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Impact of Planting Depth on *Fraxinus pennsylvanica* 'Patmore' Growth, Stability, and Root System Morphology

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Abstract. Trees are often deeply planted as a result of nursery and landscape practices. While past research has investigated the impact of deep planting on tree growth and survival, its impact on whole-tree stability is not well documented. Green ash (*Fraxinus pennsylvanica* 'Patmore') trees were planted at three different depths in research plots and established for nine years. In assessing aboveground growth, planting depth had no effect on stem diameter growth (measured as dbh) ($P = 0.421$; $n = 32$) or tree height ($P = 0.501$; $n = 32$). Static pull tests were conducted to evaluate the consequences of deep planting on tree stability. Using structure from motion (SfM) photogrammetry-derived computer models to assess root architecture, we found the most significant factors affecting tree stability were: 1) root volumes in the top 10 cm of the soil in a 90° wedge on the side opposite of the pull direction; 2) root volumes 40.1 to 50 cm deep in a 90° wedge on the side opposite of the pull direction; and 3) root volumes deeper than 60.1 cm deep in a 90° wedge on the side opposite of the pull direction (final model: $P < 0.001$; $n = 30$; adjusted $R^2 = 0.852$). The importance of structural root morphology throughout the soil profile and implications for urban root-soil relations on tree stability are discussed.

Keywords. Bending Moment; Photogrammetry; Root Architecture; Tree Biomechanics; Tree Physiology; Tree Planting.

INTRODUCTION

Deep tree planting (i.e., planting trees with the root collar below grade) is a common issue in urban landscapes. Urban trees can become deeply planted during nursery production and during installation at the planting site (Day et al. 2009). In the nursery, trees are often deeply planted to reduce the need for staking (Rathjens et al. 2007) and allow for weed control in field nurseries via cultivation (Day et al. 2009). Once in the landscape, trees may be planted deep unintentionally if past production practices are not corrected or intentionally to provide a range of anecdotal benefits ranging from increased water availability to decreased suckering (Gilman and Grabosky 2011). However, planting trees too deeply can negatively affect tree establishment and health. Deep planting has been linked to an increased likelihood of premature mortality in landscape palms and trees (Broschat 1995; Wells et al. 2006; Arnold et al. 2007). Similarly, some studies found that planting trees too deeply negatively affected tree growth (Arnold et al. 2007; Bryan et al. 2011; Harris et al. 2016). That said, there are conflicting results among planting depth studies, as several authors found no differences in growth between deeply planted trees and trees planted at grade (Day and Harris 2008; Gilman and Grabosky 2011; Harris et al. 2016).

Beyond growth and survival, root defects (e.g., girdling, circling, or kinked roots) may occur in deeply planted trees (Wells et al. 2006; Day and Harris 2008; Harris et al. 2016). These defects can adversely impact the long-term growth and stability of trees. In addition to the presence or absence of root defects, root architecture and distribution within the soil profile affects resistance to uprooting (Mickovski and Ennos 2003). Gilman and Harchick (2008) found that *Quercus virginiana* Mill. trees planted deeply in container production had root systems with fewer, smaller, and deeper roots.

Several researchers have studied the effects of deep planting on resistance to uprooting. Gilman and Grabosky (2011) found planting depth had no impact on bending stress of *Q. virginiana* trees planted in sandy soils. Similarly, Gilman and Wiese (2012) found no difference in stability between *Q. virginiana* 'Highrise' trees planted deeply in containers during nursery production and those with the root collar at grade throughout production. However, Harris et al. (2016) reported that *Acer rubrum* L. 'Franksred' planted with the root flare 30 cm deep were more resistant to uprooting (i.e., had greater bending moment and bending stress) than those planted at grade. Peltola et al. (2006) observed that increased depth of the root plate was positively correlated with maximum resistive bending moment. In contrast, Papesch et al. (1997) found that diameter of the root plate had a significant effect on resistance to overturning while root plate depth did not.

