Race and affluence shape spatio-temporal urbanization trends in Greater Houston, 1997 to 2016

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Abstract:

Urbanization results in increasing impervious surfaces with the potential to threaten fragile environments and heighten flood risks. In the United States, research on the social processes driving urbanization has tended to focus on the twenty-first century, but less is known about how temporal trends arose from the spatial layout of developed land upon which this growth was founded. To address this gap, we present a novel interdisciplinary synthesis using neighborhood-level census data in tandem with a satellite-derived annual land cover change time series to assess the role of race, affluence, and socioeconomic status in shaping spatio-temporal urbanization in the Houston metropolitan area from 1997-2016. Results from cross-sectional and temporal regression models indicate that while social dynamics associated with historical versus recent urbanization are related, they are not identical. Thus, while temporal change in urbanization is driven primarily by socioeconomic status, the social dynamics associated with spatial disparities in urbanization relate primarily to race, regardless of socioeconomic status. The results are noteworthy as urbanization in Houston does not fully comport with existing theoretical perspectives or with empirical findings nationally. Instead, we suggest these findings reflect the city's politics and culture surrounding land use. Thus, beyond its important social and environmental implications, this study affirms the utility of fusing socio-demographic data with satellite remote sensing of urban growth, and highlights the value of the socioenvironmental succession framework for characterizing urbanization as a recursive process in space and time.

Key Words: Land Use; Land Cover Change; Remote Sensing; Environmental Change; Urban Development; Spatial Privilege

1. Introduction

Environmental perils in the age of the Anthropocene abound. One anthropogenic change at the root of global environmental degradation is urbanization (Seto, Sánchez-Rodríguez, and Fragkias 2010; Duveiller et al. 2020). As forests, grasslands, and wetlands are converted to housing developments, factories, and shopping centers, environmental problems proliferate: biodiversity declines, impacts of dangerous emissions increase, and flood risks from impervious surfaces rise.

Social scientific investigation of urbanization has often focused on the socio-spatial processes that animate how cities are changing. In the United States, this often means studying how neighborhood changes are propelled by trends like suburbanization and, more recently, back-to-the-city movements – both of which are predominantly driven by imbalances in levels of privilege, especially among white residents and those with greater affluence as a product of their higher socioeconomic status (Drier, Mollenkopf, and Swanstrom 2001; Hyra 2015). But this body of research has largely ignored the environmental changes entailed by the physical transformation of the land surface underlying these urbanization trends. Emergent research, though, seeks to address this glaring lacuna in the literature by utilizing disparate data sources, advanced statistical methods, and novel technologies to integrate environmental change with social analyses of urbanization. While this emergent literature's emphasis on relating environmental change to back-to-the-city migration (and corresponding processes inherent in the suburbanization of poverty) is compelling for theorizing recent changes in the twenty-first century (*sensu* Clement and Alvarez 2020; Wilson and Brown 2015), it neglects historically pertinent factors, especially the fact that much of the physical footprint of American cities had already experienced urbanization well before recent decades.

This study advances research pairing neighborhood-level urbanization and land cover change by analyzing not just recent *temporal* trends in urbanization, as is common in emergent work on the topic, but also by assessing *spatial* disparities in the distribution of urban land cover, independent of those temporal trends. We conceptualize the interplay of the spatial and temporal factors underlying urbanization using a socioenvironmental succession perspective that conceives of urbanization as a layered, historical process where social and biophysical dynamics intertwine recursively across time (Elliott and Frickel 2015; Frickel and Elliott 2018).

Using cross-sectional spatial and temporal models of land cover change in the fast-growing Houston metropolitan area from 1997 to 2016, this study poses two critical questions: (1) what are the social, racial, and economic characteristics of neighborhoods associated with *spatial* disparities in Houston's urban land cover for the years 1997 and 2016? and (2) what are the social, racial, and economic characteristics of neighborhoods that experienced *temporal* changes in urban land cover over the course of the study period from 1997 to 2016? In addressing these questions, this framework for analyzing urbanization details not only the types of neighborhoods that are urbanizing most rapidly in contemporary times, but also the characteristics of those neighborhoods that urbanized prior to the 21st century. Of particular interest in this study is to trace how environmental change relates to two key indicators of socio-spatial differentiation in American cities – race and socioeconomic status – by uncovering how spatial privilege relates to land cover change.

For the purposes of this study, we define urbanization as a temporal process: the conversion of land from natural or semi-natural land cover (e.g. forests, grasslands, grazing land, and agriculture) to a developed land cover class, defined as land area chiefly characterized by its impervious surfaces including buildings, pavement, and other anthropogenic constructions resistant to natural water infiltration. In the article, we refer to these temporal land conversion processes variously and interchangeably as urbanization, increasing impervious surface, and development (the latter referencing a specific land cover change term, and not "development" more broadly).

2. Literature Review

2.1 Perspectives on temporal urbanization processes in the United States

Social scientists interested in urbanization have sought to elucidate the social and demographic characteristics that have enabled it (Hersperger et al. 2010). Studies in the United States, often conducted at the county level, have found that land cover change is predominantly conditioned by increases in population size (Clement, Chi, and Ho 2015; Clement and York 2017; Ducey et al. 2018; Chi and Ho 2018; Tong and Qiu 2020) and socioeconomic status (Wilson and Brown 2015). Less research, though, has been conducted on how these social processes operate at the neighborhood scale (for exceptions, see Clement and Alvarez 2020; Wilson and Brown 2015). But neighborhoods matter as a key area of interest because county-level analyses tend to be conducted at a relatively coarse scale. Social and demographic measures like race and socioeconomic status are too heterogeneous across space to capture within-county spatial disparities that are otherwise evident at the more granular neighborhood scale. Land cover also varies considerably within a county. These concerns underlie the imperative for analyses conducted at the neighborhood scale to better account for the social and environmental heterogeneity only observable at these finer spatial scales.

