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Housing Market Activity is Associated with Disparities in Urban and Metropolitan Vegetation

K. Arthur Endsley,[1]* Daniel G. Brown,[2] and Elizabeth Bruch[3,4,5,6]

[1]*School for Environment and Sustainability, University of Michigan, 440 Church St, Ann Arbor, Michigan 48109, USA;* [2]*School of Environmental and Forest Sciences, University of Washington, Box 352100, Seattle, Washington 98195, USA;* [3]*Population Studies Center, Institute for Social Research, University of Michigan, 426 Thompson St, Ann Arbor, Michigan 48109, USA;* [4]*Department of Sociology, University of Michigan, 500 S. State St, Ann Arbor, Michigan 48109, USA;* [5]*Center for the Study of Complex Systems, Suite 700, Weiser Hall, 500 Church Street, Ann Arbor, Michigan 48109, USA;* [6]*Santa Fe Institute, 1399 Hyde Park Rd, Santa Fe, New Mexico 87501, USA*

ABSTRACT

In urban areas, the consistent and positive association between vegetation density and household income has been explained historically by either the capitalization of larger lawns and lower housing densities or landscaping and lifestyle districts that convey prestige. Yet cities with shrinking populations and rising land burdens often exhibit high vegetation density in declining neighborhoods. Because the observed associations do not directly address the causal connection between measures of social privilege and vegetation in urban landscapes, it is difficult to understand the forces that maintain them. Here, we compare patterns of household income with new measures derived from housing market data and other parcel-level sources—sale prices, tax foreclosures, new housing construction, demolitions, and the balance of construction and demolition. Our aim is to evaluate whether these spatially, temporally and semantically finer measures of neighborhood social conditions are better predictors of the distribution of urban vegetation. Furthermore, we examine how these relationships differ at two scales: within the City of Detroit and across the Detroit metropolitan area. We demonstrate, first, that linear relationships between income or home values and urban vegetation, though evident at broad metropolitan scales, do not explain recent variations in vegetation density within the City of Detroit. Second, we find that the real estate and demolition records demonstrate a stronger relationship with changes in vegetation density than corresponding changes in US Census measures like income, which suggests they hold at least as much interest for understanding how the relationships between biophysical changes and neighborhood change processes come about.

Key words: land cover; urban vegetation; vegetation cover; vegetation change; urbanization; shrinking cities; urban ecology; social stratification; remote sensing.

INTRODUCTION

Urban vegetation in the form of lawns, parks, and tree canopy cools neighborhoods, reduces stormwater runoff, cleans the air, and improves quality of life for urban residents. Yet urban vegetation is often distributed unevenly among residents, creating social disparities in access to these

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Author Contributions: KAE conceived of and designed the study, executed all the research, analyzed all the data, developed the software used, contributed new methods and wrote the paper. DGB conceived of and contributed to the design of the study, assisted with the analysis and interpretation of the results and wrote and edited the paper. EB conceived of and contributed to the design of the study assisted with the analysis and interpretation of the results and wrote and edited the paper.

**Corresponding author; e-mail:* endsley@umich.edu

important benefits. In growing cities, higher household income or wealth enables residents to choose larger lots, purchase more extravagant landscaping, and live closer to green spaces, all of which signal higher prestige and further segregate access to scarce urban greenery. On the other hand, cities with declining populations and investments typically experience housing abandonment and the breakdown of the built environment, which in temperate climates often result in buildings covered or displaced by overgrown shrubs, grasses, and trees. Because of these countervailing influences, we cannot draw simple conclusions about the social and economic processes (for example, income segregation, sorting by lot size, neighborhood turnover) that lead to social disparities in urban vegetation without expanding the scope of cross-sectional studies of correlations between vegetation and income to include richer descriptions of the social environment and its changes through time.

Our aim is to improve understanding of the link between spatial patterns of urban vegetation and socio-economic change through new empirical work. First, we improve on existing measures of social conditions. Although socio-economic status (SES), particularly household income, has been shown repeatedly to relate strongly to the spatial distribution of environmental amenities like trees and parks (Patino and Duque 2013; Schwarz and others 2015), understanding the processes producing these associations requires direct observation of neighborhood social and economic conditions over time. However, decennial US Census or American Community Survey (ACS) data (commonly relied on for SES measures), although of great value to the study of multi-decadal neighborhood changes, have limited use for studies of gradual or highly dynamic neighborhood change due to their lack of temporal granularity. Here, we test new measures of social conditions that better characterize neighborhood biophysical conditions and can be linked to fine-scale, continuous measures of vegetation change from remote sensing.

We also assess how the relationship between urban vegetation and SES varies (1) across geographic scales and (2) between different urban contexts. Few studies have pursued these questions despite the recognition of both within-city and between-city differentiation in land management patterns (Pearsall and Christman 2012; Polsky and others 2014). We question whether the findings from existing studies of urban vegetation and SES in growing cities generalize to shrinking cities (cities with declining population) or legacy cities (cites experiencing deindustrialization or which experienced other severe economic restructuring). Although there is reasonably good theory to describe the effects of neighborhood change and vegetation in places undergoing urban growth, the ecological consequences of urban decline or revitalization in cities have received comparatively little attention (Großmann and others 2013). Even within a single city, neighborhood socio-ecological conditions vary dramatically. We can hypothesize that, while well-established socio-ecological relationships—in particular, that vegetation density increases monotonically with SES measures—may hold at broad spatial scales, there is fine-scale heterogeneity that is masked in pooled, metropolitan-wide studies. As a result of the aforementioned conceptual and technical limitations, our understanding of the connection between vegetation and neighborhood conditions is tenuous, as is our understanding of the factors that drive changes in this association over time.

In this paper, we compare SES patterns with new measures of social conditions derived from real estate inventory data and other parcel-level sources: sale prices, tax foreclosures, new housing construction, demolitions, and the balance of construction and demolition. We expected that these more spatially, temporally, and semantically refined measures of neighborhood housing markets would also have stronger associations with the distribution of urban vegetation. We focused on Detroit, Michigan, a city that figures prominently in the sparse literature available on urban vegetation and decline (Emmanuel 1997; Ryznar and Wagner 2001; Hoalst-Pullen and others 2011), but with a metropolitan area that had yet to be examined under the same lens. Although both the City of Detroit and its surrounding metropolitan area are shrinking (Figure 1), neighborhood conditions vary, with some neighborhoods experiencing net growth and new suburban development. To facilitate comparison with US Census measures, we investigated cross-sectional models of Census districts in three time periods and at two scales: between the City of Detroit and the wider metropolitan area, here defined as the three counties that include or are adjacent to the City of Detroit (Wayne, Oakland, and Macomb counties). We also investigated whether the new, property-level measures of social conditions demonstrate a stronger association with vegetation change than Census measures. Taken together, these contributions allow investigation of the mechanisms that drive the association between vegetation and neighborhood conditions and how those mechanisms might operate differently in different cities.

