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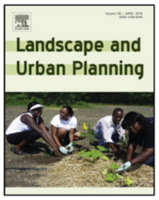

Research Paper

Explaining planted-tree survival and growth in urban neighborhoods: A social–ecological approach to studying recently-planted trees in Indianapolis

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HIGHLIGHTS

- We examined the relationship between social–ecological system (SES) factors & street tree success.
- Variables from all SES factors influence recently-planted tree survival & growth.
- The impact of neighborhood watering strategy on tree success depends on planting season.
- Future research should consider social–ecological context of planted urban trees.

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ABSTRACT

This research seeks to answer the question, what factors of the urban social–ecological system predict survival and growth of trees in nonprofit and neighborhood tree-planting projects? The Ostrom social–ecological system framework and Clark and colleagues' model of urban forest sustainability inform our selection of variables in four categories in the social–ecological system; these categories are the trees, the biophysical environment, the community, and management institutions. We use tree inventory methods to collect data on the survival, growth, and the social–ecological growing environment of recently-planted street trees in Indianapolis, IN to answer our research question. We use a probit model to predict tree survival, and a linear regression model to predict tree growth rate. The following variables are positively related to tree success (survival and/or growth): ball-and-burlap or container packaging, a visible root flare, good overall condition rating, the size of the tree-planting project, planting area width, median household income, percent of renter occupied homes, resident tenure, prior tree planting experience, correct mulching, and a collective watering strategy. The following variables are negatively related to tree success: caliper at planting, crown dieback, and lower trunk damage. Additional variables measured have less clear connections to tree success and should be examined further. Given that models including variables from all four categories of the social–ecological system generally outperform models that exclude some components, we recommend that future research on urban tree survival and growth should consider the holistic social–ecological systems context of the urban ecosystem.

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1. Introduction

In the last two decades, many cities in the United States have increased tree planting activities and set tree planting or canopy cover goals (McPherson & Young, 2010). However, relatively little is known about the factors that influence the success of these young urban trees. Trees in urban environments face challenges to their survival and growth that are different from those faced by trees in forests or nurseries (Whitlow & Bassuk, 1987). Trees in urban settings are affected not only by environmental conditions, but by the people who plant, own, maintain, pass by, and benefit from these trees. However, much research on tree outcomes has taken place as experiments in greenhouses or nurseries, which cannot simulate the actual growing conditions of urban trees that grow in such close proximity to people. This paper studies the survival and growth of young trees planted along city streets. It uses a holistic framework to explain recently planted urban tree success that accounts for characteristics of the trees, the biophysical environment, the surrounding community, and maintenance institutions. We build upon previous research in urban forestry and on social–ecological systems by conducting *in situ* research on urban tree survival and growth and by explicitly considering that planted trees are part of a larger urban social–ecological system.

1.1. Studying urban tree survival and growth in situ

Our review of the literature finds that the majority of research about urban tree success comes from experiments conducted in relatively controlled nursery settings rather than in the urban environment where street trees grow. Few studies attempt to control for the additional stresses that come from the urban environment. Few comprehensively measure the combined effects of biophysical conditions and management factors on tree success, much less combine social or community influence with these biophysical factors. One exception is the recent study by Lu et al. (2011), which examined the influence of local biophysical factors (urban design, biological condition, etc.) and social factors (e.g., a weeded tree plot as evidence of tree stewardship) on the mortality rates of young street trees in New York City. Jack-Scott, Piana, Troxel, Murphy-Dunning, and Ashton (2013) also make use of information about tree surroundings to inform their study of tree success.

1.2. Urban forests as social–ecological systems

The urban forest can be understood as a social–ecological system of linked human and natural components (Mincey, 2012; Mincey et al., 2013; Vogt & Fischer 2014). This perspective (see Table 1) builds on two theories of sustainable resource management: the model of urban forest sustainability (Clark, Matheny, Cross, & Wake, 1997) and the social–ecological system framework (Ostrom, 2009) and highlights potential factors that might influence tree survival and growth. The model of urban forest sustainability was developed in the field of urban forest management in the mid-1990s. The model identities three elements that are necessary for an urban forest to be sustainable (i.e., able to continue producing benefits at the same level over time): (1) a healthy vegetative resource (the trees and their growing environment), (2) a supportive community, and (3) an adequate management regime (Clark et al., 1997). The social–ecological system (SES) framework suggests similar categories of factors that appear most relevant to social and ecological outcomes in rural natural resource systems. The late Nobel Laureate Elinor Ostrom and colleagues developed the SES framework through decades of case study research on common pool resource management in rural forests, fisheries, and irrigation systems (Ostrom, 2009). The SES framework uses four core sets of variables to categorize influences on outcomes of linked human and natural systems: (1) the resource units (e.g., fish, trees), (2) the attributes of the biophysical resource system (e.g., size of a lake or forest), (3) the characteristics of the community of actors, or resource users (e.g., number of users), and (4) the institutional factors of the governance system (e.g., rules for fishing or timber harvesting; Ostrom, 2009). Specific variables in these four categories interact with one another and with the larger ecological and socio-political context to produce social and ecological outcomes (Ostrom, 2009; Epstein, Vogt, Mincey, Cox, & Fischer, 2013, Vogt, 2014). As coupled human-natural systems (Liu et al., 2007) of trees and people, urban forests are social–ecological systems, and the SES framework can help explain observed outcomes. However, the original SES framework was developed largely using research conducted in extractive resource systems in rural settings; thus, we adapt this framework for our application to urban forests that provide non-extractive benefits.

Our urban forests as social–ecological systems perspective (Table 1) contains four broad categories of variables that might influence the success of the urban forest: (1) the trees, (2) their biophysical environment, (3) the surrounding community, and (4) the maintenance institutions that affect the tree. We use this theoretical framework to model tree success. In the rest of this section, we describe what previous research tells us about how each of these categories might influence tree success in the urban forest.

1.2.1. Trees

The survival and growth of planted trees is influenced by the characteristics of those trees. Previous horticultural and arboricultural research provides some insight here. For instance, the size of the tree when it is planted (Neal & Whitlow, 1997; Struve, Burchfield, & Maupin, 2000; Watson, 2005; Lambert, Harper, & Robinson, 2010), the type of plant packaging (Gilman & Beeson, 1996; Lambert et al., 2010), and the tree species (e.g. Iakovoglou, Thompson, Burras, & Kipper, 2001; Grabosky & Gilman, 2004) may influence its survival and growth. Planting depth can impact tree survival: trees that are planted too deeply, with too much soil covering the rootball, are at greater risk of mortality (Gilman & Grabosky, 2004). Additionally, tree health and condition reflect overall tree vigor and should also be related to the survival (e.g. Roman, 2013) and growth (Berrang, Karnosky, & Stanton, 1985; Achinelli, Marquina, & Marlats, 1997) of the tree.

1.2.2. Biophysical environment

The biophysical environment also influences tree success. Evidence suggests that tree survival is influenced by surrounding land use type (Miller and Miller, 1991; Rhoades & Stipes, 1999; Lu et al., 2011), as well as available growing space (Lu et al., 2011) and rooting volume, which constrains root growth and therefore also aboveground growth (Krizek & Dubik, 1987; Grabosky & Gilman, 2004; Day, Wiseman, Dickinson, & Harris, 2010). Tree growth is also impacted by water stress (Kramer, 1987; Krizek & Dubik, 1987; Graves, Joly, & Dana, 1991), poor soil conditions (Smith, May, & Moore, 2001; Scharenbroch, Lloyd, & Johnson-Maynard, 2005; Scharenbroch, 2009) and competition for space with other urban infrastructure both above and below ground (Green & Watson, 1989; Gilman, 1990a; Kjelgren & Clark, 1992; Grabosky & Gilman, 2004). Competition with other trees for rooting space, nutrients and water belowground and for space and light aboveground influences growth rates (Nowak, McBride, & Beatty, 1990; Rhoades & Stipes, 1999; Iakovoglou et al., 2001), as can the season in which a tree is planted (Solfjeld & Hansen, 2004).