The emergent research on neighborhood-scale environmental change and urbanization is especially interested in assessing *temporal* change occurring in recent decades. A key social process underlying these environmental changes concerns spatial privilege. Rudel et al. (2011) theorizes this privilege as the ability to control urban development to preserve green space among urbanizing areas as an environmental amenity (see also Rudel 2009a; Rudel et al. 2011; Rudel 2013). Greater affluence or socioeconomic status, Rudel notes, plays a critical role in powering what Molotch (1976) terms "aristocratic conservation," namely that the environmental privilege inherent in preserving landscapes is more likely in more affluent areas (see also Clement and Podowski 2013).

In the most comprehensive work to date on the topic, Clement and Alvarez (2020) show evidence for this idea of environmental privilege in a national analysis of land cover change from 2001 to 2011, finding that neighborhoods increasing in income did not experience as large an increase in urbanization compared to neighborhoods with declining economic fortunes during the same time period. Clement and Alvarez (2020) attribute the occurrence of greater urbanization in economically disadvantaged places to two simultaneous processes: the suburbanization of poverty and the "back-to-the-city" movement (Kneebone and Garr 2010; Raphael and Stoll 2010; Hyra 2015). The upshot of these two urbanization processes is that while more affluent, and often white, residents have been leaving the suburbs and moving to the urban core, less affluent residents of the urban core are concurrently moving out of the central city, or being displaced through gentrification, and moving to the suburbs. In all, explanations for environmental privilege, the suburbanization of poverty, and the back-to-the-city movement suggest a critical implication for urban environmental change: as areas become more affluent and more privileged, we expect urbanization rates to slow, thereby preserving natural space as an environmental amenity.

2.2. Perspectives on spatial urbanization processes in the United States

Our second research question is centrally interested in how social and demographic neighborhood changes relate to temporal change in land cover, and specifically that of urbanization. While this question has been addressed in theoretical frameworks on defensive environmentalism like those discussed above (e.g. Clement and Alvarez 2020; Rudel 2013), our first research question - regarding the spatial characteristics of urbanized places regardless of recent temporal changes has not been the central issue of empirical study or clearly theorized in previous work. Put another way, existing explanations for the drivers of neighborhood-level urbanization relate primarily to *temporal changes* in the pattern of urbanization over recent decades, but largely leave aside the issue of the underlying *spatial differences* in urbanized land, whether recently urbanized or urbanized long ago.

To bridge this gap, we employ a *socioenvironmental succession* perspective (Rudel 2009b; Elliott and Frickel 2015; Frickel and Elliott 2018; Elliott, Korver-Glenn and Bolger 2019). Re-examining ecological theory that was highly influential to early urban studies and sociology (Park and Burgess 1925) alongside a political economic approach to urban space (Logan and Molotch 1987), Elliott and Frickel (2015:5) describe socioenvironmental succession as the "…interactions among social and biophysical phenomena that situate urban land use patterns recursively and reciprocally in place." Key to conceptualizing socioenvironmental succession is following the intertwined dynamics of environmental change and urbanization that occur across time *and* space.

Following from this, an important point of departure in our study is that while back-to-the-city migration and the suburbanization of poverty typify twenty-first century American urbanization, these processes do not characterize urbanization in previous time periods. For example, prior to World War II, urbanization in American cities like Houston was driven primarily by population growth and industrialization, resulting in relatively compact urban footprints, at least partly because transportation systems that facilitated extensive motor vehicle use did not yet exist. These compact cities – now subsuming the urban core of contemporary urban areas – exhibit two counteracting environmental impacts: their density ensured that while the extent of their environmental footprint was smaller compared to the sprawl of later periods, their impervious surfaces were simultaneously far more concentrated, and thus their environmental impact was more acute. It was a lack of green space in these places that influenced later patterns of urbanization, as multiple related social movements in the late-nineteenth and into the twentieth century advocated for greener (and therefore less impervious) locales for human residence such as Olmstead's approach to urban planning or the garden cities of Ebenezer Howard (Mumford 1961). By the second half of the twentieth-century, suburbanization – and, by extension, urban environmental change – by upper-middle-class, often white residents became the more dominant trend (Jackson 1985; Drier, Mollenkopf, and Swanstrom 2001). In all, these historical changes set in place the structures – in the physical footprint of the city, its socio-spatial segregation, and its local cultures – upon which any future changes took place. Therefore, a key insight from the socioenvironmental succession theoretical framework is that insight into recent urbanization trends can only take place with an adequate understanding of how they relate to those urbanization trends preceding them.

An additional factor critical to understanding spatio-temporal drivers of urbanization analyzes variation among cities to discern how historical conditions sponsor different patterns of land use (Chi and Ho 2018; Xu and Chi 2019). Analyzing differences among cities involves accounting for differences in economic paths, political cultures, and urban form across a city's history (Molotch, Freudenberg, and Paulsen 2000; Emerson and Smiley 2018). One readily available metric for comparing trajectories among urban areas relies on relative differences in population growth in recent decades. For example, compared with the “Rust Belt” cities of twentieth-century manufacturing hubs where populations have held largely constant or declined, cities in the “Sun Belt” region have seen dramatic increases in population in recent decades.

