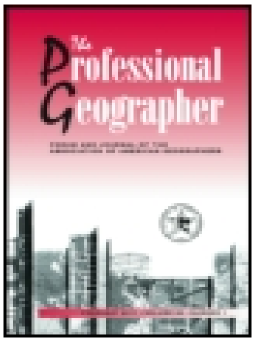

The Professional Geographer

ISSN: 0033-0124 (Print) 1467-9272 (Online) Journal homepage: http://www.tandfonline.com/loi/rtpg20

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Brendan L. Lavy & Ronald R. Hagelman III

To cite this article: Brendan L. Lavy & Ronald R. Hagelman III (2017): Spatial and Temporal Patterns Associated with Permitted Tree Removal in Austin, Texas, 2002–2011, The Professional Geographer, DOI: 10.1080/00330124.2016.1266953

To link to this article: http://dx.doi.org/10.1080/00330124.2016.1266953

Published online: 15 Feb 2017.

Spatial and Temporal Patterns Associated with Permitted Tree Removal in Austin, Texas, 2002–2011

Brendan L. Lavy and Ronald R. Hagelman, III
Texas State University

A wide-ranging set of physical, urban, demographic, socioeconomic, and policy characteristics determines the spatial distribution of urban forests. Information on the characteristics surrounding tree removals on both public and private properties has received less attention in the literature. The purpose of this research was to analyze the spatiotemporal trends and geographic patterns of tree removals in Austin, Texas, between 2002 and 2011 in an effort to understand how site-specific characteristics influence urban tree removal and affect the overall distribution of Austin's urban forest. We examined permitted tree removals using a geographic information system (GIS) as well as spatial and statistical analyses. Specifically, we evaluated the degree to which variables related to various physical, urban, and socioeconomic conditions predicted tree removals. The results indicate that permitted tree removals and their associated characteristics in Austin have varied over the ten-year study period. Permitted tree removals increased over the study period and took place in the urban core and along the urban periphery. Permitted tree removals were more likely to be undertaken by college graduates and owner-occupants and to occur in more densely populated areas, closer to major streets, and on properties with older structures. The results of this research provide urban forest professionals with information on the location and intensity of permitted tree removals and the significant characteristics driving urban tree loss. **Key Words: municipal policy, tree ordinance, urban environment, urban forest.**

一系列广泛的物理、城市、人口、社会经济与政策特徵组合，决定了城市森林的空间分佈。但在文献中，有关公共与私人产权上的树木移除特徵之信息却鲜少受到关注。本研究的目的在于分析德州奥斯汀在2002年至2011年之间，树木移除的地理模式之时空趋势， 致力于理解特定的场所特徵如何影响城市树木移除以及奥斯汀城市森林的总体分佈。我们运用地理信息系统 (GIS) 以及空间与统计分析，检视批准的树木移除。我们特别评估与各种物理、城市和社会经济条件有关的变项预测树木移除的程度。研究结果显示，奥斯汀批准的树木移除及其相关特徵，在过去十年的研究期间有所变异。在研究期间，批准的树木移除有所增加，并发生在城市中心与城市产权之上。批准的树木移除更可能由大学学历持有者和自有居住者进行，并且发生在人口更为密集的地区、邻近主要街道，以及结构较为老旧的地产。本研究的结果，为城市森林专业者提供了批准树木移除的区位与密度之信息，以及驱动城市树木丧失的显着特徵。 **关键词：市政政策，树木法令，城市环境，城市森林。**

Un amplio conjunto de características físicas, urbanas, demográficas, socioeconómicas y de políticas determina la distribución espacial de los arbolados urbanos. La información sobre las características que rodean las remociones de árboles, tanto en propiedades públicas como privadas, ha recibido poca atención en la literatura. El propósito de esta investigación era analizar las tendencias espaciotemporales y los patrones geográficos de remoción de árboles en Austin, Texas, entre 2002 y 2011, dentro del esfuerzo por entender como las características específicas del sitio influyen sobre la remoción de árboles urbanos y afectan la distribución general de los bosques urbanos de Austin. Examinamos las remociones permitidas de árboles usando un sistema de información geográfica (SIG) lo mismo que análisis espaciales y estadísticos. Específicamente, evaluamos el grado con el que las variables relacionadas con varias condiciones físicas, urbanas y socioeconómicas predecían la remoción de árboles. Los resultados indican que las remociones permitidas y sus características asociadas en Austin han variado a lo largo del período de estudio de diez años. Las remociones de árboles permitidas se incrementaron durante el período del estudio y se efectuaron en el núcleo urbano y a lo largo de la periferia urbana. Estas remociones permitidas más probablemente eran emprendidas por graduados de universidades y ocupantes propietarios y probablemente ocurrirían en las áreas más densamente pobladas, más cercanas a las calles principales y en propiedades con estructuras más antiguas. Los resultados de esta investigación proporcionan a los profesionales de bosques urbanos información sobre la localización e intensidad de remociones de árboles permitidas y las características significativas de las que depende la pérdida de árboles urbanos. **Palabras clave: políticas municipales; ordenanza sobre árboles; entorno urbano; bosque urbano.**

Urban forests provide a range of important ecological, economic, and social benefits (Nowak and Dwyer 2000; McPherson et al. 2005). Yet, a large number of trees die prematurely in urban landscapes each year. Urban trees are damaged or lost to age and natural events, such as hurricanes (Burley, Robinson, and Lundholm 2008; Thompson et al. 2011) and drought (Holopainen et al. 2006). A changing climate also poses increasing risks to urban trees (Nowak 1993; Tubby and Webber 2010). Rising urban temperatures associated with increases in impervious surface area decrease native tree species' growth, permitting the establishment and spread of invasive tree species, tree diseases, and harmful tree pests (Yang 2009; Chen et al. 2010). Each year in the United States, as many as 4 million trees are lost to new land development (Nowak and Greenfield 2012). Other urban processes, including urban infill, soil contamination, and utility

The Professional Geographer, 0(0) 2017, pages 1–14 © 2017 by American Association of Geographers.
Initial submission, September 2016; revised submission, October 2016; final acceptance, November 2016.
Published by Taylor & Francis Group, LLC.

trenching, also contribute to tree loss (Jim 2002). These examples illustrate broad-scale impacts responsible for urban forest loss. Fine-scale characteristics of urban forest loss remain less clear. An examination of the spatially explicit characteristics of urban tree loss can provide an additional, important component to understanding urban forest dynamics (Kirkpatrick, Davison, and Daniels 2013; Conway 2016).

Recent research, focused on factors contributing to tree planting and tree removals, has concentrated on residential decision making using qualitative methods. Surveys and interviews conducted in four Canadian neighborhoods revealed that residents removed trees because of concerns about tree health and about the risk trees posed to property or people (Conway 2016). Similarly, residents in six eastern Australian cities removed trees because of disease or advanced age and because of root damage to residential infrastructure (Kirkpatrick, Davison, and Daniels 2012). A majority of residents in Sacramento, California, removed trees because of poor health (Summit and McPherson 1998). Cultural dynamics, including individual preferences, influence the removal of healthy trees, and socioeconomic and demographic characteristics also play a role in tree removal decisions (Kirkpatrick, Davison, and Daniels 2012, 2013); however, further research is needed to uncover site-specific characteristics and citywide patterns associated with urban tree removals.

