

Determinants of urban tree canopy in residential neighborhoods: Household characteristics, urban form, and the geophysical landscape

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Abstract The aesthetic, economic, and environmental benefits of urban trees are well recognized. Previous research has focused on understanding how a variety of social and environmental factors are related to urban vegetation. The aim is often to provide planners with information that will improve residential neighborhood design, or guide tree planting campaigns encouraging the cultivation of urban trees. In this paper we examine a broad range of factors we hypothesize are correlated to urban tree canopy heterogeneity in Salt Lake County, Utah. We use a multi-model inference approach to evaluate the relative contribution of these factors to observed heterogeneity in urban tree canopy cover, and discuss the implications of our analysis. An important contribution of this work is an explicit attempt to account for the confounding effect of *neighborhood age* in understanding the relationship between human and environmental factors, and urban tree canopy. We use regression analysis with interaction terms to assess the effects of 15 human and environmental variables on tree canopy abundance while holding neighborhood age constant. We demonstrate that neighborhood age is an influential covariate that affects how the human and environmental factors relate to the abundance of neighborhood tree canopy. For example, we demonstrate that in new neighborhoods a positive relationship exists between street density and residential tree canopy, but the relationship diminishes as the neighborhood ages. We conclude that to better understand the determinants of urban tree

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canopy in residential areas it is important to consider both human and environmental factors while accounting for neighborhood age.

Keywords Urban vegetation · Urban ecology · Urban tree canopy · Geographic information systems · Interaction effects · Multi-model inference

Introduction

At the turn of the 21st century, more than half the world's population lived in urban areas, and the number of people moving to urban areas is expected to increase over the next 25 years (UNU/IAS 2003). Designing cities to be more livable is an important priority for this century, and urban vegetation is increasingly recognized as a key condition for human well-being in urbanized areas (Bolund and Hunhammar 1999; Brown 2008). Beyond aesthetic benefits, urban trees have been shown to reduce energy consumption (Huang et al. 1990) and control storm-water runoff (McPherson 1992; Xiao et al. 1998). There is also evidence that urban trees improve air quality (Nowak et al. 2006) and aid in carbon sequestration (Nowak and Crane 2002). It is not surprising that many cities in the U.S. and elsewhere are campaigning to cultivate more urban trees (Brown 2008; McPherson et al. 2008). A better understanding of how human and environmental factors are related to urban forests will provide planners with information to improve residential neighborhood design, and will guide foresters in tree planting campaigns aimed at encouraging the cultivation of urban trees.

Factors influencing urban vegetation

Urban ecosystems consist of multiple interlinked social, economic, institutional, ecological, and physical sub-systems (Pickett et al. 1997; Alberti et al. 2003; Grimm and Redman 2004; Alberti 2008). Within the urban ecosystem, patterns of human activities influence patterns and processes of biotic systems (Grimm et al. 2000), and ecological processes and patterns are influenced by human activity (Whitney and Adams 1980). Within the last decade, considerable attention has been given to the relationship between the socio-economic status of neighborhoods and urban vegetation (Iverson and Cook 2000; Hope et al. 2003; Martin et al. 2004; Grove et al. 2006b; Troy et al. 2007). A common finding is that income and level of education are positively correlated with a greater abundance (Iverson and Cook 2000; Grove et al. 2006a; Troy et al. 2007) and a greater diversity of urban vegetation (Hope et al. 2003; Martin et al. 2004). Several complementary social theories have been posited to explain why socio-economic status is highly correlated with urban vegetation patterns.

Grove et al. (2006b) suggest that homeowners are likely to maintain landscapes similar to their neighbors' because of peer influences and the social status associated with lifestyle. In this case, income is an important component of lifestyle, but not the only driver of residential vegetation pattern (Grove et al. 2006b). Social stratification theory suggests that neighborhoods are able to influence public and private investments at a municipal level based on their position within the social hierarchy of a community. The implication is that social power influences patterns of urban vegetation. Yet another theory suggests that differentiation in urban vegetation patterns is primarily explained by the simple availability of financial resources (Grove 1996). Hope et al. (2003) and Martin et al. (2004) call this the "luxury effect." Neighborhoods with the wherewithal to maintain diverse or abundant vegetation do so primarily because they have the economic means.

Cultural factors are also believed to provide an explanation for heterogeneous patterns of urban vegetation. Choices about where to live or how residential vegetation is maintained may be linked to cultural values associated with race and/or ethnicity. Based on the observation that Oleander (*Nerium oleander*) is a popular landscape plant among Hispanics/Latinos, Martin et al. (2004) hypothesized that the abundance of Oleander might be correlated with the percentage of a neighborhood population that is Hispanic/Latino in Phoenix, AZ. They found however that a statistically significant relationship could not be established. Troy et al. (2007) investigated the relationship between the percent African-American families in a neighborhood and urban tree canopy cover, and found a positive relationship exists in Baltimore, MD. Rather than attribute this to a cultural affinity for denser tree canopy, they suggest the relationship is most likely explained by historical legacy (e.g. past tree plantings). Whether or not there is a relationship between cultural values and observed heterogeneity of urban vegetation is a matter that is not clearly resolved.

A factor that has received little attention, but may be related to urban vegetation heterogeneity is family life-stage. Zimmerman (1984) notes that the family life-cycle is a useful concept commonly used in social ecology to better understand demands and uses of natural resources by different social groups. She shows for example, that demand for air conditioning, and number of vehicles used per family fluctuates during the family life-cycle—mid stage families demand more air conditioning and have more vehicles than early or late-stage families (Zimmerman 1984). The possible relationship between family life stage and urban vegetation heterogeneity has been noted, but not explicitly tested in previous studies (Grove et al. 2006b; Troy et al. 2007). One hypothesis may be that as people pass through different stages of the family life cycle, the value placed on amenities such as urban vegetation changes.

Much of the social science research to-date on urban vegetation has focused on the relationship between urban vegetation (abundance and diversity) and the social, economic, and demographic characteristics of households within neighborhoods (Martin et al. 2004; Grove et al. 2006b; Troy et al. 2007). Little research has addressed the role of the built environment—the spatial structure of urban areas and how it relates to urban vegetation. Conway (2009) and Conway and Hackworth (2007) studied the relationship between residential vegetation and urban design and found that New Urbanist design principles (e.g. compact, pedestrian friendly neighborhoods, and mixed land uses (Leccese et al. 2000)) did not necessarily support more vegetation than neighborhoods designed under conventional planning patterns. Whitford et al. (2001) found that indicators of ecological performance, such as surface temperature, carbon storage and sequestration, and biodiversity were lower in compact cities than those with low-density development (i.e. sprawl) due to the lack of green space, particularly urban trees. Both of these studies raise questions about the merits of urban design principles focused primarily on structural design without regard for its impact, or relationship, with urban vegetation.

