Long-Term Growth of Highway Rights-of-Way Trees

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Abstract. Background: Highway rights-of-ways (ROWs, or verges) contain multiple stressors which can influence tree growth, including compacted soils, soils with little topsoil, poor drainage, air and soil pollutants, construction activities, and de-icing salts in cold climates. Yet highway ROWs often provide ample planting space for growing trees, which can contribute to the mitigation of negative environmental impacts associated with highways. Methods: For this study, we assessed the trunk diameter of 1,058 trees from 11-, 22-, and 31-year-old planting cohorts along a highway in the Chicago metropolitan region (Illinois, USA) to examine factors which could influence long-term growth. We analyzed the impact of location factors within the ROW (e.g., distance and elevation relative to highway, slope, and aspect) on trunk diameter at breast height (DBH), since these factors are relevant to the landscape design process. Using estimates from i-Tree, we compared carbon sequestration, carbon storage, runoff reduction, and air-pollution removal within and among the 3 cohorts. Results: Of the 6 site location characteristics we evaluated, no single characteristic consistently impacted DBH, though some characteristics were significant within a single cohort. DBH measurements of most species were smaller than model predictions based on existing urban tree models. Since all cohorts included large- and small-statured trees, and even within species DBH could be highly variable, the range in per-tree ecosystem services varied substantially within cohorts, especially the 31-year-old cohort. Conclusions: These findings highlight both the potential for and challenges of growing trees alongside highways.

Keywords. Ecosystem Services; i-Tree; Roadside Woody Vegetation; Site Conditions; Urban Tree Growth.

INTRODUCTION

Urban forests are expected to provide a variety of benefits for their communities while minimizing costs and disservices (Turner-Skoff and Cavender 2019; Roman et al. 2021). However, a range of human and biophysical factors can increase tree mortality (Hilbert et al. 2019) and compromise growth in urban landscapes (Vogt et al. 2015). Observing and modelling the effects of exposure to disturbances and stressors on the structure and function of the urban forest is a necessary step to assess the overall vulnerability of urban forests and take actions to limit potential losses of ecosystem services (Steenberg et al. 2017). While there are multiple ways to evaluate the structure of urban forests (Leff 2016), tree size is a particularly valuable metric. Many urban-forest functions such as building energy-usage reduction, air-pollutant removal, and carbon sequestration directly scale with tree size (Nowak et al. 2008).

Conditions in the built environment often, though not always, lead to reductions in tree growth and consequently the benefits provided by mature trees.

Within urban environments, growth is often greater in park or garden settings compared to street trees grown in strips or planting cutouts in close proximity to nonarterial streets (De Lacy and Shackleton 2014; North et al. 2018). The presence of pavement can limit soil moisture, aeration, and nutrient availability (Hodge and Boswell 1993) and increase surface temperatures (Chen et al. 2017), reducing growth. In some cases, open growing conditions found in some urban planting sites favor greater aboveground growth compared to trees in forest settings (Rhoades and Stipes 1999; Smith et al. 2019). Smith et al. (2019) also observed that any potential benefits to carbon sequestration resulting from faster growth of urban trees was offset by shorter life spans. Growth responses to urban settings in the first several years after planting can also vary among species and be influenced by management decisions and practices such as planting season, initial caliper, irrigation, and mulching (Lawrence et al. 2012; Koeser et al. 2014; Vogt et al. 2015). While land-use type can also influence growth (Lawrence et al. 2012), factors that

influence tree size within other urban landscapes beyond street trees and residential areas are less studied though no less critical for identifying management interventions to improve growth.

One such urban land-use type that could have the potential to support substantial tree growth is highway rights-of-way (ROW; also referred to as road verges or road reserves). Highways, high-speed and high-volume roadways which can be flanked by strips of undeveloped land, are sources of air and noise pollution, stormwater runoff, and habitat and neighborhood fragmentation (Forman et al. 2002). Trees planted adjacent to highways can help mitigate these negative impacts (Rogers and Evans 2015), provided they can grow to maturity in a reasonable time frame. Unlike street trees which are often planted in limited soil volumes and in close proximity to the road, highway trees are generally planted in much larger soil volumes with open growing conditions and set farther back from the highway to provide clear zones for run-off-road accidents. The highway construction process can significantly alter the land adjacent to the road by topsoil removal and compaction, creating site conditions unfavorable for tree survival and growth (Somerville et al. 2018; McGrath et al. 2020). Highway trees are also exposed to pollution as well as de-icing salts in cold climates (Bryselbout et al. 2000; Fay and Shi 2012). While typically a narrow strip of land, ROW can have highly variable growing conditions, as many soil properties exhibit distance-dependent relationships with the road (Bryson and Barker 2002; Akbar et al. 2012; Werkenthin et al. 2014). Highway ROW can also contain multiple microtopographic features such as drainage ditches, foreslopes, and backslopes (Jimenez et al. 2011; Neher et al. 2013). Identifying the relationship between locations and features in the highway ROW and tree growth could inform decisions about where and what species to plant in a setting that would greatly benefit from trees.

The goal of this study was to examine the impacts of species and cultivar choices and location within the highway ROW on tree size and consequently ecosystem service provision in a highway setting. We used a set of trees planted between 1988 and 2008 along a highway in northern Illinois to investigate the following questions:

1) Do location and site factors in the ROW (e.g., the distance from the highway or location on sloped ground) influence tree growth?

2) How does highway tree size compare to allometry estimates of similarly aged urban trees as documented in existing growth models?

3) What is the potential for highway trees to provide carbon storage, carbon sequestration, stormwater reduction, and air pollutant removal according to ecosystem service estimation programs such as i-Tree (USDA; Madison, WI, USA)?

The results of this study can inform decisions about species and planting-site selection for highway planting projects in order to maximize the potential growth and benefits of these trees.

MATERIALS AND METHODS

The study trees were located next to Interstate 355 (I-355) in the greater Chicago region (United States; 41.932118, −88.037547; 41.538545, −87.960314) (Figure 1). This region has a temperate, continental climate with 10 °C average annual temperature; daily temperature extremes ranging from 40 °C to −32 °C; 94 cm average annual rainfall; and a median growing season of 177 days (Illinois State Climatologist 2007). The natural soils in the study area formed on glacial deposits, primarily moraines and till plains (Calsyn 1999; Hanson 2004). I-355 has 6 lanes, runs primarily north to south for 48 km, and has an average daily traffic volume of 271,980 cars per day (Illinois State Toll Highway Authority 2019).