Research into the impact of root architecture on tree stability is limited, as root systems are complex and their architecture is difficult to quantify. One of the measures commonly employed in addressing this challenge is the root cross-sectional area (Coutts et al. 1999; Gilman and Grabosky 2011; Gilman et al. 2013) at different depths, directions, and distances from the trunk. Utilizing this approach, Gilman and Grabosky (2011) found bending stress to be positively correlated with root cross-sectional area 20 to 30 cm and 40 to 50 cm below the soil surface for *Q. virginiana* trees six years after being planted into sandy soil. Despite its demonstrated utility, cross-sectional area only provides a snapshot of root architecture and distribution at the point of measurement. What lies beyond this measurement point (either towards the trunk or outward beyond the measurements) is unknown. In contrast, measurements of root volume or surface area in different locations within the root ball can offer a more complete measure of root architecture. Submerging roots in water to observe displacement (Harrington et al. 1994) is one potential means of measuring the former metric, though this becomes difficult when one works with larger root systems. However, calculating the amount of root surface area in contact with the surrounding soils is challenging (if not impossible) with traditional assessment methods.

Noting these limitations, several programs have been developed to create three-dimensional models and estimates of root volumes. Examples include, AMAPmod, FSPM, GROGRA, and SimRoot (Danjon and Reubens 2008). Beyond these purpose-built programs, other programs exist which may be useful for digitally recording tree root systems for architectural characterization and analysis. Derived from remote sensing technologies, numerous programs exist which allow users to generate 3D models from data derived via laser scanning (i.e., LiDAR) or structure from motion (SfM) photogrammetry. Of these two means of collecting spatial data, SfM photogrammetry requires relatively basic equipment (a digital camera) making it more accessible for arboriculture researchers (Morgenroth and Gomez 2014).

In their proof of concept paper, Morgenroth and Gomez (2014) found that aboveground tree height and stem diameter could be obtained using SfM photogrammetry with minimal error (RMSE < 4%). While somewhat less accurate, they were also able to obtain estimates of aboveground volume from digital models derived from SfM photogrammetry. Volume estimates for the main stem had an associated RMSE of 12%, while estimates of branch volume had a higher RMSE of 47.5% (Miller et al. 2015). In using SfM photogrammetry to model diameter at breast height (dbh), Liang et al. (2014) obtained a similar, though smaller RMSE value (6.6%).

The accuracy of the latter work was deemed to be on par with results typical for terrestrial laser scanning (Liang et al. 2014). Following these findings, Koeser et al. (2016) utilized SfM photogrammetry to model volume and surface area for individual root segments and whole root systems. In comparing their computer model-derived volumes to volumes derived via water displacement, they observed an RMSE of 12.2%, with the SfM photogrammetry-based measurements having a positive bias of 5.3% (Koeser et al. 2016).

Building on these past works, the purpose of this study was to: 1) determine the effects of planting depth on above- and belowground tree growth; 2) use root architecture measures derived from SfM photogrammetry to assess the impact of root depth and distribution on resistance to uprooting; and 3) determine what impact planting depth had on root architecture. This study serves as a continuation of past efforts to demonstrate the potential of SfM photogrammetry in tree root system modeling and serves as preliminary evidence for the utility of the method in tree biomechanics research.

MATERIALS AND METHODS

In April 2004, a block of 60 three-year-old Patmore green ash (*Fraxinus pennsylvanica* 'Patmore') bare root liners were planted at the University of Illinois Agricultural Experiment Station in Urbana, IL (USDA Hardiness Zone 5b)(Jarecki et al. 2005). The predominant soil type on the site was a Drummer silty clay loam with a 0 to 2% slope (USDA Natural Resources Conservation Service 2013). Trees were 2 to 2.75 m (7 to 10 ft) in height. At planting, trees were assigned one of three planting depth treatments: 1) deep-planted trees were planted with the graft union 15 cm (6 in) below the soil surface; 2) moderately deep-planted trees were planted with the graft union at the soil surface; and 3) properly planted trees were planted with the root flare at the soil surface. Trees were planted in a completely randomized design with 20 replicates per planting depth treatment. Trees were planted at a spacing of 3.7 m (12 ft) within the rows, and rows were spaced 4.6 m (15 ft) apart. A subset of 32 trees (i.e., 11 deep planted, 11 moderately deep planted, and 10 properly planted) were selected for growth comparisons and stability testing. To avoid edge effects created by trees growing on the predominantly windward (west) or leeward (east) sides of the block, only trees from interior rows were selected for final assessment.