While vegetation patterns in human-dominated ecosystems are highly influenced by a variety of human factors, the physical environment is also important. Geomorphic gradients, particularly in arid and semi-arid environments, influence plant diversity and abundance by controlling water and nutrient supply (Parker and Bendix 1996; Wondzell et al. 1996). In their study of urban plant diversity in Phoenix, AZ, Hope et al. (2003) found that elevation was a significant predictor of variation in plant diversity. However they noted that elevation was also highly correlated with financial wealth, and conclude that diversity in urban vegetation has less to do with limiting natural resources than human factors that control the availability of those resources (Hope et al. 2003).

Previous research (Hope et al. 2003; Martin et al. 2004; Grove et al. 2006b; Troy et al. 2007) has shown that a key factor influencing the abundance and diversity of vegetation in residential urban and suburban neighborhoods is the amount of time since the land was developed. Grove et al. (2006a, b) and Troy et al. (2007) found that in Baltimore, MD, the abundance of neighborhood tree canopy cover increases with median house age to a point at about 45 or 50 years, whereupon tree canopy decreases as neighborhoods get older. Hope et al. (2003) and Martin et al. (2004) found an opposite effect in Phoenix, AZ. They looked at urban vegetation in neighborhoods up to 50 years old, and found that both abundance and diversity decreased with neighborhood age—newer neighborhoods had higher plant abundance and diversity. Hope et al. (2003) noted that newer neighborhoods tended to be wealthier, suggesting that neighborhood wealth may be a covariate linked to neighborhood age that explains variations in urban vegetation. Another explanation for these observations in Baltimore and Phoenix could be the stark environmental differences between the two cities, and the types of landscaping common in each.

Study area

Salt Lake County lies on the eastern rim of the Great Basin ecoregion of the western United States (41°N, 111°W) at an elevation of 1,280 m above sea level. The region is considered a temperate desert, with a mean annual precipitation of 380–760 mm and mean potential evaporation of 910–990 mm (Banner et al. 2009). At the center of the county is the Salt Lake Valley. When Mormon settlers first arrived in 1847 they encountered a valley dominated by sagebrush (*Artemisia tridentata* spp.) and a variety of bunchgrasses (Whitney 1892). No trees were present, though gamble oak (*Quercus gambelii*) and two species of maple (*Acer glabrum* and *Acer gradidentatum*) could be found on the surrounding mountainsides (Whitney 1892). Within the first year of their arrival the pioneers began developing canals to divert mountain stream water from the Wasatch Range and Jordan River to irrigate crops (Arrington 1958). An extensive irrigation system soon provided water for both agriculture and residential landscaping that is still in use today.

One million people live in Salt Lake County (U.S. Census Bureau 2009) and the population is expected to rise to 1.6 million by 2050 (Salt Lake County 2010). Nearly all of the county's population resides in 15 cities within the valley, which has an area extent of approximately 800 km². The earliest residential structures were built at the northeast end of the valley near City Creek Canyon. As the valley population grew, residential development extended south primarily along the foothills of the Wasatch Range. The valley bottom remained in agricultural production through the 19th century until an era of suburban expansion started shortly after World War II, pushing residential development into agricultural lands in the central valley. Residential development continues today with growth to the south and western fringes of the valley. The spatial distribution of urban vegetation throughout the valley generally follows the course of residential expansion. In an arid environment that does not naturally support trees, human dominance on the landscape appears to be the primary factor driving the growth and expansion of urban forests.

Study objectives

This study aims to better understand how a broad range of factors relate to residential urban tree canopy density in Salt Lake County, Utah. Previous studies have focused on how neighborhood household characteristics (social and economic variables) relate to urban vegetation cover (Iverson and Cook 2000; Hope et al. 2003; Martin et al. 2004; Grove et al.

2006b; Troy et al. 2007), and a few (Whitford et al. 2001; Conway and Hackworth 2007; Conway 2009) have studied the relationship of urban form to urban vegetation. One of our objectives is to broaden the scope of analysis by examining the determinants of urban forest canopy in a more comprehensive fashion. We use the term “determinants” in the sense that by examining these variables one may determine something about tree canopy heterogeneity in urban areas (Sanders 1984), and not in the sense that these variables cause the observed heterogeneity. We explicitly consider neighborhood age (time since development) a confounding, or moderating, factor to be controlled. In other words, our question is if we hold neighborhood age constant, what is the relationship between human and physical dimensions of neighborhoods and residential tree canopy abundance? We frame this question within the context of three theories explaining variability in urban tree canopy abundance for residential neighborhoods.

- 1) *Variation in residential tree canopy is explained by social, economic and demographic characteristics of neighborhood households.* Building on the work of others (Grove et al. 2006b; Troy et al. 2007) we test the hypothesis that income and social status are positively related to the abundance of urban tree canopy. In addition we explore the hypotheses that racial/ethnic background of households and family life-stage are related to the abundance of neighborhood tree canopy. A better understanding of how these household characteristics of neighborhoods relate to urban tree canopy will help urban foresters target certain social and/or demographic groups in tree planting and maintenance efforts.
- 2) *Variation in residential tree canopy is explained by the spatial structure (urban form) of residential neighborhoods.* Previous studies (Whitford et al. 2001; Conway and Hackworth 2007; Conway 2009) suggest that the spatial form of residential development is correlated with the abundance of urban vegetation. Using spatial metrics of urban form (e.g. median lot size, street connectivity, land use heterogeneity, etc.) we test the hypothesis that the spatial structure of residential neighborhoods is related to tree canopy abundance. Addressing this question is particularly relevant in light of current planning efforts that encourage specific types of urban form as a measure to curb urban sprawl.
- 3) *Variation in residential tree canopy is explained by gradients in physical geography.* Given the well-recognized influence of the physical environment on plant growth and production (Parker and Bendix 1996; Wondzell et al. 1996) we hypothesize that urban vegetation, measured as tree canopy cover, will be correlated to these gradients in an urban setting.

As a final objective we evaluate the relative contribution of human and physical factors to observed heterogeneity in urban tree canopy cover. We address the question does any one theory have a stronger relationship with variation in tree canopy abundance than the others? Or can observed heterogeneity in tree canopy abundance be explained by a combination of all three theories?