To locate the I-355 trees, we reviewed landscaping drawings that were annotated to indicate the final quantity and species of planted trees (i.e., as-built landscape record drawings) from 3 planting projects on I-355 from 1988, 1997, and 2008. These plans documented a total of 14,806 total trees planted along the highway during these 3 time periods. We refer to the study trees as part of the 1988, 1997, and 2008 planting cohorts, which are based on the year when the landscaping projects were begun. The 1988 and 1997 cohorts are located in the northern portion of I-355 while the 2008 cohort is located in the southern, newer section of the highway. Northern I-355 is an older stretch of highway in a more densely developed area and typically has a narrower ROW with more sloped planting areas compared to the southern section. In a survey of the I-355 trees in 2018, we documented survival of trees from a randomly selected subset representing 20% of the total 14,806 trees documented in the landscape drawings for the 3 cohorts
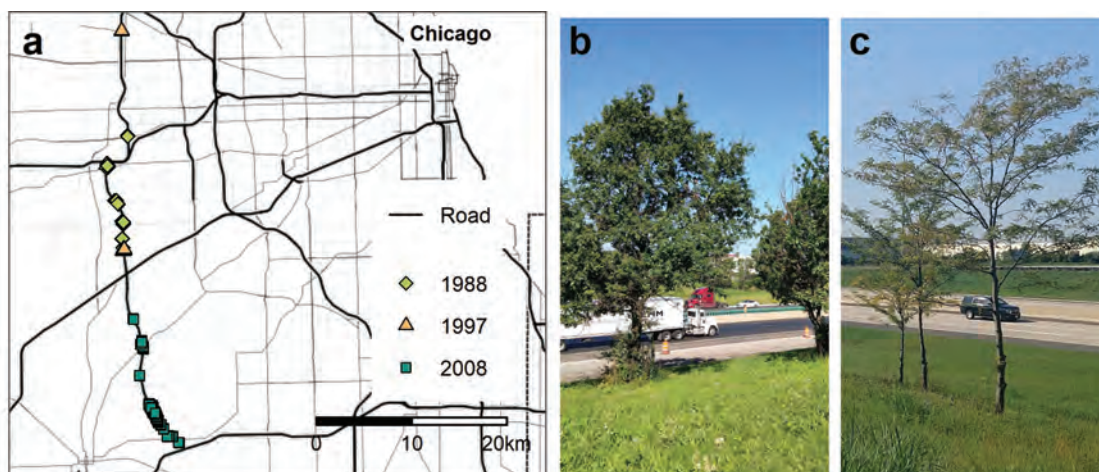
Figure 1. Map of study area in Chicago metropolitan region of Illinois, USA, which shows the location of study trees from the 1988, 1997, and 2008 cohorts (Panel a). Also shown are example trees from the 1988 cohort (Panel b) and the 2008 cohort (Panel c).

(Salisbury et al. 2022). Of this subset, 1,675 out of 2,944 surveyed trees (57%) were still alive in 2018.

The as-built records documented the location of planting sites along the highway and the quantity of trees originally in each planting site. Within a given planting site, all trees were the same species (or cultivar in some cases) and were the same stock size (recorded as nursery caliper, tree height, or container size). Planting sites typically contained between 5 to 50 trees which were planted in rows, usually no more than 3 trees deep with trees approximately 4.5 m to 6 m apart. For the purposes of analysis in this study, the planting site can be considered analogous to the concept of a stand in forest ecology. The planting sites randomly selected for this study resulted in the analysis of a total of 29 tree species (Table A1). Records of the time of year when the trees were planted as well as irrigation practices for the projects were not available.

In Spring 2019, we measured the trunk diameter at breast height (DBH) of 1,058 trees from randomly selected planting sites that had been used in the 2018 survival survey (Salisbury et al. 2022). Tree location was recorded using a GPS unit with sub-meter accuracy (Trimble TDC100 Handheld Unit with R1 GNSS Receiver; Westminster, CO, USA). We measured trees with single stems and codominant or multiple forked stems where pith separation occurred aboveground and below 1.4 m (multi-stemmed trees)(United States Forest Service 2021). In all cases, up to 6 of the largest stems with a diameter greater than 2.5 cm at 1.4 m above the ground surface were measured (United States Forest Service 2021). Multi-stem DBH was

calculated using a quadratic sum equation (Equation 1) where DBH_i is the DBH of an individual stem and DBH_{MS} is the DBH-equivalent of the entire multi-stem tree (Magarik et al. 2020):

$$DBH_{MS} = \sqrt{\sum_{i=1}^{6} DBH_i^2} \qquad (1)$$

Dead stems were not measured and trees located on a slope were measured from the uphill side. Of the 1,058 DBH trees, 99% were planted as balled-and-burlap trees (excavated rootball wrapped in burlap, also known as caliper trees) while the remaining 1% were container grown (5-gallon [19-L] container or unspecified size). We report cohort age as the time elapsed since the year the planting project was started, recognizing that it is not possible to precisely know tree age in this setting because we lack records on the exact time each tree was planted and the trees' ages at the time of planting.

GPS data was used to extract site-context data for each tree using ArcGIS (Version 10; ESRI; Redlands, CA, USA). An outline of the highway and associated ramps was created from aerial photos (United States Department of Agriculture 2017) while a digital elevation model (DEM) of the ROW with 1.2-m resolution was created using light detection and ranging (LiDAR) data (Illinois Geospatial Data Clearing-House 2015). To reduce the effects of potential errors in the combination of spatial data from different sources, we extracted average elevation, slope, and aspect data from a 2-m radius around each GPS point. For each tree, the geospatial data were used to

Figure 2. Site factors used to predict tree size on I-355.

determine the distance from the highway edge to the tree, the elevation of the tree relative to the highway, the slope of the ground, and the slope's aspect (Figure 2). Aspect is the compass direction a slope faces as observed by a viewer facing downslope. Aspect is a circular variable and was decomposed into northing and easting components (the cosine and sine of aspect, respectively) for analysis. A northing value of 1 indicates a perfectly north facing slope while −1 is south facing. An easting value of 1 indicated a slope faces east while −1 faces west.

The effects of distance from the highway, elevation, slope, northing, easting, and stem type (single or multi-stem) on DBH were tested for each cohort using a mixed-effects linear model (Table 1). Species and planting site were set as random intercepts since it is reasonable to assume different species will grow at different rates, and we observed variability in tree size among planting sites containing the same species. Models were visually checked for normality, homoscedasticity, and independence of residuals, which showed no adjustments were needed. Multicollinearity of predictor variables was checked using generalized variance inflation factors (GVIF)(Zuur et al. 2007). GVIF for all variables was less than 3, indicating multicollinearity was not an issue. Variable significance was assessed using a χ^2 test that compared the full- and single-term deletion model. Significance was determined using a threshold of $P = 0.05$. Model performance was assessed using Akaike Information Criterion (AIC)(Petrov and Csaki 1973); conditional R-squared, which accounts for the contribution of fixed and random effects; and marginal R-squared, which accounts for only fixed effects (Nakagawa and Schielzeth 2013). The intraclass correlation coefficient (ICC) is another statistic that quantifies the proportion of variance explained by random factors and can be calculated as conditional ICC (including both fixed and random effects) and adjusted ICC (random effects only)(Nakagawa et al. 2017). All analyses were conducted using R (Version 3.6.2)(The R Foundation 2019) and the following packages: *dplyr* (Wickham et al. 2020), *tidyr* (Wickham 2020), *ggplot* (Wickham

Table 1. Site context model variables.