1.2.3. Community

We define community to be the people within and surrounding a resource system who provide, use, and benefit from that resource (whether they know it or not). The community has potential to

Table 1
Urban forests are social–ecological systems. This perspective combines the social–ecological system (SES) framework developed in rural common pool resource management settings (Ostrom, 2009) and the model of urban forest sustainability developed in the field of urban forest sustainability (Clark et al., 1997).

Social–ecological system (SES) framework (Ostrom, 2009)	Model of urban forest sustainability (Clark et al., 1997)	Urban forests as social–ecological systems
Resource system	Vegetative resource	Biophysical environment
Resource units		Trees
Users	Supportive community	Community
Governance system	Adequate management	Institutions[a] and management

[a] "Institutions" are defined as rules, norms and strategies that govern interactions between the biophysical resource and the community of users or beneficiaries (Ostrom, 2005).

influence tree success (Clark et al., 1997). Research behind the SES framework has demonstrated that certain community characteristics can be linked to success of the resource system (Ostrom, 1990). For instance, in rural community-managed forests, Yang et al. (2013) find that the largest contributions toward resource monitoring efforts came from intermediate community size and social capital across groups and among group members, leading to the biggest gains in forest cover (Yang et al., 2013).

Residents of communities (i.e., neighborhoods) in which trees are planted vary in their capacity and resources to maintain trees and in their level of commitment to a long-term neighborhood improvement project like tree planting. Higher tree planting success should in part be driven by neighborhood characteristics linked to higher capacity for – or norms of – better tree planting and care. Nowak et al. (1990) identify a positive correlation between percent unemployment and tree mortality rates. These authors speculate that, "increased unemployment signifies more time spent in the neighborhood and increased activity in the street environment," which may lead to greater street tree mortality (: p. 128). This same study also finds a negative correlation between the ratios of owner-to-renter occupied houses and tree mortality rates, and hypothesizes that lower rates of home ownership transfer to a lack of street tree 'ownership' and therefore higher mortality rates (Nowak et al., 1990). Recent research in Connecticut, U.S., by Jack-Scott et al. (2013) demonstrated the relevance of other community group characteristics to tree survival and growth (Jack-Scott et al., 2013). They observed that the longevity of the group engaging in tree planting and prior tree planting experience of a neighborhood are positively related to tree survival and growth, and that more people participating in planting during a planting year also yielded greater survival and growth (Jack-Scott et al., 2013). Other studies have examined motivations for individual involvement in tree planting. For example, Austin (2002) reported that individuals involved in tree planting and maintenance activities in Detroit, Michigan, U.S. were motivated by a desire to work in nature and an opportunity to better the neighborhood. Trees might fare better in neighborhoods where residents are more interested in working in nature and in bettering the neighborhood.

1.2.4. Institutions and management

Institutions are the rules, norms, and shared strategies – formal and informal – that structure the interactions between the community, resources, and biophysical environment (Ostrom, 2005). Any rules, norms or management strategies related to neighborhood maintenance of planted trees might influence the success of planted street trees. Evidence exists that institutions can influence urban forests: Larsen et al. (2008) reported that rules of homeowners' associations actively regulated the composition and maintenance of residential landscapes. In addition to evidence about strict rules, Grove et al. (2006) found that homeowners are likely to maintain landscapes similar to their neighbors' because of social status or norms. In multiple cities in Michigan, Nassauer, Wang, and Darrell (2009) found that community norms regarding landscape appearance influenced exurban household preferences for front yard design.

Maintenance strategies – the type, frequency, duration, and intensity of maintenance performed on trees – can also influence outcomes in the urban forest (Vogt et al. *in review*). Importantly, maintenance throughout a tree's life may actually mitigate the impacts of poor biophysical growing conditions. For example, irrigation and proper soil drainage can reduce water stress (Gilman, 1990b, 2001, 2004). Research in nurseries and greenhouses reveals that consistent watering of young trees is linked to greater tree survival and growth (Gilman, 2001, 2004). Thus, we expect that any strategy that produces more consistent watering will lead to higher neighborhood tree survival rates.

Pruning and mulching strategies also influence tree success. Pruning of roots during planting (Gilman, 1990b; Solfjeld & Hansen, 2004) or of branches (Carvell, 1978) can have a significant influence on tree growth and survival, depending on the proportion of a tree's root system or canopy removed. In particular, pruning branches from a tree removes photosynthetic area and thus we expect trees to grow more slowly if they are pruned (Whitcomb, 1979; Nowak et al., 1990). Incorrect pruning can leave a large and slow-to-heal wound, exposing a tree to diseases that may decrease tree vigor (Clark & Matheny, 2010). However, minimal, correctly performed pruning at the time of planting can actually enhance tree growth rates (Evans and Klett, 1985).

Additionally, mulching can have positive or negative impacts on tree success depending on the depth, placement, type, and timing of mulch applications. Mulch that is less than about 5 cm (2 in.) deep and is pulled away from the base of the trunk helps retain soil moisture and prevents weed growth and can improve tree success (Gilman & Grabosky, 2004). However, improper mulching (i.e., mulch that is too deep around the base of a tree) may increase a tree's irrigation needs (Gilman & Grabosky, 2004) and can also encourage adventitious root growth or girdling roots.

2. Methods

To examine tree success in the urban growing environment, this study uses data collected during a re-inventory of planted urban trees to create statistical models of tree survival and growth. We partnered with Keep Indianapolis Beautiful, Inc. (KIB), an urban greening nonprofit in Marion County, Indiana. KIB works with neighborhood groups in Indianapolis to plant trees through its NeighborWoods program. In their proposal for a tree planting project, groups that plant trees through the NeighborWoods program must identify a strategy that they will follow to water the planted trees. We sorted tree-planting projects that occurred between 2006 and 2009 by the type of watering strategy adopted by the neighborhood and chose a stratified sample of 23 projects (in 16 neighborhoods) where trees were watered by individual residents (*individual* watering strategy) and 12 projects (in 9 neighborhoods) where at least some trees were watered by groups of residents together (*collective* watering strategy). Overall, our sample included 35 projects in 25 neighborhoods.

In the summer months of 2011 and 2012, we re-inventoried street trees that were planted in our sample neighborhoods. We assessed mortality status for all planted trees in sample neighborhoods (1462 trees) and systematically sampled and re-inventoried 20–30 living trees per project (673 living trees in total). Some of these observations had missing information about particular variables and were not used for analysis. Overall, our useable sample contains 1345 trees for survival models and 616 trees for growth models.

During the summer of 2011 we gathered information about the tree, biophysical information about the planting site and evidence of tree maintenance activities according to a data gathering guide (Author et al., 2014 *masked for blind review*). High school student employees of KIB's Youth Tree Team were trained by two of the authors and collected additional tree data during the summer of 2012. Additional information about the biophysical environment came from the City of Indianapolis and the National Land Cover Dataset (NLCD) 2006. KIB provided information from the time of planting about the trees and the tree-planting project.

Socio-demographic community characteristics came from the U.S. Census Bureau (U.S. Department of Commerce Census Bureau, 2012). Each tree was assigned the values for socio-demographic variables of the census tract in which the tree was planted. Sources for all variables can be found in Table 2.

Select information about institutions related to tree management (in addition to our knowledge of the watering strategy) was gathered from semi-structured interviews with neighborhood leaders and nonprofit employees (see Mincey & Vogt [2014] for complete interview methods). Interview responses were used to generate hypotheses and to inform interpretation of the statistical models.

2.1. Dependent variables

We measure tree success in two ways: tree survival and growth rate. Survival and its converse, mortality, are common measures of tree success in urban forestry studies, though specific estimates of survival rates within the first few years after planting are rare (Nowak et al., 1990; Roman & Scatena, 2011), as are general estimates of urban tree mortality (L. Roman, personal communication, November 13, 2013). Our measure of survival is a binary indicator of whether the planted tree was still alive at the time of re-inventory.