Methods

Data

A common spatial unit of observation for neighborhood level studies in the U.S. is the census block group (Grove et al. 2006a, b; Troy et al. 2007). Census block groups are

considered fairly homogeneous areas with similar social, economic, and demographic characteristics, and with populations of typically around 1,500 people (Peters and MacDonald 2004). Block group boundaries however may include non-residential land uses. Given that our focus is on residential vegetation, we modified the census block group boundary to include *only* the single family residential (SFR) portion of the block group. We did this by selecting SFR parcels from the county parcels GIS dataset, dissolving them to create residential land use polygons, buffering them by 10 m, and intersecting those polygons with the census block group dataset. By doing this we excluded townhomes, condominiums, and apartment complexes which often have different mechanisms for landscaping stewardship. This created a GIS dataset of 542 “neighborhoods” defined as the *single family residential portion of census block groups*.

We generated a GIS dataset of urban tree canopy from color-infrared digital orthophotography (NAIP 2006) for Salt Lake County using an object-oriented image segmentation approach (Jensen 2005). This dataset provided complete coverage of urban tree canopy as polygons for the study area, from imagery with 1-meter spatial resolution. To assign a measure of tree canopy to each residential neighborhood, we intersected the tree canopy GIS dataset with the neighborhood GIS dataset and calculated the percent (i.e. proportion) of the neighborhood covered by canopy (from a plan view). Figure 1 shows the study area with 542 neighborhoods and percent tree canopy cover for each neighborhood depicted in graduated gray scale.

To investigate the relationship of various aspects of household characteristics, urban form, and the geophysical landscape to neighborhood tree canopy, we assembled a GIS database from a variety of sources (Table 1). The data were prepared within the GIS so that each observation unit (i.e. neighborhood) was populated with information for each of the database variables. Data on median household income and the percent of high school graduates have been used in previous studies (Grove et al. 2006b; Troy et al. 2007) as a measure socio-economic status. To measure race/ethnicity we calculated the percent of non-white persons using available census data. In Utah, Hispanics are the largest minority population group (U.S. Census Bureau 2009). Average household size and median population age, are intended to measure family life-stage, with the assumption that neighborhoods with larger household sizes and mid to lower population age indicate neighborhoods predominated by middle-stage families in the family life cycle.

Measurements of urban form come largely from urban sprawl literature (Galster et al. 2001; Ewing et al. 2002; Song and Knapp 2004). Median lot size and street density both measure the density of the built environment (Ewing et al. 2002; Song and Knapp 2004). Median block perimeter may be thought of as a measure of urban density, but also measures the spatial structure of neighborhood design—suburban era neighborhoods typically have larger block perimeters because of a less-connected street network (Song and Knapp 2004). A common method to measure street connectivity is the ratio of streets to intersections (Weston 2002; Song and Knapp 2004). Well-connected neighborhoods have a high ratio of streets to intersections; a poorly connected design—with many cul-de-sacs—have a low ratio. Another common measure of urban form is land use mix, or land use heterogeneity (Galster et al. 2001). Sprawling urban form, typical of the suburban era, is commonly believed to be more homogeneous in both social/demographic characteristics, and land uses (Galster et al. 2001). For this metric we measure interspersion and juxtaposition (IJ) of commercial land uses within and around residential neighborhoods using a spatial index borrowed from landscape ecology (McGarigal et al. 2002).

A predominant limiting factor to plant growth in arid and semi-arid environments is water availability. Environmental gradients such as elevation, slope, and aspect, in addition

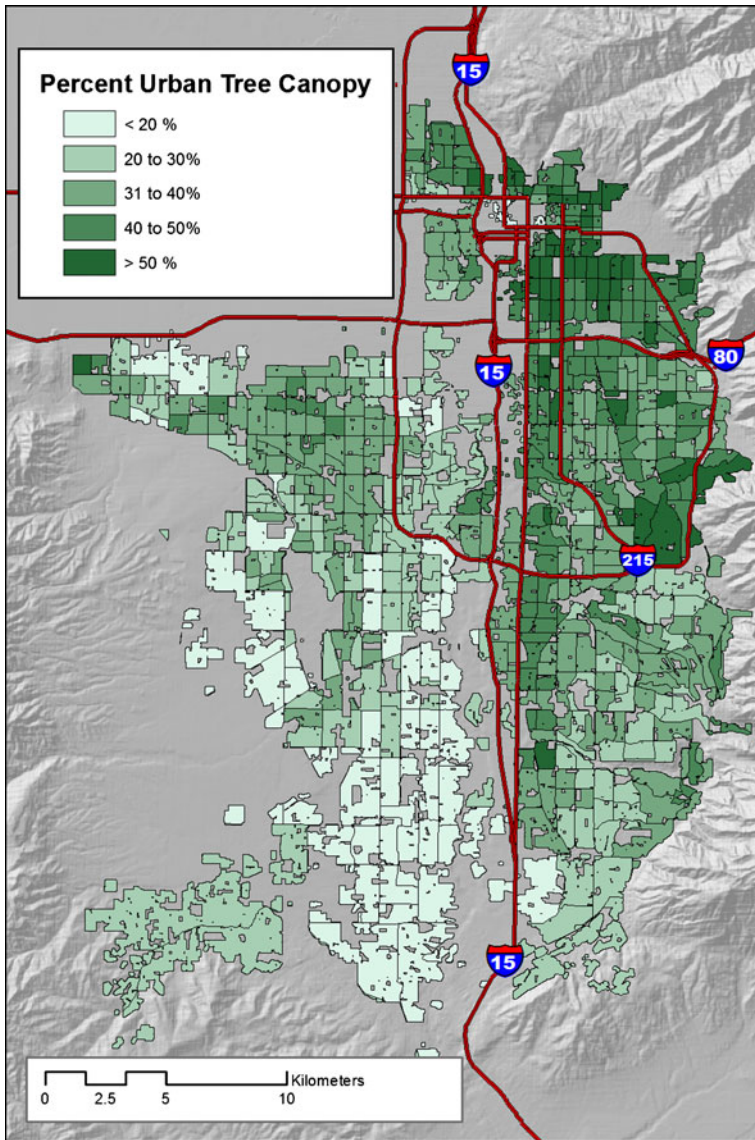


Fig. 1 Spatial distribution of urban tree canopy by neighborhood in Salt Lake County, Utah in 2006

to the water holding capacity of soils, are important factors influencing water as a resource to plants (Parker and Bendix 1996; Wondzell et al. 1996). We selected five variables, readily available in spatial format, to measure these environmental gradients. We found slope and elevation to be highly correlated with mean annual precipitation, so chose only mean annual precipitation as a measure of water (non-irrigated) availability. Because both streams and canals tend to provide ground water to surrounding areas, we included a measure of the distance to these water bodies—measured as the neighborhood’s mean Euclidean distance to the stream or canal. Available water storage capacity was obtained from a soils GIS dataset and is measured as the volume of water the soil is capable of storing that is available