Variable	Definition	Type	Mean	SD	Median	Min	Max
DBH (cm)	Trunk diameter measured 1.4 m above ground	Response	12.40	7.60	9.90	1.90	53.00
Distance (m)	Distance from tree to highway edge	Fixed Effect	76.70	52.30	61.20	4.60	314.00
Elevation (m)	Tree elevation relative to highway edge	Fixed Effect	0.90	2.60	0.50	−7.40	9.50
Slope (deg)	Slope of ground	Fixed Effect	7.10	6.60	3.60	0.20	23.50
Slope aspect – easting	East-west component of slope aspect (−1 = west, 1 = east)	Fixed Effect	−0.11	0.78	−0.20	−1.00	1.00
Slope aspect – northing	North-south component of slope aspect (−1 = south, 1 = north)	Fixed Effect	−0.24	0.58	−0.23	−1.00	1.00
			Quantity				
Stem type	Single or multi-stem tree (0 = multi-stem, 1 = single)	Fixed Effect	Single = 983 trees		Multi-Stem = 75 trees		
Species	Tree species	Random Effect	29				
Planting sites	Name of planting site where tree was located	Random Effect	111				

2016), *lme4* (Bates et al. 2015), and *performance* (Lüdecke et al. 2021).

For 14 of the 29 observed species, we estimated the expected DBH of the trees using DBH-age allometric equations developed by McPherson et al. (2016). These equations are based on measurements of thousands of urban park and street trees from across the conterminous United States for the 20 most abundant species in a set of climate regions (McPherson et al. 2016). These trees were sampled from a range of land uses, including residential (single- and multi-family); commercial; industrial; and parkland (Table A2). For species with allometric equations from multiple climate regions, we used the equation from the climate region most similar to northern Illinois. Recognizing that the I-355 trees were likely planted over multiple years following the start of each planting project (i.e., trees were likely planted between 1988 and 1990 for the 1988 cohort), we estimated tree size for trees between the ages of 27 and 30 years for the 1988 cohort, 17 to 20 for 1997, and 7 to 10 for 2008.

We also used the I-355 DBH data to estimate the per-tree carbon sequestration, carbon storage, pollution removal, and runoff removal provided by all of the measured trees using i-Tree (Eco Version 6)(United States Forest Service 2020a). Since tree height, crown dimensions, and crown-condition data were not collected, we relied on i-Tree's estimates of these parameters using allometric equations. We also used i-Tree's default value of 13% missing crown, which should not seriously affect carbon sequestration estimates since no dead or dying trees were measured in our study (United States Forest Service 2020b).

RESULTS

Each planting cohort had a different combination of site context variables in the final model (Table 2). Northing (the north-south component of slope aspect) was significant in both the 1988 and 2008 cohort models, though interestingly north-facing slope trees were more likely to have smaller DBH in the 1988 cohort but were more likely to be larger in the 2008 cohort. For the 1997 cohort, both elevation relative to the road and slope had positive effects, i.e., trees at higher elevations and on steeper slopes had larger DBH. Stem type was also a significant predictor for the 2008 cohort with single-stem trees more likely to be smaller than multi-stemmed. For all 3 cohorts, marginal *R*-squared (representing the contributions of fixed effects only) tended to be substantially lower

than conditional *R*-squared (contributions of fixed and random effects). In the 1997 and 2008 models, species random effects variance was greater compared to the planting site random effect. In the 1988 model, species and planting site random effects variances were similar. The adjusted intraclass correlation (ICC, evaluated with only random effects) was higher than the conditional ICC (fixed and random effects) for the 1988 and 1997 full and reduced models. There was no difference between the adjusted and conditional ICC for the 2008 full and reduced models.

Of the 8 species in the 1988 planting cohort with allometric age-DBH equations in the Urban Tree Database (McPherson et al. 2016), only *Quercus macrocarpa* Michx. and *Gleditsia triacanthos* f. *inermis* 'Imperial' had DBH measurements which were similar to predicted values (Figure 3). DBH for the
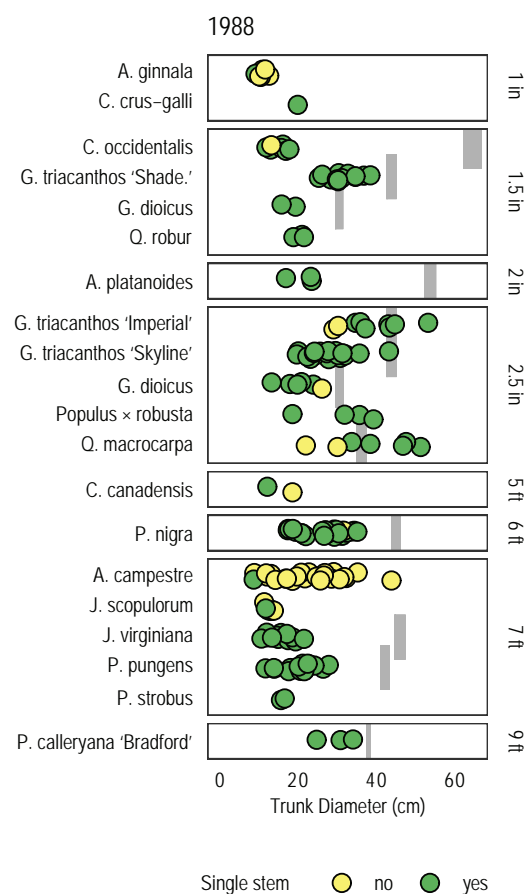
Figure 3. DBH of tree species in the 1988 cohort. Species are grouped by stock size recorded in planting plans. Circles represent DBH for each individual tree. Gray bars indicate the estimated DBH at age 27 to 30 years for species included in the Urban Tree Database (McPherson et al. 2016). 'Shade.' = Shademaster cultivar. Full species names in Table A1.

Table 2. Full, final reduced (Red), and null model results for context variables in the 1988, 1997, and 2008 planting cohorts.