2.3 Houston: A Case Study

This study’s case, Houston, Texas, epitomizes a Sun Belt city. The Houston metropolitan area grew sevenfold in population from less than one million residents in 1950 to its present status as America’s fifth most populous metropolitan area. Land use patterns in Houston are partly driven by the fact that it is the only major American city without zoning, possessing a culture and governance that has engendered ever-expanding urban growth to the fringes of the metropolitan area (Qian 2010; Shelton 2017; Emerson and Smiley 2018). Houston is also an unequal city, exhibiting pronounced spatial disparities in racial and economic residential segregation (Bullard 1987; Howell and Emerson 2018), as well as environmental degradation and risk (Chakraborty et al. 2014; Elliott and Smiley 2019). In all, this “market city” is emblematic of large-scale environmental change in a highly unequal urban area with lax land use policies (Emerson and Smiley 2018). Clement and Alvarez (2020) argue that Houston typifies national urbanization trends, namely that suburban areas with decreasing incomes or lower income growth tend to be experiencing the most rapid land cover change, with already highly-urbanized and increasingly affluent central city neighborhoods experiencing slower urbanization rates. Importantly, these urbanization trends hold special significance for Houston’s ability to mitigate climate change impacts as its vast areas of impervious surface have been directly linked to heightened flood risk and impacts, a fact exemplified by the devastation wrought by Hurricane Harvey (Zhang et al. 2018).

3. Materials and Methods

3.1 Data Sources

To answer this study's research questions, we synthesized socio-demographic census tract data from the United States Census and satellite-derived, remotely-sensed land cover change maps from the Kinder Institute for Urban Research (Table 1). For the former, we created a dataset of all census tracts for each of the 20 years between 1997 and 2016, for nine counties in the Houston metropolitan area: Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties. Census tracts, which conventionally represent "neighborhoods" in geographic research, have on average 4,000 to 5,000 residents. Census tracts missing key study variables or possessing a population of less than 100 were excluded, resulting in 28 cases being dropped from the analysis. The final number of valid cases was 1,041 census tracts across 20 years for a total of 20,820 tract-years.

Social and demographic data were drawn from the U.S. Census Bureau's 1990, 2000, and 2010 decennial censuses, as well as the American Community Survey (ACS) five-year pooled estimates for 2008 to 2012 from the Longitudinal Tract Database (LTDB; see Logan, Xu, and Stults 2014) and from the National Historical Geographic Information Systems (Manson et al. 2019) for 2014 to 2018. Because census tract boundaries change over time, tracts were harmonized to 2010 boundaries to make analyses comparable across time. To match the annual temporal resolution of the Greater Houston land cover change dataset, we performed a linear interpolation on the U.S. Census and ACS data to generate estimates for the social and

Table 1. Descriptive Statistics for Census Tract Characteristics

Variable Name	Mean (SD)	Min	Max
1997 Census Tract Characteristics (n=1,041)			
Prop. Developed Land (Impervious Surfaces)	0.36 (0.22)	0.004	0.89
Land Area (Square Km)	21.11 (61.47)	0.16	662.49
Population	4,169 (1,646)	118	9,874
Median Home Built pre-1967 (binary)	0.18 (0.38)	0	1
Prop. White	0.52 (0.29)	0.00	0.97
Median Income	61,195 (28,499)	9,767	255,701
Median Home Value	124,883 (90,739)	27,606	1,151,001
Prop. Owner-Occupied Homes	0.61 (0.24)	0.01	0.98
Prop. Unemployed	0.06 (0.04)	0.01	0.32
Prop. College Educated	0.25 (0.19)	0.00	0.79
Prop. Manufacturing Workers	0.13 (0.05)	0.02	0.4
Prop. Vacant Properties	0.09 (0.06)	0.02	0.7
2016 Census Tract Characteristics (n=1,041)			
Prop. Developed Land (Impervious Surfaces)	0.44 (0.2)	0.01	0.89
Land Area (Square Km)	21.11 (61.47)	0.16	662.49
Population	6400 (4690)	570	70271
Median Home Built pre-1967 (binary)	0.18 (0.38)	0	1
Prop. White	0.36 (0.26)	0.00	0.91
Median Income	68,318 (37,519)	12,615	250,001
Median Home Value	184,681 (173,627)	16,192	1,820,001
Prop. Owner-Occupied Homes	0.58 (0.24)	0.00	0.99
Prop. Unemployed	0.06 (0.04)	0.00	0.43
Prop. College Educated	0.29 (0.22)	0.01	0.95
Prop. Manufacturing Workers	0.1 (0.04)	0.01	0.29
Prop. Vacant Properties	0.1 (0.07)	0.00	0.79
1997-2016 Pooled Census Tract Characteristics (n=20,820)			
Prop. Developed Land (Impervious Surfaces)	0.41 (0.21)	0.00	0.89
Land Area (Square Km)	21.11 (61.47)	0.16	662.49
Population	5,213 (2977)	117	70,271
Median Home Built pre-1967 (binary)	0.18 (0.38)	0	1
Prop. White	0.43 (0.28)	0.00	1
Median Income	61,716 (31649)	9100	256,001
Median Home Value	146,305 (119,668)	1236.8	1820001
Prop. Owner-Occupied Homes	0.61 (0.24)	0.00	0.99
Prop. Unemployed	0.07 (0.04)	0.00	0.43
Prop. College Educated	0.27 (0.2)	0.00	0.95
Prop. Manufacturing Workers	0.11 (0.05)	0.00	0.6
Prop. Vacant Properties	0.09 (0.07)	0.00	0.79

Note: All variables are shown before log transformations.

demographic variables for years between 1997 and 2016. For the purposes of the interpolation, we assigned the mean of the 2008-2012 ACS pooled estimates to 2010, and the 2014-2018 estimates to 2016.