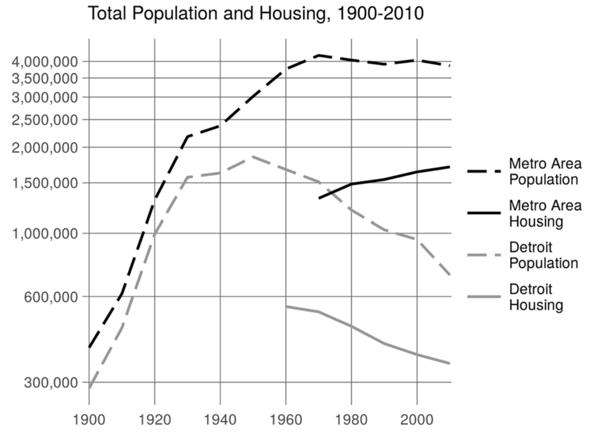

Figure 1. Population and housing totals taken from the US Census Bureau Decennial Census of Population and Housing, filled in with totals from Social Explorer (SocialExplorer.com) where necessary. Here, the Metro Area is defined as Wayne, Oakland, and Macomb counties. Dashed curves indicate population totals and solid curves indicate housing totals.

Our results demonstrate, first, that linear relationships between income or home values and urban vegetation, though evident at a broad metropolitan scale, do not explain recent patterns of vegetation density within the City of Detroit. Second, we find that the housing market and demolition rate measures demonstrate a stronger relationship with changes in vegetation density than corresponding changes in US Census measures like income, which suggests they hold at least as much interest for explaining the relationships between biophysical changes and neighborhood change processes.

A Framework to Integrate Social and Biophysical Changes

Spatial variations in urban vegetated area have long been associated with such social factors as population density, income, and prestige. In particular, home values and socio-economic status (SES) have consistently been associated with higher vegetation densities (Patino and Duque 2013) and a recent comparative study of tree canopy cover in multiple US cities summarized this well-established relationship as ''trees grow on money'' (Schwarz and others 2015). This ''ecology of luxury'' has prompted concerns about green space access for certain socio-economic and demographic groups (Clarke and others 2013). The ''ecology of prestige'' (Grove and others 2006, 2014), by contrast, explains unevenness in the spatial distribution of urban vegetation as primarily due to differences in lifestyles or life stages between households or neighborhoods. Because trees are long-lived and a neighborhood's income and demographic composition changes over time, a ''legacy effect'' on the amount and type of urban vegetation has also been documented (Locke and Baine 2015). A long and precise time series record of neighborhood conditions, as offered with the datasets used here, could allow for investigation of legacy effects in the links between social and vegetation patterns in ways that are not possible with Census data alone.

What SES measures like income fail to capture about neighborhood conditions are the associated housing market conditions and their dynamics that more directly reflect the value of properties that people occupy and manage. Income is a highly mobile quantity; it can move with residents in and out of neighborhoods; and its relationship with vegetation and the built environment is likely more complex than previous studies have acknowledged (as noted by Grove and others 2014) High incomes facilitate high vegetation densities (for example, through larger parcel sizes, more extravagant lawns, and so on) but much of a neighborhood's biophysical elements—building setbacks, street and sidewalk size and configuration, street trees—are essentially fixed once they are laid down. Large setbacks, large parcel sizes, close proximity to urban parks, and a dense urban tree canopy are all signals of wealth and prestige rather than those of incomes per se. Household income is also inadequate in describing wealth, as there is substantial heterogeneity within neighborhoods and between households, for a fixed level of income, in terms of the factors that determine wealth (including debts and generational wealth) and which make wealth itself hard to measure. Home values, to the extent that they are accurately reflected in sale prices, convey information about the physical condition of the housing stock, amenities and disamenities in the neighborhood, the residents (in terms of what they can afford), as well as market signals related to care and maintenance of properties.

Sale prices and other housing market variables therefore convey social, economic, and biophysical conditions in changing neighborhoods. These market variables are available on monthly or yearly intervals and can be tied to individual residential parcels. As high-resolution spatio-temporal data on neighborhood conditions, they enable us to investigate dynamic neighborhood changes in new ways and to link theories of neighborhood change to observed biophysical changes (Hoalst-Pullen and others 2011). Census measures will continue to play a role in such studies, as it is not possible to understand the socio-ecological relations of a neighborhood without understanding the wider urban context. The exact socio-ecological relations in any one city may not generalize to others, particularly across climatic and cultural gradients, but the differences *within* a city are just as important as the differences *between* cities (Polsky others 2014). What these new variables provide are the data needed to understand multi-scale, dynamic neighborhood changes that may operate differently across neighborhoods and between cities.

Background and Study Area

Our study area, Detroit, Michigan, can be contextualized in a number of different ways. Detroit can be seen as an extreme case of Rust Belt deindustrialization, a so-called *legacy city*, or as part of a broader trend in *shrinking cities* across the USA. These two characterizations refer to different pathways with similar physical outcomes (for example, abandoned buildings, vacant lots, underutilized infrastructure). They include different social and economic processes (Haase and others 2014) that commonly involve the migration of human capital, financial capital, and/or economic opportunities from one neighborhood, city, region, or country to another. Some scholars have framed this migration as movement from the city center to the periphery, which is certainly true for much of Detroit's history. Present-day Detroit is also grappling with broader industrial and economic trends affecting the automobile industry.

We refer to Detroit as a shrinking city as it is embedded in a regional and state-wide context of population loss. The term ''shrinking city'' is favored here because the mechanisms we identify are related to population and housing loss, but also because the term refers to a widely recognized theme of research in the USA and particularly in Europe, where some cities exhibit shrinkage due to demographic changes that are not necessarily implied in the characterization of legacy cities. Our study is also multi-scalar, as measuring shrinkage itself is scale dependent (Franklin 2017). In shrinking cities, some neighborhoods may be stable or growing, retaining their housing stock and maintaining or increasing home values, while others may be in decline, losing homeowners and even housing units to abandonment and eventual demolition. Detroit's decline can be traced to the relocation of manufacturing jobs in the mid-twentieth century to non-unionized Sun Belt cities, along with pernicious economic racism (Sugrue 1996). Though centers of prestige in the urban core of Detroit were less affected, the recent subprime mortgage crisis has exacerbated neighborhood destabilization within the city while freezing or reversing growth in outlying suburban and exurban neighborhoods (Wilson and Brown 2014). Even in the surrounding suburbs, population growth has stagnated for the past 40 years while housing development continued apace (Figure 1), demonstrating that population loss and urban sprawl are not mutually exclusive.

