Research Note: The Tripping Point – Minimum Planting Widths for Small-Stature Trees in Dense Urban Developments.

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Research Highlights:

- Allometric equations explain minimum planting widths for small stature trees.
- Trunk flare diameter is related to species, stem diameter, and measurement height.
- Cost savings for increased planting widths were created for sidewalk replacement.
- Minimum planting width is provided for planners, urban foresters, and engineers.

Abstract

As urban development increases in density, the space to grow urban trees becomes more constrained. In heavily developed areas, small stature trees can be planted to reduce both above- and below-ground conflicts with infrastructure elements. However, even these species have their limits when placed in extremely confining conditions. In this study, we build on past work to determine the minimum planting space widths of small stature urban trees. Species, stem diameter, and the height at which stem diameter measurements occurred were all strong predictors of trunk flare diameter (adjusted R^2 of 0.843). Additionally, we modelled the relationship between planting space and the presence or absence of hardscape conflicts – using the predictions derived from this effort to project the potential cost savings in two United States cities. Study results provide a guideline to create sufficient space for urban trees and minimize infrastructure damage and associated cost savings.

Keywords: Ecosystem Disservices, Green Infrastructure, Sidewalks, Site Design, Tree Selection, Urban Forestry

1. Introduction

Urban trees are often integrated into urban planning and design efforts to increase the walkability of neighborhoods (Choi et al., 2016), calm traffic (Van Treese et al., 2017), and shade parking areas (Koeser et al., 2021; Grabosky and Gilman, 2004). Their ability to cool localized environments through the absorption of the sun's light energy and the transpiration of soil moisture has been used to mitigate the impacts of urban heat island buildup (Petri et al., 2019), as well as to extend the life of some paving materials (McPherson and Muchnick, 2005). This noted, conflicts between tree roots and the paved surfaces that facilitate pedestrian and vehicular traffic are a common ecosystem disservice (Roman et al., 2020) and a major municipal expense (McPherson, 2000; Randrup et al., 2003).

From an engineering perspective, trees and their roots represent a significant factor contributing to the lifting, cracking, or general degradation of paved surfaces. In his assessment of the costs of tree and hardscape conflicts in 18 California (United States) communities, McPherson (2000) estimated that $114.3 million total or $4.48 per capita (USD; CPI adjusted to 2021 values) was spent annually due to tree conflicts and replacing sidewalks, curbs, and gutters across the whole of the state. In more recent conversations with local transportation engineers, tree and sidewalk conflicts are still seen as the primary cause necessitating sidewalk replacement (Gorman, City of Tampa; personal communication).

Root and hardscape conflicts can be similarly damaging to the trees involved. The replacement or repair of paved surfaces near trees can sever or injure roots – reducing tree health (Benson et al., 2019; Hauer et al, 2020; Koeser et al., 2013) and undermining overall stability in the face of storm events (Johnson et al., 2019). To reduce root and hardscape conflicts, researchers have investigated how planting widths relate to sidewalk damage (Francis et al., 1996; Randrup et al., 2003) and created allometric models to predict trunk flare diameter (i.e., the diameter of the enlarged area at the base of the tree where the trunk connects to the main structural roots) based on tree species and stem diameter (Hilbert et al., 2020; North et al., 2015).

In this extension of past research by North et al. (2015) and Hilbert et al. (2020), we developed allometric models linking stem diameter to trunk flare diameter in small-stature urban trees. While the large stature shade trees assessed by the two research teams cited above are important contributors of ecosystem services, modern compact development patterns leave less space for the sustained growth of large trees (Daniel et al. 2016). As cities continue to densify, small understory trees may be the best choice for urban greening efforts (North et al., 2015). This noted, even small-stature trees have their limits with regard to minimal space allotments. Given the general lack of knowledge surrounding the planting space requirements of small stature trees, we set the following research objectives for this study: 1.) Develop a set of equations that can be used to estimate root space requirements for small-stature urban tree species; and 2.) Determine the minimum allowable planting space for trees typically selected for space-limiting planting conditions. In addressing these two aims, we provide planners, policy makers, engineers, urban foresters, and others with guidelines for better informed planting and design strategies in compact urban developments.