Growth rate is also a useful measure of tree success; as larger-sized (i.e., mature) trees provide greater ecosystem services, a tree with a faster growth rate that reaches maturity sooner yields faster rate of return (Nowak et al., 1990). Also, trees that grow well early in life are considered more likely to be established and free to grow with reduced need for watering or other maintenance during normal weather conditions. Our measure of growth is the "relative growth rate," calculated as

$$\text{relative growth rate} = \frac{\ln C_2 - \ln C_1}{(t_2 - t_1)/365}$$

where C_1 and C_2 are measurements of tree caliper at the time of planting (t_1) and time of re-inventory (t_2), respectively (after Brand, 1991as adapted by Samyn and de Vos (2002)). The difference in the time of planting and time of re-inventory is measured in days, so we divide the number of days in the denominator by 365 days per year to obtain relative growth rate in years.

2.2. Analysis

We model survival and growth as a function of the four categories of social–ecological variables described above.

We use maximum likelihood estimation (probit) to predict the likelihood that a planted tree was still alive at the time of re-inventory. We use data on all trees that were planted between 2006 and 2009 in our selected neighborhoods (a total sample of 1345). Our basic survival model (Model S.1) includes indicators of the size and the condition of each tree at planting, indicators of the surrounding environment that are not tree-specific (the percent of impervious surface and the speed limit), and all of the social and institutional indicators described below. In Model S.2, we also include the interaction between collective watering and if a tree was planted in the fall. We suspect that the effect of collective watering might vary across circumstance. We expect the positive effect of collective watering to be greater in spring plantings because the trees face a potentially long, hot, dry summer and collective watering may provide more consistent watering.

We use linear regression to predict annual caliper growth for the trees that were living at the time of re-inventory. Our first model (Model G.1) includes the tree, biophysical environment, community, and institutional indicators described below as well as nursery and taxonomic family dummy variables. In our second model (Model G.2), we add the interaction between fall planting and collective watering. We also suspect the effect of collective watering might differ across overall tree condition. To measure these effects, we also interact collective watering with our binary indicators of tree condition.

The data are clustered in two ways—by tree species and by neighborhood. To account for observed and unobserved species-level variation, we include dummy variables for tree family in all models, with an "other" category for families in our data with fewer than 20 trees, and the beech/oak family (the most numerous family in our dataset) as the baseline. Tree survival and growth may also vary across neighborhood in ways we cannot observe. We control for some neighborhood variation by including a suite of community covariates (socio-demographic variables). Using neighborhood-level random effects would control for unobserved neighborhood-level characteristics. We tested whether random effects were necessary using an intraclass correlation coefficient (ICC). Given the low ICCs for both survival (ICC = 0.087) and growth (ICC = 0.187) datasets, neighborhood random effects models are not shown. Robust standard errors are used in all models.

2.3. Independent variables

2.3.1. Tree characteristics

We include indicators of tree size and condition at planting: caliper-at-planting and whether the tree was packaged in ball-and-burlap packaging, a container, or other type of packaging (bare-root or nylon bags; the excluded packaging type). We include dummy variables for tree family (with the most numerous family, Oak, being the excluded, or baseline family), and also for nursery (i.e., origin of planting stock; the most numerous nursery – nursery 5 – is excluded as the baseline). We control for age of the tree at re-inventory (years since planting). Transplanted trees may take a few growing seasons to become fully established in the landscape (Gilman, Black, & Dehgan, 1998; Struve et al., 2000), and years since planting helps control for this. These data came from KIB records.

We also include indicators of tree condition at re-inventory in our growth models. Condition variables include binary indicators of leaf chlorosis, a visible root flare, and damage on the lower trunk of the tree. A canopy dieback rating (modified from International Union of Forest Research Organizations, International Society of Arboriculture, United States Forest Service, & Urban Natural Resources Institute, 2010) is also used to indicate condition of the tree. We include a rating of the overall condition of the tree as two dummy variables for good condition and poor condition (the excluded condition was fair). We also account for light availability by including a crown exposure rating (after International Union of Forest Research Organizations et al., 2010). Post-planting tree characteristics were gathered during the planted tree re-inventory.

Table 2
Categories of variables and sources of data used in analyses.

UF as SES component	Variables	Data source
Outcome variables	*Alive*	Protocol, V13
	Annual caliper growth (cm)	KIB/Protocol, V5
Tree	*Tree species* (aggregated to family level)	KIB/Protocol, V3
	Nursery	KIB
	Caliper at planting (cm)	KIB
	Ball-and-burlap packaging (0, 1)	KIB
	Containerized packaging	KIB
	Age (# years since planting)	KIB
	Crown dieback rating	Protocol, V9
	Lower trunk damage (0,1)	Protocol, V12
	Leaf chlorosis (0, 1)	Protocol, V10
	Root flare visible (0, 1)	Protocol, V11
	Good overall condition rating (0, 1)	Protocol, V13
	Poor overall condition rating (0, 1)	Protocol, V13
Biophysical environment	*% Impervious surface*	NLCD 2006
	Speed limit	Indianapolis
	# Trees planted in project	KIB
	Fall planting season	KIB
	Planting area width (natural log)	Protocol, V26
	Tree lawn planting area (0, 1)	Protocol, V24
	Crown exposure rating	Protocol, V9
	# Trees within 10 m (natural log)	Protocol, V29
	# Trees within 10-20 m (natural log)	Protocol, V29/V30
Community	*Neighborhood name* (used for random effects)	KIB
	% Unemployment	ACS, 2011
	Median household income ($)	ACS, 2011
	% Less than high school education	ACS, 2011
	% Single parent households	Census, 2010
	% Nonwhite population	Census, 2010
	% Renter occupied homes	Census, 2010
	% Moved in last 5 years	ACS, 2011
	% Vacant houses	Census, 2010
	# Total tree-planting projects	KIB
Institutions and management	*Planting year*	KIB
	Correct pruning (0, 1)	Protocol, V35
	Incorrect pruning (0, 1)	Protocol, V34
	Correct mulching (0, 1)	Protocol, V34
	Collective watering strategy (0, 1)	Interviews

Protocol, Vogt et al., 2014 masked for blind review, including the variable number from the Protocol (e.g., V4). *KIB*, Keep Indianapolis Beautiful, Inc. data collected at time of planting. *NLCD 2006*, National Land Cover Dataset 2006 (http://www.mrlc.gov/nlcd2006.php). *ACS, 2011*, United States Department of Commerce, Census Bureau, 2011 American Community Survey from American FactFinder (http://facfinder2.census.gov). *Census, 2010*, United States Department of Commerce, Census Bureau, 2010 complete U.S. Census from American FactFinder (http://facfinder2.census.gov). *Indianapolis*, Indianapolis City Government geographic information system shapefile of city streets, obtained from KIB. *Interviews*, interviews with KIB employees about the tree planting project, including review of tree planting project applications.

2.3.2. Biophysical environment

We account for the surrounding biophysical environment using several indicators. For all models, we use the percent of impervious surface in the 30 × 30 m cell surrounding the tree as a proxy for additional stress on the root zone (e.g., limited rainfall infiltration). These data come from the National Land Cover Dataset 2006. The speed limit on the street adjacent to the tree serves as a proxy for how busy a street is and whether it is likely to be highly salted in the winter. This data came from City of Indianapolis road layer files. We also account for whether the tree was planted in the fall or spring and include the number of trees planted in a project to control for project size. These variables came from KIB records.

For growth models, we also include two measures of growing space—a binary indicator of whether the tree was planted in a tree lawn and a measure of the width (narrowest dimension) of the planting area. We use the natural log of the width of the planting area around the tree as a proxy for available rooting volume. We also include measures of competition: crown exposure rating (reflecting shading), and the number of other trees within a 10-m radius and between 10 and 20 m of the planted tree, both in natural log form. These variables were gathered during re-inventory.