The purpose of this research is to analyze permitted tree removals undertaken by residents, business owners, and public entities in Austin, Texas, between 2002 and 2011 to illuminate city-scale geographic patterns of tree loss and to understand how neighborhood-scale landscape characteristics influence tree removal and affect the overall distribution of Austin's urban forest. Informed by the literature on the spatial distribution of urban forests, we hypothesized that the distribution of tree removal occurrences is the result of a set of interrelated physical and social geographic determinants. These determinants manifest themselves as characteristics of the physical, urban, and socioeconomic landscape that occur across urban space and influence spatial patterns of tree removals. Our analysis combines cadastral, census, and physical features data, with occurrences of permitted tree removals in a geographic information system (GIS) to visualize spatial patterns and analyze spatial and temporal trends via statistical methods, including a model to predict tree removal occurrences. A more spatially refined understanding of landscape characteristics associated with urban tree loss should allow managers to anticipate vulnerable areas of urban forests and move from reactive management responses to proactive management plans. Therefore, this research addresses the following question: What are the geographic patterns of tree removals over the study period and to what degree can landscape characteristics explain occurrences of tree removals?

Material and Methods

Site and Situation

Austin is located in central Texas and has a population of approximately 812,000 and a footprint of 795 km^2 (Figure 1; City of Austin 2011c). Austin is located in one of the fastest growing urban areas in the United States. Between 2000 and 2010, the Austin–Round Rock–San Marcos Metropolitan Statistical Area population grew by 37 percent (Mackun et al. 2011). Austin has a dense stream network, and the city occupies two distinct geographical provinces. The western half of the city lies on the Balcones Escarpment (running just west of and parallel to Interstate 35), known as the Texas Hill Country. The eastern half of the city sits in the Blackland Prairies of the Gulf Coastal Plain, the gently sloping land that drains to the Gulf of Mexico. Austin's climate is classified as humid subtropical but is highly variable. Summer temperatures reach 38°C, and winter temperatures occasionally dip below freezing (Woodruff 1979). Despite the climatic variability and extreme heat, Austin is home to a variety of tree species. Many pecan trees, the Texas state tree, thrive in Austin neighborhoods, along with a variety of oak, elm, juniper, and cypress species.

In 1984, the Austin City Council adopted a progressive ordinance to protect trees on public and private property. The City Council has amended and expanded the ordinance over the years, and it added a heritage tree clause in 2010. The tree and natural area protection and heritage tree ordinance outlines the rules and regulations in regard to the removal of protected and heritage trees on public and private property. A tree is considered protected if it has a trunk diameter at breast height (DBH; measured 4.5 ft from the base of the tree) of 19 in (48 cm) or greater, whereas a heritage tree is defined as having a trunk DBH equal to or greater than 24 in (64 cm). Only native tree species are subject to the regulations of the heritage tree ordinance, including all oak species, Texas ash, bald cypress, American elm, cedar elm, Texas madrone, bigtooth maple, pecan, Arizona walnut, and eastern black walnut (City of Austin 2011d).

A landowner must submit an application requesting a permit to modify a protected or heritage tree on public or private property. Depending on the request, an approved permit allows for the removal, encroachment into the critical root zone, or crown reduction of more than 30 percent of a protected or heritage tree. The city grants or denies permit applications based on a variety of factors during a site inspection. Factors taken into consideration include variables such as age, condition, type, size, and the overall aesthetic of the tree. For permitted removals, the city generally requires the property

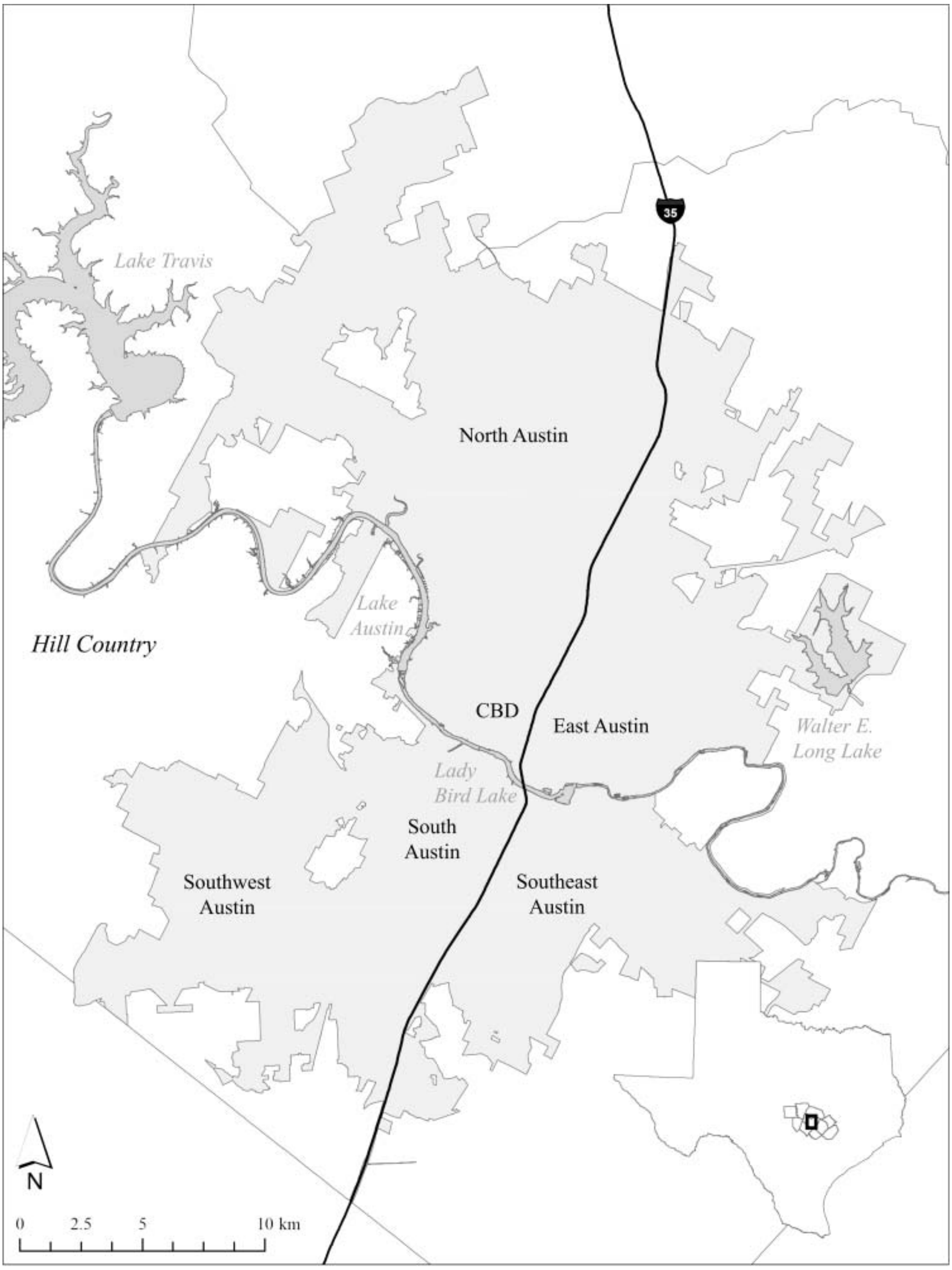

Figure 1 *Map of Austin city limits in central Texas. CBD = central business district.*

owner to mitigate the loss by planting new trees. The primary goal of the ordinance is "to achieve a balance of re-forestation and preservation, frequently emphasizing one of the two elements to achieve the best long-term benefit for the community" (City of Austin 2011a). Austin's forested landscape, rapid growth, formal commitment to sustainable development and green design, and its relatively long-standing capture of urban forestry data make it a compelling site for this analysis.