One of the most significant challenges for Detroit after the subprime mortgage crisis has been to identify where to maintain and improve its housing stock and where to transition residential neighborhoods to alternative uses. Although many of its residents have left, Detroit's housing stock—an uncommonly large number of detached, single-family homes—and much of its infrastructure remained behind. The economic vulnerability of the less-socially mobile residents who remain translates into housing foreclosure and abandonment when they can no longer afford to pay the mortgage or property taxes. Thus, Detroit's chief problem is one of entropy: the city is saddled with deteriorating foreclosed or abandoned properties scattered across too large an area for so few people. Demolition has been one of Detroit's strategies for tackling this problem since the early 1970s (Sternlieb and others 1974). When a house is demolished, even if the foundation remains or is capped, there is more space and light available for vegetation to grow. Initially, vegetated area may be quite low, as the clearing of the parcel leaves areas of bare soil that recover vegetation at variable rates and with varying levels of vegetation quality, depending on planting and maintenance. Vegetation changes are also expected for foreclosed properties as owners may invest more or less effort in upkeep, depending on their capabilities and goals (Deng and Ma 2015; Minn and others 2015).

Data and Methods

In this study, we refer to the tri-county area of Oakland, Macomb, and Wayne counties as the ''metropolitan area'' and it forms the ''metropolitan level'' in our models. We also include the cities of Hamtramck and Highland Park, which are separate municipal entities surrounded by the City of Detroit proper, as part of the ''Detroit level'' in our models. The spatial extent of the metropolitan level includes that of the Detroit level.

Vegetation Abundance from Remote Sensing

Vegetated area was estimated from radiometrically and atmospherically corrected surface reflectance (SR) images from Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+). All ''leaf-on'' (summer-time) images matching a maximum cloud cover criterion (to facilitate interpretation of the spectral mixture space) in the years 1990 (4 images), 2000 (8 images), and 2010 (9 images) were acquired from the US Geological Survey and analyzed using linear spectral mixture analysis (LSMA). In this approach, the reflectance of any pixel in the scene—assumed to be a mixture of multiple land-cover types—is modeled as a linear combination of spectra from two or more ''pure'' surface materials, termed endmembers. While multiple scattering can lead to nonlinear interactions between endmembers for which LSMA is not suitable, this effect is widely thought to be of minor importance, especially in urban settings (Small 2003; Wu and Murray 2003). The result is a sub-pixel estimate of the vegetation abundance: the physical amount of vegetation within a pixel.

To reduce computational complexity and to improve data quality by mitigating band-to-band correlation, the minimum noise fraction (MNF, a dimension-reduction technique) is applied to the Landsat TM/ETM+ data prior to unmixing with LSMA. Sub-pixel land cover was estimated as being some fractional combination of substrate (impervious surface or soil), vegetation, and photometric shade (Small and Lu 2006). A fully constrained least-squares (FCLS) inversion was conducted in which the abundance estimates of each land-cover type are constrained to be positive and to sum to one within each pixel. The abundance maps produced for each date were then combined in annual, pixel-wise composites by taking the median value for each abundance type. The median pixel-wise composite was found to reduce the error, described below, more than other compositing methods.

Sub-pixel vegetation abundance was validated against high-resolution aerial photographs in 2000 and 2010. In 1990, no high-resolution aerial photographs could be obtained. For 2000, a series of color-infrared digital ortho-rectified quarter-quad (DOQQ) images, taken in April of that year, were acquired from the USGS. For 2010, natural-color DOQQ images, taken in July of that year, were also acquired. 90-meter plots were randomly sampled where the available DOQQ images intersected the study area. In each sample plot, the proportion of vegetated area was estimated by manual interpretation. From the high-resolution DOQQ images, a single analyst traced polygons of all vegetated areas or all non-vegetated areas (depending on which required less drawing) within each 90-meter sample and divided the result by the total area to estimate the vegetated (or non-vegetated) proportion. The root-mean-squared error (RMSE) between the vegetation estimates manually derived and those from LSMA is used as an estimate of the error in vegetation abundance. For the 2000 composite image, the RMSE is 13.9%; in 2010, it is 11.8%. These can be interpreted as the amount of area within each 90-meter square plot by which LSMA under- or overestimates vegetation density.

Measures of Neighborhood Condition

Census data at the block-group level were acquired for 1990, 2000, and 2010. In 1990, data from the decennial US Census, Summary Tape File 3A were acquired from the Inter-University Consortium for Political and Social Research (ICPSR and Research 1999). In 2000, comprehensive data from the decennial US Census were acquired from Social Explorer (2015). In 2010, because 2000 was the last year in which the long-form decennial census was conducted, data from the 5-year American Community Survey (ACS) in 2012, which represents an average of conditions from 2008 to 2012 (centered on 2010), were used in place of the 2010 decennial US Census. The 2012 ACS data were also acquired from Social Explorer.

In each year, only the Census variables that are commonly available across all three years were retained (namely, population density, age and sex structure, racial group proportions, housing size distribution, type of heating, and poverty rate). These measures, excluding median household income, then entered into a factor analysis in each year and at both spatial extents in order to derive minimally correlated factors to use as controls in the subsequent autoregression analyses. Variance inflation factors calculated for the weighted least-squares (WLS) models indicated no serious collinearity between Census factors and the additional contextual variables (county code, distance to central business district, and water-land ratio) nor the treatment variables.

Home sales, sale prices, notices of tax foreclosure, and year built were obtained from tax assessor and deed sales data purchased from RealtyTrac (''Assessor,'' ''Recorder,'' and ''Pre-Foreclosure'' data in ''DLP 3.0'' format), a private company specializing in real estate data. Property addresses were geocoded using ESRI's ArcGIS Address Locator and spatially joined to Census block-group boundaries. As a measure for sale price, we used Census home values in 1990 but used deed sale prices in 2000 and 2010. We confirmed that deed sale prices, summarized by Census block group, have a very strong correspondence with home values measured by the Census (Pearson's correlations of 0.9 or higher). Sale prices in all years were escalated for inflation to 2010 US Dollars (USD) using the unadjusted Consumer Price Index (CPI) for housing for ''all urban consumers'' (Federal Reserve Bank of St. Louis 2016). Deed sales within ''arm's length'' were removed from consideration. Among the recorded foreclosure events, notices of default were filtered out, leaving notices of tax sale as the primary identifier of a foreclosure event. Census block groups where no sale or foreclosure is recorded in a given year are assumed to have experienced none.

Demolitions in 2009 and 2010 were obtained from Data Driven Detroit, which, in turn, acquired the data from the Michigan Department of Environmental Quality's National Emissions Standards for Hazardous Air Pollutants (NESHAP) notification records (Data Driven Detroit 2017). They are assumed to be a good proxy for demolitions in Detroit because they are required for virtually all types of structures, including residential homes demolished by the city. Although private homeowners may demolish their own home without a NESHAP notification, such a case is exceedingly rare. New housing starts were derived from the tax assessor data as the year of construction. Along with foreclosures, demolitions, and the balance of demolition and construction, block groups that contained no record were assumed to have experienced no event and all event totals were normalized by the total housing according to the US Census, in each block group in each year. Median home values from the 1990 decennial US Census was used in place of missing sale price data for that year. All address-level data described in this section were summarized at the block-group level in the R statistical computing environment (version 3.4.0).