The annual Greater Houston land cover change dataset consists of a time series of fractional impervious surface maps from 1997-2017 at a 30m pixel resolution (Hakkenberg 2018; Hakkenberg et al. 2020), where "fractional impervious" corresponds to the estimated percentage of impervious cover in each pixel. The land cover change time series was created by classifying 262 Landsat satellite images across the Greater Houston area into four levels of imperviousness following the National Land Cover Database (NLCD) categories: (1) Developed–open (developed areas with less than 20% impervious cover), (2) Developed–low (20-49% impervious), (3) Developed–medium (50-79% impervious), and (4) Developed–high (greater than 80% impervious) (Homer et al. 2015).

Driven by a demand for spatio-temporal accuracy and consistency across the multi-decadal imagery time series (where individual images may vary due to seasonal illumination angles and atmospheric conditions), the land cover change dataset was generated using a three-part algorithmic procedure: (1) automatic adaptive signature generalization (Dannenberg et al. 2016) for automated training data selection from NLCD classifications from 2001, 2006, and 2011 (Homer et al. 2015), (2) machine learning image classification using random forests to classify atmospherically-corrected image spectra to one of the four aforementioned developed classes (Hakkenberg et al. 2020), and (3) spatio-temporal filtering to reduce erroneous classifications due to clouds, atmospheric contamination, and other sources of data noise and model errors among the 153 billion pixels classified (Hakkenberg et al. 2019). All classifications were validated using independent, multi-temporal fine-resolution imagery from the Ikonos, Quickbird, and Worldview sensors (Hakkenberg et al. 2019).

3.2 Annual urbanization trends

We adopt annual urbanization at the neighborhood scale as the dependent variable for all analyses in our study (see *Analytical Strategy*). To determine this neighborhood-level proportion, we used the annual Greater Houston land cover change dataset to estimate urbanization as the proportion of land developed each year in each census tract. To do this, we first assigned a single fractional impervious value to each 30 m pixel based on the mean of the two values that define its range. For example, the developed-open class (0-20% impervious) was assigned a value of 0.1, while the developed-high class (80-100% impervious) was assigned a value of 0.9. Next, these subpixel-scale (<30m) impervious values were multiplied by total pixel area (900 m^2) and then summed across a given census tract to generate a single value for total impervious area. We then divided this value by each census tract's land area to derive the proportion of impervious surface at the neighborhood scale. This calculation was conducted for each year of the data. To facilitate computation of pixels that overlapped multiple census tracts, the land cover change dataset was converted from a raster to a vector data set that was then intersected with census tracts, and overlapping pixels were apportioned by the percentage of the area within a given census tract.

3.3 Social and Demographic Characteristics

Socio-demographic indicators from the U.S. Census and ACS capture neighborhood characteristics and record how they change through time. For this study, we focused on variables associated with race and socioeconomic status as they most closely relate to the study's emphasis on the relationship between urbanization and spatial privilege. For race, we used the proportion of non-Hispanic white residents (as opposed to minority racial groups) to retain the theoretical emphasis on spatial privilege. For socioeconomic status, we assembled several variables on affluence, including median household income, median home value, proportion of owner-occupied homes, proportion of college educated residents, and proportion unemployed residents. To adequately contextualize these analyses, we include three baseline controls: (1) population, which is long linked to environmental impacts; (2) land area, as change may tend to occur in larger areas while smaller areas may already be more densely developed; and (3) a binary variable denoting older neighborhoods if the median home in the neighborhood in 2016 was built before 1967 (i.e. 50 years earlier). Finally, we include two secondary control variables: the proportion of vacant properties and the proportion of manufacturing workers.

3.4 Analytical Strategy

To assess how land cover in Greater Houston relates to race, socioeconomic status, and privilege, we employed cross-sectional and temporal regression models. The cross-sectional models include two separate spatial autoregressive models with spatial autoregressive disturbances (SARAR models) that predict the proportion of developed land in a census tract in 1997 and 2016, respectively. The SARAR model is:

$$\mathrm{y} = \sum_{k=1}^{K} \beta_k \mathrm{x}_k + \sum_{p=1}^{P} \gamma_p \mathrm{W}_p \mathrm{x}_p + \sum_{r=1}^{R} \lambda_r \mathrm{W}_r \mathrm{y} + \mathrm{u}$$

$$\mathrm{u} = \sum_{s=1}^{S} \rho_s \mathrm{M}_s \mathrm{u} + \epsilon$$

where y is an n x 1 vector of observations of the dependent variable, X are independent regressors, λ is a spatial lag for the dependent variable, u refers to spatially lagged errors, and W and M are spatial weights matrices. The SARAR model controls for spatial autocorrelation both in the dependent variable (as with a spatial lag model) and the error term (as with a spatial error model). Akaike Information Criterion (AIC) statistics indicate that the SARAR model is preferable to alternative model specifications such as spatial lag or spatial error models. The SARAR model was parameterized with a queen-one contiguity spatial weights matrix, which outperformed a distance-based weights matrix based on AIC. Because each of these models is cross-sectional, the number of cases used in the analysis is 1,041, one for each of the valid census tracts in the Houston metropolitan area.