Table 1 Determinants of urban tree canopy

	Variable name	Description & source
	Neighborhood age	Median age of single family residences. Source: SLCo Parcel GIS data. ¹
Household characteristics	Median household Income	Median household income (dollars). Source: Estimated 2007 Census. ²
	Ave. Household Size	Average household size (number of people in household). Source: Estimated 2007 Census.
	Med. Population Age	Median population age. Source: Estimated 2007 Census.
	Non-White Population	Percent non-white population. Source: Estimated 2007 Census.
	High School Graduates	Percent high school graduates. Source: Estimated 2007 Census.
Urban form	Street Connectivity	Street connectivity index; ratio of links (streets) to nodes (intersections). Source: SLCo Street Centerline GIS data.
	Land Use Mix	Land use mix, or contiguity. Measured by Interspersion & Juxtaposition (IJI) index. Source: SLCo Parcel GIS data.
	Median Lot Size	Median single family lot size (acres). Source: SLCo Parcel GIS data.
	Res. Street Density	Residential street density. Line density function in ArcGIS. Source: SLCo Parcel GIS data.
	Median Block Perimeter	Median length of neighborhood block perimeter (m.). Source: SLCo Parcel GIS data.
Geophysical landscape	Mean Annual Precip.	Mean annual precipitation (mm) average for neighborhood. Source: PRISM GIS data. ³
	Avail. Water Storage	Available water storage capacity (cm) of soils to the depth of 150 cm. Source: STATSGO GIS data. ⁴
	Dist. to Streams/Canals	Average Euclidean distance to streams/canals for each neighborhood. Source: SLCo stream/canal GIS data.
	Aspect (Westness)	Transformed azimuth measuring degree to which topographic location is facing west (west = 180). Mean azimuth for neighborhood. Source: USGS 10 m DEM. ⁵
	Aspect (Southness)	Transformed azimuth measuring degree to which topographic location is facing south (south = 180). Mean azimuth for neighborhood. Source: USGS 10 m DEM.

¹ Salt Lake County GIS data obtained from http://www.surveyor.slco.org/gis/gis_data/ and <http://gis.utah.gov/agrc>. ² U.S. Census data obtained from GeoLytics, Inc. <http://www.geolytics.com/>

³ PRISM data obtained from <http://www.prism.oregonstate.edu/>. ⁴ NRCS STATSGO data obtained from <http://www.soils.usda.gov/survey/geography/statsgo/>. ⁵ DEM data from: <http://gis.utah.gov/agrc>

to plants (NRCS 2009). Because measurements of aspect using conventional azimuths are problematic (north measured as both 0 and 360°), we created two transformed metrics, one measuring westness and the other southness (Chang and Li 2000).

A critical component of the GIS database is a variable measuring neighborhood age, or time since the land was developed. Neighborhood age was measured as the median age of residential homes in the neighborhood, based on the year the structure was built.

Regression analysis

Fundamentally our analytical approach utilizes linear regression (Faraway 2005) to assess the relationship between urban tree canopy and variation in household characteristics, urban form, and physical geography of residential neighborhoods. As a parametric model, linear regression assumes normally distributed data and often percentage data are not normally distributed. Deviation from normality, however, tends to be more pronounced at small and large percentages, approximating normality when data range between 30 and 70% (Zar 1999). We tested for normality in the dependent variable (percent tree canopy) and found normality not to be a problem with our data. As a bounded variable, another potential problem with percentage data is that the model can conceivably predict values outside the legitimate bounds of 0 and 100%. A common solution is to either transform the percentage variable, or use another modeling approach such as logistic regression (Zhao et al. 2001). We did not encounter problems with unbounded predictions. We tested for constant variance of residuals and non-linearity and did not find enough of a problem to warrant transformation of any of the independent variables. We checked for outliers and leverage points, finding 21 unusual or influential observations among the 542 samples. These were removed from further analysis. To test for collinearity among the independent variables we computed the variance inflation factor (VIF) for each independent variable, and examined a Pearson's moment correlation matrix for large pairwise correlations (Table 2). With the exception of one pair of variables (percent non-white population and percent high school graduates) correlation among independent variables was below 0.80. We used the Moran's I test for spatial autocorrelation and found high positive spatial dependence among model residuals. To account for spatial autocorrelation we adopted a simultaneous autoregressive model (SAR) for the regression analysis using spatial weights defined by the nearest neighborhood centroid (Bivand et al. 2008).

Interpreting interaction terms

Evidence (Martin et al. 2004; Grove et al. 2006b; Troy et al. 2007) suggests that the age of a neighborhood is an important covariate explaining tree canopy abundance in urban residential neighborhoods. The more time that has passed since a neighborhood was developed, the more time there has been for trees to grow. If we wish to test the hypothesis that household income, for example, is positively related to tree canopy abundance, we must recognize the moderating effect of neighborhood age. One way to account for the moderating effects of a covariate in multiple linear regression is to use interaction terms (Aiken and West 1991; Jaccard and Turrisi 2003). For example, in the equation (following Aiken and West (1991) we place the intercept (b_0) term in the last position):

$$\hat{Y} = b_1X + b_2Z + b_3XZ + b_0$$

The XZ interaction term signifies the regression of Y on X is dependent on specific values of Z . So if Y is percent tree canopy, X is household income, and Z is neighborhood age, the regression equation above estimates the slope of canopy cover (Y) on household income (X)

Table 2 Pearson's r correlations for Neighborhood Age and 15 explanatory variables

