16	-0.35
Livingston	0.06	-0.1	-0.04
Macomb	0.47	-0.22	-0.52
Monroe	0.09	-0.02	-0.11
Oakland	0.33	-0.20	-0.36
St.Clair	0.28	-0.08	-0.3
Washtenaw	0.27	-0.11	-0.36
Wayne	0.17	-0.18	-0.3

Fig. 9 Bivariate Pearson correlation between key Landscape Metrics and distance to single-family housing in southeast Michigan, 1985–2015

low-density, single-family housing. Surprisingly, this expansion was followed by an aggregate increase in forests in the same region. However, our landscape metrics analysis revealed that this low-density, single-family housing is responsible for increased forest fragmentation and decreased cohesiveness. In addition, the distance to built-up patches appears to be a factor determining the magnitude of impact of urban development on landscape functionality. Our discussion of these findings is organized into four sections: (1) the causes and broader context of the observed changes; (2) the ecological significance of decreasing landscape functionality; (3) the relationship between urban sprawl and landscape change, which can inform urban planning policies to mitigate the ecological harm of urban development; and (4) he significance of this study for future research.

Causes and broader context for observed changes

Based on our primary and supplementary analysis, we speculate that several dynamics explain the observed changes in metropolitan Detroit landscapes. As noted above, we observed an increase in both forested areas and built-up areas for Oakland, Macomb, and Washtenaw counties. This is likely explained by maturing tree canopies in older residential neighborhoods and public lands, perhaps by additional trees planted on these lands, such as on streets and in parks. Additional land conservation activities may also explain some of these changes. For example, within Washtenaw County, the City of Ann Arbor created a greenbelt program that has protected $\sim$ 20 km^2 of land (The Conservation Fund 2019). Conversely, Wayne County displays a different overall pattern in our data. Despite containing the City of Detroit, which lost significant population over the time period studied, and despite not experiencing any increase in built-up area between 2005 and 2015 (largely because it was already urbanized), it experienced a loss of forest cover since 2005.

The ortho-photo showing the boundary between the City of Detroit and the immediately adjacent suburb of Grosse Pointe illustrates some of the explanations (Fig. 3 in SM). Despite having a much higher density of homes, Grosse Pointe is much greener than Detroit due to a greater number and maturity of trees on both privately owned land and along streets. Although forests may increase on Detroit's vacant land through public and private tree planting and natural processes, other forces may slow the growth of urban forests in Detroit. These include degraded soils, limited public sector capacity for street tree planting and maintenance, residents with fewer resources for landscaping, and the practice of mowing vacant lots to deter dumping and criminal activity (Safransky 2014; Kinder 2016; Jay et al. 2019).

Consequences of decreasing landscape functionality

Although the net increase in forests across the region is a positive finding, given that these trees provide habitat for many species as well as valuable ecosystem services for residents, such as improving air quality and mitigating the urban heat-island effect (Ziter et al. 2019). However, our analysis shows decreasing landscape functionality, as measured by our three landscape metrics. This section discusses the ecological significance of these findings in light of recent research.

This study analyzed changes in landscape structure and composition, without being species-specific. We calculated three indices (meff, patch cohesion, patch density), which, when used in conjunction, complement each other. Our focus was forested patches and street trees. These smaller patches are crucial for the spatial cohesion of habitats, serving as stepping-stones and enhancing the dispersal capacity for many species (Ricketts 2001; Grashof-Bokdam et al. 2009). To rapidly identify fragmentation hotspots across the region, we also visualized changes in tandem with statistics at multiple levels and at varying distances from built-up areas.

Our results indicate an increase in urban sprawl, especially single-family housing expansion. Areas close to the urban cores appear more fragmented. Studies that empirically associate fragmentation metrics and the response of forest biota are scarce, since they require a systematic assessment of area requirements for specific species or groups of species. Some notable studies in this tradition include Schmiedel and Culmsee (2016), who found that meff largely influenced richness of neophytes; Li et al. (2010), who found that high levels of fragmentation measured by meff near cities coincided with hotspots of threatened plant species; Girvetz et al. (2007), who used meff to assess habitat suitability for mountain lions and mule deer. Patch density has also proven to be a critical determinant of bird abundance (van Dorp and Opdam 1987; Yuan et al. 2014), as well as the diversity of amphibians, reptiles (Atauri and De Lucio 2001), and mammals (Chambers et al. 2016). Isolation of the remaining habitat fragments is also key to species richness and composition, since it fundamentally affects their dispersal capacity (van Dorp and Opdam 1987; Vieira et al. 2009) and determines their core habitat quality (Alderman et al. 2005). Schumaker (1996) found that patch cohesion correlated strongly with dispersal success after testing a broad range of territory sizes and dispersal abilities. Wilson (2007) compared bird occurrences for species that were dependent on forest interiors as well as those that were not dependent on them, finding that patch cohesion was among the most significant determinants of bird occurence. Grashof-Bokdam et al. (2009) analyzed the relationship between both plant and animal species in forests, on the one hand, and the spatial cohesion of the surrounding forest patches, on the other, and found that, for the majority of species, higher cohesion had positive effects on species occurrence. Moreover, their results stress the crucial role of smaller forest patches as corridors and stepping-stones for species.