Spatial Errors Models and Rank Correlations with Vegetation Change

We assumed and verified that spatial dependence is present in the vegetation density estimates at the Census block-group level. The forms of spatial dependence tested in the spatial errors models were selected by examining empirical variograms of the response and treatment variables. Our approach is to treat spatial dependence as a nuisance parameter (in a spatial errors model) rather than as a parameter of substantive interest (in a spatial lag model). This approach is justified by Lagrange multiplier tests (Anselin 2007) conducted on the income, income-squared, and sale price models in all three years at both geographic extents, which consistently indicated that the spatial errors model was a better fit than a spatial lag formulation.

Because the spatial errors models use optimization in fitting, the covariates must be on a similar scale. As such, we transformed the median household income, median sale price, and the contextual variables outside the factor analysis (distance to the central business district and water-land ratio) to standard scores (Z-scores). The other treatment variables are all normalized by the number of housing units and are therefore numerically small. For each treatment variable, we tested several different forms of spatial dependence. The resulting models were compared in a multi-model inference using Akaike's information criterion (AIC) as the goodness-of-fit measure. Multiple testing was corrected for using Bonferroni correction. All weighted least-squares (WLS) models were fit using the linear regression function in R. All spatial errors models were fit in R using functions provided by the ''spdep'' package.

There are two parts to the central analysis. First, we determined the association between levels of vegetated area and neighborhood social conditions and housing market conditions at the city and metropolitan scales, accounting for neighborhood characteristics and spatial dependence. Second, we compared associations between change in vegetated area and change in neighborhood social and housing market conditions.

A central goal of the first analysis is to assess whether housing market variables, including data on the condition of the housing stock, better explain cross-sectional variation in vegetated area than do SES measures from the US Census, like household income. Before accounting for spatial dependence, the proportional abundance of vegetated area (summarized by Census block group) was regressed on each treatment variable, with 1–2 year lags as appropriate, using weighted least squares (WLS) with the total number of housing units as weights. Because of the importance of race in Detroit's housing history, we later examined potential disparities in green vegetation density between demographic groups by interpreting the loadings of Census variables onto our contextual factors and the directions and magnitudes of these effects.

To facilitate the calculation of change in Census statistics, the correlation tests between the natural logarithm of greenness change index (GCI) and Census, real estate, or demolition measures were carried out at the Census tract level, rather than block-group level (as block groups do not permit interannual comparisons). For this analysis, data from the 2000 decennial Census, described by 2000 Census tract boundaries, were cross walked to 2010 Census tract boundaries using the tract correspondence tables developed by Logan and others (2016). Then, relevant Census measures in 2000 were subtracted from their 2010 counterparts. Differencing the real estate and demolition data were achieved by summarizing these address-level data by 2010 Census tract boundaries and then subtracting aggregates in each year or calculating derivatives. Spearman's rank correlation (Spearman's rho) was then calculated between log GCI and each variable of interest. Confidence intervals for Spearman's rho were calculated in R (version 3.4.0) using Fisher's z-transformation, available in the ''mada'' package in R.

RESULTS

The initial WLS models demonstrated reasonably good fit to the data (adjusted R^2 values >/ = 0.56 at the metropolitan level) using only contextual factors, which indicates a good baseline model (Table 1). Model fit is comparably lower at the city level (adjusted R^2 values ranging from 0.37 in 1990 to 0.25 in 2010). A list of the treatment variables, their effect sizes, and significance, averaged across the multiple SAR error models, can be found in Table 2.

Comparing Associations with Vegetated Area

Consistent with previous studies, our results indicate that sale prices and household incomes have strong, positive associations with vegetated area across neighborhoods (Table 2). At the metropolitan scale, household income is a stronger covariate than all other neighborhood measures in both 1990 and 2000. However, by 2010, models with contemporary or lagging sale prices performed best. In the City of Detroit, the declining importance of income and sale price is more pronounced: by 2010, neither household income nor sale prices are significant predictors of vegetated area. Instead, demolition rates are the best predictors of vegetated area in Detroit in 2010. Foreclosures and demolitions have often been hypothesized to directly affect vegetation amount and characteristics at the parcel scale in neighborhoods (Deng and Ma 2015; Minn and others 2015). We found that neighborhood-scale foreclosure rates are a significant (negative) effect on vegetated area only at the metropolitan level. As expected, higher demolition rates in Detroit (in 2010) are associated with higher vegetated area. Importantly, we find that if neighborhoods that do not experience any demolition are left out of the model, demolition rates have no association with vegetated area.

We also fit models with a squared term for income or sale price (and lags) to see whether both high and low extremes in income or price were associated with high or low levels of vegetated area. Together with positive coefficients on the linear terms, significant and positive coefficients on the squared terms of household income and median sale price indicated that higher levels of vegetated area are, indeed, found at both the highest and the lowest levels of household income or sale price (Table 2). This quadratic relationship between income and vegetation is found in every year at both spatial scales. However, while sale price, squared or not, is consistently significant at the metropolitan scale, it is often not a significant predictor of vegetated area in Detroit. This suggests that although sale prices reflect broad patterns in vegetated area across the metropolitan area, local heterogeneity in neighborhood conditions within the city, time-de-

Table 1. Model Fits from WLS Models with the Same-year Median Household Income Treatment

Geographic scale	Year	Base Adj. R^2	Adj. R^2 with income	Improvement (%)
Detroit	1990	0.367	0.388	2.14%
Detroit	2000	0.327	0.346	1.96%
Detroit	2010	0.242	0.244	n.s.
Metropolitan	1990	0.637	0.682	4.46%
Metropolitan	2000	0.571	0.609	3.85%
Metropolitan	2010	0.560	0.578	1.76%

Here, the base model is the model with contextual variables only.

Table 2. Minimum, Maximum, and Mean Z-scores of Effect Sizes Along with Maximum *P* values for Each Relevant Treatment Among All SAR Error Models in the Multi-model Inference, Organized by Model Geographic Extent and Year