Growth Measurements

Both height and diameter measurements were made at the end of the nine-year study period. Nails were used to mark the location of the graft union at planting. This reference point was used to help adjust the measurement height for diameter and to adjust height measurements (i.e., to separate the impact to height associated with initial starting depth from actual differences in growth). Tree diameter was measured with a diameter tape. Tree height was measured with a measuring pole.

Static Pull Tests

Static pull tests were conducted in October 2013 to evaluate root anchorage. The soil in the test plot was saturated prior to assessment to simulate conditions present during a large-volume rain storm event, as well as to provide consistent soil moisture among all trees. Soil survey information was used to calculate the volume of water required to bring the top 1.2 m (4 ft) of soil up to field capacity using a traveling water wheel sprinkler system. Volumetric soil water content at the soil surface (approximately 5 cm deep) was measured at the time of pull for each tree at a distance of 0.5 m and 1 m from the trunk in the direction of the winch and the direction opposite the winch using a time domain reflectometry (TDR) soil moisture probe (SM150T, Delta-T Devices, Cambridge, United Kingdom).

All trees were pulled in the 0° azimuth (due north). To measure trunk tilt, a digital level was secured to the trunk at a height of 15 cm above the soil following the methods described in Smiley (2008). Pull force was measured with a 2,000 kgf capacity dynamometer (Dillon EDX-2T, Fairmont, Minnesota, United States) placed in-line between the winch cable and a webbing sling that was girth hitched to the trunk at a height between 1 and 2 meters. The vertical distance between the soil surface and the pull height was recorded for each tree. The dynamometer had a remote reading device that was placed next to the digital level. This allowed us to use a video camera to record the force and tree tilt simultaneously. The winch, secured to a tractor at a height of 1 m, applied a load to each tree until trees tilted to 5° from the resting position. The winch was stopped, the angle of the winch cable from horizontal was measured with a digital level, and tension was released.

After pull tests were completed, videos were downloaded to a computer for visual analysis. The force required to tilt trees to 1°, 2°, 3°, 4°, and 5° was recorded based on simultaneous readings on the digital level and the dynamometer remote communicator. Bending moment (M) was calculated using the formula:

$$M = Pl \cos\alpha \qquad (1)$$

where P was the applied load, and l was the vertical distance from the soil surface to the pull point (i.e., moment arm) and α is the angle of the winch cable from horizontal (Ghani et al. 2009; Ow et al. 2010; Gilman and Wiese 2012). An initial correlation matrix was developed that showed a very strong correlation between 1°, 2°, 3°, 4°, and 5° (all correlations were between 0.96 and 0.99), so only the values for 1° were analyzed.

Root Excavation

After pull tests were completed, root systems were harvested using a 244-cm (96-in) hydraulic tree spade. Once harvested, the majority of the soil inside the root ball was removed using air excavators (Airspade 2000, Guardair Corporation, Chicopee, MA, United States; X-LT; Supersonic Air Knife, Inc., Allison Park, PA, United States). Any remaining soil was washed away with water. After soil was removed, all small-diameter roots (i.e., roots < 1 cm in diameter) were identified with a fixed caliper gauge (i.e., a piece of metal with a 1 cm notch cut into it) and removed with a hand pruner. These were oven-dried at 105° C for one week and weighed twice (three days apart) to ensure the samples were fully dried. Of the 32 harvested rootballs, one replicate fell back into its original hole. Having lost access to the contracted hydraulic spade, this was too heavy to retrieve, and the root system was omitted from any analyses below where root volumes and surface area were used to predict stability. Similarly, one of the root systems failed to model properly using the SfM photogrammetry and was also omitted from any analyses related to root volume and surface area.