The temporal regression model is a spatial fixed effects model that predicts drivers of temporal change in the proportion of land developed from 1997 to 2016 and is parameterized as:

$$\tilde{y}_{nt} = \lambda \mathrm{W}\tilde{y}_{nt} + \widetilde{\mathrm{X}}_{nt}\beta + \mathrm{X}_{n} + \tilde{\mathrm{u}}_{nt}$$

$$\tilde{\mathrm{u}}_{nt} = \rho \mathrm{M}\tilde{\mathrm{u}}_{nt} + \tilde{\mathrm{v}}_{nt}$$

where $\tilde{y}_{nt}$ is an n x 1 vector of observations for the dependent variable for time period t with n number of panels, λ is a spatial lag for the dependent variable, $\widetilde{\mathrm{X}}$ are time-varying independent regressors, X are time-invariant regressors, u are spatially lagged errors, and W and M refer to spatial weights matrices. Based on a comparison of AIC statistics, the temporal regression model was parameterized with a SARAR model that controls for spatial dependence using a queen-one contiguity spatial weights matrix. Following convention for fixed effects models (Alisson 2009), two time-invariant predictor variables (land area and the binary variable denoting whether the median home was built before or after 1967) were included in an interaction term with the year variable, which is measured with dummy variables using 1997 as the reference category. The model employs the full range of temporal data including 20 distinct years of data, such that the total cases over the period correspond to 20,820 tract-years.

Both the cross-sectional and the temporal regression models employ an elasticity approach for coefficients whereby all independent variables and the dependent variable were log transformed. In terms of interpretation, the coefficient of a log-transformed independent variable is the estimated percentage change in the dependent variable for a 1% increase in the independent variable. While the cross-sectional spatial models for 1997 and 2016 measure differences *across* units, the temporal fixed effects model measures differences *within* units. In other words, the cross-sectional models measure how neighborhoods compare to each other, while the temporal model compares how a single neighborhood changed between dates.

4. Results

4.1 Descriptive Statistics

Urbanization trends in the Greater Houston metropolitan area are represented in Figure 1, which illustrates the contrasts between spatial and temporal patterns in land cover. Spatially, the areas with the highest proportions of impervious surface (Figure 1a) are often different from the areas possessing the most rapid increases in urbanization in recent years (Figure 1b). Figure 1b likewise highlights the fact that most of Houston's recent urbanization occurred outside its second ring road (Beltway 8), although there is a degree of heterogeneity even in these suburban and exurban areas, with some census tracts experiencing growth alongside others that did not. Temporally, the median neighborhood (by degree of urbanization) increased its proportion of developed land by 5.1% from 1997 to 2016. This percentage increase equates to the addition of 0.24 km^2 of impervious surfaces in the median neighborhood during that time period, and