Extent	Year	Treatment	Minimum Z	Mean Z	Maximum Z	Maximum *P* value
Detroit	1990	Household Income	5.875	5.948	6.060	0.00000*
Detroit	1990	Household Income Sq.	6.346	6.391	6.435	0.00000*
Detroit	1990	Sale Price	8.505	8.781	9.048	0.00000*
Detroit	1990	Sale Price Sq.	7.680	7.832	8.102	0.00000*
Detroit	2000	2009–2010 Construction Rate	− 0.106	0.452	0.825	0.91549
Detroit	2000	Household Income	4.925	5.365	5.660	0.00000*
Detroit	2000	Household Income Sq.	5.032	5.485	5.743	0.00000*
Detroit	2000	Sale Price	2.796	3.069	3.551	0.00517*
Detroit	2000	Sale Price, 1-year Lag	2.622	2.948	3.437	0.00873
Detroit	2000	Sale Price, 1-year Lag Sq.	2.951	3.157	3.453	0.00317*
Detroit	2000	Sale Price, 2-year Lag	1.719	1.971	2.260	0.08567
Detroit	2000	Sale Price, 2-year Lag Sq.	1.847	2.159	2.391	0.06476
Detroit	2000	Sale Price Sq.	3.827	4.110	4.351	0.00013*
Detroit	2010	2008 Foreclosure Rate	0.982	1.057	1.313	0.32628
Detroit	2010	2009–2010 Construction Rate	0.002	0.143	0.344	0.99855
Detroit	2010	2009–2010 Demolition Rate	3.110	3.259	3.428	0.00187*
Detroit	2010	2009 Demolition Rate	0.316	0.532	0.743	0.75199
Detroit	2010	2009 Foreclosure Rate	1.531	1.705	1.837	0.12569
Detroit	2010	2010 Demolition Rate	3.329	3.443	3.569	0.00087*
Detroit	2010	2010 Foreclosure Rate	− 0.142	0.238	0.447	0.88702
Detroit	2010	Household Income	1.624	1.825	1.953	0.10440
Detroit	2010	Household Income Sq.	3.090	3.296	3.400	0.00200*
Detroit	2010	Net Change in Units	− 3.359	− 3.215	− 3.065	0.00218*
Detroit	2010	Pre-2007 Foreclosure Rate	0.932	1.460	1.726	0.35121
Detroit	2010	Sale Price	− 0.436	0.063	0.423	0.93870
Detroit	2010	Sale Price, 1-year Lag	− 1.107	− 0.484	− 0.246	0.80545
Detroit	2010	Sale Price, 1-year Lag Sq.	− 1.698	− 0.991	− 0.736	0.46198
Detroit	2010	Sale Price, 2-year Lag	1.119	1.440	1.692	0.26334
Detroit	2010	Sale Price, 2-year Lag Sq.	1.919	2.250	2.448	0.05505
Detroit	2010	Sale Price Sq.	− 1.467	− 0.933	− 0.541	0.58843
Metro Area	1990	Household Income	15.783	16.488	17.761	0.00000*
Metro Area	1990	Household Income Sq.	12.552	13.331	14.623	0.00000*
Metro Area	1990	Sale Price	14.352	14.983	16.166	0.00000*
Metro Area	1990	Sale Price Sq.	9.379	10.038	11.206	0.00000*
Metro Area	2000	2009–2010 Construction Rate	− 0.900	− 0.722	− 0.584	0.55900
Metro Area	2000	Household Income	13.250	13.394	13.543	0.00000*
Metro Area	2000	Household Income Sq.	10.862	10.988	11.124	0.00000*
Metro Area	2000	Sale Price	9.160	9.284	9.504	0.00000*
Metro Area	2000	Sale Price, 1-year Lag	8.992	9.155	9.345	0.00000*
Metro Area	2000	Sale Price, 1-year Lag Sq.	8.038	8.173	8.280	0.00000*
Metro Area	2000	Sale Price, 2-year Lag	9.616	9.791	9.992	0.00000*
Metro Area	2000	Sale Price, 2-year Lag Sq.	8.982	9.118	9.262	0.00000*
Metro Area	2000	Sale Price Sq.	8.609	8.744	8.931	0.00000*
Metro Area	2010	2008 Foreclosure Rate	0.646	0.902	1.094	0.51832
Metro Area	2010	2009–2010 Construction Rate	0.461	0.546	0.647	0.64509
Metro Area	2010	2009 Foreclosure Rate	− 2.666	− 2.368	− 2.113	0.03460
Metro Area	2010	2010 Foreclosure Rate	− 3.738	− 3.534	− 3.426	0.00061*
Metro Area	2010	Household Income	8.430	8.664	8.997	0.00000*
Metro Area	2010	Household Income Sq.	7.798	8.068	8.301	0.00000*
Metro Area	2010	Pre-2007 Foreclosure Rate	2.587	2.752	2.881	0.00968
Metro Area	2010	Sale Price	9.245	9.558	9.882	0.00000*
Metro Area	2010	Sale Price, 1-year Lag	8.262	8.691	9.221	0.00000*

Table 2. continued

Extent	Year	Treatment	Minimum Z	Mean Z	Maximum Z	Maximum *P* value
Metro Area	2010	Sale Price, 1-year Lag Sq.	6.110	6.521	7.011	0.00000*
Metro Area	2010	Sale Price, 2-year Lag	9.007	9.298	9.541	0.00000*
Metro Area	2010	Sale Price, 2-year Lag Sq.	8.563	8.772	8.872	0.00000*
Metro Area	2010	Sale Price Sq.	8.088	8.290	8.495	0.00000*

The P values are marked as significant (*) if they are less than the Bonferroni-corrected threshold of 0.05/m = 0.00625 where m is the number of tests.

pendent processes related to decline, or both can confound these broad trends.

We are interested in differences in effect sizes for the same model between the two geographic levels, as these would suggest scale-dependent effects on vegetated area and call into question generalizations to the metropolitan scale drawn from city-scale analyses. The average effects of household income and sale prices are relatively constant across years at the metropolitan level (Figure 2). In Detroit, however, the effect of income declines between 2000 and 2010 and the effect of sale price, including a 1-year lag, consistently declines between 1990 and 2010. This stark decline in effect size in Detroit is consistent with the aforementioned declining model fit, for these variables, over time and may reflect a decoupling of long-standing socio-ecological relationships as a city declines. At the metropolitan scale, these relationships persist because the contrast between the city and suburbs is so strong.

To facilitate meaningful comparisons, effect sizes are converted to an amount of vegetated area in acres (Figure 3), based on the average block-group size in each year and each spatial extent. For example, in Detroit in 2010, a one-standard-deviation increase in sale price is associated with 1.1–1.4 more acres of vegetated area in the average block group. Because foreclosures, demolitions, and new-construction-related treatments were not standardized, their effect sizes are expressed as the result of one more foreclosure, one more demolition, or one new housing unit than the average number in the average block group. Nonetheless, the magnitudes of a single parcel change in the average neighborhood, in terms of acreage of vegetated area, are only one order less than that of a one-standard-deviation increase in sale price or median household income (Figure 3).

In general, Detroit neighborhoods with high vegetation density but low incomes or sale prices are characterized by a high density of vacant lots (empty parcels where housing used to be) and high tree densities. High-vegetation, low-income neighborhoods increase in number in Detroit over this period. In 2000 and 2010, high-vegetation, low-income neighborhoods are increasingly found on the east side of Detroit. They generally have a high density of vacant lots but some, like Elmwood Park, also include large urban green spaces. Conversely, low-vegetation and high-value or high-income neighborhoods generally have intact housing stock (very few vacant lots). From aerial photographs, these neighborhoods appear to have slightly larger lot sizes, fewer trees, and intact housing stock. At the metropolitan scale, these neighborhoods are almost exclusively characterized by adjacency to business parks and large retail centers.

Comparing Associations with Change in Vegetated Area

Finally, we compared measures of *change* in socio-economic status (from the Census) with real estate and demolition records in regard to the strengths of their relationships with *change* in vegetation (the greenness change index, GCI). We calculated Spearman's rank correlation coefficients between change in the natural logarithm of GCI and three classes of neighborhood-level data: socio-economic measures differenced between the 2000 Census and 2012 American Community Survey (ACS); US Environmental Protection Agency (EPA) National Emission Standards for Hazardous Air Pollutants (NESHAP) notifications of demolitions; and the real estate inventory, including foreclosures and sale prices (Figure 4).