Data Analysis

Trees were planted as a completely randomized design with the three discrete planting treatment levels noted earlier (i.e., deep planting, moderately deep planting, and proper planting). Analysis of variance was used to assess differences in height, diameter, and the dry weight of small root growth (i.e., all roots under 1 cm in diameter). The lm() function in R (version 3.5.1 [R Core Team 2018]) was used for this analysis.

In excavating the roots, we noted that some of the root systems appeared to have settled, while others developed adventitious root flares above the original root flare. As such, we used the root volumes measured at various root depths to predict bending moment. Analysis of variance was then used to assess the impact of initial planting depth on measured root architecture after nine years. Additionally, we noted the presence of girdling roots (i.e., roots that are encircling all or part of the trunk base), ascending roots (i.e., deeply originating roots growing toward the soil surface), kinked/circling/tangential (i.e., roots growing back toward the trunk but not yet in contact with it) roots (if above the root flare), and adventitious roots. Differences in these defect counts among the three treatments were

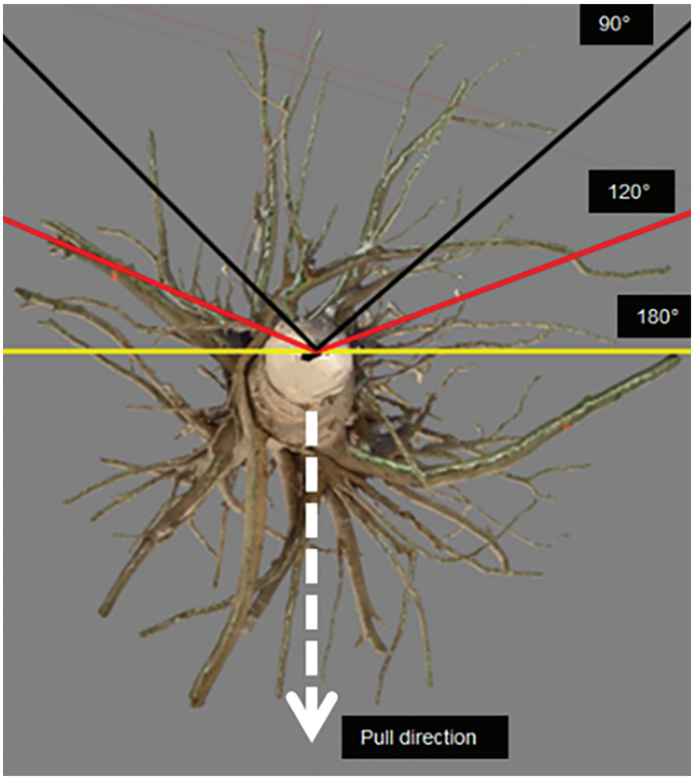

Figure 1. Depiction of the 90°, 120°, and 180° root system sections calculated for assessment of stability. Root volumes were derived for each section. Though not shown (for ease of interpretation), this sectioning was repeated on the side towards the pull direction. Regression analysis indicated that root volumes in the 90° section away from the pull direction were the strongest predictors of bending moment.

assessed using a test of equal proportion using the prop.test () function in R (R Core Team 2018).

Using the lm() function, bending moment was regressed against measured soil moisture, planting depth, and measured root volumes in different locations within the rootball. Root volumes measured in 90°, 120°, and 180° wedges (toward and away from the direction of the winch) were modeled to see which produced the best model fit (determined by adjusted R^2) (Figure 1). Working with the best model (90°), we further divided the root volumes into 10-cm layers to capture the effect of rooting depth (Figure 2). A backward and forward stepwise regression function was used as a coarse filter to eliminate nonsignificant predictors. Any remaining nonsignificant predictors were removed one at a time (based on highest *P*-value) with the reduced model compared against the initial model using the anova() function to assess if a difference in fit existed. Diagnostic plots were referenced to confirm the appropriate assumptions were met for all analyses employed. All decisions were made at $\alpha \leq 0.05$ significance level of type I error.