	1988			1997			2008		
	Full	**Red**	**Null**	**Full**	**Red**	**Null**	**Full**	**Red**	**Null**
Fixed effects – Coefficient (95% confidence interval)									
Intercept	26.0 (19.7, 32.2)	21.9 (18.1, 25.6)	22.1 (18.2, 25.9)	15.7 (9.2, 23.0)	13.6 (8.8, 18.1)	17.2 (15.2, 19.4)	11.9 (10.1, 13.8)	11.9 (10.2, 13.6)	10.3 (8.8, 11.9)
Distance	0 (–0.1, 0)			0 (0, 0)			0 (0, 0)		
Elevation	–0.3 (–1.0, 0.3)			0.7 (0.4, 1.1)	0.8 (0.5, 1.1)		0.2 (0, 0.3)		
Slope	–0.2 (–0.5, 0.2)			0.3 (0.1, 0.5)	0.3 (0.1, 0.5)		0 (–0.1, 0)		
Northing	–3.4 (–6.5, –0.1)	–3.3 (–6.5, –0.2)		0.2 (–1.0, 1.7)			0.3 (0, 0.5)	0.3 (0, 0.5)	
Easting	1.4 (–0.8, 3.6)			0.3 (–0.7, 1.0)			0 (–0.2, 0.3)		
Stem type (single)	–1.0 (–4.1, 2.5)			–1.5 (–4.2, 1.4)			–1.5 (–2.2, –0.8)	–1.5 (–2.2, –0.8)	
Random effects – Variance									
Planting site	33.5	33.7	27.7	0.5	0.5	4.5	4.4	4.5	4.4
Species	34.6	32.8	38.9	22.5	10.6	10.8	9.1	8.3	8.3
Residual	23.5	23.7	24.7	10.6	10.6	10.9	2.4	2.4	2.5
Model performance									
Model χ^2 *P*-value	0.103	0.037		0.023	0.002		< 0.001	< 0.001	
AIC	1187	1183	1186	455	450	458	3181	3179	3196
ICC conditional	0.67	0.71	0.73	0.62	0.45	0.58	0.84	0.84	0.84
ICC adjusted	0.74	0.74		0.68	0.51		0.85	0.84	
R^2 conditional	0.77	0.75	0.73	0.71	0.57	0.58	0.85	0.84	0.84
R^2 marginal	0.10	0.03		0.09	0.11		0.01	0.01	

remaining species was lower than would be expected based on the allometric equations. In the 1997 cohort, *Gymnocladus dioicus* (L.) K. Koch DBH was similar to predicted values, though this species' DBH was smaller than expected in the 1988 and 2008 cohorts (Figure 4). For the 2008 cohort, *Q. macrocarpa* and *Pinus nigra* 'Arnold Sentinel' were the only 2 species whose DBH was within the range of predicted values out of the 10 species with predicted DBH (Figure 5). Notably, DBH was generally more variable in the 1988 cohort compared to the 2008 cohort with the standard deviations for each species ranging from 0.6

to 10.6 for 1988 and from 0.4 to 4.8 for 2008. Multi-stem trees tended to have larger DBH (Equation 1) compared to single-stem trees within a given species, with the exceptions of *Celtis occidentalis* L. (1988), *Populus* × *robusta* (1988), and *G. triacanthos* 'Skyline' (1997).

Median per-tree estimated carbon sequestration and estimated carbon storage were fairly similar between the 22- and 31-year-old cohorts, while median per-tree estimated pollution removal and estimated runoff removal were higher in the 30-year-old cohort (Figure 6). The ranges of per-tree estimated
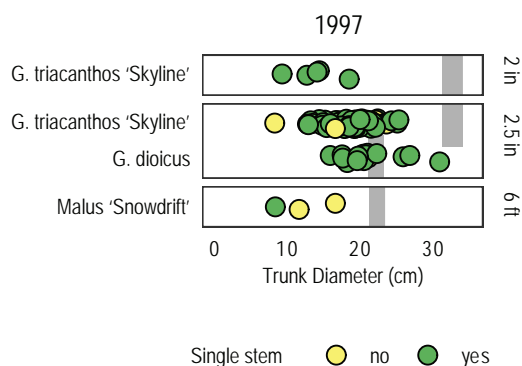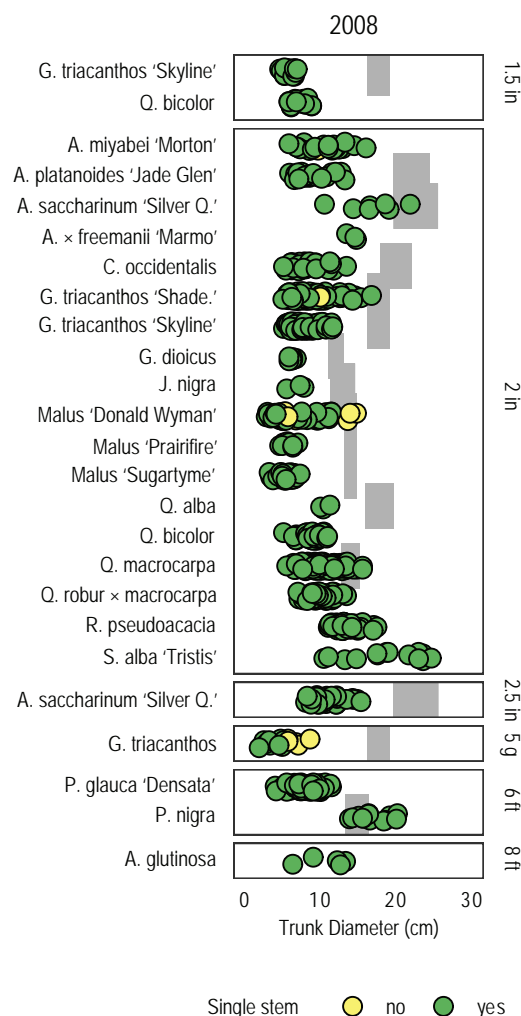
1997

Figure 4. DBH of tree species in the 1997 cohort. Species are grouped by stock size recorded in planting plans. Circles represent DBH for each individual tree. Gray bars indicate the estimated DBH at age 17 to 20 years for species included in the Urban Tree Database (McPherson et al. 2016). Full species names in Table A1.

benefits overlap among all 3 planting cohorts reflecting differences in species composition as well as tree size. For example, the 2008 cohort *Acer × freemanii* with a mean DBH of 13 ± 3 cm had 1.7-times more estimated carbon storage than the small-statured *Acer ginnala* Maxim. in the 1988 cohort with a mean DBH of 11 ± 1 cm (Table A1). For estimated air-pollution removal, 2008 *P. nigra* and 1988 *Pinus strobus* L. had similar DBH (17 ± 2 cm and 16 ± 0.6 cm, respectively) but the 2008 *P. nigra* had 1.4-times greater air-pollution removal rates compared to the 1988 *P. strobus*.