2.3.3. Community

We use socio-demographic indicators to proxy community capacity and commitment to tree care. To capture community capacity we include the following variables from the U.S. 2010 Census: a measure of the percentage of individuals in the labor force that are unemployed, the median household income, the percentage of individuals that have less than a high school degree and the percentage of households that are headed by a single parent. We include a measure from KIB's records of whether the tree was planted as part of the community's first project with KIB, the second, the third, etc., to capture capacity specific to tree-care and learning with experience. To capture commitment we include a measure of the percentage of individuals that have lived in the same residence for at least five years (i.e., resident tenure) and the percentage of housing units that are occupied by renters. We include the percent of units that are vacant. Vacancies might reflect two things: an indication of deeper neighborhood problems and lack of capacity and/or conditions in which neighbors are anxious to restore the neighborhood's appearance and thus may be more dedicated to tree care. We also control for the percent of individuals in the neighborhood that are non-white. Commitment variables come from the U.S. Census.

2.3.4. Institutions and management

To measure tree maintenance institutions, we include a measure of whether the neighborhood's application for trees proposed a collective watering strategy in which at least two neighbors would water the trees together. We suspect a collective watering strategy

Table 3
Descriptive statistics for survival models. For binary variables, the mean represents the proportion of observations with that indicator.

UF as SES component	Variables	*N*	Mean	Median	Std. dev.
Outcome variable	*Alive (0, 1)*	**1345**	**0.894**	**1**	**0.307**
Tree	*Caliper at planting (cm)*	1345	3.536	3.81	0.506
	Ball-and-burlap packaging (0, 1)	1345	0.125	0	0.331
	Containerized packaging (0, 1)	1345	0.573	1	0.495
	Age (# years since planting)	1345	4.545	4.72	0.970
Biophysical environment	*% Impervious surface*	1345	43.903	46	19.115
	Speed limit (mph)	1345	32.093	30	6.605
	# Trees planted in project	1345	67.297	57	36.070
	Fall planting season (0, 1)	1345	0.460	0	0.499
Community	*% Unemployment*	1345	7.488	6.5	4.082
	Median household income ($1000s)	1345	$45.552	$43.221	$17.213
	% Less than high school education	1345	15.716	13.8	9.883
	% Single parent households	1345	10.987	11.1	4.642
	% Nonwhite population	1345	29.362	28.8	14.417
	% Renter occupied homes	1345	43.021	49.5	18.995
	% Moved in last 5 years	1345	54.043	56.1	9.941
	% Vacant houses	1345	16.105	14.6	11.004
	# Total tree-planting projects	1345	1.317	1	0.561
Institutions and management	*Planting year*	1345	2007	2007	1.149
	Collective watering strategy (0, 1)	1345	0.410	0	0.492
Tree—nursery dummy variables (nursery 5 excluded)	*Nursery 3 (0, 1)*	1345	0.093	0	0.290
	Nursery 6 (0, 1)	1345	0.371	0	0.483
	Nursery 7 (0, 1)	1345	0.082	0	0.274
	Other nursery (0, 1)	1345	0.062	0	0.241
Tree—family dummy variables (beech/oak [Fagaceae] family excluded)	*Maple (Aceraceae) family (0, 1)*	1345	0.150	0	0.357
	Birch (Betulaceae) family (0, 1)	1345	0.087	0	0.282
	Dogwood (Cornaceae) family (0, 1)	1345	0.057	0	0.231
	Legume (Fabaceae) family (0, 1)	1345	0.083	0	0.276
	Pine (Pinaceae) family (0, 1)	1345	0.029	0	0.168
	Planetree (Platanaceae) family (0, 1)	1345	0.029	0	0.168
	Rose (Rosaceae) family (0, 1)	1345	0.139	0	0.346
	Other[+] family (0, 1)	1345	0.076	0	0.265

[+] The “Other family” category includes trees of the following families, each represented by fewer than 20 individuals in our dataset: Altingiaceae, Apocynaceae, Celastraceae, Cupressaceae, Ebenaceae, Ginkgoaceae, Juglandaceae, Lauraceae, Magnoliaceae, Malvaceae, Oleaceae, Styracaceae, and Ulmaceae.

will yield more consistent watering because it might support de facto or formal monitoring (Wade, 1994), and because Author and Author (2014a *masked for blind review*) found a significant influence of watering strategy on tree survival. For our growth models, we include whether there was evidence during re-inventory that the tree was correctly pruned, incorrectly pruned or lacked evidence of pruning. We include a binary measure of whether there was evidence of correct mulching at time of re-inventory. We expect correct pruning and correct mulching to increase growth rate.

There are some types of rules and decision-making processes that affect tree success that occur at the nonprofit level, such as choice of tree species, depth of tree planting (which affects presence of a root flare), and other methods of planning and organizing tree planting activities. Many nonprofit decisions are represented in tree, biophysical environment, and community categories of variables. The single nonprofit-level institution we included in our model is year of planting, which we believe may represent organizational learning and institutional change, and varies across trees. Interviews and informal conversations with Keep Indianapolis Beautiful, Inc. employees revealed that over time they changed tree-planting strategies, adapting and responding to informal observations that KIB employees were making about their tree-planting projects. For this reason, we include year of planting as a separate variable, distinct from – although still correlated with – the age of the tree. Nonprofit rules and decisions that do not vary across projects have no variation in our dataset and so are not included in this single-city analysis.

3. Results

Descriptive statistics for variables included in survival and growth models are displayed in Tables 3 and 4. Overall, 89.4% of trees planted between 2006 and 2009 were alive at the time of re-inventory. Average caliper growth rate of living trees was 1.12 cm/year.

3.1. Tree survival models

Table 5 presents complete results from tree survival probit models. Coefficients in probit models are difficult to interpret, so we rely heavily on significance and expected direction to interpret our results. Positive, significant coefficients in Table 5 indicate that an increase in the value of a variable increases the probability of a tree's survival; negative coefficients indicate that an increase in the value of a variable reduces the probability of a tree's survival. Fig. 1 presents the odds ratios (exponential form of the coefficients in Model S.2 in Table 5) for each independent variable. The odds ratio is the odds of a tree surviving given a one-unit change in the mean of the independent variable. For presence/absence independent variables, the odds ratio is the odds of a tree surviving given the presence of that variable relative to the odds of a tree surviving in the absence of that variable. Odds ratios greater than one indicate increased probability of tree survival, while odds ratios less than one indicate decreased probability of tree survival. Odds ratios not significantly different from one indicate an independent variable that does not affect the odds of tree survival.

Tree and biophysical variables are not as strongly related as we expected to survival. In our best models that control for tree family, we find no significant relationships between survival and the characteristics of the tree except for nursery where it was grown. However, we find some relationship between survival and the biophysical environment: impervious surface negatively influences survival, and the number of trees planted in a given project positively impacts survival.

Table 4
Descriptive statistics for variables in growth models. For binary variables, the mean represents the proportion of observations with that indicator.