	Neighborhood age	Median income	Ave. household size	Med. population age	Non-white population	High school graduates	Street connectivity	Land use mix	Median lot size	Res. street density	Median block perimeter	Mean annual precip.	Avail. water storage	Dist. to streams/canals	Aspect (westness)	Aspect (southness)
Neighborhood age	1.00	-0.50	-0.65	0.24	0.26	-0.22	0.41	0.10	-0.60	0.73	-0.35	0.21	0.09	0.05	0.52	0.32
Median income		1.00	0.48	0.15	-0.58	0.58	-0.12	-0.28	0.58	-0.54	0.31	0.49	-0.33	-0.06	-0.05	0.03
Average household size			1.00	-0.46	0.01	-0.04	-0.36	-0.25	0.43	-0.51	0.40	-0.20	-0.16	0.11	-0.56	-0.27
Median population age				1.00	-0.34	0.24	0.18	-0.06	0.02	0.15	-0.11	0.41	-0.02	-0.11	0.46	0.13
Non-white population					1.00	-0.84	0.15	0.21	-0.45	0.50	-0.20	-0.46	0.04	0.08	-0.13	-0.18
High school graduates						1.00	-0.09	-0.21	0.35	-0.37	0.17	0.52	-0.08	-0.11	0.16	0.25
Street connectivity							1.00	0.28	-0.31	0.29	-0.31	0.23	-0.10	-0.12	0.37	0.28
Land use mix								1.00	-0.01	-0.02	-0.38	-0.13	0.10	-0.20	0.10	0.04
Median lot size									1.00	-0.68	0.34	0.08	-0.10	-0.14	-0.22	-0.10
Residential street density										1.00	-0.25	-0.03	0.07	0.05	0.26	0.12
Median block perimeter											1.00	-0.01	-0.06	0.15	-0.23	-0.11
Mean annual precip.												1.00	-0.45	0.03	0.54	0.45
Available water storage													1.00	-0.11	-0.18	-0.06
Distance to streams/canals														1.00	-0.06	-0.04
Aspect (westness)															1.00	0.30
Aspect (southness)																1.00

along a continuous range of neighborhood ages (Z). To determine the slope of Y on X for any value Z , we restructure the regression equation through simple algebra,

$$\hat{Y} = (b_1 + b_3Z)X + (b_2Z + b_0),$$

substitute the desired value Z , and reduce the equation. Aiken and West (1991) refer to $(b_1 + b_3Z)$ as the simple slope of the regression of Y on X at the single value of Z . Using this approach we can graph simple slopes for different values of Z to visualize the relationship of Y to X conditional on values of Z . It is also possible to test whether the slopes are statistically different from zero, and to determine whether the simple slopes are statistically different from one another (an interaction effect). In terms of our analysis this allows us to determine whether there is a statistically significant relationship between percent tree canopy and household income, for example, at any given neighborhood age, and to determine whether that relationship differs between neighborhood ages.

Model selection and multi-model inference

Our second objective was to explore the question of which theory—based on data available for our study—best explains variation in the abundance of tree canopy in residential neighborhoods. We follow the information-theoretic approach of Burnham and Anderson (2002) to evaluate and compare a set of candidate models. This approach is both philosophical and procedural in nature. Philosophically it asserts that the goal of scientific data analysis is to make inferences from models by separating the information in the data from the noise (Burnham and Anderson 2002). Consistent with the philosophy of “multiple working hypotheses” (Chamberlin 1965), the approach begins with thoughtful selection of a set of plausible candidate models based on sound theoretical reasoning. All candidate models are considered reasonable approximations of the issue at interest. To evaluate the relative “correctness” of the models Burnham and Anderson (2002) adopt the Akaike information criterion (AIC). As an information-theoretic criterion AIC operates under the principle of parsimony—it seeks to measure how well the model fits the data while penalizing unnecessary complexity. Alone, the AIC score is simply a measure of model fit taking into consideration model complexity. As a relative measure, it can be used to compare alternative models with different parameters as long as the set of observations remains the same (Burnham and Anderson 2002).

To assess the relative contribution of the three theories (household characteristics, urban form, and geophysical landscape) as explanations of variation in residential vegetation we used AIC to compare eight models: a model for each of the three theories with interaction terms, and without interaction terms; and two full models (all three theories combined) with and without interaction terms.

Results

Figure 2 presents plots of calculated simple slopes for the 15 explanatory variables tested. Each plot represents a regression model of percent tree canopy (Y) on one explanatory variable (X) with the inclusion of the covariates neighborhood age (Z) and the two-way interaction of neighborhood age with the X variable (XZ). For each explanatory variable we calculated simple slopes for three neighborhood ages: 15 years, 55 years, and 95 years. Table 3 provides a numerical account of the plots in Fig. 2 and is useful to illustrate which simple slopes are statistically different from zero.

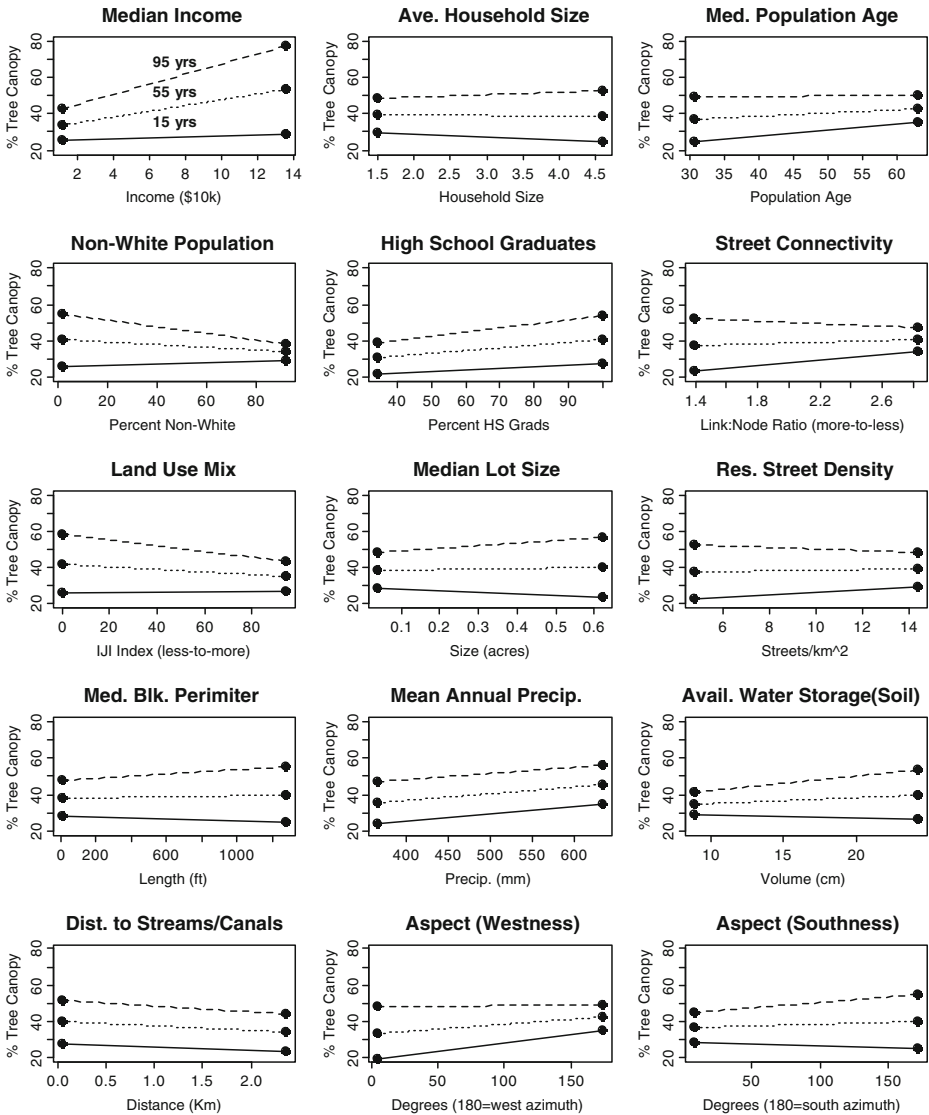


Fig. 2 Plots of simple slopes for 15 explanatory variables. Slope of Y (percent tree canopy) on explanatory variable (X) at neighborhood age (Z)