DISCUSSION

Contrary to our initial hypotheses, no single planting location characteristic had a consistent effect on DBH. We expected trees growing closer to the highway edge to have smaller DBH since highway soil conditions are often the worst close to the roadway (Akbar et al. 2012). Soils adjacent to road pavement tend to receive highway runoff and are more likely to have been subject to intensive modification during construction activities (Trammell et al. 2011). For trees in this study, distance effects may have been unimportant since they were planted at least 9 m away from the highway (typical clear zone distance), avoiding the soil in close proximity to the pavement (with the exception of a few *G. triacanthos* planted in 1988, which were growing above a small retaining wall adjacent to an exit ramp). Differences in elevation relative to the highway may reflect differences in microtopography among planting sites since roadside microtopography can produce variable soil conditions

2008

Figure 5. DBH of tree species in the 2008 cohort. Species are grouped by stock size recorded in planting plans. Circles represent DBH for each individual tree. Gray bars indicate the estimated DBH at age 7 to 10 years for species included in the Urban Tree Database (McPherson et al. 2016). 'Silver Q.' = Silver Queen cultivar; 'Shade.' = Shademaster cultivar; "5 g" = 5-gallon container. Full species names in Table A1.

within the ROW (Karim and Mallik 2008). Elevation relative to the roadside can also correlate with de-icing salt damage, with greater damage occurring below grade (Munck et al. 2010). The slope and aspect of hillsides can influence tree growth by affecting soil moisture, microclimate, and soil formation (Stage and Salas 2007). Increasing slope had a positive effect on DBH for the 1997 cohort, suggesting that in this case slope steepness may be a proxy for another variable such as soil conditions influencing tree size. Northing was an important model variable for both the 1988 and 2008 cohorts, though it had opposite
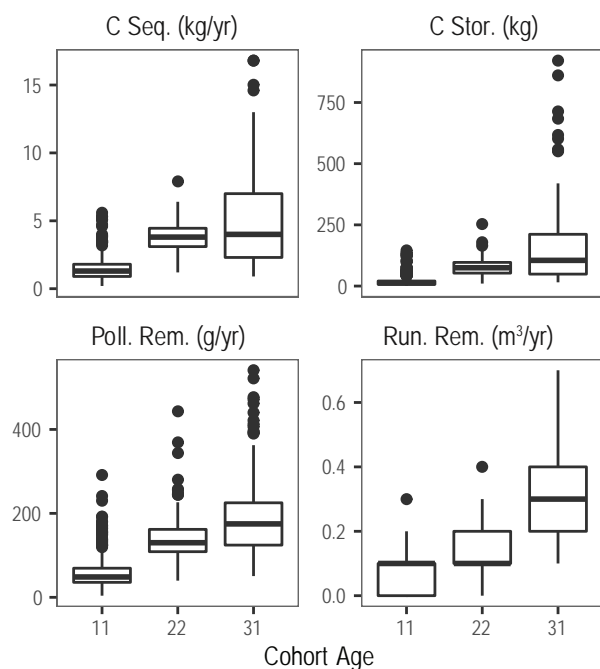
Figure 6. Per-tree carbon sequestration (C Seq.), carbon storage (C Stor.), air-pollution removal (Poll. Rem.), and run-off removal (Run. Rem.) of I-355 study trees in the 3 planting cohorts.

effects on the 2 groups. Smaller DBH on north-facing slopes (northing = 1), seen in the 1988 cohort, could reflect changes in the height-DBH relationships in response to aspect and limited light (Long et al. 2020). Larger DBH on south-facing slopes, observed in the 2008 cohort, could be the result of cooler temperatures and less moisture loss from the soil which would reduce water stress (Stage and Salas 2007). The planting location characteristic models for I-355 demonstrate the difficulty in providing generalized recommendations for optimal tree planting locations in the ROW and suggest there may be other factors exerting a stronger influence on DBH in this setting.

Observations of trunk diameter of 10- to 30-year planted highway trees suggest highway ROWs in the Midwestern United States are a challenging environment for tree growth. Most of the species in this study with allometric equations from the Urban Tree Database (McPherson et al. 2016) had smaller DBH compared to model estimates for similarly aged trees found in other urban settings (e.g., residential, commercial, and parks). Granted, not all species could be evaluated in this manner since they lacked allometric

equations in the Urban Tree Database. This gap highlights a need to continue collecting allometric data for multiple species in multiple urban settings to improve our expectations for long-term urban tree growth. Though by contrast, in Florida, *Quercus virginiana* Mill. and *Taxodium distichum* (L.) Rich. caliper growth in open lawns and park settings was lower compared to highway medians, parking lots, and other urban sites 38 months after planting (Koeser et al. 2014). Findings from Koeser et al. (2014) indicated that many factors in addition to land use, including planting practices, maintenance, and other site conditions, were necessary to predict tree growth in different urban settings.

Poor soil conditions following construction is likely an important driver of reduced highway tree growth. Research on soil restoration in highway settings indicated high bulk density and low organic-matter content following construction impeded tree growth (Somerville et al. 2018; McGrath et al. 2020). Trees growing near a highway in Finland also exhibited changes in leaf anatomy typically associated with drought stress, possibly caused by roadside microclimate and soil conditions (Nikula et al. 2011). Drought stress is highly relevant in northern Illinois where approximately every 2 out of 10 years experience well below average rainfall in the growing season (Calsyn 1999). Additionally, climate models predict this region could experience greater temperatures in the future which would worsen short-term droughts (Wuebbles et al. 2021). Such periodic drought conditions may worsen stress caused by post-construction soils and limit tree growth, though soil restoration prior to planting can improve tree growth in compacted soils while reducing the need for irrigation (McGrath et al. 2020).

Weather-related stress may have also played a role in limited growth for some of these tree species. The region has experienced several droughts during the planting period for the cohorts. These include extreme droughts (Palmer Drought Severity Index [PDSI] less than –4) from 1988 to 1989, early in the establishment period for the 1988 cohort, and in 2012 as well as several moderate to severe droughts (PDSI between –2 and –4) between 1989 and 2015 (Illinois State Climatologist 2021). There were also several years with severe to extreme wet spells from 2008 to 2011 (PDSI greater than 3)(Illinois State Climatologist 2021). Such unusually dry and unusually wet weather

patterns occurring during the planting and establishment periods for the 1988 and 2008 cohorts, respectively, could have also contributed to the less-than-expected growth for some species. Considering predictions of more frequent droughts and intense rain events for Illinois (Wuebbles et al. 2021), it is reasonable to expect such weather-related stressors will continue to be relevant to urban tree growth in the future. Additionally, management practices can influence survival and growth (Vogt et al. 2015), potentially offsetting or exacerbating unfavorable weather. Unfortunately, we lack records documenting practices such as irrigation and the season when trees were planted and cannot draw conclusions about their possible effects.