RESULTS

Aboveground Growth

Nine years after the initial planting, we found no relationship between planting depth and diameter ($P = 0.421$; $n = 32$). Similarly, we found no relationship between planting depth and tree height ($P = 0.501$; $n = 32$).

Root Growth

On average, the depth to the root flare was 14.7 cm for the properly planted trees, 17.1 cm for the moderately deep planted trees, and 20.7 for the deep planted trees. We found no relationship between planting depth and average total

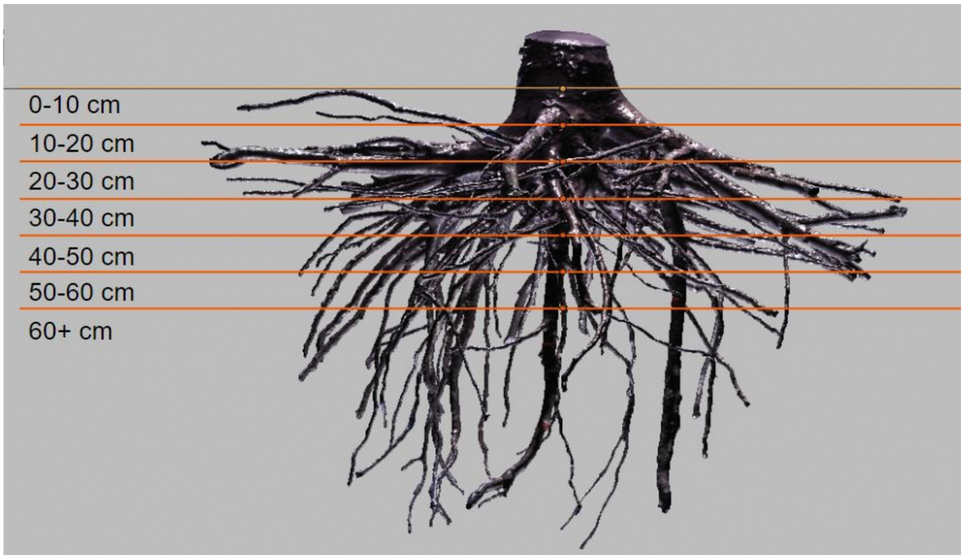

Figure 2. Each 90° section of root volumes was further divided into 10-cm deep layers to assess the impact of root depth on stability. Root volumes in the first layer (0 to 10 cm) and the lower layers (40.1 to 50 cm and greater than 60.1 cm) were the strongest predictor of bending moment.

root volume for the root systems ($P = 0.918$; $n = 30$). Similarly, we failed to detect any difference in the dry weight of small and fine roots given the different planting depth treatments ($P = 0.644$; $n = 30$).

In addition to the overall size (i.e., volume of larger roots and dry weight of roots < 1 cm) of the root systems, we looked at quality with regard to root defects and other notable characteristics (Table 1). Of the 30 root systems excavated and modelled, five had girdling roots present (Table 1). Three of the girdling roots were found among the deeply planted trees. In contrast, the moderately deep trees and the properly planted trees had one girdling root each among their replicates, though this difference in girdling root counts was not significant ($P = 0.494$; $n = 30$; Table 1). In contrast, there was a marginally significant difference in the number of kinked, circling, and tangential roots, with most instances occurring among the moderately deep and deep planted trees ($P = 0.058$; $n = 30$; Table 1). Similarly, fewer ascending roots ($P < 0.001$; $n = 30$) and adventitious roots ($P = 0.050$; $n = 30$) were found among the properly planted trees as compared to the moderately deep and deep planted trees (Table 1).