Simple slopes that are zero are interpreted to mean that there is no relationship between percent tree canopy and a given explanatory variable for that neighborhood age. For example, in the *median income* model we find that the simple slope for neighborhoods that are 15 years old is not significantly different from zero, suggesting that there is no relationship between household income and percent tree canopy in newer neighborhoods. For older neighborhoods a significant positive relationship between income and percent tree canopy emerges, and the relationship becomes more pronounced in 95 year old neighborhoods.

The Z -scores presented in Table 3 provide a means to compare the relative importance, or strength of effect, of each of the variables at the three neighborhood ages. For example,

Table 3 Estimated simple slopes for 15 explanatory variables. Slope of Y (percent tree canopy) on explanatory variable (X) at neighborhood age (Z)

	Independent variable	15 years old		55 years old		95 years old		Interaction effect [§]
		Slope Z-score		Slope Z-score		Slope Z-score		
		Slope	Z-score	Slope	Z-score	Slope	Z-score	
Household characteristics	Median Income	0.25	0.92	1.49	6.67**	2.74	6.07**	yes
	Ave. Household Size	-1.71	-2.08*	-0.17	-0.23	1.37	1.00	no
	Med. Population Age	0.32	3.41**	0.17	2.51	0.02	0.13	no
	Non-White Population	0.04	1.07	-0.07	-3.14**	-0.18	-4.74**	yes
	High School Graduates	0.09	1.59	0.15	4.75**	0.22	4.04**	no
Urban form	Street Connectivity	3.23	2.25**	4.09	4.52**	4.96	2.83**	no
	Land Use Mix	0.01	0.55	-0.07	-3.92**	-0.15	-4.22**	yes
	Median Lot Size	-8.56	-1.72	2.97	0.60	14.49	1.49	no
	Res. Street Density	0.69	2.55**	0.16	0.57	-0.37	-0.68	no
	Median Block Perimeter	0.00	-1.50	0.00	0.92	0.01	1.55	no
Geophysical landscape	Mean Annual Precip.	0.04	3.29**	0.04	3.89**	0.04	1.80	no
	Avail. Water Storage	-0.16	-1.28	0.32	2.76**	0.81	3.20**	yes
	Dist. to Streams/Canals	-1.59	-1.28	-2.37	-2.28*	-3.16	-1.44	no
	Aspect (Westness)	0.09	8.41**	0.05	4.38**	0.01	0.33	yes
	Aspect (Southness)	-0.02	-1.27	0.02	1.50	0.06	2.45*	yes

Probability that slope is not equal to zero denoted by * $p < 0.05$; ** $p < 0.01$. [§] Interaction significant at $p < 0.05$

we note that the variable measuring west-facing aspects is the most influential variable for younger neighborhoods (Z -score = 8.41) but in older neighborhoods is not significant. With a Z -score of 6.07 in very old neighborhoods, and 6.67 in moderately old neighborhoods, median income is the most influential of the 15 variables analyzed.

The plots of simple slopes in Fig. 2 also inform us about the interaction between neighborhood age and the explanatory variable. Simple slope lines for different neighborhood ages that run parallel to one another indicate there is no interaction effect between neighborhood age and that variable. Thus the *mean annual precipitation* model suggests there is a positive relationship between annual precipitation and tree canopy, and that the relationship remains the same regardless of neighborhood age. The *median income* model suggests a strong positive interaction (i.e. strengthening) effect with neighborhood age. The effects of income combined with neighborhood age increase the likelihood of greater urban tree canopy. An example of a negative interaction (i.e. weakening) effect is presented in the *land use mix* model, which suggests that the combined effect of greater land use heterogeneity and neighborhood age is correlated with lower tree canopy.

Table 4 presents the results of an AIC information-theoretic approach to evaluation the three theories explaining urban tree canopy variation. The eight candidate models are ranked from the best model to the poorest model according to AIC score. To evaluate the set of candidate models, AIC is scaled so that the best model has a value of 0 and all other models are ranked relative to the best model (Δ_i AIC). Burnham and Anderson (2002) suggest that relative differences between 1 and 2 AIC scores of the best model should be considered as good as the best model. Models between 4 and 7 AIC scores larger than the best model are moderately good relative to the best model, and models with AIC scores

larger than 10 AIC scores are considerably less good in terms of fit and complexity than the best overall model. The weighted AIC (w_i) score gives the probability that any candidate model is as good as the best model (Burnham and Anderson 2002).

The results indicate that taking into consideration model fit and accounting for model complexity, the best model is the full model with neighborhood age interactions. The next best model (full model without interactions) is 23.57 AIC scores higher, and by Burnham and Anderson's recommendation not a suitable alternative to the best model. According to this analysis, all other candidate models are considerably poorer at explaining the relationship between urban tree canopy and their respective model variables. Because the probability that the alternative models are as good as the best model is zero, averaging the models to make inferences on the entire set of models is not advantageous (Burnham and Anderson 2002). Instead, our analysis suggests that the level to which each model differs from other candidate models is quite pronounced—none of the models rank equally with each another.

Following Burnham and Anderson's (2002) AIC multi-model inference approach it is possible to assess the relative importance of individual predictor variables. This is carried out by fitting separate models for all possible combinations of the model variables and summing the AIC weights (w_i) for all models in which the variable occurs. We did this for the 16 explanatory variables, producing $2^{16}-1 = 65,536$ models. The results presented in Tables 5 identifies the probability that each variable is the most important variable among the set of variables analyzed. The results suggest that *neighborhood age*, and *aspect (westness)* are the most important model variables, and that *available water storage (soils)* and *median household income* are essentially just as important. The most important urban form variable is *street connectivity* with *land use mix* coming in a close second. The variable least likely to be important in understanding the determinants of urban tree canopy variation is *mean annual precipitation*.