Permitted Tree Removal Data

Using Austin's City Arborist Program data set, we derived tree removals from 2002 to 2011 (City of Austin 2011e). The data set records information from tree removal applications, including the address or site of requested tree modification, the date the application was submitted, the type of modification requested, whether the modification was requested for development or non-development reasons, and whether a permit was granted. Requests for tree removal fall into one of three categories: (1) total removal of the tree, (2) encroachment into the tree's critical root zone (CRZ), and (3) excessive removal of the tree's canopy. Although the latter two categories do not remove the tree entirely, both can impinge on tree health and structure. Encroachment into a tree's CRZ could destabilize the tree and damage its vitality. Excessive canopy removal also damages a tree's vitality (Miller 2007). Because each category places the tree at risk of failure, this research considers all categories as tree removals.

The data set contained 7,749 applications submitted to the city between 11 January 2002 and 12 October 2011. The city approved 3,204 applications (41.3 percent), approved with conditions 2,800 applications (36.1 percent), and denied 409 applications (5.2 percent). The city labeled the remaining 1,336 applications (17.2 percent) in the database as closed, in review, or review completed. Because the data set does not expand on the status of the 1,336 remaining applications as either approved or denied, we omitted them from the study. After removing the 1,336 applications with no clear indication of their final status, the data set included 6,413 applications for tree removal in Austin from 2002 to 2011. Of these applications, 6,004 applications (93.6 percent) were approved or approved with conditions and 409 applications (6.4 percent) were denied. We omitted the denied applications to focus exclusively on permitted tree removals. Approximately 73 percent of the approved and approved with conditions permits resulted in the removal of a tree. The remaining 27 percent granted permission to encroach into the tree's CRZ, remove an excessive amount of tree canopy, or both. In addition, recent proposed state-level legislation has questioned municipalities' rights to enforce tree ordinances in their extraterritorial jurisdiction (ETJ). After further examination of the 6,004 approved applications, it was determined that 119 tree removals occurred in Austin's ETJ, and we removed these from the final analysis. After the geocoding process, the final tree removal data set contained 5,693 approved tree removal applications.

Physical, Urban, and Socioeconomic Landscape Data

Drawing from recent urban forestry literature, this research hypothesized that a mixture of physical, urban, and socioeconomic landscape characteristics would influence the number and location of tree removals in Austin. The physical landscape variables chosen for this research were percent slope and distance to hydrologic features for each tree removal. Past research has shown that these physical landscape characteristics play a role in the distribution of urban forests (Heynen and Lindsey 2003; Davies et al. 2008). We obtained data sets containing physical characteristics from the city and the Texas Natural Resource Information System (TNRIS). The data sets include major hydrologic features and digital elevation models (DEMs) for the Austin area. The DEM data files are products of the U.S. Geological Survey (USGS), representing ground surface topography in 30×30 m cells (TNRIS 2011). We derived hydrologic features from the city's major lakes (City of Austin 2003) and creek lines (City of Austin 1997) data sets.

Urban landscape features also influence the distribution of urban forests (Troy et al. 2007; Landry and Pu 2010). Therefore, we included four variables related to urban landscape characteristics and their effects on tree removal: (1) age of structure, (2) distance to major roads, (3) land use, and (4) population density. We acquired major road data from the city. We obtained cadastral data, including descriptive parcel information, for Austin from the Travis Central Appraisal District (2012) and the Williamson Central Appraisal District (2012). From these data sets, we extracted information regarding the year the structure was constructed and the appraised value of the property for parcels with tree removals. We gathered land use information at the parcel scale from the city's GIS data sets (City of Austin 2006). This data set depicts land use at the parcel level as of 2006, which was derived from Austin's 2003 land use study and county appraisal district GIS and computer aided design (CAD) files. General land use classifications were included in the analysis because they cover the major land use categories relevant to this research. The final data set distinguished between residential and nonresidential land uses for tree removals. Finally, we calculated population density for each U.S. Census block group (BG) in the study area from BG areas and population counts.

Socioeconomic landscape characteristics also affect the distribution of urban forests (Heynen and Lindsey 2003; Perkins, Heynen, and Wilson 2004; Landry and Chakraborty 2009). As such, we included five socioeconomic landscape characteristics: (1) percentage white, (2) percentage owner occupancy, (3) percentage college graduates, (4) median income, and (5) market value (including both land and structures). We obtained demographic and socioeconomic data sets from the U.S. Census Bureau's 2010 Census (U.S. Census Bureau 2010b) and from the American Community Survey five-year estimates (2006–2010; U.S. Census Bureau 2010a), respectively. We obtained the market values of properties through cadastral information supplied by the appraisal districts. Because socioeconomic patterns differ from east to west in the city, we included the variable east of Interstate 35. Table 1 displays a list of our conceptual variables, as well as how we operationalized them through the compilation of the data sets, calculations, and measurements discussed.

Spatial and Statistical Analyses

We used spatial and statistical analyses to illuminate linkages between the geographic distribution of tree removals and the variables under consideration, and we employed a GIS to discover relationships between urban tree removals and neighborhood-landscape

Table 1 *Conceptual and operational variables relative to research design and analyses*

Conceptual variables	Operational variables
Urban landscape characteristics	Population density
	Age of structure
	General land use
	Distance to major roads
	East of Interstate 35
Socioeconomic landscape characteristics	Percentage white
	Percentage college graduate
	Percentage owner occupied
	Median income
	Market value
Physical landscape characteristics	Percentage slope
	Distance to hydrologic features

characteristics. We used ESRI's ArcMap software (Version 10.1) to map and calculate all measurements and spatial statistics. We exported data from the GIS into IBM's Statistical Package for the Social Sciences (SPSS) software (Version 21) for further statistical analyses.