UF as SES component	Variables	*N*	Mean	Median	Std. dev.
Outcome variable	*Annual caliper growth (cm)*	675	1.126	1	0.605
	Relative growth rate	675	0.192	0.189	0.070
Tree	*Caliper at planting (cm)*	675	3.477	3.81	0.530
	Ball-and-burlap packaging (0, 1)	675	0.079	0	0.269
	Containerized packaging	675	0.607	1	0.489
	Age (# years since planting)	675	4.472	4.69	1.067
	Crown dieback rating	673	0.201	0	0.816
	Lower trunk damage (0,1)	656	0.474	0	0.500
	Leaf chlorosis (0, 1)	630	0.144	0	0.352
	Root flare visible (0, 1)	658	0.274	0	0.446
	Good overall condition rating (0, 1)	646	0.853	1	0.354
	Poor overall condition rating (0, 1)	646	0.023	0	0.151
Biophysical environment	*% Impervious surface*	675	43.947	47	18.361
	Speed limit	675	31.785	30	5.710
	# Trees planted in project	675	59.939	49	35.339
	Fall planting season	675	0.447	0	0.498
	Planting area width (natural log)	650	1.806	1.5	1.241
	Tree lawn planting area (0, 1)	675	0.535	1	0.499
	Crown exposure rating	674	4.733	5	0.782
	# Trees within 10 m (natural log)	675	1.372	1.39	0.467
	# Trees within 10–20 m (natural log)	675	1.813	1.79	0.482
Community	*% Unemployment*	675	7.557	6.8	3.923
	Median household income ($1000s)	675	$45.609	$39.375	$16.798
	% Less than high school education	675	16.316	15	9.438
	% Single parent households	675	11.110	11.1	4.397
	% Nonwhite population	675	28.347	25.8	14.986
	% Renter occupied homes	675	41.620	46.8	19.546
	% Moved in last 5 years	675	55.641	58.1	10.005
	% Vacant houses	675	15.954	14.6	10.214
	# Total tree-planting projects	675	1.320	1	0.572
Institutions and management	*Planting year*	675	2007.23	2007	1.209
	Correct pruning (0, 1)	658	0.169	0	0.375
	Incorrect pruning (0, 1)	658	0.207	0	0.405
	Correct mulching (0, 1)	658	0.105	0	0.307
	Collective watering strategy (0, 1)	675	0.450	0	0.498
Tree—nursery dummy variables (nursery 5 excluded)	*Nursery 3 (0, 1)*	675	0.062	0	0.242
	Nursery 6 (0, 1)	675	0.419	0	0.494
	Nursery 7 (0, 1)	675	0.044	0	0.206
	Other nursery (0, 1)	675	0.030	0	0.170
Tree—family dummy variables (beech/oak [Fagaceae] family excluded)	*Maple (Aceraceae) family (0, 1)*	675	0.099	0	0.299
	Birch (Betulaceae) family (0, 1)	675	0.096	0	0.295
	Dogwood (Cornaceae) family (0, 1)	675	0.052	0	0.222
	Legume (Fabaceae) family (0, 1)	675	0.080	0	0.271
	Pine (Pinaceae) family (0, 1)	675	0.031	0	0.174
	Planetree (Platanaceae) family (0, 1)	675	0.041	0	0.200
	Rose (Rosaceae) family (0, 1)	675	0.159	0	0.365
	Other^{+} *family (0, 1)*	675	0.062	0	0.242

[+] The “Other family” category includes trees of the following families, each represented by fewer than 20 individuals in our dataset: Altingiaceae, Apocynaceae, Celastraceae, Cupressaceae, Ebenaceae, Ginkgoaceae, Juglandaceae, Lauraceae, Magnoliaceae, Malvaceae, Oleaceae, Styracaceae, and Ulmaceae.

Some community characteristics are related to tree survival. Median household income, the percent of renter occupied units and the percent of people who have moved in within the last 5 years are all significantly and positively related to tree survival in Model S.2 (our theoretically preferred model).

We see evidence that trees that were planted in later years have a higher probability of surviving, even after controlling for age of the tree. This could be a result of organization learning and improvements in planting methods by KIB. However, the summer of 2007 was a particularly dry year and rainfall during the summer months (May–August) was more than 7 inches below average (National Weather Service Indianapolis, IN Weather Forecast Office, 2013). We cannot disentangle whether a positive coefficient on the year of planting picks up the impact of a dry summer on trees planted in earlier years or of organizational learning resulting in improved planting techniques in later years. Additionally, mortality could simply be higher for earlier planting years because earlier cohorts of trees have had more time to accrue higher mortality (Roman, 2013). Whatever the causal mechanism, mortality rates do differ significantly by year of planting, ranging from a high of 16.4% for trees planted in 2007 to a low of 7.5% for trees planted in 2008.

The significance of fall planting season, collective watering strategy, and the interaction term between these variables means that the combined impact of these variables is different for each of the four sub-populations of trees divided by these variables (Table 7). Holding all other variables constant, we find that trees planted in the spring and watered collectively have greater odds of survival than trees planted in the spring and watered individually and than all trees planted in the fall. However, trees planted in the fall and watered collectively have slightly lower odds of survival than trees planted in the fall and watered individually. We note that the interaction term (collective watering × fall planting) is highly negatively correlated with ball-and-burlap planting packaging (polychoric correlation coefficient of −0.96; see Supplementary material), and highly positively correlated with experience (project number; polychoric correlation coefficient of 0.90; see Supplementary material); these variables could be confounding the relationship between collective watering, fall planting season, and tree survival.

Table 5

Survival model results. Coefficients shown with standard errors in parentheses. Variables that are significant in Model S.2, the most theoretically sound survival model, are in **bold.** *Model S.1:* probit model (no interaction term, no neighborhood random effects). *Model S.2:* probit model with interaction term (no neighborhood random effects). *Reduced Model:* significant variables from Model S.2 only (including all nursery dummy variables).

UF as SES component	Variables	Model S.1	Model S.2	Reduced Model
Tree	*Caliper at planting (cm)*	−0.142 (0.167)	−0.141 (0.170)	
	Ball-and-burlap packaging (0, 1)	−0.081 (0.394)	−0.212 (0.408)	
	Containerized packaging (0, 1)	0.063 (0.225)	−0.003 (0.228)	
	Age (# years since planting)	0.492* (0.273)	0.430 (0.286)	
Biophysical environment	***% impervious surface***	−0.007** (0.004)	−0.007** (0.004)	−0.009*** (0.003)
	Speed limit (mph)	0.005 (0.016)	0.006 (0.016)	
	# trees planted in project	0.009*** (0.003)	0.011*** (0.003)	0.010*** (0.002)
	Fall planting season (0, 1)	0.336 (0.220)	0.681*** (0.262)	0.307** (0.127)
Community	*% unemployment*	0.003 (0.022)	−0.001 (0.023)	
	Median household income ($1000)	0.016 (0.010)	0.017* (0.010)	0.018*** (0.005)
	% less than high school education	−0.017 (0.012)	−0.020 (0.012)	
	% single parent households	0.066* (0.039)	0.049 (0.040)	
	% nonwhite population	0.005 (0.008)	0.009 (0.008)	
	% renter occupied homes	0.036*** (0.011)	0.033*** (0.011)	0.024*** (0.007)
	% moved in last 5 years	0.015 (0.013)	0.024* (0.012)	0.017** (0.008)
	% vacant houses	−0.033* (0.018)	−0.009 (0.019)	
	# total tree-planting projects	−0.128 (0.165)	0.078 (0.182)	
Institutions and management	***Planting year***	0.752*** (0.262)	0.681** (0.273)	0.372*** (0.059)
	Collective watering strategy (0, 1)	0.466** (0.201)	1.030*** (0.241)	0.853*** (0.154)
Interactions	***Collective watering × Fall planting***		−1.193*** (0.313)	−0.986*** (0.262)
Tree—nursery dummy variables (nursery 5 excluded)	***Nursery 3 (0, 1)***	−0.430* (0.254)	−0.486* (0.262)	−0.309 (0.197)
	Nursery 6 (0, 1)	0.055 (0.245)	−0.025 (0.250)	0.179 (0.113)
	Nursery 7 (0, 1)	−0.124 (0.313)	−0.190 (0.316)	0.146 (0.240)
	Other nursery (0, 1)	−0.944*** (0.270)	−0.957*** (0.279)	−0.734*** (0.214)
Tree—family dummy variables (beech/oak family excluded)	*Maple family (0, 1)*	0.272 (0.275)	0.334 (0.266)	
	Birch family (0, 1)	−0.264 (0.244)	−0.067 (0.255)	
	Dogwood family (0, 1)	−0.082 (0.233)	−0.089 (0.238)	
	Legume family (0, 1)	0.329 (0.273)	0.361 (0.275)	
	Pine family (0, 1)	−0.287 (0.368)	−0.240 (0.382)	
	Planetree family (0, 1)	0.088 (0.324)	0.033 (0.322)	
	Rose family (0, 1)	−0.247 (0.210)	−0.324 (0.213)	
	Other family (0, 1)	0.131 (0.219)	0.053 (0.225)	
	Constant	−1512.816*** (526.900)	−1372.498** (549.493)	−749.010*** (118.372)
	No. of observations	1345	1345	1345
	Log-likelihood	−389.192	−384.031	−396.350
	Model signif. (*p*-value)	0.000	.	0.000
	Pseudo-R2	0.142	0.153	0.126
	AIC	840.383	832.063	820.699
	BIC	1001.712	998.595	893.557

* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

Our model is fairly robust to changes in model specification; the coefficients are quite consistent across models. While there are a few changes in significance across models, there are no sign changes in significant variables. In the reduced model where insignificant variables are dropped, coefficients change slightly, although not in sign or significance.

