Communication

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

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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 can interfere with pavement 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 (i.e., the interface region between large structural roots and the trunk) diameter (adjusted $R^2$ of 0.843). Additionally, we modelled the relationship between planting space and the presence or absence of pavement 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 [1], calm traffic [2], and shade parking areas [3,4]. 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 [5], as well as to extend the life of some paving materials [6]. This noted, conflicts between tree roots and the paved surfaces that facilitate pedestrian and vehicular traffic are a common ecosystem disservice [7] as tripping hazards can arise and replacements are a major municipal expense [8,9].

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 pavement conflicts in 18 California (United States) communities, McPherson [8] 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 [10].
Root and pavement 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 [11–13] and undermining overall stability in the face of storm events [14]. To reduce root and pavement conflicts, researchers have investigated how planting widths relate to sidewalk damage [9,15] and created allometric models to predict trunk flare diameter (TFD; 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 [16,17]. From these efforts, minimum planting width requirements can be estimated given species and growth potential to limit root and sidewalk or curb conflicts (Figure 1).

Figure 1. Minimum planting width is the spacing required to avoid root and paving conflicts (e.g., lifting, cracking, etc.) for the expected lifespan of a tree. This planting width accounts for the trunk flare diameter (TFD) of the tree as well as a buffer to allow for large structural roots hidden below the soil.

In this extension of past research by North et al. [17] and Hilbert et al. [16], we developed allometric models linking stem diameter to TFD 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 [18]. As building developments continue to densify, small stature trees may be the best choice for urban greening efforts [17]. This noted, even small-stature trees have their limits with regard to minimal space allotments when trying to prevent pavement conflicts. Given the general lack of knowledge surrounding the planting space required to avoid conflicts between pavement and the root systems of small trees, we set the following research objectives for this study: (1) Develop a set of equations that can be used to estimate planting width requirements for small-stature urban tree species; and (2) determine the minimum allowable planting width 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 laurelcherry), 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. [16]. 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 TFD used in the analysis described later. For each tree, the location, species, stem diameter, distance from trunk flare to nearest paved surface, and any pavement damage were noted. Stem girdling roots and buried structural roots were also recorded since these might influence TFD and tree health [19]. 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 (Figure 2). 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).

Figure 2. Stem diameter was measured at 137 cm, 15.25 cm, or 5 cm depending on tree form and height of the lower canopy.
Multiple linear regression was used to model the relationship between TFD and species, Dx, and Hx. These analyses were conducted using the lm() function in R [20]. 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, and distance to pavement influenced the presence or absence of pavement lifting or cracking. Modelling was conducted using the glm() function [20]. Cross validation error rate was determined using the cv.glm() function from the boot package [21]. Additionally, an ROC curve and its associated AUC value were created/calculated using the ROCR package [22]. 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). However, the overall predictive power of a simplified model excluding species as a predictor ($R^2 = 0.790$) was similar to the more inclusive full model ($R^2 = 0.843$; 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 = 1.246 Dx; simplified model = 1.193 Dx) were consistent with observations by Hilbert et al. [16] and North et al. [17], especially when estimated at Hx = 137 cm (Table 1).

Table 1. Our final full model (e.g., species coefficients included) and simplified model (e.g., 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–I. 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 chrysotricha| 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        |

Of the 288 trees measured, only 33 (11.5%) were associated with damaged pavement. 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 pavement 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 pavement is the factor professionals have the greatest control over, we adopted a simple model with this as the sole variable for predicting pavement damage ($p$-value < 0.001; cross-validation error rate = 6.7%; AUC = 0.742). In calculating the odds ratio from the distance from pavement 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 3.
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 sidewalk replacement budget of $500,000 (USD), which it exhausts before the year’s end [10]. 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 [10].

The City of Milwaukee, Wisconsin (population 590,157) has a sidewalk replacement budget of $1.5 million (USD) annually [23]. 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 shows the estimated per tree savings in sidewalk replacement costs as the distance between the base of a tree and neighboring pavement is increased. In Tampa, increasing distance to pavement from 0 cm to 100 cm would save approximately $120 (USD) per tree. It would take 200 cm to achieve 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. [16] and North et al. [17]):

$$PW_{min} = \frac{TFD}{100} + 1.2$$

where:

- $PW_{min}$ = minimum planting width (m)
- $TFD$ = predicted trunk flare diameter (cm)
Table 2. Potential sidewalk replacement cost savings as distance from pavement 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 Pavement (cm) | Estimated Cost Savings per Tree (USD) |
|----------------------------|---------------------------------------|
|                            | Milwaukee $^z$ | Tampa $^y$ | Milwaukee $^z$ | Tampa $^y$ |
| 25                         | $9.50         | $37.50     | $4.75          | $18.75     |
| 50                         | $16.15        | $63.75     | $9.5           | $37.5      |
| 75                         | $24.70        | $97.50     | $13.3          | $52.5      |
| 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    | $28.5          | $112.5     |
| 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.

Predicted TFD 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. TFD is divided by 100 to convert cm to m and a 1.2 m buffer is added to account for belowground structural roots. This buffer is halved from the large tree equations proposed by Hilbert et al. [16] and North et al. [17] given the reduced potential for damage noted in Figure 3.

4. Conclusions

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. Moreover, this work provides estimates of sidewalk replacement cost savings associated with increased planting widths.

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