We used address points that correspond to parcel centroids to geocode approved applications and create a GIS point layer of tree removals (City of Austin 2011b). We extracted site-specific characteristics of each permitted tree removal point by overlaying the permitted tree-removal point layer along with its attribute data onto Austin area DEMs, hydrologic, major road, land use, and cadastral shapefiles. We also calculated percentage slope and distance to major roads and to hydrologic features for each permitted tree removal. The permitted tree removal point layer along with its attribute data were overlaid onto U.S. Census Bureau BGs cartographic boundary files. We aggregated site-specific data from the permitted tree removal point layer to the BG level and included U.S. Census Bureau 2010 decennial census information (i.e., population density, race and ethnicity, and housing tenure) and five-year American Community Survey data (i.e., educational attainment and median income). We aggregated the landscape characteristics of tree removals to the BG level by taking the median percentage slope, median market value, median age of structure, median distance to major roads and hydrologic features, and the mode for general land use for each BG.

Next, we calculated the Getis-Ord Gi* statistic to identify whether BGs with low or high tree removals clustered together over the study area. The Getis-Ord Gi* statistic evaluated the sum of tree removals in a BG and its neighboring BGs in relation to the sum of all tree removals. The resulting statistic is returned as a z score for each BG, where high, positive z scores represent clusters of BGs with statistically significant larger values of tree removals. Low, negative z scores represent clusters of BGs with statistically significant smaller values of tree removals. To observe spatial differences in motivations for tree removals, the Getis-Ord Gi* analysis was performed on three categories of tree removals: (1) all tree removals, (2) development-related tree removals, and (3) non-development-related tree removals.

Finally, we grouped BGs into high, medium, and low categories of tree removals using natural breaks. We conducted a correlation analysis to test for collinearity between variables and ran a stepwise-selected multinomial logistic regression on the three categories of tree removals to determine which neighborhood-scale landscape characteristics explain patterns of observed urban tree removals in Austin. Categories of tree removals by BG served as the outcome variable. The predictor variables were the twelve variables related to the physical, urban, and socioeconomic landscape characteristics of tree removals in Austin. Figure 2 presents a flowchart of the data and methods used.

Results

Descriptive Statistics

Permitted tree removals increased over the study period (Figure 3). The city approved 93 applications in 2002 and 1,258 applications in 2011. This represents a 125

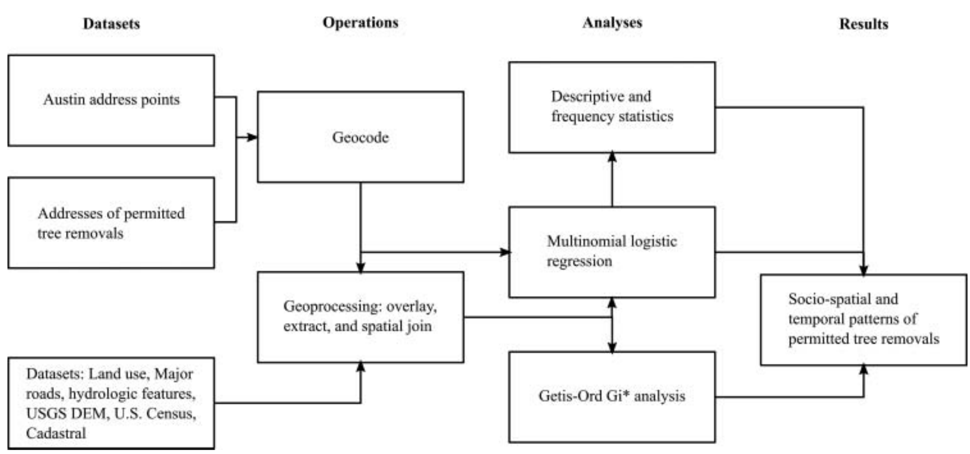

Figure 2 *Flowchart of data sets, geographic information system operations, statistical and spatial analyses, and results.*

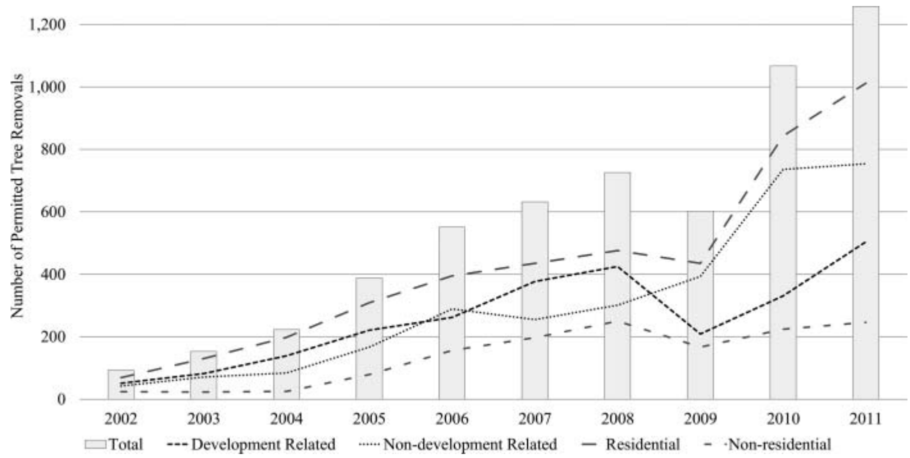

Figure 3 *Permitted tree removals by year, reason (development or non-development related), and land use (residential or nonresidential).*

percent increase in tree removals from 2002 to 2011 and a growth rate of 30 percent over the ten-year study period. The increase and growth rate of tree removals corresponds to an overall rise in the number of tree removal applications received by the city from 2002 to 2011. In 2002, the city received 99 applications and in 2011, the city received 1,643 applications. An evaluation of the yearly rates of change for tree removals portrays similar increases. Yearly rates of change ranged from 15 percent to 77 percent. The only outlier is 2009, where there was a 17 percent decrease from 2008. Tree removals rebounded in 2010 with a 77 percent increase from 2009. On average, the yearly rate of change for tree removal over the ten-year study period was 37 percent. Tree removals on residential properties accounted for 76 percent (4,302) of the total tree loss. In 2010 and 2011, the number of trees removed on residential properties was four times greater than the number of trees removed on nonresidential properties.

Non-development-related tree removals accounted for 54 percent (3,092) of the total tree loss during the study period, and development-related tree removals accounted for 46 percent (2,601). At the beginning of the study period, the percentage of tree removals for development reasons was higher than that of tree removals for non-development reasons. At the end of the study period, the percentage of tree removals for non-development reasons had risen markedly. Percentages of development-related tree removals remained relatively stable between 2002 and 2008, averaging 56 percent of the total approved tree removals. In 2009, 2010, and 2011, development-related permits averaged 35 percent of the total approved tree removals. Non-development-related permits remained relatively low and steady between 2002 and 2008 and surged in 2009, 2010, and 2011, making up 65 percent of total tree removals.

Spatial Distribution

The geocoding process returned 5,693 good matches (a 96.7 percent accuracy rate) for tree removal sites (Figure 4). The remaining 192 approved permit application addresses could not be rectified and located. The results of this study reflect the 5,693 good matches produced by the geocoding process.