2. Materials and Methods

We worked with local urban foresters to locate and measure small stature urban trees in Lakeland (28.0395° N, 81.9498° W), Sarasota (27.3364° N, 82.5307° W), Tampa (27.9506° N, 82.4572° W), Venice (27.0998° N, 82.4543° W), Pinellas County (27.8764° N, 82.7779° W), and Hillsborough County (27.9904° N, 82.3018° W), Florida (United States). We collected biometric and location data on 29 *Cordia sebestena* L. (Geiger tree), 22 *Handroanthus impetiginosus* (Mart. ex DC.) Mattos (pink trumpet tree), 35 *Ilex vomitoria* Sol. ex Aiton (yaupon holly), 28 *Ilex* x *attenuata* Ashe (East Palatka holly), 38 *Lagerstroemia indica* (L.) Pers. (crape myrtle), 26 *Ligustrum japonicum* Thunb. (Japanese privet), 18 *Myrcianthes fragrans* (Sw.) McVaugh (Simpson's stopper), 37 *Podocarpus macrophyllus* (Thunb.) Sweet (yew plum pine), 17 *Prunus caroliniana* (Mill.) Aiton (Carolina laurelcherrry), 33 *Tabebuia aurea* (Silva Manso) Benth. & Hook.f. ex S.Moore (silver trumpet tree), and 5 *Tabebuia chrysotricha* (A. DC.) Toledo (golden trumpet tree) for a total sample of 288 trees. The trees selected represented a range of diameters spanning from the newly established (2.1 cm) to the largest specimens found in their respective locations (77.3 cm).

Trunk flare circumference was determined using the method of Hilbert et al. (2020). In brief, marking flags delineated points at the base of the tree where the root-stem transition zone transitioned to root tissue. A nylon measuring tape was placed against the outside of each flagged point in a circular manner to measure the circumference which was converted to trunk flare diameter (TFD) used in the analysis described later. For each tree, the location, species, stem diameter, distance to nearest hardscape, and any hardscape damage were noted. Stem girdling roots and buried structural roots were also recorded since these might influence trunk flare diameter and tree health (Hauer and Johnson, 2021). Trunk diameter (Dx) and height of diameter measurements (Hx) were collected at one of three heights on the tree (i.e., at 137 cm, 15.25 cm, or 5 cm), since measuring at a standard height of 137 cm was not possible in all cases. If the tree was of sufficient height and pruned to elevate the crown, then diameter was measured at 137 cm (i.e., Hx = 137). If the tree's stem split at or below 137 cm, but the stems merged above ground, then the diameter was measured at caliper height (Hx = 15.25 cm). If the tree was multi-stemmed, then the diameter was recorded at the base of the tree (Hx = 5 cm).

A series of multiple linear regression models were used to determine the relationship between trunk flare diameter and species, Dx, and Hx. These analyses were conducted using the lm() function in R (R Core Team, 2021). Diagnostic plots (e.g., residuals versus fitted values, Q-Q plots, and residuals versus leverage) demonstrated that model results adhered to underlying linear regression assumptions and lacked high-leverage outliers which could influence predictions.

To predict sidewalk damage, we used logistic regression to determine if Dx, Hx, distance to hardscape, or some combination of these factors influenced the presence or absence of hardscape lifting or cracking. Modelling was conducted using the glm() function (R Core Team, 2021). Cross validation error rate was determined using the cv.glm() function from the boot package (Canty and Ripley, 2021). Additionally, an ROC curve and its associated AUC value were created/calculated using the ROCR package (Sing et al., 2005). An $\alpha=0.05$ was adopted as a threshold of statistical significance.

3. Results and Discussion

Species, Dx, and Hx were all significant predictors of TFD (Table 1). This noted, the overall predictive power of a simplified model excluding species as a predictor (adjusted $R^2 = 0.790$) was similar to the more inclusive full model (adjusted $R^2 = 0.843$; Table 1). Use of the former model may be preferred for simplicity or when working with species beyond those included in this study. To this point, the coefficients for Dx (full model = 1.246Dx; simplified model = 1.193Dx) were consistent with observations by Hilbert et al. (2020) and North et al. (2015) – especially when estimated at Hx = 137 cm (Table 1).

Of the 288 trees measured, only 33 (11.5%) were associated with damaged hardscape. Cracking was the most common damage category (n=19), followed by pavement lifting (n=10), and other (n=4). Both stem diameter (Dx) and distance from hardscape were significant predictors of the presence of damage when modelled singly, though when modelled together the latter predictor dropped out given non-significance. As distance from hardscape is the factor professionals have the greatest control over, we adopted a simple model with this as the sole variable for predicting hardscape damage (P-value < 0.001; cross-validation error rate = 6.7%; AUC = 0.742). In calculating the odds ratio from the distance from hardscape coefficient, we found damage was 1.015 times less likely to occur if planting width was increased by 1 cm. More meaningful spacing comparisons are featured in Figure 1.