In summary, the research literature suggests that the decrease in meff and cohesion, along with the increase in patch density we observed across the region most likely have been accompanied by negative effects on a variety of plant and animal species. As illustrated in Figs. 7, 8, and 9, many of the declines have occurred at the urban periphery, where sprawl is most intense. However, the analysis also reveals a complex pattern of change across the entire region, which deserves further study.

Discussion of functionality and proximity

One objective was to spotlight the role of specific building types, forms, and density in shaping the adjacent landscape. Our results show that forests appear more fragmented and less cohesive in areas experiencing urban sprawl, in accordance with findings worldwide (Haddad et al. 2015). We also demonstrate that sprawling patterns of single-family housing appear to have higher magnitude of impacts on the adjacent landscape. This finding is apparent in rapidly growing US cities, as demonstrated in the existing literature (Marzluff et al. 2001; Irwin and Bockstael 2007; Radeloff et al. 2010).

Densities along with spatial patterns are also key to determining the depth and intensity of impacts on adjacent ecosystems and biodiversity (Hansen et al. 2005). Low-density urban sprawl in general occupies more space, and the impacts might be less intense but widespread (Theobald et al. 1997). Conversely, higher density has more intense impacts but affects smaller areas. Radeloff et al. (2005) analyzed 60 years of housing growth and forest fragmentation across the US Midwest and found that housing density negatively correlates with the amount of interior forests. They also concluded that the environmental effects per house are higher in low-density, dispersed sprawl areas. In their study of western Massachusetts, Kluza et al. (2000) found that low-density rural sprawl caused forest fragmentation, with direct impacts on forest birds. Moreover, in a study focusing in the northern Wisconsin, Gonzalez-Abraham et al. (2007) found that fragmentation and habitat loss were limited in areas with higher clustering of buildings. Pidgeon et al. (2007) also found housing density to be associated with avian species richness across the conterminous US. In their study of two Canadian sites, Gagné and Fahrig (2010) examined breeding bird populations over a range of building densities and found lower impacts in areas with higher-density housing patterns. Finally, a study in north-central Virginia also confirmed that low-density development altered the adjacent forest habitats by increasing fragmentation, with direct implications on forest bird populations (Suarez-Rubio et al. 2013).

A variety of urban planning policies could be useful to prevent or mitigate habitat fragmentation caused by urban expansion. Smart-growth policies raise barriers to urban growth, preserve agricultural land use, and promote land conservation, through measures to discourage urban sprawl by protecting land from development, increasing costs of sprawling development, and incentivizing urban infill (Resnik 2010). One of the most important tools in the smart growth lexicon is the investment in public transit instead of highway infrastructure. However, smart-growth recommendations for land use and transportation have proven to be politically unpopular in states such as Michigan (Boyle and Mohamed 2007). Nevertheless, residents and organizations at the community level can advocate for cluster subdivision or other best practices that maximize preservation of habitat patches and corridors (Arendt 1994), or they can implement programs such as tree planting. Finally, at the level of individual homeowners, ecologically-informed landscape design can maximize ecosystem benefits and functionality (Nassauer 2012).

The promise of high-resolution landscape analysis

Our study suggests several fruitful avenues for further research. First, our results point to the importance of spatial resolution in landscape analysis. Our analysis was based on high-resolution data, which allowed us to map and quantify smaller forest patches as well as individual buildings and roads. Comparison with coarser spatial resolution data confirmed the potential underestimation of urban trees and buildings, since smaller entities cannot be detected from coarser pixel sizes (Zhou et al. 2018). Smaller patches of forest and street trees, for example, are often excluded from analysis due to data limitations, overlooking the crucial role trees play in providing ecological functions and enhancing connectivity by serving as stepping-stones or corridors for many species (Mexia et al. 2018). Landscape metrics are especially sensitive to the spatial resolution of input maps (Wickham and Riitters 2019; Wu et al. 2002), and the results might be misleading in cases when pixel size and scope of analysis do not match. More broadly, conducting this type of analysis at the regional scale provides an assessment of the state of urban forests, which fall under the broader urban category in many land use datasets (Walton et al. 2008).

Conclusions

This paper described the methods, results, and analysis of a research project that applied three landscape metrics to high-resolution imagery to understand the evolution of forest landscape and built-up areas in southeast Michigan over a 30-year period (1985–2015). The analysis revealed that the overall area of forest increased, but landscape functionality decreased primarily due to expansion of low density singling family housing. In this area increased in aggregate area over the study period, however, our analysis of landscape metrics indicates that the functionality of forested landscapes decreased over the same study period and that this decrease spatially coincided with single-family housing expansion. Considering our findings relating landscape metrics to ecosystem functionality, urban sprawl has had a detrimental environmental impact in the region. To mitigate or prevent the detrimental impacts of urban growth on forest landscape, state, regional, and local decision-makers can turn to a suite of land use planning policies and practices.

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