Results of the Getis-Ord Gi* analysis for all tree removals show statistically significant clustering of high instances of tree removals in and around Austin's urban core, as well as a statistically significant cluster of high instances of tree removals in the city's northern periphery (Figure 5A). Statistically significant areas of low tree removals exist along two clustered bands north and south of Austin's urban core. Results of the Getis-Ord Gi* analysis for development-related tree removals show statistically significant clusters on the northern and southern peripheries, as well as the urban core (Figure 5B). In relation to the non-development and all tree removals' Getis-Ord Gi* analyses, the southern band has disappeared, and there is no statistically significant clustering for development-related tree removals, either low or high, across a large swath of south Austin. Results of the Getis-Ord Gi* analysis for non-development-related tree removals from 2002 to 2011 are similar to the all tree removals analysis (Figure 5C). Statistically significant instances of high tree removals in the urban core expand slightly north and south, however, and statistically significant instances of low tree removals extend into the northern and southern peripheries.

Multinomial Regression

Block groups with high (thirty-nine to ninety-three removals) and medium (fifteen to thirty-eight removals) tree removals cluster near Austin's urban core and appear on the northern and southern periphery (Figure 6). The majority of BGs (341) make up the low (one to fourteen removals) tree removal category. The mean values and standard deviations for the predictor variables provide some insight into the differences between tree removal categories (Table 2). Slope remains relatively consistent across categories. Tree removals within the low category occurred further

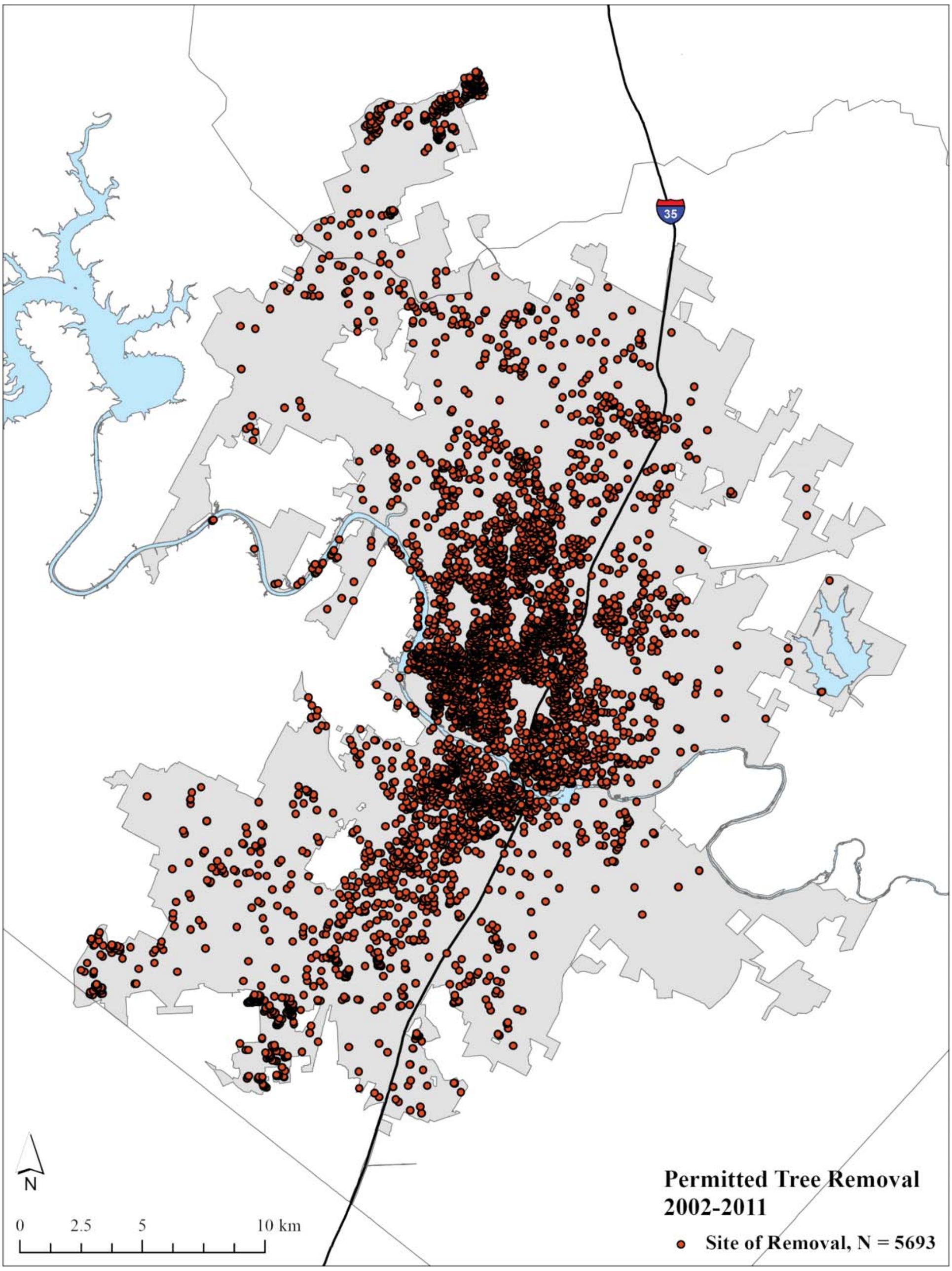

Figure 4 *Sites of permitted tree removals from 2002 to 2011 (N = 5,693). (Color figure available online.)*

from major roads than those in the other categories. Structures in the low tree removal category are on average two decades younger than the other categories. The low category has the lowest percentage of white population and college graduates. Median income in the high tree removal category is greater than the other categories. The market value of structures in the low category is much greater than those in the other categories. The low tree removal category contains multi-million-dollar homes, industrial complexes, and public facilities.

Tests for collinearity showed that percentage white and median income were strongly correlated with other variables (see Appendix). As such, both were removed from the stepwise-selected multinomial logistic regression. The final regression model retained the following independent variables: distance to major roads, age of structure, population density, percentage college graduates, and percentage owner occupied (Table 3). A test of the final model against a constant-only model suggests that the stepwise selected set of predictors are useful for distinguishing