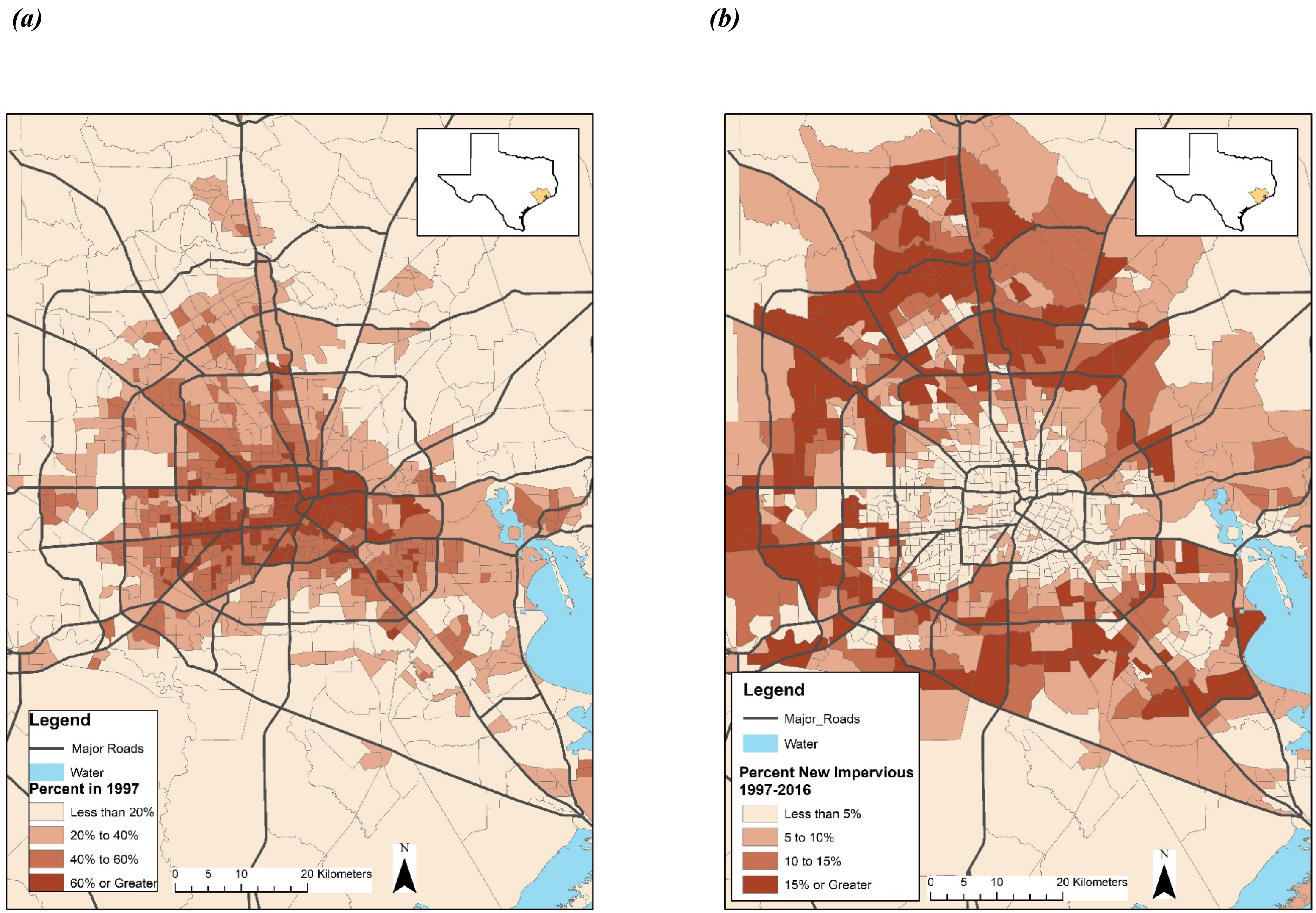

Figure 1: Impervious Surfaces in Greater Houston. (a) Percent impervious surfaces in 1997; (b) percent new impervious surfaces, 1997 to 2016; Insets: Houston Metropolitan Area in Texas.

approximately 1,000 km^2 for the overall metropolitan area. This 1,000 km^2 increase bespeaks extremely large-scale urbanization, approximately 1.25 times larger than the total land area of New York City (784 km^2).

Despite dramatic urbanization from 1997 to 2016, Figure 1 also reveals that most neighborhoods were already relatively urbanized by 1997, with a median level of imperviousness of 36.5% per census tract. The distribution of these densely urbanized areas in 1997 is highly variable across the metropolitan area, with 26.4% of census tracts possessing less than 20% impervious surface, compared to 15.9% of census tracts where at least 60% was developed. By 2016, the overall area of impervious surface in Greater Houston grew to 2,614 km^2, an area nearly equal to that of the state of Rhode Island. Not surprisingly, even in a fast-growing metropolitan area that added nearly three million residents during the twenty-year time period, a majority (62%) of impervious surfaces in 2016 were already present in 1997. Figure 1a showcases those areas characterized by the highest proportions of impervious surface in 1997. While urban core areas possess the highest levels of impervious surface, great spatial variation exists both within the urban core and in some more developed census tracts alongside major roads beyond the urban core. Moreover, these highly urbanized areas contrast sharply with the areas of increasing urbanization seen in Figure 1b.

4.2 Regression Results

Table 2 provides cross-sectional spatial model coefficients predicting neighborhood-scale proportion impervious surfaces in 1997 (Model 1) and 2016 (Model 2). Two findings stand out in Model 1. First, independent of important controls like population and land area, census tracts that had a higher proportion of white residents in 1997 had, on average, a greater proportion of developed land. Second, the primary controls on urbanization were found to have significant and large effects: areas with more population and smaller land areas tend to also possess a greater proportion of impervious surfaces.

Table 2. SARAR Regression Results Predicting Proportion Developed Land in 1997 and 2016 in Greater Houston.

	Model 1 (1997)			Model 2 (2016)		
	Coef.		SE	Coef.		SE
Land Area (Square Km)	-0.537	***	0.017	-0.384	***	0.014
Population	0.339	***	0.024	0.27	***	0.019
Median Home Built pre-1967 (binary)	0.014		0.038	0.02		0.029
Prop. White	0.059	**	0.019	0.045	***	0.013
Median Income	0.026		0.078	-0.039		0.04
Median Home Value	-0.081		0.048	-0.078	**	0.028
Prop. Owner-Occupied Homes	0.046	†	0.027	0.019		0.016
Prop. Unemployed	0.06		0.039	-0.02		0.016
Prop. College Educated	0.033		0.029	0.029		0.02
Prop. Manufacturing Workers	0.049		0.04	0.015		0.018
Prop. Vacant Properties	0.055	†	0.03	0.013		0.014
Constant	-1.589		0.85	-0.786		0.481
ρ	0.363	***	0.027	0.427	***	0.03
λ	0.227	***	0.059	0.306	***	0.059
Pseudo R^2	0.885			0.858		
N	1,041			1,041		

Note: †<0.1; *p < 0.05; **p < 0.01; ***p < 0.001.

Model 2 uses data from 2016 to assess how spatial patterns from 1997 (Model 1) hold nearly 20 years later. Results indicate that race remains a statistically significant and positive predictor of proportion impervious in 2016. However, unlike in 1997 (where home value is negative but not statistically significant), home values in 2016 are statistically significant: the negative association showing that neighborhoods with higher home values tend to have less proportional impervious surface. The relatively large R^2 values (0.89 in Model 1 and 0.86 in

Model 2) are largely due to the explanatory power of the baseline controls of population and land area, which retain their directionality and large effect size in both models.

Table 3. SARAR Fixed Effects Regression Results Predicting Increases in Proportion Developed Land from 1997 to 2016 in Greater Houston.