Table 1. Our final full model (i.e., species coefficients included) and simplified model (i.e., species coefficients excluded) for predicting trunk flare diameter (TFD) given stem diameter (Dx) and height where diameter was measured (Hx). Measurements for the response (i.e., TFD), Dx, and Hx are all in cm. The adjusted R^2 values for the full and simplified models were 0.843 and 0.790, respectively.

Model	Factor	Coefficient	SE	*P*-value	95% CI - Lower	95% CI - Upper
Full Model	Intercept	-5.971	1.491	<0.001	-8.906	-3.037
	Species – *Cordia sebestena*	4.820	1.654	0.004	1.564	8.076
	Species – *Handroanthus impetiginosus*	3.800	1.846	0.040	0.166	7.434
	Species – *Ilex vomitoria*	4.368	1.478	0.003	1.459	7.276
	Species - *Ilex* x *attenuata*	8.546	1.698	<0.001	5.204	11.887
	Species - *Lagerstroemia indica*	9.974	1.404	<0.001	7.210	12.738
	Species – *Myrcianthes fragrans*	6.882	2.094	0.001	2.759	11.004
	Species – *Prunus caroliniana*	14.588	1.934	<0.001	10.780	18.394
	Species – *Tabebuia chysotricha*	13.738	3.376	<0.001	7.087	20.379
	Dx^z	1.246	0.038	<0.001	1.170	1.321
	Hx	0.051	0.008	<0.001	0.035	0.067
Simplified Model	Intercept	-0.055	1.157	0.962	-2.332	2.222
	Dx^z	1.193	0.037	<0.001	1.121	1.265
	Hx	0.052	0.008	<0.001	0.035	0.068

[z] Stem diameter measured at one of three different heights depending on the tree and its form (i.e., diameter at breast height or 137 cm; diameter at caliper or 15.24 cm; or diameter at ground level or 5 cm).

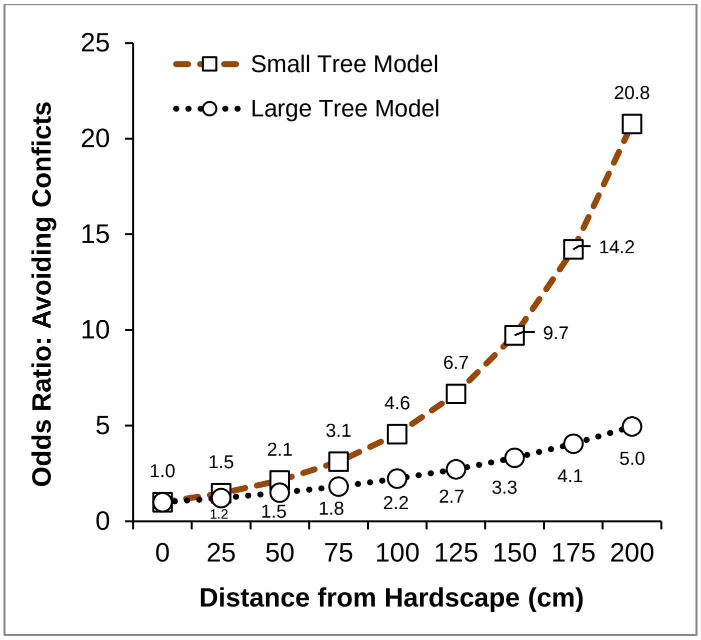

Figure 1. Odds of avoiding hardscape conflicts as the distance between the tree and paved surface increases. All values are compared against the 0 cm benchmark (i.e., a tree growing in contact with the adjacent hardscape). For example, a small tree is ~20 times less likely to cause hardscape damage when its trunk is 200 cm away from pavement as compared to the 0 cm benchmark. Results of this research are contrasted against the model results for large trees (i.e., "large tree model") reported by Hilbert et al. (2020).

To put this into perspective for urban planners, urban forest managers, and transportation engineers, we present two examples of sidewalk replacement costs from U.S. cities. The City of Tampa, Florida (population 399,700) has a replacement budget of $500,000 (USD) which it exhausts before the year's end (Gorman, personal communication). It would take an estimated $2,000,000 (USD) to address all sidewalk issues in a more proactive manner. The replacement cost per sidewalk slab (~1.5 m wide by ~1.5 m long) is $375 (USD). This includes all costs associated with the removal of the old slab, associated tree work, and the pouring of the replacement slab (Gorman, personal communication). In Tampa, increasing distance to hardscape from 0 cm to 100 cm would save approximately $120 (USD) per tree (Table 2). It would take 200 cm to achieve a similar savings for large stature trees in Tampa city.