3.2. Relative growth rate models

Table 6 presents complete results from the tree growth models. As expected, we find that nearly all tree characteristics included in our models significantly influence growth. Trees that are smaller at planting appear to grow faster. We find that trees packaged as ball-and-burlap or containers grew faster relative to other packaging types. Trees from other nurseries also exhibited slower growth rates relative to the baseline nursery (nursery 5, the most common). Many of the family dummy variables are also significant and in the expected direction given previous work on tree growth: trees in the dogwood, pine, and rose family grow more slowly than oak trees (the baseline and most common family of trees), whereas trees in the legumes and planetree families exhibit higher growth rates, holding all other variables constant.

Indicators of tree condition at the time of re-inventory help predict relative growth rate. Trees exhibiting higher dieback ratings and trees with damage to the lower trunk grew more slowly, and trees with a visible root flare and those rated in good condition grew more quickly.

General characteristics of the surrounding environment impact tree growth less than tree characteristics. Wider planting area is associated with faster growth. We find no evidence of a relationship between tree growth and impervious surface, speed limit, project size, tree lawn planting area, crown exposure, or number of nearby trees.

There is some evidence of a relationship between community characteristics and tree growth. We find that the percent of single parent households is negatively related to tree growth, which may be indicative of the capacity for tree care by single parent households. The number of previous projects that the neighborhood has undertaken is also significant—trees that are planted as part of a later project grow faster. None of the other demographic or housing variables appeared to influence tree growth.

We find evidence that some institution and management variables matter. Planting year is negatively and significantly related to growth rate (see following paragraph). Correct mulching also is positively and significantly related to growth rate, as expected.

Both the age of the tree and the year of planting are negatively and significantly related to tree growth rate; these findings are conflicting. The age of the tree (number of years, to the day,

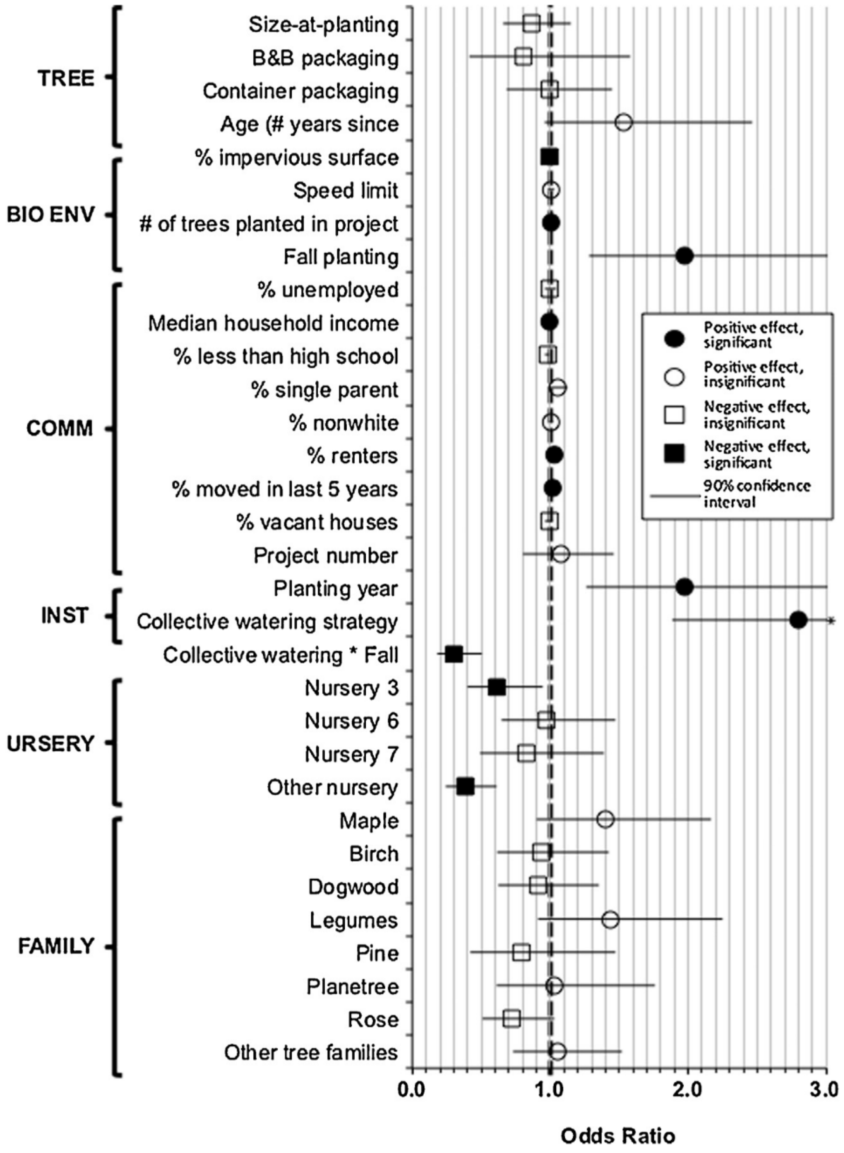

Fig. 1. Odds ratios for variables included in survival Model S.2, the most theoretically sound model. Odds ratios greater than 1 (circles) indicate a variable with a positive effect on survival; odds ratios of less than 1 (squares) indicate a variable with a negative effect on survival. +Confidence interval extends outside of the range shown on the graph to 4.16.

between planting and re-inventory) and the year of planting (2006, 2007, etc.) are negatively correlated. A negative coefficient for age of the tree indicates that older trees (i.e., planted less recently) have slower average growth rates. A negative coefficient for year of planting means that trees planted in more recent years (i.e., younger trees) have grown more slowly. Because of this, we suspect year of planting does not indicate learning and instead might capture the impact of an establishment period characterized by slower growth.

The significance of the fall planting season indicator and the interaction between collective watering strategy and fall planting, but not of collective watering strategy means that the watering strategy only has a significant impact on growth for trees planted in the fall (Table 7). Holding all other variables constant, fall planting has a negative impact on growth, but its impact is magnified by choice of a collective watering strategy.

Our model for tree growth is fairly robust. Most significant environmental and institution coefficients are significant across both Model G.1 and G.2, and remain significant in the reduced model. Percent vacant houses are significant in Model G.1, but not when the interaction terms are added in Model G.2. Collective watering strategy is highly significant in Model G.1, but the addition of the interaction between watering strategy and planting season in Model G.2 completely captures the effect of collective watering. Coefficients change slightly between Model G.2 and the reduced model, when all insignificant variables are dropped, but no variables change sign.

3.3. Joint significance of SES categories and model selection

One of our objectives is to determine whether including characteristics of the community and of institutions improves our understanding of tree success in urban environments. We jointly test the significance of categories of SES variables by comparing Akaike and Bayesian information criteria (AIC, BIC) values between models excluding one category of variables (restricted models—results shown in Supplementary material) to Model S.2 and G.2, the theoretically superior models. For example, we compare the AIC of Model S.2 to a model that excludes all of the community variables to determine whether the community variables are

Table 6

Relative growth rate model results. Standardized coefficients shown with standard errors in parentheses; coefficients with larger magnitude have a greater relative influence on growth rate. Variables that are significant in Model G.2, the most theoretically sound growth model, are in **bold.** Note that select variables are included in natural log form to achieve a more normal distribution. *Model G.1:* ordinary least squares (OLS) regression model (no interaction terms, no neighborhood random effects). *Model G.2:* OLS model with interaction terms (no neighborhood random effects). *Reduced model:* only significant variables from Model G.2 (including all nursery and family dummy variables).