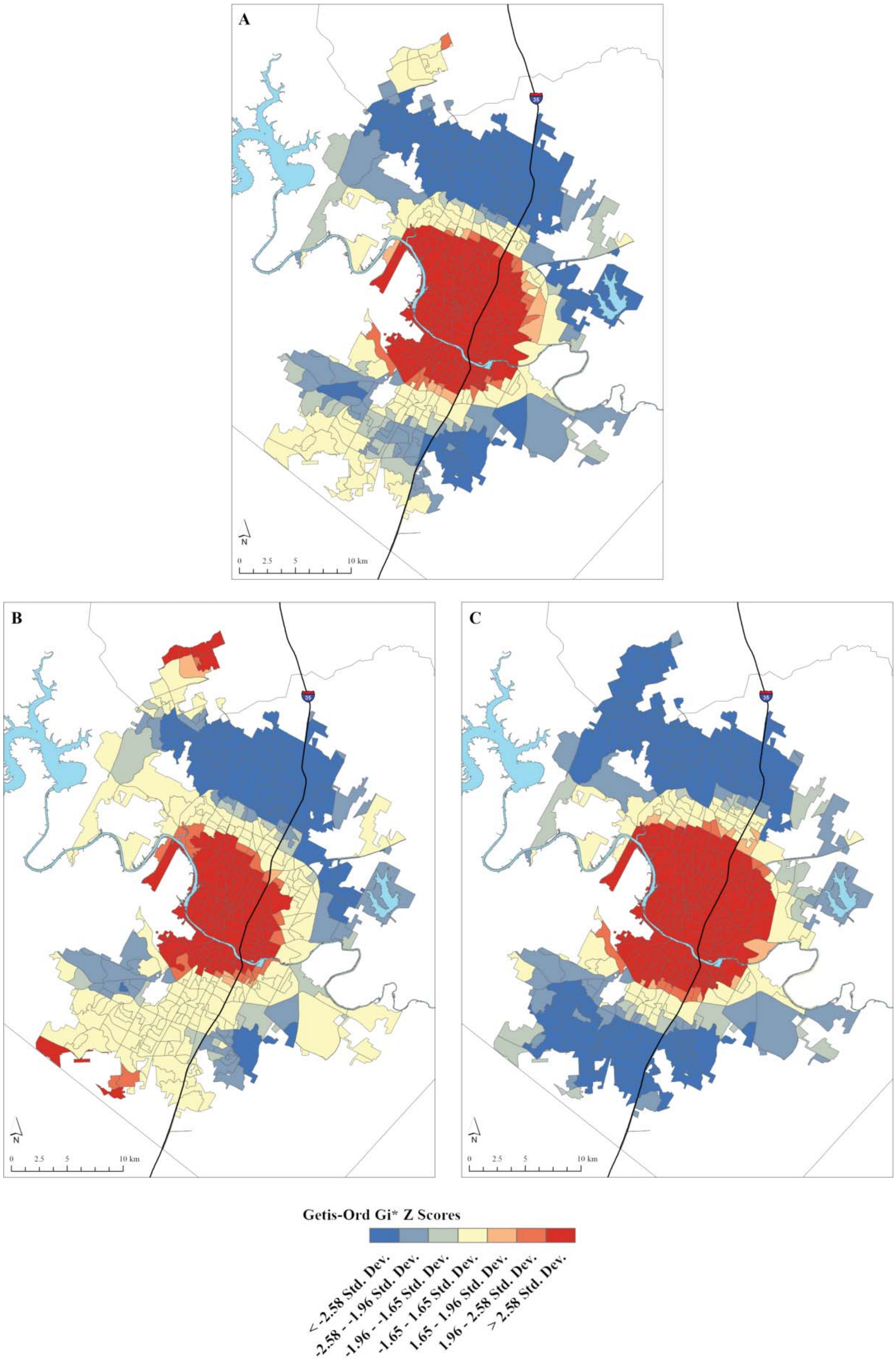

Figure 5 *Getis-Ord Gi* results for (A) all tree removals, (B) development-related tree removals, and (C) non-development-related tree removals. (Color figure available online.)*

between categories of tree removals, χ^2 (10, $N = 460$) $= 192.425$, $p < 0.001$. The pseudo R^2 indicated that the model accounted for 44.5 percent of the total variance. Overall prediction success for the cases used in the development of this model was high, with 79.6 percent classified correctly. The prediction rate for the low tree removal category was 96.2 percent. The prediction rates for the medium tree removal category

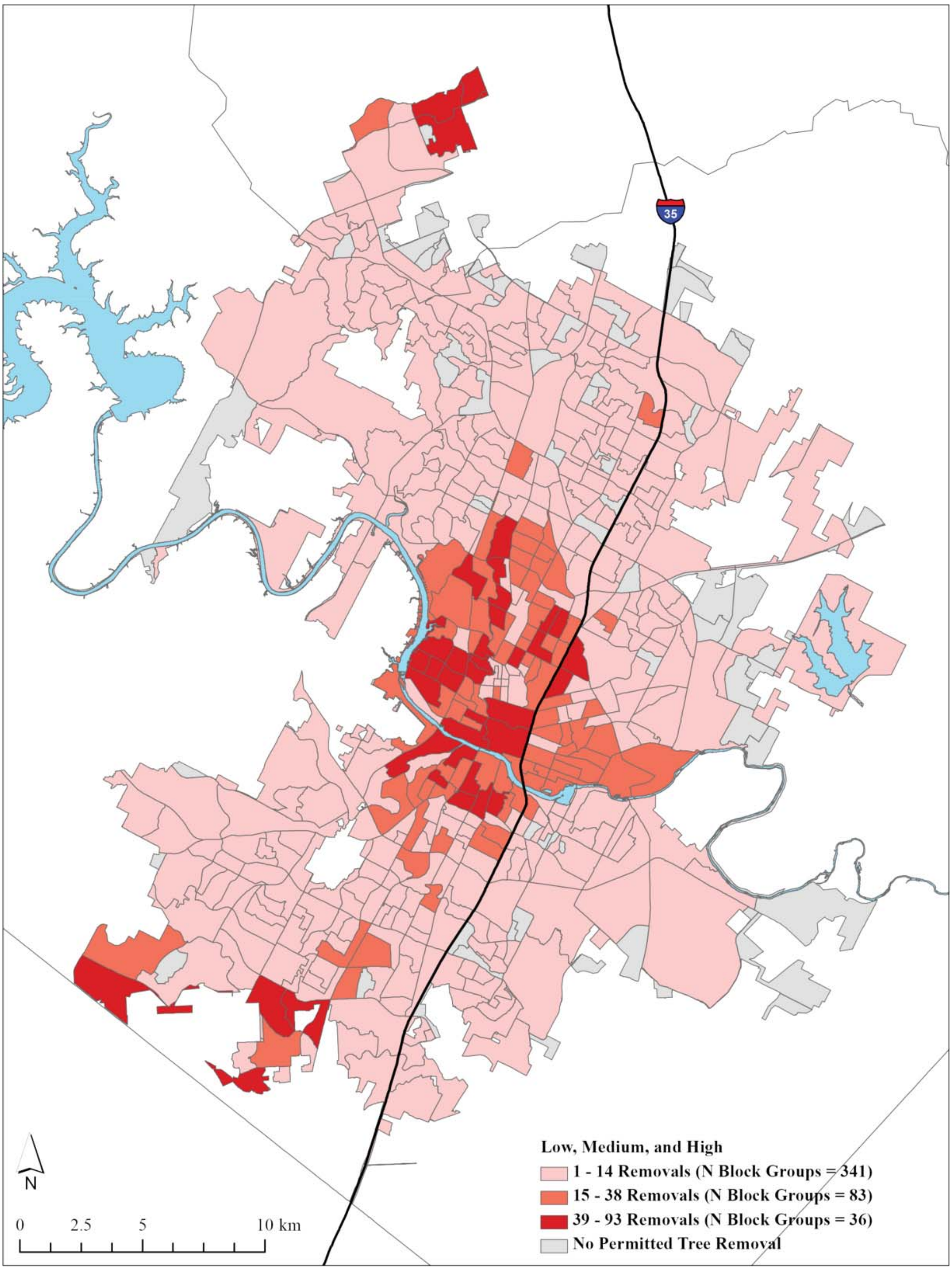

Figure 6 *Low, medium, and high tree removal categories. (Color figure available online.)*

and high tree removal category were lower, at 32.5 percent and 30.6 percent, respectively. The reference category for the response variable is the low tree removal category. The results of the regression show that permitted tree removals in the high category were more likely to be undertaken by college graduates and owner-occupants and to occur in more densely populated areas, near major streets, and on properties with older structures (99 percent confidence level). Permitted tree removals in the medium category were more likely to occur in more densely populated areas, on properties with older structures (99 percent confidence level), and near major streets (90 percent confidence level).