Discussion

This analysis makes at least two important contributions to the growing body of theory aimed at understanding the social and physical determinants of urban tree canopy in residential neighborhoods. First, we have attempted to disentangle the role of neighborhood age from other factors (i.e. household characteristics, urban form, geophysical landscape)

Table 4 AIC information-theoretic multi-model analysis of eight candidate models from three theories explaining tree canopy abundance in residential neighborhoods

Model name	Log-likelihood	K	AIC	Δ AIC	AIC weights (w_i)
Full model w/age interactions	-1619.08	25	3288.17	0.00	1.00
Full model	-1636.87	19	3311.73	23.57	0.00
Geophysical landscape w/age interactions	-1649.52	12	3323.05	34.88	0.00
Household characteristics w/age interactions	-1669.59	11	3361.18	73.01	0.00
Urban form w/age interactions	-1687.46	10	3394.93	106.76	0.00
Geophysical landscape	-1736.63	8	3489.25	201.09	0.00
Urban form	-1778.37	8	3572.73	284.57	0.00
Household characteristics	-1788.93	8	3593.85	305.69	0.00

AIC Akaike Information Criterion, K number parameters estimated

Table 5 Computed variable importance for 16 determinants of urban tree canopy in residential neighborhoods using the sum of AIC weights (w_i) from analysis of $2^{16}-1 = 65,535$ models in which the explanatory variable appears

Variable	Σ AIC weights (w_i)	Theory
Neighborhood age	1.0000	N/A ^a
Aspect (westness)	1.0000	Geophysical Landscape
Available water storage (soils)	0.9977	Geophysical Landscape
Median household income	0.9973	Household Characteristics
Street connectivity	0.9497	Urban Form
Land use mix	0.9050	Urban Form
Percent non-white population	0.8998	Household Characteristics
Percent high school graduates	0.8089	Household Characteristics
Distance to streams/canals	0.7606	Geophysical Landscape
Median lot size	0.6587	Urban Form
Aspect (southness)	0.6510	Geophysical Landscape
Residential street density	0.5657	Urban Form
Median block perimeter	0.4499	Urban Form
Average household size	0.3583	Household Characteristics
Median population age	0.3467	Household Characteristics
Mean annual precipitation	0.2856	Geophysical Landscape

^aNeighborhood Age is not considered pertaining to any single theory

determining urban forest structure to better understand how they relate to tree canopy variation in residential neighborhoods. Second, we have illuminated the relative influence of multiple determinants of urban forest canopy and have attempted to quantify their relative importance in a semi-arid urban environment.

The importance of *time since development* is revealed through both our analysis of the interaction effects of neighborhood age with other explanatory variables, and through the AIC multi-model analysis. We demonstrate empirically what is often logically assumed by social theory—that while social, economic, and demographic factors are related to urban vegetation abundance, the relationship is moderated by the amount of time the vegetation has had to grow. The “luxury effect” (Hope et al. 2003; Martin et al. 2004) or the positive relationship between household income and vegetation abundance is influenced by the age of the neighborhood, and in fact, we see that in relatively new neighborhoods there is no relationship. However, as time progresses the luxury effect becomes more pronounced. Time strengthens (multiplies) the effect of income on neighborhood canopy abundance because wealthy homeowners have the financial resources to invest in growing vegetation.

Troy et al. (2007) observed a positive relationship between variables measuring family life stage (marriage rates and household size) and tree canopy in Baltimore, and hypothesized that families with more children either plant and maintain more trees or self-select by moving to neighborhoods with more trees. In Salt Lake County we hypothesized a negative relationship exists between mid-stage families with children and tree canopy, not because families in Salt Lake County are adverse to trees, but because urban trees are a rare commodity in this environment, and the opportunity cost of either planting and maintaining trees or moving to an established neighborhood with mature trees

is high. We find that our analysis supports this hypothesis only in new neighborhoods. At the 15-year-old level, tree canopy decreases with household size, and increases with median population age. In Utah it is common for mid-stage families to build a new home where they invest most of their wealth in the house and only gradually invest in landscaping. This is less likely to occur in new neighborhoods with older or younger populations where landscaping expenses might be covered by a homeowners association or by the developer. In our study we did not make a distinction among different types of single-family residential neighborhoods. It should be pointed out that the type of residential neighborhood, whether traditional piecemeal development, or large Planned Unit Development (PUD) style neighborhood, may influence the mechanisms of urban vegetation stewardship. We hypothesize that infill of urban trees will likely be more rapid in planned neighborhoods where the developer is required to adhere to neighborhood landscaping ordinances. In our study there appears to be no relationship between family life-stage and tree canopy in older neighborhoods, which are less likely to be planned developments. We interpret this to mean that mid-stage families with children are not self-selecting for neighborhoods with either more or less tree canopy.

When we consider the relationship of race/ethnicity to urban tree canopy our analysis indicates that taking neighborhood age into consideration makes a difference. Troy et al. (2007) note a positive relationship between percent African-American population and urban vegetation in Baltimore. Our analysis suggests that in new neighborhoods there is no relationship between race/ethnicity and tree canopy abundance, but in older neighborhoods with higher percentages of non-white populations, tree canopy abundance is likely to be lower. The immediate explanation might be that older neighborhoods with higher percentages of minorities are less likely to have the financial resources (luxury effect) or social capital (social stratification) required to replace trees that die after their natural life span is complete. Whether income, social capital, transiency, racial or ethnic values, or some other factor explains this relationship is not clear, and suggests that additional studies of race/ethnicity and urban vegetation are needed.

Our study of how household characteristics are related to urban tree canopy provides useful information to urban foresters interested in cultivating and maintaining urban forests. Many municipalities around the nation are sponsoring campaigns to increase urban tree canopy for the benefits it provides (Brown 2008; McPherson et al. 2008). Knowing more about how urban tree canopy is related to different social groups provides practitioners with information about how to distribute scarce financial resources. For example, according to our models, new neighborhoods dominated by mid-stage families will not have much tree canopy to start with, but will eventually increase the amount of tree canopy over the course of time. On the other hand, older neighborhoods with high percentages of non-white populations appear unlikely to increase tree canopy without some kind of assistance. Given these two situations, a tree planting campaign would benefit most by directing its resources to the older neighborhood.