Overall, the measures derived from the demolition records and real estate inventory have stronger bivariate correlations with log GCI than Census-derived statistics. One notable exception is the change in housing density, which has the strongest relationship with log GCI for the City of Detroit and is a Census-derived statistic. Most measures exhibit much weaker correlations at the metropolitan level, which is likely due to the greater variation in neighborhood characteristics at that scale. How-

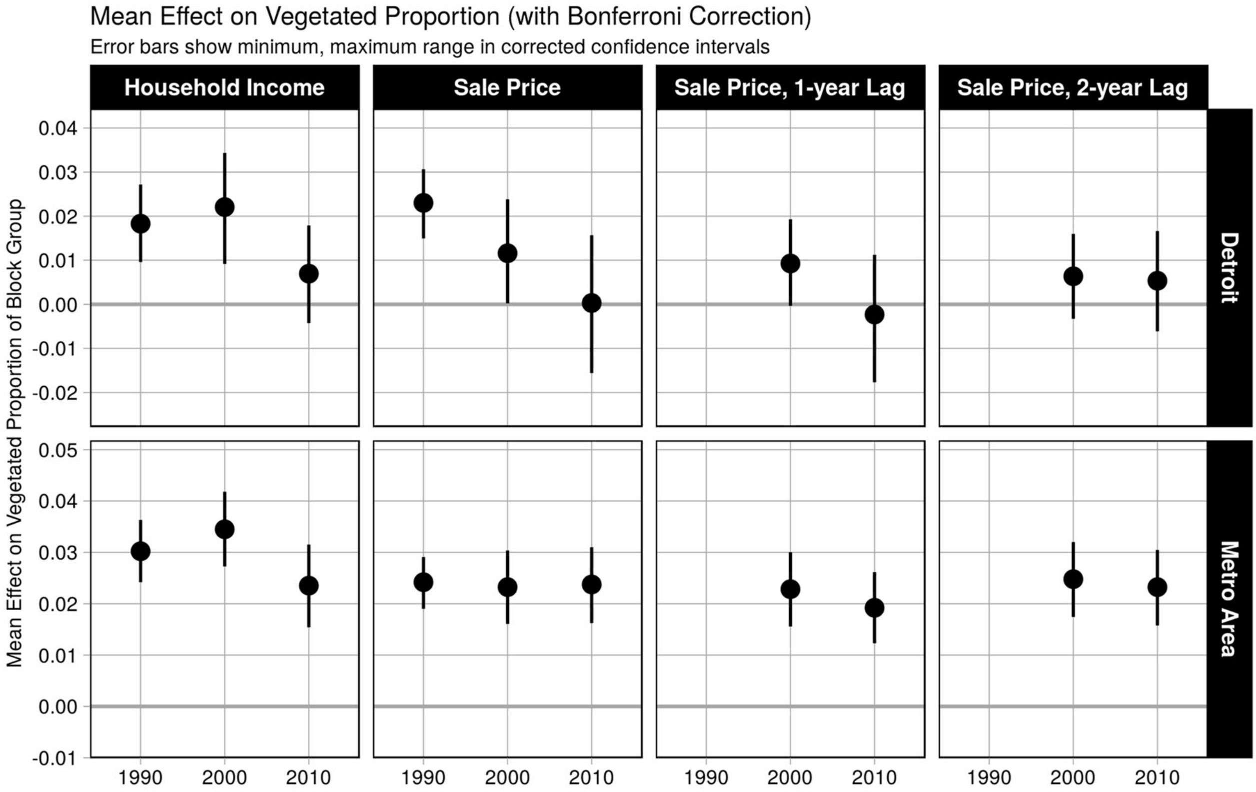

Figure 2. Mean effect sizes and minimum/ maximum confidence intervals for household income and lagged sale price from the multiple-model inference. Effect sizes are corrected for multiple testing with Bonferroni correction and can be interpreted as the change in the proportion of a block group's vegetated area for a one-standard-deviation increase in each treatment.

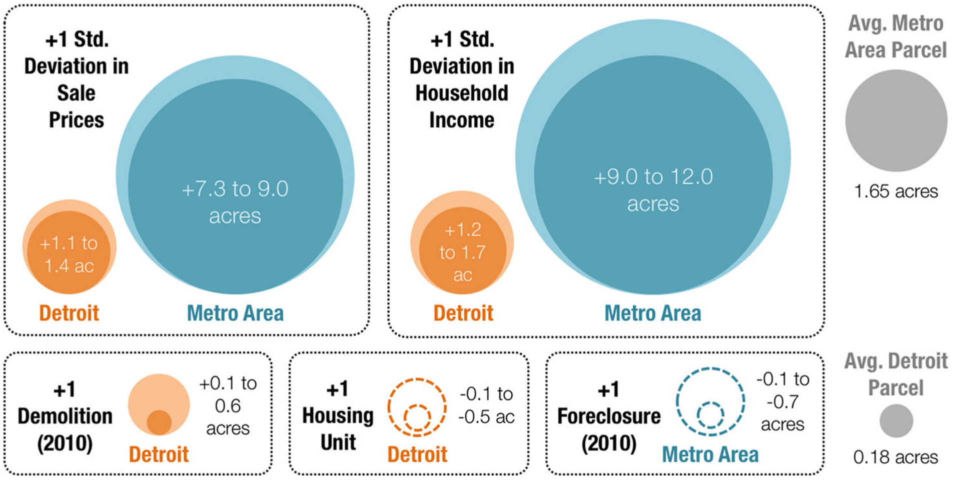

Figure 3. Range of average effect sizes across years on vegetated area, presented in terms of acres of vegetation, holding all else constant. Effect sizes are averaged in each year from across the multi-model inference. Acreage is calculated assuming the average block-group size in each year for either Detroit or the metropolitan area. Only effects that were consistently significant under all of the spatial dependence structures considered are presented here. Solid circles (and positive acreage) represent a positive effect on vegetated area; dashed circles (and negative acreage) represent a negative effect on vegetated area.

ever, we observe stronger correlations at the metropolitan level for housing increase (over the 2000 baseline), the change in the density of vacant housing, the number of new housing starts, and the first derivative of new housing starts. The foreclosure rates in any period are not strongly correlated, on their own, with log GCI at the metropolitan level, even though contemporary foreclosures had a consistent association with lower vegetation density at metropolitan scale in the multi-model inference.

How do specific neighborhoods in our study area fare differently in this period? We found that all neighborhoods in the study area increased in greenness, on average, between 2000 and 2010. Our finding of metro-wide vegetation growth is not surprising, as the construction rate in the City of Detroit is at this time is essentially zero and outside of Detroit, lower-density development patterns lead naturally toward vegetation growth and maintenance in a temperate climate. Changes in household income were not found to be significantly associated with greenness changes between 2000 and 2010 at any scale. Neighborhoods that experienced the most foreclosures between 2003 and 2010 and had the lowest increase in greenness are exclusively in Detroit and its closest suburbs. In general, these suburban neighborhoods are characterized by medium housing densities, high canopy cover, and an intact housing stock. With the exception of one Morningside neighborhood in Detroit, all of the City's neighborhoods with high foreclosure rates and low greenness change are located along the northern and eastern boundaries of Detroit and have very few, if any, vacant lots.