	Model 1		
	Coef.		SE
Land Area (Square Km)[1]	+		
Population	0.342	***	0.003
Median Home Built pre-1967 (binary)[2]	-, +		
Prop. White	-0.001		0.002
Median Income	-0.024	***	0.006
Median Home Value	0.027	***	0.004
Prop. Owner-Occupied Homes	0.015	***	0.003
Prop. Unemployed	-0.005	**	0.002
Prop. College Educated	0.01	***	0.003
Prop. Manufacturing Workers	0.01	***	0.002
Prop. Vacant Properties	0.03	***	0.002
Year[3]	-		
ρ	0.313	***	0.009
λ	0.102	***	0.016
Pseudo R^2	0.202		
N	20,820		

Note: †<0.1; *p < 0.05; **p < 0.01; ***p < 0.001.

[1] The interaction between time-invariant land area and the year variable is statistically significant and positive for each year (1998-2016).

[2] The interaction between time-invariant median home year built and the year variable is statistically significant in 2000 and from 2002-2007. It is negative from 1998-2012 and positive from 2013-2016.

[3] The year variable is negative for all years and statistically significant from 2003-2016.

Table 3 presents the results of the temporal model that predict changes in the proportion of developed land. Several relationships merit mention. Results indicate that neighborhoods that experienced increases in home values, college educated residents, owner-occupied homes, and employed residents all tend to have experienced an increase in proportional impervious surface. In contrast, median income is negatively associated with increases in proportional impervious surface, indicating that increasing incomes lead to comparatively slower rates of urbanization. While cross-sectional models show that census tracts with more developed land tend to have more white residents, we find no statistically significant temporal trend for the effect of race. Importantly, these socio-demographic effects on urbanization are statistically significant even after controlling for population and land area, where neighborhoods experiencing more rapid urbanization tend to be growing in population and have larger land areas.

5. Discussion and Conclusion

Urbanization transforms natural landscapes into anthropogenic ones. In a region like Greater Houston, this transformation of pervious to impervious surface entails not only the potential loss of local ecological integrity, but also increased flood risk and impacts because high levels of impervious surfaces serve comparatively poorly as sponges of excess water compared to the landscapes that preceded them (Brody et al. 2013; Zhang et al. 2018). In this study, we present a novel inter-disciplinary synthesis, fusing remotely-sensed data on land cover change from space-borne sensors with data on neighborhood-level socio-demographics to investigate the factors driving recent decades of urbanization, as well as the characteristics that tend to be associated with higher levels of urbanization in the first place.

The overarching finding of this study is that the nature of the relationship between temporal urbanization trends are related, but not identical, to those driving spatial differences in impervious surface. The social dynamics that tend to be associated with spatial differences in urban cover primarily relate to race: neighborhoods with more white residents have higher levels of impervious surfaces, while variables relating to socioeconomic status were not strongly linked to spatial differences in impervious surface. The social dynamics that tend to be associated with temporal change, on the other hand, primarily relate to changes in socioeconomic status: namely, increases in socioeconomic status (such as owner-occupied homes, home values, college educated residents, and employment) drive urbanization, and that increases in median income tend to be associated with slower urbanization trends. Changes in neighborhood racial composition had no significant effect on this temporal trend. These countervailing factors driving spatial and temporal urbanization trends hold even after considering important baseline controls for population and land area. While population was positively associated with proportion impervious both spatially and temporally, cross-sectional results for land area show that smaller geographic areas tend to possess a greater proportion of developed land and a slower rate of change. Taken together, these findings indicate that the areas characterized by historical urbanization (prior to 1997) have notably different social characteristics compared to those experiencing more recent urbanization (between 1997 and 2016).

We interpret the socio-demographic drivers of urbanization trends in Houston through the theoretical perspective of socioenvironmental succession, which views environmental change and urbanization as operating through historically layered and recursive processes (Elliott and Frickel 2015; Frickel and Elliott 2018). Given that much of the previous literature on neighborhood land cover has focused on temporal dimensions of land cover change (e.g. Ducey et al. 2018; Clement and Alvarez 2020), we offer this socioenvironmental succession perspective to simultaneously account for temporal *and* spatial dimensions of urbanization. As descriptive statistics indicate, an analysis based solely on temporal change in the Greater Houston area would include an enormous amount of new land cover (approximately 1,000 km^2). But even in fast growing Houston, this is still only accounts for 38% of the total urban cover. This simple observation – that the majority of urban cover was developed before recent decades – should be a central part of analyses of land cover in the United States and beyond.

Notably, existing theoretical perspectives on temporal change in urbanization that relate to defensive environmentalism, back-to-the-city movements, and the suburbanization of poverty find support in the Houston area as it relates to changes in income, while other changes in socioeconomic status run counter to expectations. If they held, these perspectives would have predicted that temporal trends like increasing socioeconomic status should result in attenuated land cover change, as was the case for income. But in the Houston area, increasing socioeconomic status in the form of increasing home values, owner-occupied homes, college educated residents, and employment levels actually accelerated urbanization trends. The exception to these findings for socioeconomic status – that increasing incomes is associated with slower urbanization – mirrors those from national findings and theoretical perspectives, though (Clement and Alvarez 2020). It is worth noting that in a model with only income and two critical controls (population and land area), income is not statistically significant, indicating that the effect is revealed only in models that are holding other socioeconomic status measures constant. Given this additional insight, results indicate that income only matters when coupled with other socioeconomic status indicators but is decoupled from the directionality of those measures. This finding suggests that measures of socioeconomic composition such as changes in home characteristics (like home value and home ownership) and social composition (such as college educated residents) are more directly related to urban expansion in Houston than strictly economic measures like income. More than this, the combined effect sizes of the socioeconomic variables of variables not including income outweigh that of income, meaning that the general trend is that increasing socioeconomic status increases impervious land cover in Houston.