Discussion

Spatial and Temporal Trends

The increase in permit applications and tree removals might be partially attributed to a growing awareness

Table 2 *Mean and standard deviation for low, medium, and high tree removal categories at the block group level*

Variable	High tree removal block groups ($n = 36$)		Medium tree removal block groups ($n = 83$)		Low tree removal block groups ($n = 341$)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Distance to hydrologic features[a]	173.96	86.88	143.5	91.35	174.58	100.95
Percentage slope	1.14	0.62	0.99	0.61	1.21	1.07
Distance to major roads[a]	273.46	145.75	288.96	189.8	366.41	271.29
Age of structure[b]	56.01	26.13	57.98	20.6	32.53	16.96
Population density	2,849.99	3,002.77	2,468.84	2,870.30	1,788.77	1,342.42
Percentage white	87	9	78	15	68	17
Percentage college graduate	71	15	53	22	41	24
Percentage owner occupied	62	24	49	23	49	29
Median income[c]	$86,361	$37,271	$55,201	$38,082	$57,634	$34,875
Market value[c]	$498,637	$353,889	$431,361	$664,401	$2,291,357	$17,910,286

[a]Measured in meters.
[b]Measured in years.
[c]Measured in US dollars.

by property owners of Austin's tree ordinance. Despite being enacted in 1984, the tree ordinance received little public consideration until the proposal and passage of the heritage tree ordinance in 2010. The heritage tree ordinance garnered much attention in the media as developers and environmental groups sought to ease or strengthen the proposed regulations put forward by the city council regarding the removal of heritage trees. Since its passage, varying applications of the heritage tree ordinance have kept the ordinance in the media spotlight. Ongoing media coverage might have helped educate property owners of the rules and regulations pertaining to heritage and protected trees, and this could have resulted in an increase in applications for tree removals.

The peak percentage for development-related removals was in 2007, and the peak percentage for non-development-related permits was in 2011. The subprime mortgage crisis of 2007 to 2010 coincides with the peak of development-related tree removals and most likely played a role in the decline of development-related tree removal requests and permits in 2009 and 2010. At the same time, the central Texas region was experiencing a prolonged drought that peaked in 2011 (Combs 2012). In 2012, an estimated 5.6 million urban trees died due to ongoing drought conditions in Texas cities (Texas A&M Forest Service 2012). Increases in non-development-related tree removals over the years 2008 to 2011 could be the result of tree death due to extreme heat and severe drought.

Residential areas contain up to 75 percent of total urban tree numbers (McPherson 1998). Our results follow the location of the urban forest. The majority of tree removals take place on residential properties, and in recent years, residential requests have far surpassed nonresidential requests. We attribute the increase in residential permits in 2010 and 2011 to growing awareness of the ordinance again, as well as lingering drought conditions and increased development; however, other reasons undoubtedly exist. The prevalence of residential tree removals underscores the role that residential landowners play in shaping and managing the urban forest and the importance of understanding the motivations behind residents' actions, including factors influencing tree removals (Kirkpatrick, Davison, and Daniels 2012, 2013; Conway 2016).

Beyond the development or non-development specification, a detailed reason for why a tree was

Table 3 *Results of the multinomial logistic regression analysis between tree removal categories*

Tree removal categories[a]		Coefficient	*SE*	Wald	Significance	Exp (BCoef.)	95% confidence interval for Exp(B) Lower bound	Upper bound
High	Intercept	−8.577	1.117	58.957	0.000			
	Population density	3.44E-04	9.10E-05	14.303	0.000	1.000	1.000	1.001
	Age of structure	0.051	0.012	19.281	0.000	1.052	1.029	1.076
	Distance to major roads	−0.003	0.001	7.559	0.006	0.997	0.995	0.999
	Percentage college graduates	0.053	0.012	20.960	0.000	1.055	1.031	1.079
	Percentage owner occupied	0.023	0.009	6.772	0.009	1.023	1.006	1.041
Medium	Intercept	−5.200	0.619	70.600	0.000			
	Population density	2.53E-04	7.87E-05	10.354	0.001	1.000	1.000	1.000
	Age of structure	0.067	0.009	58.821	0.000	1.070	1.051	1.088
	Distance to major roads	−0.001	0.001	3.310	0.069	0.999	0.997	1.000
	Percentage college graduates	0.008	0.007	1.464	0.226	1.008	0.995	1.021
	Percentage owner occupied	0.006	0.006	0.817	0.366	1.006	0.993	1.018

[a]The reference category is low.

requested or permitted to be removed was not part of the data set. We offer some broad trends, however, based on the clustering of both development- and non-development-related tree removals. Developed land area in Austin increased by 20 percent from 2003 to 2010, and new development along the urban periphery outpaced redevelopment and infill development in and around established areas (City of Austin 2012). The clustering of development-related tree removals along the city's northern and southern peripheries suggests that new development influenced tree removals in these areas. Even though central Austin has not experienced the same amount of development as its peripheral areas, the cluster of development-related tree removals near Austin's urban core indicates that recent revitalization efforts influenced tree removals near downtown and in east Austin. For instance, recent municipal urban renewal efforts and redevelopment policies have targeted central and east Austin, resulting in an influx of businesses and new housing developments (Austin Revitalization Authority 1999; Lavy, Dascher, and Hagelman 2016). Therefore, redevelopment could explain the prevalence of development-related tree removals in central and east Austin.

On the other hand, non-development-related tree removals cluster exclusively around the urban core. Studies have shown that residents remove trees because they pose a risk to property or are dead or dying (Summit and McPherson 1998; Kirkpatrick, Davison, and Daniels 2012; Conway 2016). Residents also remove trees based on preference (Kirkpatrick, Davison, and Daniels 2013). Yet, permission to remove a protected or heritage tree for non-development reasons in Austin is based on tree health and the risk it poses to the community or property. As such, the significant cluster of non-development-related tree removals in and near Austin's urban core is assumed to be trees that were dying or dead or that posed a risk to the community or property. Taken together, the patterns observed in development and non-development tree removals indicate that the loss of urban trees might be occurring in areas with the least canopy cover—in established urban areas in and near the urban core—and with the most canopy cover—along the city's periphery.