UF as SES component	Variables	Model G.1	Model G.2	Reduced Model
Tree	***Caliper at planting (cm)***	−0.496*** (0.00740)	−0.485*** (0.00731)	−0.450*** (0.00578)
	Ball-and-burlap packaging (0, 1)	0.302*** (0.0252)	0.290*** (0.0246)	0.293*** (0.0220)
	Containerized packaging (0,1)	0.205*** (0.00870)	0.185*** (0.00907)	0.136*** (0.00701)
	Age (# years since planting)	−0.922*** (0.0112)	−0.934*** (0.0113)	−0.690*** (0.00900)
	Crown dieback rating	−0.107*** (0.00598)	−0.108*** (0.00641)	−0.096** (0.00585)
	Lower trunk damage (0,1)	−0.101*** (0.00497)	−0.098*** (0.00497)	−0.097*** (0.00484)
	Leaf chlorosis (0, 1)	0.067* (0.00722)	0.080** (0.00720)	0.087** (0.00691)
	Root flare visible (0, 1)	0.061* (0.00554)	0.066* (0.00547)	0.073** (0.00530)
	Good overall condition rating (0, 1)	0.131*** (0.00700)	0.173*** (0.0110)	0.139*** (0.00657)
	Poor overall condition rating (0, 1)	−0.001 (0.0223)	0.068 (0.0349)	
Biophysical environment	*% impervious surface*	0.031 (0.000203)	0.038 (0.000200)	
	Speed limit	−0.054 (0.000762)	−0.069 (0.000759)	
	# trees planted in project	0.059 (0.000122)	0.092 (0.000124)	
	Fall planting season	−0.350*** (0.00919)	−0.261*** (0.0101)	−0.141*** (0.00618)
	Planting area width (natural log)	0.131* (0.00376)	0.141** (0.00379)	0.079** (0.00209)
	Tree lawn planting area (0, 1)	−0.001 (0.00748)	0.012 (0.00755)	
	Crown exposure rating	0.015 (0.00309)	0.020 (0.00303)	
	# trees within 10 m (natural log)	0.024 (0.00646)	0.023 (0.00657)	
	# trees within 10–20 m (natural log)	0.053 (0.00510)	0.030 (0.00523)	
Community	*% unemployment*	0.034 (0.00106)	0.026 (0.00106)	
	Median household income ($1000)	−0.028 (0.000531)	0.045 (0.000532)	
	% less than high school education	0.093 (0.000639)	0.111 (0.000640)	
	% single parent households	−0.203* (0.00181)	−0.207* (0.00182)	−0.152*** (0.000546)
	% nonwhite population	0.077 (0.000397)	0.116 (0.000409)	
	% renter occupied homes	−0.085 (0.000490)	−0.070 (0.000491)	
	% moved in last 5 years	−0.013 (0.000567)	0.016 (0.000594)	
	% vacant houses	−0.197* (0.000781)	−0.126 (0.000812)	
	# total tree-planting projects	0.202*** (0.00729)	0.259*** (0.00781)	0.314*** (0.00610)
Institutions and management	***Planting year***	−1.095*** (0.0107)	−1.086*** (0.0107)	−0.820*** (0.00750)
	Correct pruning (0, 1)	−0.040 (0.00631)	−0.043 (0.00628)	
	Incorrect pruning (0, 1)	−0.013 (0.00599)	−0.024 (0.00611)	
	Correct mulching (0, 1)	0.065 (0.00994)	0.079* (0.00989)	0.072* (0.00952)
	Collective watering strategy (0, 1)	−0.270*** (0.00847)	−0.025 (0.0150)	
Interaction terms	***Collective watering × Fall planting***		−0.201*** (0.0155)	−0.281*** (0.0111)
	Collective watering × Good condition		−0.107 (0.0133)	
	Collective watering × Poor condition		−0.084 (0.0421)	
Tree—nursery dummy variables (nursery 5 excluded)	***Nursery 3 (0, 1)***	−0.086* (0.0133)	−0.097** (0.0134)	−0.100** (0.0117)
	Nursery 6 (0, 1)	0.021 (0.0109)	0.014 (0.0113)	−0.039 (0.00942)
	Nursery 7 (0, 1)	0.055 (0.0146)	0.050 (0.0148)	0.061 (0.0130)
	Other nursery (0, 1)	−0.162*** (0.0241)	−0.168*** (0.0237)	−0.204*** (0.0220)
Tree—family dummy variables (beech/oak family excluded)	*Maple family (0, 1)*	−0.077 (0.0118)	−0.073 (0.0116)	−0.043 (0.0113)
	Birch family (0, 1)	−0.061 (0.0111)	−0.034 (0.0113)	−0.020 (0.00932)
	Dogwood family (0, 1)	−0.124*** (0.0127)	−0.117*** (0.0131)	−0.089** (0.0117)
	Legume family (0, 1)	0.106** (0.0133)	0.103* (0.0132)	0.120** (0.0124)
	Pine family (0, 1)	−0.097** (0.0280)	−0.096** (0.0273)	−0.109** (0.0275)
	Planetree family (0, 1)	0.194*** (0.0152)	0.191*** (0.0156)	0.177*** (0.0147)
	Rose family (0, 1)	−0.314*** (0.0102)	−0.318*** (0.0104)	−0.331*** (0.0100)
	Other family (0, 1)	0.105** (0.0136)	0.101** (0.0136)	0.109** (0.0129)
	No. of observations	605	605	605
	F	14.07	14.21	.
	Model significance (*p*-value)	6.13E − 66	4.50e − 69	.
	Adjusted-R^2 *(overall* R^2 *for r.e. models)*	0.471	0.436	0.435
	AIC	−1796.3	−1801.5	−1816.9
	BIC	−1598.1	−1590.0	−1689.2

* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

jointly significant. AIC and BIC values weigh the benefits of additional information when more variables are added to the model against the costs of fewer degrees of freedom and the addition of irrelevant variables. Significantly lower AIC and BIC values indicate better models; BIC penalizes more harshly than AIC for addition of irrelevant variables. However, AIC and BIC should only be used to guide model selection, and not to define the "best" model with absolute certainty.

For survival models, we find coefficient estimates for significant variables to be fairly consistent across models (see Supplementary material). AIC and BIC values indicate that Model S.2 outperforms most models excluding entire categories of SES variables. We find that although BIC values for restricted models are slightly lower than for Model S.2, AIC values are typically much higher. The four models that exclude all tree characteristics, all environmental variables, all community variables, or all institutional variables are outperformed by our theoretically preferable model (S.2); only the restricted model that excludes project characteristics (a subset of community variables) performs better than our theoretically preferable model.

Table 7
Interaction between fall planting and collective watering strategy. Coefficients for the combined effects of planting season and watering strategy, based on coefficients from Model S.2 (survival, Table 5 and Model G.2 (growth, Table 6).

	Planting season	Watering strategy	
		Collective	Individual
Survival (probit model odds ratios)	Fall	1.679	1.976
	Spring	2.801	1.000
Growth (standardized coefficients)	Fall	−0.462	−0.261
	Spring	0	0

For growth models, coefficients across models are consistent in sign and significance, except for age and year variables, each of which flip sign (to positive) and lose their significance when the SES component containing the other is excluded from the model (see Supplementary material). AIC and BIC values indicate that our theoretically best model (Model G.2) outperforms restricted growth models that exclude all tree characteristics, all community variables, or subsets of community variables; a model that excludes all biophysical environment variables performs slightly better than Model G.2 (see Supplementary material).

4. Discussion

Our results suggest that biophysical, social and institutional factors are all important in explaining the success of young urban planted trees, but that the factors that affect survival and growth are different. Fig. 2 compares the most theoretically sound models for survival and growth (Models S.2 and G.2). Sometimes the same factor significantly influences both outcomes, but in opposite directions.

In general, tree variables appear to matter more for tree growth than for survival. The only tree characteristic that affects survival is the nursery, while tree growth is significantly influenced by nearly all tree variables, including several tree family variables (Fig. 2). This is not surprising, because we do not have information on perhaps the most vital tree-level factor that might influence survival—a tree's condition while it was alive and presumably declining in health and vigor. Other authors have linked tree condition to probability of survival (e.g., Koeser, Hauer, Norris, & Krouse, 2013).