Highway environments can contain elevated levels of de-icing materials in cold-weather climates (Fay and Shi 2012), heavy metals in roadside soil (Werkenthin et al. 2014), and other air-borne (Kuttler and Strassburger 1999) and soil pollutants (Bryselbout et al. 2000; Marusenko et al. 2011), which all have the potential to affect tree growth. Exposure to sodium-based de-icing salts has been associated with diminished stem growth in roadside trees, though these impacts vary among species and roadside conditions (Blomqvist 1998). Street trees (*Tipuana tipu* [Benth.] Kuntze) in São Paulo, Brazil, had reduced annual increment growth in association with elevated levels of particulate matter (PM10), zinc, barium, and aluminum (Locosselli et al. 2019). By contrast, in Finland, *Populus tremula* L. × *P. tremuloides* Michx. clones growing along highways had greater metal concentrations compared to rural sites, though concentrations were not at levels considered toxic and likely did not severely impact tree growth (Nikula et al. 2011). Considering the many potential stressors trees can encounter in the highway roadside in addition to other challenges associated with transplanting trees (Watson 2014), it is likely that multiple stressors could be impairing growth in the highway setting. Though notably, ameliorating compaction in highway soil using deep ripping or subsoiling and the incorporation of compost improved tree growth (Somerville et al. 2018; McGrath et al. 2020), offering a potential approach for alleviating at least some stressors in the roadside.

Stressful conditions in the highway ROW not only impair growth, they also limit trees' ability to provide size-dependent ecosystem services. Nevertheless, highway trees have the potential to contribute substantial ecosystem services. For instance, the 303,000 trees in the United Kingdom's Area 1, a 972-ha ROW (or soft estate), were estimated to annually remove 29 tons of air pollution, sequester 1,980 tons of carbon, and avoid over 75,000 m^3 of runoff (Rogers and Evans 2015). And in Florida the 37,660 ha of vegetated ROW in the State Highway System (estimated to be about 40% woody vegetation) were estimated to provide approximately $5.95 million in air-pollution removal, $39.5 million in carbon sequestration, and $465 million in runoff reduction (USD, 2014 prices)(Harrison 2014). In our study, we observed that small-stature 31-year-old trees (e.g., *Malus* spp.) and large-stature 10-year-old trees (e.g., *Acer saccharinum*) had similar estimated carbon sequestration rates and storage quantities. This observation highlights how even after multiple decades, species with small-growth forms contribute little to carbon storage and sequestration, though small-statured species can provide other benefits such as aesthetics and can be appropriate for sites with space constraints. Additionally, size alone is not the only factor which influences ecosystem service provision. *Q. macrocarpa* on average is estimated to store and sequester the most carbon on a per-tree basis in the 1988 cohort, while other 1988 species have greater contributions to estimated avoided runoff. With the proliferation of large-scale tree planting initiatives across the globe (Eisenman et al. 2021), our results illustrate the role species selection can play in a planting project's ability to provide meaningful ecosystem services. Indeed, in order for highway plantings to effectively provide particular benefits such as air-pollution removal, thoughtful species selection and arrangement are necessary (Baldauf 2017; Barwise and Kumar 2020) in addition to mitigating site stressors such as poor soil conditions.

Study Limitations

Diameter is only 1 metric of tree performance, and on its own does not capture long-term growth patterns or a tree's overall condition (North et al. 2018). However, for the purposes of this research, diameter provided an efficient way to compare large numbers of similarly aged trees. Planting density is 1 factor which influences a tree's allocation of resources to growing taller or wider, consequently influencing caliper (Drew and Flewelling 1979). For the I-355 planting sites, tree spacing was consistent among planting sites (ranging from 4.6 m to 6 m) and tree planting areas

were rarely more than 2 rows wide, suggesting edge and interior effects would be negligible. While there are multiple methods for measuring the DBH of multi-stemmed trees with different advantages and disadvantages (Magarik et al. 2020), we used the 6-largest-stems approach in order to be consistent with i-Tree protocol (United States Forest Service 2021). Since cohort age is based on the year the planting projects started and we lack records of exactly when each tree was planted, cohort age may overestimate the amount of time a tree has been in its planting site. The accuracy of i-Tree estimates of ecosystem services are limited by the applicability of their allometric models to particular local conditions (Timilsina et al. 2017). Consequently, comparing estimates as ratios or percentages rather than absolute values is likely a more informative approach.

CONCLUSION

The highway ROW presents many challenges for planting and growing trees, but also great potential. We evaluated the current size of 3 planting cohorts along a highway in the Chicago metropolitan region to assess factors which could influence long-term tree growth. Our observations demonstrated that planting location within the ROW can impact tree size and consequently some of the ecosystem services provided by those trees. However, the effects of planting location on tree size were inconsistent among tree species, and it is difficult to draw generalized recommendations about choosing planting sites within the ROW from the data. These results emphasize the point that highway ROWs are not a homogenous planting environment. Consequently, careful on-the-ground site assessments and soil restoration when needed should increase the likelihood of trees realizing their full potential for growth along highways.

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Résumé. Contexte: Les emprises résiduelles d'autoroutes (servitudes ou accotements) comportent de multiples facteurs de stress susceptibles d'influencer la croissance des arbres, dont des sols compactés, des sols avec peu de terre végétale, un mauvais drainage, des polluants atmosphériques ainsi qu'au niveau du sol, des activités de construction et des fondants salins pour les climats froids. Pourtant, les emprises des autoroutes offrent souvent de vastes aires dégagées pour la plantation d'arbres, ce qui peut contribuer à atténuer les impacts environnementaux négatifs associés aux autoroutes. Méthodes: Dans le cadre de cette étude, nous avons évalué le diamètre du tronc de 1 058 arbres provenant de cohortes plantées depuis 11, 22, et 31 ans, le long d'une autoroute de la région métropolitaine de Chicago (Illinois, États-Unis), afin d'examiner les facteurs à risque d'influencer la croissance à long terme. Nous avons analysé l'impact des facteurs de localisation à l'intérieur de l'emprise (par exemple, la distance et l'élévation par rapport à l'autoroute, la pente et l'orientation) sur le diamètre à hauteur de poitrine (DHP) des troncs, puisque ces facteurs sont pertinents dans le processus de conception et d'aménagement du paysage. En utilisant les estimations de i-Tree, nous avons comparé la séquestration et le stockage du carbone, la réduction du ruissellement et la diminution de la pollution atmosphérique parmi les trois cohortes et entre elles. Résultats: Parmi les 6 caractéristiques de localisation des sites qui furent évaluées, aucune caractéristique n'a eu un impact invariable et régulier sur le DHP, bien que certaines caractéristiques aient été significatives pour une même cohorte. Les mesures du DHP de la plupart des espèces étaient inférieures aux prédictions du modèle basées sur les modèles d'arbres urbains connus. Considérant que toutes les cohortes comportaient des arbres de petite et de grande dimension et que pour une même espèce le DHP pouvait être très variable, la gamme des services écosystémiques générés par arbre variait considérablement au sein des cohortes, en particulier celle de 31 ans. Conclusions: Ces résultats soulignent à la fois le potentiel et les enjeux de la culture d'arbres le long des autoroutes.