Areas where sale prices increased or only slightly decreased (top quartile of home value change between 2000 and 2010, which includes both losses and gains) and that also experienced the lowest increase in greenness (lowest quartile of log GCI) include neighborhoods in Mexicantown in Detroit, Hamtramck, and neighborhoods west and north of Highland Park. Conversely, areas where sale prices increased or only slightly decreased and with the greatest increased in greenness in Detroit between 2000 and 2010 include neighborhoods situated

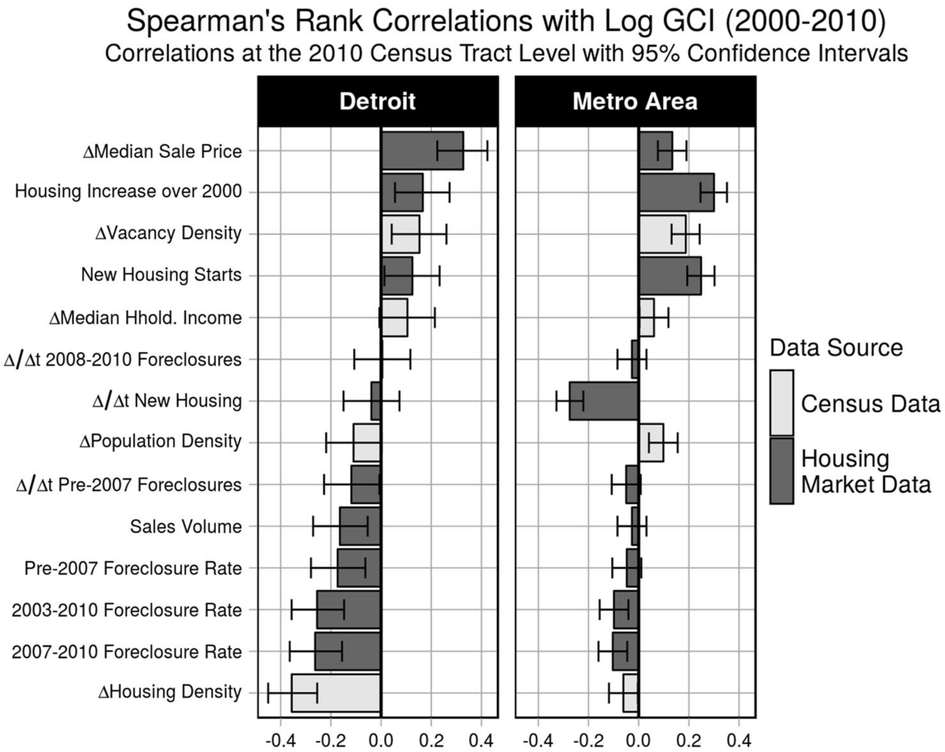

Figure 4. Spearman's rank correlations, shown with 95% confidence intervals, between log GCI and three classes of neighborhood-level measures at the Census tract level. The 2012 ACS class includes socio-economic measures that were observed in the decennial 2000 and 2012 5-year ACS surveys and then differenced. The Real Estate Inventory class includes counts of foreclosures, the number of sales, the number of new housing starts, or the change in median sale price. In general, these latter two classes have stronger correlations with log GCI. EPA NESHAP notifications are not available at the metropolitan level.

relatively close to downtown Detroit and, with the exception of the Springwells neighborhood (which includes a very large outdoor green space), with very high vacant lot densities. Outside of Detroit, neighborhoods that maintained value and increased in greenness are exurban neighborhoods in western and northern Oakland County; these feature very large lots mixed among golf courses and forested wetlands. Previous research on exurban developments in southeast Michigan indicate they increase in greenness over time—to the extent that they are carbon sinks over the long-term—due to their large lot size and land management behaviors (Visscher and others 2014).

Demographics and Vegetated Area

In 1990, at the metropolitan scale, neighborhoods that scored high on the factor associated with white and Asian populations (eigenvalue of 16.29) had higher vegetation densities (median model t-statistic of 4.0); this same factor was associated with high single-family and owner-occupied housing and low poverty rates. In the City of Detroit, high vegetation densities are associated with a very similar factor (eigenvalue of 10.75) but these neighborhoods have mixed white and black populations; neighborhoods that scored high on the factor(s) associated with white population proportion exclusively (eigenvalue of 2.18) or mixed white and Asian populations (eigenvalue of 1.29) actually tend to have *lower* vegetation densities in Detroit (t-statistics of − 4.9 and − 2.6, respectively). From this template in 1990 emerges a consistent, scale-dependent pattern in the associations of vegetation density with white and black populations that persists in 2000 and 2010. The example of 2010 proves the rule: high-black population neighborhoods in Detroit have *higher* vegetation densities (eigenvalue of 8.87, t-statistic of 4.4), whereas similar neighborhoods at metropolitan scale have *lower* vegetation densities (eigenvalue of 6.02, t-statistic of − 8.7). Mixed white and Asian neighborhoods in Detroit have *lower* vegetation densities (eigenvalue of 8.37, t-statistic of − 2.8), whereas similar neighborhoods at the metropolitan scale have *higher* vegetation densities (eigenvalue of 15.48, t-statistic of 4.4). Because the metropolitan model extent includes the City of Detroit, we might conclude that the unexpected (compared to previous studies) negative association between high white population scores and vegetation density is driven in large part by the pattern in Detroit. This pattern, in turn, may reflect a spatial concentration of the majority-black City's non-black residents in the more dense and more central areas. It is also apparent that, unlike socio-economic status, demographics are consistent in their associations with vegetation density over this 20-year period.

DISCUSSION AND CONCLUSIONS

Understanding dynamic neighborhood change processes is important because they influence how disparities in human health well-being are created and enforced through socio-ecological interactions. Increasingly precise spatial and temporal data are available to study these dynamics (Sampson and others 2002). Incorporating new annual, parcel-level data from real estate inventories into studies of urban socio-ecological disparities requires understanding how well these new measures of social condition compare to US Census data, which are well established for broad, cross-sectional studies of neighborhood conditions. For these reasons, we compared how well these different measures of neighborhood conditions and neighborhood changes explain urban vegetation disparities across space and changes in urban vegetation over time.

Our analysis focused on two questions: (1) How do well-established measures of socio-economic status (SES) compare in their associations with vegetated area and vegetation change with new measures of social conditions focused on the housing market? (2) How do these associations hold up in the context of a shrinking metropolitan area and at multiple scales? We discuss the implications of our findings below.