Contrary to expectations, trees exhibiting leaf chlorosis experienced faster growth. We recognize this could be from misidentification of chlorosis by the data collectors. While chlorosis – lack of chlorophyll – is theoretically linked to stunted tree growth (Graves, 1994), other causes of leaf discoloration appearing as chlorosis to the untrained eye and that might have been recorded as such in the re-inventory may not be linked to stunted growth. We also recognize that the presence of chlorosis is a metric of present tree condition and may be more reflective of recent tree stresses rather than the stresses over the (albeit short) lifetime of the tree.

We find evidence that the biophysical environment affects survival and growth. Planting width (a proxy for area) limits growth but not survival in our models. Planting area may represent available rooting volume, which limits growth as other authors have found (Kopinga, 1991; Kjelgren & Clark, 1992; although Nowak et al., 1990 find no significant impact of planting area on growth). Alternatively, it might be that planting width is a proxy for water availability (i.e., a smaller planting area means a smaller area into which rainfall may infiltrate), which may be more tightly tied to the success of small, recently planted trees that may not yet be limited by available rooting volume

We find evidence that people (i.e., characteristics of the community and maintenance institutions used by people to manage trees) influence the survival and growth of trees. Some

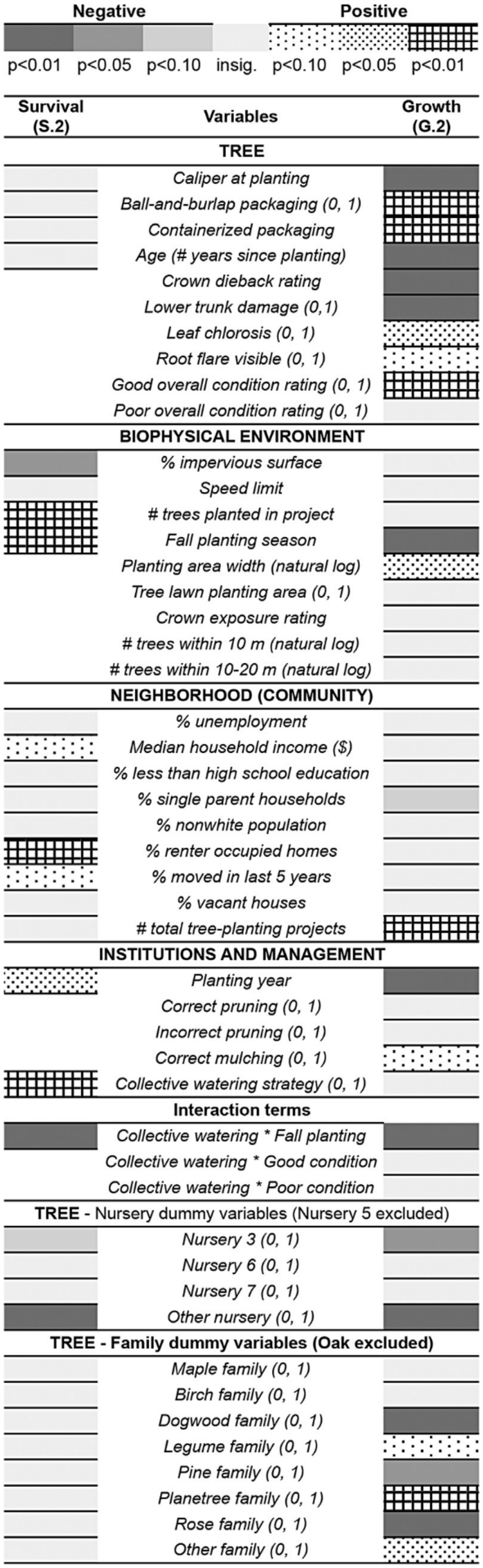

Fig. 2. Comparison of best survival (S.2) and growth (G.2) models.

socio-demographic characteristics of neighbors around a planted-tree are significantly related to tree survival and growth. However, a positive coefficient on percent renters in survival models is contrary to the finding of Nowak et al. (1990). We also find evidence that neighborhood experience with tree planting contributes to tree success—trees planted in later projects in the same neighborhood had faster growth. These findings suggest that more detailed research about maintenance motivations might illuminate why particular socio-demographic characteristics might be related to tree success.

There is evidence that institutions matter, particularly for tree survival, but also that *how institutions impact tree outcomes depends on planting season*. We expected trees planted in the fall to be more likely to survive because they do not experience a summer of hot, dry weather immediately after transplanting (although, a dry fall without sufficient watering can be potentially deadly for trees, since the trees are being planted into a potentially very dry soil). However, when planting season is considered in combination with watering strategy, we find that a fall planting season only improves survival rates for trees that are individually watered (Table 7). A collective watering strategy was positively related to tree survival for spring plantings. For growth models, collective watering strategy compounds the negative impact of fall planting on tree growth, but watering strategy has no impact on tree outcomes for spring plantings. We suspect these findings may reflect differences in how a collective watering strategy may be implemented for plantings in different seasons. Recall that our collective watering strategy variable is an indicator of the watering strategy *chosen* by the neighborhood, and that we can only infer to what extent this strategy was actually *implemented* by the neighborhood (i.e., how consistently trees were watered). Trees planted in the spring must be watered immediately during the summer following planting. However, for trees planted in the fall, watering activities might not commence until the following spring and summer. It may be that collective watering is easier to implement when watering activities immediately follow planting activities, and therefore watering happens more consistently during the first summer after planting.

We included planting year as a variable we thought might indicate institutional learning and change in tree planting methods by the nonprofit. However, our results indicate that this variable may actually be capturing more information about tree age and establishment than about institutions. Trees planted in later years exhibit a higher likelihood of survival and lower growth rates. Higher survival rates are expected if we think the nonprofit has improved its planting techniques over time. But higher survival rates are also expected due to the fact that cumulative mortality is lower for cohorts of trees (i.e., trees planted in the same year) that have been in the ground for less time (Roman, 2013). Lower growth rates makes sense in the context of tree biology: trees planted more recently are also younger and less likely to be out of the establishment period during which trunk diameter growth is slowed (Gilman et al., 1998).

5. Conclusion

We find that attributes of the tree, biophysical environment, and surrounding community, as well as management institutions appear to impact urban tree planting outcomes. Several findings from this work can inform decision-making. Nonprofits have a reasonable degree of choice over the size of planted trees: planting smaller trees will yield trees that become established and grow more quickly in the landscape. They also have some choice in planting location, including the size of the planting area: choosing larger, wider planting areas where possible may yield higher tree growth rates. And locating trees in areas with lower amounts of impervious surface cover may improve survival rates. However, we also recognize that areas with narrow tree lawns and high impervious cover are also some of the areas in highest need of the benefits of trees (Wilson & Lindsey, 2009). We also find that many characteristics of the surrounding environment do *not* significantly affect tree growth for the trees in our sample, which suggests nonprofits might not need to be concerned about these characteristics when choosing planting locations: for instance, the number of other nearby trees, the speed limit of the adjacent road, and whether the location is a tree lawn or other type of planting spot appear not to influence tree success. Maintenance practices, however, do matter: Correct mulching practices positively impact tree growth rates, suggesting that investment in mulching or training the community to mulch will yield improvements to tree success.

There are other potential decision points for which the evidence is less clear. Although we observe a negative coefficient on the relationship between fall planting and tree growth, we hesitate to say that fall plantings should be avoided due to our inability to disentangle the relationship between water availability – a combination of neighborhood-determined watering strategy (known), precise watering frequency/amount (unknown), and uncontrollable weather/rainfall conditions – and planting season. The underlying relationship between collective watering and tree success is unclear and dependent on the season of planting. More fine-grained information on the frequency of watering and variation in seasonal rainfall will help to detail the relationships between watering strategy, environmental conditions, and tree outcomes. Nursery also appears to influence survival and growth, but this variable may be confounded by relationships with plant packaging tree and species; it is also not something that can be controlled easily by nonprofits purchasing trees where they are available.

This paper offers a more holistic model of the survival and early growth of trees planted in cities. Future research that examines tree success should examine trees across multiple cities to test the generalizability of these results. Longitudinal monitoring of tree populations would help build a stronger causal case for the factors that contribute to tree survival and growth over time.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2014.11.021.

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