Zusammenfassung. Hintergrund: Straßenverkehrswege (ROW) enthalten zahlreiche Stressfaktoren, die das Wachstum von Bäumen beeinträchtigen können. Darunter verdichtete Böden, Böden mit wenig Oberboden, schlechte Drainage, Luft- und Bodenschadstoffe, Bautätigkeiten und Tausalze in kalten Klimazonen. Dennoch bieten Autobahntrassen oft reichlich Platz für die Anpflanzung von Bäumen, die dazu beitragen können, die mit Autobahnen verbundenen negativen Umweltauswirkungen zu mindern. Methoden: In dieser Studie haben wir den Stammdurchmesser von 1.058 Bäumen aus 11-, 22-, und 31-jährigen Pflanzkohorten entlang einer Autobahn im Großraum Chicago (Illinois, USA) untersucht, um Faktoren zu ermitteln, die das langfristige Wachstum beeinflussen könnten. Wir analysierten die Auswirkungen von Standortfaktoren innerhalb der Fahrbahn (z. B. Entfernung und Höhe im Verhältnis zur Autobahn, Neigung und Aspekt) auf den Stammdurchmesser in Brusthöhe (DBH), da diese Faktoren für den Landschaftsgestaltungsprozess relevant sind. Anhand von Schätzungen aus i-Tree verglichen wir die Kohlenstoffbindung, die Kohlenstoffspeicherung, die Verringerung des Abflusses und die Beseitigung von Luftverschmutzung innerhalb und zwischen den drei Kohorten. Ergebnisse: Von den 6 ausgewerteten Standortmerkmalen wirkte sich kein einziges Merkmal durchgängig auf die DBH aus, obwohl einige Merkmale innerhalb einer einzelnen Kohorte signifikant waren. Die DBH-Messungen der meisten Arten waren kleiner als die Modellvorhersagen, die auf bestehenden Stadtbaummodellen basieren. Da alle Kohorten sowohl große als auch kleine Bäume enthielten und selbst innerhalb der Arten der DBH-Wert stark variieren konnte, variierte die Bandbreite der Ökosystemleistungen pro Baum innerhalb der Kohorten erheblich, insbesondere in der 31-jährigen Kohorte. Schlussfolgerungen: Diese Ergebnisse verdeutlichen sowohl das Potenzial als auch die Herausforderungen des Anbaus von Bäumen entlang von Autobahnen.

Resumen. Antecedentes: Los derechos de paso de las carreteras (ROW, o bordes) contienen múltiples factores estresantes que pueden influir en el crecimiento de los árboles, incluidos los suelos compactados, los suelos con poca capa superficial, el drenaje deficiente, los contaminantes del aire y el suelo, las actividades de construcción y las sales de deshielo en climas fríos. Sin embargo, las ROWs de carreteras a menudo proporcionan un amplio espacio de plantación para el cultivo de árboles, lo que puede contribuir a la mitigación de los impactos ambientales negativos asociados con las carreteras. Métodos: Para este estudio, evaluamos el diámetro del tronco de 1,058 árboles de cohortes de plantación de 11, 22, y 31 años a lo largo de una carretera en la región metropolitana de Chicago (Illinois, EE. UU.) para examinar los factores que podrían influir en el crecimiento a largo plazo. Analizamos el impacto de los factores de ubicación dentro del ROW (por ejemplo, distancia y elevación en relación con la carretera, la pendiente y el aspecto) en el diámetro del tronco a la altura del pecho (DBH), ya que estos factores son relevantes para el proceso de diseño del paisaje. Utilizando estimaciones de i-Tree, comparamos el secuestro de carbono, el almacenamiento de carbono, la reducción de la escorrentía y la eliminación de la contaminación del aire dentro y entre las 3 cohortes. Resultados: De las 6 características de ubicación del sitio que evaluamos, ninguna característica afectó consistentemente el DBH, aunque algunas características fueron significativas dentro de una sola cohorte. Las mediciones de DBH de la mayoría de las especies fueron más pequeñas que las predicciones del modelo basadas en los modelos de árboles urbanos existentes. Dado que todas las cohortes incluían árboles de estatura grande y pequeña, e incluso dentro de las especies, el DBH podría ser muy variable, el rango en los servicios ecosistémicos por árbol varió sustancialmente dentro de las cohortes, especialmente la cohorte de 31 años. Conclusiones: Estos hallazgos resaltan tanto el potencial como los desafíos del cultivo de árboles junto a las carreteras.

Appendix 1.

Table A1. Mean and standard deviation (in parentheses) of DBH and ecosystem services for each species and year. C seq. = carbon sequestration. C stor. = carbon storage. Poll. rem. = air-pollution removal. Run. rem. = runoff removal.