Treating neighborhood age as a moderating factor in our analysis of urban form and its relationship to tree canopy is informative and sheds light on some important questions currently debated in urban planning. The built structure of urban areas is known to change over time (Song and Knapp 2004) so controlling for neighborhood age is particularly relevant to a better understanding of urban form as a determinant of urban tree canopy. In our analysis, the 95-year-old neighborhood level corresponds roughly to the period around 1910 and is representative of the pre-suburban era prior to the end of World War II. The 55-year-old level represents the early suburban era around 1950, and the 15-year-old level represents the late suburban era around 1990. It must be remembered that our analysis

presents models based on patterns in the data, so the relationships can be thought of as empirical “trends” rather than actual observations (there are no pre-suburban neighborhoods with a connectivity index of 0.05, in fact, the mean connectivity index for the pre-suburban era is 2.4). What this means is that by modeling an urban form metric, such as street connectivity *conditional* on a given time since development (neighborhood age), we are predicting what tree canopy would be like in neighborhoods with that level of connectivity after a given number of years have passed. Because many of the questions in urban planning theory and practice involve speculating about how a particular planning strategy or design will improve urban function in the future, this approach, which could be viewed as a “place for time” substitution, is particularly useful as a tool to better understand the potential outcomes of spatial planning ideas and efforts.

Over the last two decades American urban planning has been greatly influenced by the ideals espoused by the philosophy of New Urbanism. However, despite its allure, New Urbanism, as any new planning philosophy or approach, is an experiment underway. New Urbanism has both advocates (Bressi 2002) and critics (Grant 2006). Conway (2009) and Conway and Hackworth (2007) are among the few who have begun to critically examine New Urbanism and the implications of this new planning approach to the ecological function of cities. Our study contributes to this discussion by specifically examining urban form metrics commonly associated with New Urbanism ideals, and how they relate to the biotic environment in semiarid cities.

An important tenet of New Urbanism is the idea that residential neighborhoods should be walkable, which means residential blocks should be small, and street networks dense and well-connected. Critics argue, however, that making neighborhoods more connected for humans makes them less connected for ecological processes (wildlife movement, seed dispersal, etc.) and that a cul-de-sac design may be better for natural ecosystem connectivity (Grodon and Tamminga 2002). If we consider residential tree canopy as one possible measure of natural ecosystem connectivity, an examination of the relationship between neighborhood design and tree canopy sheds some light on the question about how design influences natural urban ecosystems. What our analysis shows is that in *new* neighborhoods, there is a positive relationship (statistically significant at $\alpha=0.05$) between both street connectivity and density, and residential tree canopy. Neighborhoods with street designs that are dense and well connected *start off* with greater tree canopy than less dense and less well-connected streets, but after about 50 years street design no longer makes a difference. So the question of street design for ecosystem connectivity may not be as important in the long term as it is in the first few decades the urban forest is being established.

The other urban form metrics we tested (land use mix, block perimeter, and median lot size) suggest that the amount of time that has passed influences the “performance” of the design principle measured by the metric. Although the relationship is not statistically significant at $\alpha=0.05$, the trend in the slopes for the median lot size metric provides useful information. When we look at the 15-year time level the relationship is negative—larger lots have less tree canopy. However over the course of 50 years, the model suggests that tree canopy density is about the same for both small and large lots. After 95 years, it appears that large lots are capable of supporting more tree canopy and the relationship between lot size and tree canopy slopes in the positive direction. This highlights the importance of considering time in any assessment of how the design of residential neighborhoods influences urban vegetation.

The importance of geophysical landscape determinants becomes apparent through both our analysis of the simple slope models and through AIC multi-model analysis. Two factors

that have the same relationship with urban tree canopy regardless of neighborhood age are *mean annual precipitation* and *distance to streams/canals*. As hypothesized the farther a neighborhood is from a stream or canal the lower the tree canopy, which suggests groundwater returns from these streams/canals may be influencing urban vegetation. Another likely explanation is that homes near canals have better access to canal water, which is much less expensive than culinary water and often used for residential landscape irrigation. Mean annual precipitation is positively related to tree canopy abundance regardless of neighborhood age, however the importance of the variable is highly questionable based on the AIC multi-model analysis. That precipitation is of little importance is not surprising, however, in an environment that receives little precipitation during the summer, and where nearly all homeowners rely on irrigation water for landscape maintenance. When we look at soil water storage capacity we see that an interaction effect exists between neighborhood age and soils in determining tree canopy abundance. There is a strengthening effect between how old the neighborhood is and the type of soils in the neighborhood—older neighborhoods with good soils have higher tree canopy cover. This suggests that lands with the highest water storage capacity were the earliest to be developed.

Our analysis of topographical aspect presents an interesting case where variables chosen may not always measure what one initially expects, and demonstrates the uniqueness of the urban ecosystem relative to more natural ecosystems. Initially our choice of aspect as a determinant of urban tree canopy was to capture the effects of insolation and water availability. Upon examining the results we find that in new and moderately old neighborhoods there is a positive relationship between west-facing azimuths and tree canopy abundance, which runs contrary to our hypothesis that west-facing neighborhoods would have lower tree canopy cover. We have determined that aspect in this particular urban setting explains historic settlement patterns and homeowners preferences for view sheds, rather than limiting water resources due to insolation. We conclude that the geophysical landscape is indeed an important determinant of urban vegetation, but that ecological processes in the urban ecosystem are greatly influenced by the dominant role of humans.

Conclusion

Over 25 years ago Sanders (1984) wrote the paper “Some Determinants of Urban Forest Structure” in the journal *Urban Ecology*. One of Sanders’ objectives was to identify and examine factors that influence urban vegetation patterns in American cities. His work was largely speculative, based primarily on observation and available knowledge. He recognized “there are presently no rapid, accurate, and systematic methods for collecting inventory data for an entire urban forest complex, a fact that precludes an entirely empirical approach to the subject of urban forest science” (Sanders 1984). One of our objectives in this study has been to show that with advances in data collection and management technologies, inventories and the analysis of *complete* urban forest ecosystems are possible. Sanders (1984) suggested urban forest structure is determined by three broad factors: urban morphology, natural factors, and human management systems. He argued that urban morphology creates the spaces available for vegetation, natural factors such as precipitation and soils influence the types of biomass that are likely to thrive, and human management systems account for intra-urban heterogeneity based on variations in human choice. In this paper we have used a variety of geospatial data that, at best, are proxies for the mechanisms determining tree canopy abundance in urban areas. We have sought to determine, in a quantitative fashion, whether the associations of these variables to tree canopy abundance are consistent with Sander’s theories.

Research addressing urban tree canopy in the last decade has taken advantage of the data management and analysis technologies currently available (Grove et al. 2006a, b; Conway and Hackworth 2007; Troy et al. 2007; Conway 2009) but little has been done to integrate all the determinants of urban tree canopy in a comprehensive analysis. We suggest that our study merely scratches the surface of what can be done given currently available data and technology, and serves more to illuminate this need than to satisfy it.

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