Parcel-Level Measures Link Social and Biophysical Conditions

Although household income often exhibits the strongest association with vegetated area at the metropolitan level, home sale prices are a close second. Sale prices are a good proxy for home values, which convey the physical condition of the housing stock and its neighborhood. As owning a home is often a significant portion of household equity in the USA, home values also convey some information about the wealth of a neighborhood's residents and could affect a homeowner's interest in investing in and maintaining the house and surrounding landscape. As such, home sale prices are a strong link between neighborhood socio-economic and biophysical conditions (Figure 3).

Demolition rates (in the City of Detroit) and foreclosure rates (at the metropolitan level) are also significant effects structuring vegetated area. Demolition has been a policy instrument in Detroit since the early 1970s (Sternlieb and others 1974), used in neighborhoods with abandoned and deteriorated housing stock. We found that demolitions are occurring in neighborhoods with higher levels of vegetation and are associated with growth in vegetated area. Demolitions are therefore another link between neighborhood social and biophysical conditions. When we examined specific neighborhoods, we found that those with an intact housing stock (i.e., few, if any, vacant lots) tended to have low vegetation densities and high incomes, low vegetation *growth* (low increase in greenness), and high cumulative foreclosure rates between 2000 and 2010. This implies that stable housing stock is associated with high incomes and also that foreclosures in the Detroit area are used strategically in areas where the housing stock has not declined to the point of abandonment and demolition.

Comparing the associations of tax foreclosures with vegetation levels and vegetation change, we found that tax foreclosures typically occur in low-vegetation neighborhoods and also in neighborhoods with very little vegetation growth (in this period). However, a bivariate correlation over this length of time says nothing about whether foreclosures precede or follow vegetation change. It should be recognized that feedbacks in the urban socio-ecological system mean that many variables correlated with log GCI may be seen either as drivers of vegetation change or as driven by vegetation change. Therefore, we do not make a distinction here as to the direction of causality. In future studies, the high-frequency, parcel-level data we have introduced here will be essential for discerning the processes driving neighborhood vegetation change and the feedbacks involved.

Socio-Ecological Relationships Differ Across Scales

Our results provide new evidence of scale-dependence in urban socio-ecological relationships, highlighting important differences in the spatial patterns of vegetation between the City of Detroit and the wider metropolitan area. Although we observed consistently positive and stable associations between vegetated area and both higher incomes and higher home values across the metropolitan area, these associations are inconsistent within the City of Detroit.

Why should the well-established, invariably positive and mutually reinforcing relationship between SES and vegetated area, which persists at the metropolitan scale, be different in the City of Detroit? In some ways, Detroit neighborhoods are exceptional within the metropolitan area. Sale prices may be artificially lower in Detroit than in neighborhoods right across the city line: for instance, the same sharp discontinuities in prices can be seen across the southern and eastern boundaries that separate Detroit from neighboring municipalities.

We also find that the shape of the relationships of income and sale price with vegetated area differs between scales. At the city level, vegetated area is highest in both high-income and low-income areas (a quadratic relationship), whereas at the metropolitan level, vegetated area exhibits generally only increases with income. This finding comports with both the well-documented, mutually reinforcing relationship between social conditions and vegetation density (Patino and Duque 2013) and the observed trend of increasing vegetation in declining neighborhoods (Hoalst-Pullen and others 2011). In Detroit, this is clearly suggestive of the challenge in explaining the processes establishing and maintaining disparities in urban vegetation—simultaneously a luxury effect that can capitalize on larger lawns or nearby parks and the effect of ambient, possibly unwanted, vegetation that appears with increasing abandonment and demolition rates. The latter effect is evident in the association of neighborhoods that have high demolition rates with lower household incomes.

With the increasing vacant land burden due to rising demolitions, high incomes are not required to capitalize on more vegetated area, as in a classic metropolitan growth scenario. Detroit's land burden is higher than for similarly situated urban areas, and its disposition of vacant land is often considerably delayed or prevented under the current law (Dewar 2006). Tax foreclosure also operates differently in Detroit than in surrounding municipalities and has systematically discouraged the reuse of tax-foreclosed homes by would-be owner-occupants (Dewar and others 2014). There may also be less incentive to pursue mortgage foreclosures in Detroit due to the real or perceived quality of the housing stock and the lower demand for housing. At the metropolitan level, tax foreclosures are found to have a negative association with vegetated area, yet they exhibit no significant association with vegetated area in the City of Detroit.

This suggests that foreclosures are not consistently associated with certain biophysical conditions in Detroit neighborhoods. Lawn management practices for parcels in foreclosure have been thought to range from neglect (and overgrowth) to conspicuous maintenance (frequent mowing and trimming to maintain attractiveness). Although these processes operate at the parcel level, where the effect of neglect has been previously detected (Deng and Ma 2015), our results suggest that either: lawn management practices associated with foreclosure cannot be detected at the neighborhood level; that both processes are operating and cancel out in the aggregate; or that there are confounding effects on vegetated area associated with other, unobserved processes. Many of these apparent idiosyncrasies may be found in other major cities, particularly shrinking cities, as property laws, the efficacy of local institutions, and local housing market activity will always vary across the metropolitan area.

Socio-Ecological Relationships May Change Over Time

There is also evidence in Detroit that income and home prices have declined as correlates of vegetation density over time (Figure 2), such that we might expect they no longer exhibit any relationship with vegetated area in the near future. By 2010, neighborhood demolition rates and the net change in housing are better predictors of vegetated area in Detroit than household income or home sale prices. This suggests that widely theorized, wealth-related processes for allocating urban vegetation—the consumption of landscaping or larger lawns by private homeowners, the development of public green spaces in wealthier areas—play a diminishing role in shrinking cities. Though we only have demolitions data for the Census year 2010, it is evident that more demolitions are strongly related to increased vegetated area in Detroit neighborhoods.

This declining association between socio-economic status, as measured by income or home value, and vegetated area in Detroit (Figure 2), is inconsistent with Lowry and others' (2012) suggestion that the passage of time would strengthen income–vegetation relationships. It can be understood, however, in the context of a declining city like Detroit, where both population size and the capability to maintain residential land are declining. Urban neighborhoods can be theorized as complex adaptive systems, characterized by feedback loops: home value appraisals are based on recent sales nearby, low home values present a barrier to accessing credit for home improvements, and municipal (dis)investment in services is both a driver and a consequence of the available tax base. As social and economic feedback loops break down due to population loss and declining investment, the reproduction of certain socio-ecological relationships will also inevitably decline. This is more consistent with Watmough and others' (2013) hypothesis that correlations between socio-economic status and land cover are weaker in rural areas because local population-and-environment links are more complex. Luck and others (2009) also suggested that socio-economic factors have less influence in less established neighborhoods. In general, this result suggests that socio-economic status is unreliable as a predictor of the vegetation distribution for all cities and all spatial scales. In particular, relationships of vegetation patterns to socio-economic condition in declining cities and at the metropolitan scale may not be well-approximated by studies of growing cities at the city scale. Additionally, it points to the need for more spatially and temporally detailed investigations of neighborhood change that can support process-based explanations of socio-ecological change in urban neighborhoods. Such studies can be supported by the new measures presented here.

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