Species	Year	*n*	DBH (cm)	C seq. (kg/yr)	C stor. (kg)	Poll. rem. (g/yr)	Run. rem. (m³/yr)
Acer campestre L.	1988	29	23.3 (9.1)	5.7 (2.8)	180 (150)	298 (152)	0.36 (0.19)
Acer ginnala Maxim.	1988	6	10.7 (1.2)	2.1 (0.3)	26 (7)	144 (25)	0.33 (0.05)
Acer miyabei Maxim.	2008	24	10.6 (2.5)	2.1 (0.6)	27 (14)	99 (32)	0.11 (0.03)
Acer platanoides L.	1988	3	21.1 (3.7)	4.8 (1)	117 (42)	192 (51)	0.43 (0.12)
	2008	22	8.8 (2.1)	1.6 (0.5)	17 (10)	82 (26)	0.11 (0.03)
Acer saccharinum L.	2008	61	11.8 (3.1)	2.3 (0.7)	41 (24)	117 (47)	0.13 (0.05)
Acer × freemanii	2008	17	13.2 (2.6)	2.7 (0.7)	44 (18)	136 (39)	0.15 (0.05)
Alnus glutinosa (L.) Gaertn.	2008	25	13.3 (3)	2.4 (0.7)	36 (18)	115 (31)	0.12 (0.04)
Celtis occidentalis L.	1988	7	14.8 (2.2)	2.8 (0.6)	45 (16)	176 (43)	0.39 (0.09)
	2008	44	7.8 (1.8)	1.2 (0.4)	10 (6)	60 (20)	0.09 (0.03)
Cercis canadensis L.	1988	2	15.2 (4.5)	3 (1.2)	49 (33)	80 (33)	0.15 (0.07)
Crataegus crus-galli L.	1988	1	19.8 (0)	4.1 (0)	83 (0)	86 (0)	0.2 (0)
Gleditsia triacanthos L.	1988	47	30.8 (6.8)	7.8 (2.5)	269 (158)	178 (38)	0.27 (0.13)
	1997	72	17.9 (3.8)	3.6 (1)	71 (33)	121 (31)	0.13 (0.07)
	2008	199	7.9 (2.4)	1.2 (0.5)	11 (8)	33 (16)	0.02 (0.04)
Gymnocladus dioicus (L.) K. Koch	1988	8	19.5 (4.1)	4.1 (1.2)	89 (44)	189 (53)	0.28 (0.13)
	1997	16	21 (3.8)	4.6 (1.2)	106 (52)	257 (72)	0.22 (0.07)
	2008	6	6.2 (0.4)	0.8 (0)	5 (1)	46 (2)	0.07 (0.05)
Juglans nigra L.	2008	4	6.8 (1)	0.9 (0.2)	7 (2)	62 (12)	0.1 (0)
Juniperus scopulorum Sarg.	1988	9	12.3 (1.1)	1.1 (0.1)	22 (4)	65 (9)	0.1 (0)
Juniperus virginiana L.	1988	12	15.5 (3.3)	1.5 (0.4)	38 (17)	103 (35)	0.12 (0.05)
Malus spp.	1997	3	12.1 (4.1)	2.1 (1)	29 (22)	96 (34)	0.1 (0)
	2008	93	6.2 (2.5)	0.8 (0.5)	7 (7)	43 (17)	0.03 (0.05)
Picea glauca (Moench) Voss	2008	69	8.4 (1.8)	1.1 (0.3)	13 (5)	43 (11)	0.05 (0.05)
Picea pungens (Engelm.)	1988	16	20.1 (4.4)	3.3 (0.9)	84 (37)	129 (47)	0.18 (0.06)
Pinus nigra Arnold	1988	28	26.4 (5.5)	2.6 (0.7)	86 (37)	199 (50)	0.45 (0.12)
	2008	14	16.8 (2.1)	1.4 (0.2)	30 (8)	99 (16)	0.1 (0)
Pinus strobus L.	1988	2	15.9 (0.6)	1.6 (0.1)	26 (2)	70 (6)	0.1 (0)
Populus × robusta	1988	4	31.2 (9)	6.5 (2.5)	223 (127)	237 (121)	0.3 (0.14)
Pyrus calleryana Decne.	1988	3	29.7 (4.7)	7.3 (1.6)	228 (83)	192 (59)	0.23 (0.06)
Quercus alba L.	2008	3	10.5 (0.6)	1.7 (0.2)	18 (3)	48 (4)	0.1 (0)
Quercus bicolor Willd.	2008	68	8.2 (1.4)	1.3 (0.3)	11 (4)	42 (8)	0.03 (0.04)
Quercus macrocarpa Michx.	1988	7	38.4 (10.6)	11.2 (4.4)	473 (284)	353 (104)	0.43 (0.14)
	2008	102	10.1 (2.1)	1.6 (0.5)	17 (9)	54 (15)	0.07 (0.04)
Quercus robur L.	1988	7	22.6 (6.7)	5.9 (2.8)	151 (132)	251 (128)	0.57 (0.29)
Quercus robur × macrocarpa	2008	51	9.9 (1.5)	1.7 (0.4)	17 (7)	60 (13)	0.08 (0.04)
Robinia pseudoacacia L.	2008	48	13.2 (2.1)	2.4 (0.6)	35 (14)	91 (21)	0.1 (0.02)
Salix alba L.	2008	14	18.6 (4.8)	3.9 (1.3)	82 (44)	124 (44)	0.14 (0.06)

Table A2. Formulas used to estimate DBH based on tree age using data from the Urban Tree Database for particular species observed in different regions of the United States (McPherson et al. 2016).

Region	Species	Formula	Land use
Temperate interior west	*Juglans nigra*	$DBH = \exp\left(0.19 + 2.81 \times LN\left(LN(age) + \left(\frac{0.04}{2}\right)\right)\right)$	Single-family residential; Small commercial; Industrial/institutional/large commercial; Park/vacant/other
North	*Picea pungens*	$DBH = 2.12 + 1.61 \times age - 0.01 \times age^2$	Single-family residential; Industrial/institutional/large commercial; Multi-family residential; Park/vacant/other
Inland valleys	*Pyrus calleryana*	$DBH = 2.52 + 1.85 \times age - 0.02 \times age^2$	Not Reported
North	*Gymnocladus dioicus*	$DBH = 2.84 + 0.91 \times age$	Multi-family residential; Single-family residential; Park/vacant/other; Industrial/institutional/large commercial; Not Reported
North	*Pinus nigra*	$DBH = 3.17 + 0.67 \times age + 0.06 \times age^2 + 0 \times age^3$	Industrial/institutional/large commercial; Single-family residential; Park/vacant/other; Multi-family residential
North	*Quercus macrocarpa*	$DBH = 2.84 + 1.1 \times age$	Single-family residential; Industrial/institutional/large commercial; Multi-family residential; Park/vacant/other
Piedmont	*Juniperus virginiana*	$DBH = \exp\left(0.21 + 2.94 \times LN\left(LN(age) + \left(\frac{0.03}{2}\right)\right)\right)$	Single-family residential; Multi-family residential; Industrial/institutional/large commercial
Piedmont	*Quercus alba*	$DBH = -0.49 + 1.82 \times age$	Park/vacant/other; Single-family residential; Industrial/institutional/large commercial; Multi-family residential
Midwest	*Acer platanoides*	$DBH = -7.95 + 3.81 \times age - 0.09 \times age^2 + 0 \times age^3$	Single-family residential; Multi-family residential; Park/vacant/other; Industrial/institutional/large commercial
Midwest	*Acer saccharinum*	$DBH = -1.79 + 1.89 \times age + 0.07 \times age^2 + 0 \times age^3$	Single-family residential; Multi-family residential; Small commercial; Park/vacant/other
Midwest	*Celtis occidentalis*	$DBH = 3.55 + 1.18 \times age + 0.05 \times age^2 + 0 \times age^3$	Park/vacant/other; Single-family residential; Industrial/institutional/large commercial; Multi-family residential
Midwest	*Gleditsia triacanthos*	$DBH = 2.82 + 1.54 \times age - 0.01 \times age^2$	Single-family residential; Multi-family residential; Park/vacant/other; Small commercial; Industrial/institutional/large commercial
Midwest	*Malus* spp.	$DBH = 3.23 + 1.6 \times age - 0.07 \times age^2 + 0 \times age^3$	Single-family residential; Multi-family residential; Park/vacant/other; Industrial/institutional/large commercial
Midwest	*Tilia cordata*	$DBH = 2.4 + 1.62 \times age - 0.01 \times age^2$	Multi-family residential; Single-family residential; Industrial/institutional/large commercial; Park/vacant/other; Small commercial