The City of Milwaukee, Wisconsin (population 590,157) has a sidewalk replacement budget of $1.5 million (USD) annually (Kringer, personal communication). Sidewalk replacement is charged as an assessed fee to the associated homeowner. The expense of replacement is partially offset by a citywide tax on motor vehicle registrations. To replace the same ~1.5 m wide by ~1.5 m long slab noted above, homeowners would be assessed a $95 (USD) fee (actual contracted costs were not available to our contact). As such, the savings calculated for the Milwaukee scenario (Table 2) are savings to the associated homeowner and not the City itself.

Table 2. Potential sidewalk replacement cost savings as distance from hardscape increased from the baseline of 0 cm (trunk up against pavement) to up to 200 cm. Savings are per tree planted at that spacing.

Distance from hardscape cm	Small Trees		Large Trees	
	Milwaukee[z]	Tampa[y]	Milwaukee[z]	Tampa[y]
25	$9.50	$37.50	$4.75	$18.75
50	$16.15	$63.75	$9.50	$37.50
75	$24.70	$97.50	$13.30	$52.50
100	$30.40	$120.00	$18.05	$71.25
125	$35.15	$138.75	$21.85	$86.25
150	$38.95	$153.75	$25.65	$101.25
175	$40.85	$161.25	$28.50	$112.50
200	$42.75	$168.75	$31.35	$123.75

[z] Savings based on a $95 replacement fee (per ~1.5 m by ~1.5 m slab) assessed to the homeowner (total costs subsidized by vehicle registration tax).

[y]Savings based on a $375 contracted replacement fee (per ~1.5 m by ~1.5 m slab) paid by the city for removal and disposal of old concrete, tree maintenance, and pouring of replacement slab.

Table 3 shows the estimated per tree savings in sidewalk replacement costs as the distance between the base of a tree and neighboring hardscape is increased. In Tampa, increasing distance to hardscape from 0 cm to 100 cm would save approximately $120 (USD) per tree. It would take 200 cm to achieve a similar savings for large stature trees in the city.

Finally, in applying this research to practice, we suggest the following equation for determining minimum planting width (modified from Hilbert et al. 2020 and North et al 2015):

$$PW_{min} = \frac{\widehat{TDR}}{100} + 1.2 \qquad \text{Eq. 1}$$

Where:

PW_{min} = minimum planting width (m)

$\widehat{TDR}$ = predicted trunk flare diameter (cm)

Predicted trunk flare diameter (TDR) may be calculated using either the full or simplified model (Table 1) - drawing on existing urban forest inventory data to determine the growth potential of a tree species in one's local urban environment. TDR is divided by 100 to convert cm to m and a 1.2 m buffer is added to account belowground structural roots. This buffer is halved from the large tree equations proposed by Hilbert et al. (2020) and North et al. (2015) given the reduced potential for damage noted in Figure 1.

Conclusion

This work builds on previous research on the belowground requirements of trees planted in the built environment – demonstrating once again that stem diameter is a strong predictor of TFD. This relationship can be paired with existing urban forest inventory data to determine planting width requirements based on the growth potential for the species in the local environment. Results also provide a guide on tree root space requirements when designing tree planting sites. Moreover, this work provides estimates of sidewalk replacement cost savings associated with increased planting widths.

Authors' Contributions

AKK, DRH, RJH, RJN, and DCM conceived the experiment. AKK, DRH, and DCM secured funding for the fieldwork. AKK, DRH, and DCM adapted the field methodology from past efforts. AKK and RJH conducted the analysis and AKK, DRH, and HT collected and maintained data. AKK led the writing effort with DRH, RJH, RJN, HT, DCM, and ABS contributing to the initial drafting, internal review, and revisions of the first submission, as well as subsequent revisions made after peer review.

Declaration of Competing Interest

Author DRH is employed by Many Trees Consulting, LLC. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgments

Funding for this project was provided by the Florida Nursery, Growers and Landscape Association (FNGLA) Endowed Research Fund. A thanks goes to Charlene LaMountain and Brooke Anderson for assisting in the field data collection. Similar thanks go to Brian Dick and Stacey Smith of the City of Lakeland; Carolyn Cheatham Rhodes of Pinellas County; Frank Murray and Candie Pedersen of the City of Sarasota; Mark Miller of Sarasota County; and Jim Yelverton of the City of Venice for their assistance in locating many of the trees used this study. Finally, thanks to Keith Gorman of the City of Tampa, James Kringer of the City of Milwaukee, and user “psboonstra” from the statistical forum *Cross-Validated* (https://stats.stackexchange.com/q/541218) for their assistance in calculating the protected cost savings of increased spacing.

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