Moreover, in terms of spatial disparities, the aforementioned theoretical perspectives are also unevenly applied because, in part, they were originally intended more as frameworks to understand recent temporal change. For example, the finding that predominantly white neighborhoods host more impervious surfaces contrasts with the expectation that these areas are less densely developed in the first place, although we did find some evidence in 2016 that higher home values were linked to lower levels of impervious surfaces typical of larger properties possessing substantial pervious surface in the form of lawns. That the effect of most indicators of socioeconomic status are not significant predictors of spatial disparities in urban cover should be interpreted in the light of the fact that socioeconomic status is itself racialized such that neighborhoods with more racial minorities in Greater Houston tend to have lower incomes, lower rates of home ownership, and lower levels of college educated residents. Finally, even with the large degree of land cover change, social and demographic changes that occurred between 1997 and 2016, all but one variable (e.g. home value) retained the same relationship with overall impervious surface in both years, indicating that two decades of land cover change did not particularly change the social characteristics underlying spatial patterns in impervious surface in Greater Houston. This symmetry at the start and end of the study period indicates that a sole focus on temporal land cover change would miss spatial dynamics such as the ones found in Table 2 that endure above and beyond recent decades of land cover change.

Houston is a metropolitan area characterized by residential segregation both by race and socioeconomic status, a legacy similar to other American cities (Emerson and Smiley 2018; Feagin 1988). However, we conclude that urbanization patterns in Greater Houston neither fully comport with existing theoretical perspectives nor with empirical findings nationally, but instead reflect the city's politics and culture, especially with regard to urbanization and sprawl (Qian 2010; Emerson and Smiley 2018). The particularities of the Houston case highlight how rapid population growth in the latter half of the twentieth century, emergent educational inequalities after the end of legal segregation, comparatively lax land use planning regulation, and enduring environmental inequalities in one of America's most polluted cities all intertwine with socio-spatial segregation along racial and economic lines (Bullard 1987; Elliott and Smiley 2019; Emerson and Smiley 2018; Feagin 1988; Qian 2010). With these dynamics as the backdrop, the thread weaving together these temporal and spatial analyses is that even though we point to fundamentally different social processes at work (with socioeconomic status corresponding to temporal effects, and race associated with spatial ones), both point to the importance of the spatial privilege of advantaged groups racially and economically residing in places that have been long developed or have been developing rapidly in recent years. While the effect of greater impervious surfaces in privileged neighborhoods is the opposite that implied by defensive environmentalism and other frameworks of temporal change (Rudel 2013), the mechanism is rather similar: socially and economically advantaged populations and white residents drive urban change. In unpacking this spatial privilege and the differences between spatial and temporal urbanization trends, socioenvironmental succession holds that differences across time and space can occur because later environmental changes are layered recursively onto already existing urban space—in this case, onto the physical footprint of impervious surfaces that characterized much of Greater Houston prior to 1997.

This study's key implication – that temporal and spatial processes underlying urbanization trends differ – offers a few straightforward directions for future research. First, our study is confined to the rapidly-urbanizing Sun Belt city of Greater Houston, partly to draw on the advantage of working with a novel land cover change product. Given the disparity between existing theory for understanding neighborhood land cover change in other cities and our empirical results from the Houston area, we aver that uncovering spatially-variegated processes of urbanization among other cities would provide a greater understanding of the processes driving impervious land cover. For instance, while a recent national analysis uncovered a relationship between increasing socioeconomic status and attenuated urbanization (Clement and Alvarez 2020), our findings for the Greater Houston area (in addition to those from a different study in Greater Detroit; Wilson and Brown 2015) indicate largely opposite patterns in that increasing socioeconomic status tends to catalyze urbanization. Examining this variation from urban area to urban area is an important topic for future work. Second, extending the temporal horizon to land cover change before the 1990s could illuminate what drove urbanization during earlier periods, and expand on most studies' focus on relatively recent changes. Third, our analysis focuses on two-dimensional urbanization patterns to fully exploit the capabilities of multi-decadal satellite imagery which maximizes accuracy and minimizes bias in 2D estimates. While emerging research on three-dimensional urbanization (i.e. including building heights to estimate growth in the volume not just area of urban infrastructure) is promising (e.g. Maroko et al. 2019), these data products still lack the vast spatial extent and temporal coverage of 2D satellite imagery. In addition, these 3D urban growth models' reliance on ancillary data (e.g. cadastral data) may lead them to overlook unreported development, and thereby underestimate actual urban growth – an issue to which satellite imagery is largely not susceptible. Fourth, research on land cover change should not just focus on drivers of land cover (such as in this article), but on their implications for other social and environmental phenomena, and how these might operate in feedback loops with land cover and neighborhood change. Implications of urbanization include ecological loss, environmental justice, and redevelopment leading to green gentrification. In the Houston area, we particularly emphasize how impervious surfaces exacerbate flood risks from extreme weather events (Brody et al. 2013), as was the case with Hurricane Harvey (Zhang et al. 2018), and how these socioenvironmental risks may relate to future urbanization trends. As research increases on urbanization and its environmental impacts, there is a growing need to analyze not just what is driving recent trends but also to identify the long-term impacts of processes set in motion long ago.

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