Predicting Tree Removals

Results of the regression indicated that some of the same variables driving urban forest distribution are also implicated in urban forest loss. Block groups with increasing levels of population density, college graduates, and owner-occupants were more likely to be associated with the high tree removal category than the low tree removal category. Population density, as well as housing unit density, has been associated with declines in urban forest canopy cover (Troy et al. 2007; Landry and Pu 2010). Yet, population density has also has been shown to have no significant effect on canopy cover (Heynen and Lindsey 2003). Given the structure of the urban forest, residents in densely populated portions of Austin are in part driving urban forest loss in areas that might already possess low levels of canopy cover.

Level of educational attainment has been a reliable predictor of canopy cover across the urban landscape (Heynen and Lindsey 2003; Landry and Chakraborty 2009). In addition, homeowners have been shown to have more canopy cover than renters (Perkins, Heynen, and Wilson 2004; Heynen, Perkins, and Roy 2006; Landry and Chakraborty 2009). Our results indicate that college graduates and owner-occupants are also associated with urban forest loss. Owner-occupants possess the authority to make changes to their property. They also typically harbor direct responsibility for ongoing property maintenance. Thus, owner-occupants' prominent role in tree removals might reflect removals for property updates and additions or to mitigate properties from tree risks. The finding that college graduates more readily remove trees might reflect similar interests as owner-occupants but also could reflect a general awareness of current urban forestry regulations. It might also be that they are more likely to have paid a rental or purchase premium for their location and have the economic and political means to maintain a higher degree of tree care and management in their neighborhood. Prior research has also shown that areas with increasing proportions of minority and less educated residents often possess lower levels of canopy cover (Heynen and Lindsey 2003; Landry and Chakraborty 2009). Thus, there could be a link between urban canopy cover and tree removals, where some owner-occupants and college graduates are more likely to live in areas with greater canopy cover and are more likely to remove trees because they have them. Future research is needed to explore this link further.

Age of structure and urban canopy cover often are linked through a quadratic relationship, where structures between forty and fifty years old tend to possess greater canopy cover than newer or older structures (Grove et al. 2006; Troy et al. 2007). Our results also suggest that age of structure is associated with tree removals. Block groups with older buildings were more likely to belong to the high and medium tree removal categories than the low tree removal category. As is the case in most North American cities, older structures in Austin occupy the urban core, and the age of structures declines moving away from the central portion of the city. We attribute the relationship between older structures and high and medium occurrences of tree removals to poor health of aging trees and to some degree redevelopment efforts in central portions of the city. As discussed earlier, redevelopment projects could explain the high prevalence of tree removals in older, central portions of the city.

The finding that tree removals that occurred closer to major roads were more likely to belong to the high and medium tree removal categories reflects the density of Austin's major street network in and around the city's central area. Many of the BGs within the high and medium tree removal categories reside in Austin's urban core and its established neighborhoods (Figure 6). For BGs in the high and medium category on the city's northern and southern periphery, it appears that new suburban developments located near major transportation arterials leading into Austin spurred tree removals.

Research has shown that tree canopy cover is greater in areas with increasing stream density (Heynen and Lindsey 2003) and in hilly residential areas (Berland et al. 2015). In addition, a recent survey of select riparian areas across Austin found that canopy cover ranged from 70 percent to 99 percent (Duncan et al. 2011). Our analysis attempted to discern whether tree removals were occurring in areas of dense canopy cover across the city based on physical landscape characteristics. Neither distance to hydrologic features nor percentage slope were factors in tree removals during the study period at the scale of analysis. The mean slope of tree removals is consistent across categories of removals with little variation (Table 2) and might reflect preferences of developers to build on relatively flat terrain and mostly away from riparian areas. Yet, the use of a 30-meter DEM does not detect fine-scale changes in topography and provide the actual slope measurement at the site of tree removal. Given that steep slopes are a characteristic of the Hill Country region and the propensity for development in these areas, future research should consider whether the use of a finer resolution DEM yields a significant relationship between slope and tree removals in western portions of the city.

Conclusions

Developing successful, neighborhood-scale models of the influences of urban forestry regulations on overall urban forest patterns is important as more and more North American cities implement a range of urban forestry programs and regulations to complement and achieve urban sustainability objectives. Citywide and broad canopy assessments of urban forests are useful for some decision-making objectives but do little to inform local landowners, land developers, and urban forest managers of the neighborhood-scale impacts of development and environmental perturbations to the urban forest. Our research indicates that a variety of landscape characteristics can be operationalized to provide information on the location and intensity of tree removals at the neighborhood scale and the socioeconomic and urban landscape factors driving tree loss. More broadly, the results of this research provide urban forest managers and researchers in other rapidly growing metropolitan areas with a geographic understanding of urban tree loss. Yet, there also are broad-scale factors, such as climate variability and economic trends, influencing tree removals in Austin that might also be of concern for other urban areas. Future work should continue to evaluate both broad-scale and fine-scale factors to provide a more complete understanding of urban tree loss. Finally, this analysis was conducted using publically available data and standard GIS and statistical tools. Managers interested in developing urban forest regulations might use similar techniques to explore urban forest loss in an effort to achieve their urban forest and sustainability goals. ■

Acknowledgments

The authors thank the City of Austin's Arborist Program for providing the permitted tree removal data set. We also thank Elyse Zavar and Rusty Weaver for their helpful comments on an earlier version of this article as well as the anonymous reviewers and journal editor Barney Warf for their constructive comments. Any errors or omissions remain ours.

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BRENDAN L. LAVY is a Doctoral Candidate in the Department of Geography at Texas State University, San Marcos, TX 78666. E-mail: bl1186@txstate.edu. He is a human–environment geographer with research interests in environmental resource management, environmental policy, and the environmental effects of urbanization.

RONALD R. HAGELMAN III is an Associate Professor and the Associate Chair in the Department of the Geography at Texas State University, San Marcos, TX 78666. E-mail: rhagelman@txstate.edu. He is an environmental geographer with research interests in urban environmental management, natural hazards, and disaster reconstruction.

Appendix. *Spearman's rho correlation coefficients calculated for discrete and continuous variables*

	No. of tree removals per block group	Population density	Age of structure	Distance to major roads	Percentage white	Percentage college graduate	Percentage owner occupied	Median income	Market value	Percentage slope	Distance to hydrologic features
No. of tree removals per block group	1.000										
Population density	0.160**	1.000									
Age of structure	0.553**	0.107*	1.000								
Distance to major roads	−0.128**	0.010	−0.105*	1.000							
Percentage white	0.398**	0.068	0.348**	0.142**	1.000						
Percentage college graduate	0.334**	0.017	0.313**	0.076	0.748**	1.000					
Percentage owner occupied	0.122**	0.041	0.010	0.360**	0.392**	0.241**	1.000				
Median income	0.117*	0.047	0.058	0.322**	0.624**	0.578**	0.730**	1.000			
Market value	0.138**	0.000	0.157**	−0.082	.359**	0.537**	−0.140**	0.163**	1.000		
Percentage slope	0.040	−0.138**	0.006	−0.048	0.065	0.052	0.010	0.031	0.015	1.000	
Distance to hydrologic features	−0.027	−0.019	−0.037	0.036	0.026	-0.029	0.127**	0.064	−0.002	−0.010	1.000

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).