Connecting root architecture back to our original treatments, initial planting depth was a predictor of root volume in our three significant 90° sections. Deeply planted trees had reduced root volume at the soil surface (i.e., 0 to 10 cm in depth) after nine years compared to those planted properly (i.e., main root system at grade; $P = 0.0296$; $n = 30$). No significant difference in total root volume was noted for roots planted moderately deep compared to those planted properly or those planted deeply (min $P = 0.131$; $n = 30$; Table 2). Similarly, deeply planted trees had greater root volumes in the 40.1 to 50 cm depth than those planted properly ($P = 0.017$; $n = 30$; Table 2). No differences in measured root volumes were detected between the moderately deep trees and the other two treatments (min $P = 0.169$; $n = 30$; Table 2). There was no treatment effect on root volumes below 60.1 cm ($P = 0.854$; $n = 30$; Table 2).

Tree Stability

In predicting bending moment as a measure of tree stability, we found that root volumes in a 90° section located opposite the pull direction were the most important (Figure 1; Table 3). Specifically, within this 90° section, root volumes from 0 to 10 cm ($P < 0.001$; $n = 30$), 40.1 to 50 cm ($P < 0.001$; $n = 30$), and greater than 60.1 cm deep ($P < 0.01$; $n = 30$) were all significant predictors of bending moment. Additionally, average soil moisture content (as measured 0.5 and 1 meter away from the base of the tree at the soil surface) was a significant predictor of bending moment ($P = 0.002$; $n = 30$; Table 3). The overall significance of the model was $P < 0.001$ ($n = 30$) and its adjusted R^2 was 0.852.

Table 1. Root characteristics and defects noted among the excavated root systems. Differences in proportions among the three treatment groups tested using a test of equal proportions.

Initial treatment	Girdling	Ascending	Kinked, circling, tangential[z]	Adventitious
Properly planted ($n = 9$)	1	3	1	0
Moderately deep planted ($n = 10$)	1	10	4	5
Deep planted ($n = 11$)	3	11	7	4
Significance (P-value)[y]	0.494	<0.001	0.058	0.050

[z] only recorded if above the root flare

[y] calculated using the prop.test() function in R (R Core Team 2018)

Table 2. Impact of planting treatment on the mean root volumes of the 90° (away from pull direction) sections used to predict bending moment.

Planting treatment		Mean root volume in cm^3	(statistical significance)[z]
	0 to 10 cm	40.1 to 50 cm	60.1 and greater
Properly planted	1983.1 (a)[y]	1069.6 (bc)	556.4 (ns)[x]
Moderately deep planted	1286.1 (ab)	1788.2 (ab)	670.6 (ns)
Deep planted	1057.5 (bc)	2924.6 (a)	593.2 (ns)

[z] differences assessed using Tukey's Honestly Significant Difference (HSD) test.

[y] letters indicate significance within each column.

[x] planting treatment not significant (ANOVA).

Table 3. Final, reduced model for predicting bending moment (*n* = 30) in *Fraxinus pennsylvanica* 'Patmore' planted at three different depths. The adjusted R^2 was 0.852.

Factor	Coefficient	Standard error	*P*-value	95% Lower	95% Upper
Intercept	-2343.0	736.00	0.004	-3859.2	-827.6
Soil moisture	65.9	18.50	0.002	27.9	104.1
Root volume (0 to 10 cm)	0.8	0.07	< 0.001	0.6	1.0
Root volume (40.1 to 50 cm)	0.2	0.04	< 0.001	0.1	0.3
Root volume (60.1 cm and greater)	0.4	0.15	0.010	0.1	0.7

DISCUSSION

Aboveground Growth

In contrast with works by others (Arnold et al. 2007; Bryan et al. 2010; Bryan et al. 2011) we did not observe any differences in stem diameter growth given differences in planting depth. This is despite having one of the longer trial periods in a controlled research plot environment. Our findings were similar to those of Harris et al. (2016) who found no differences in yearly diameter growth for *Quercus rubra* L. (Northern red oak) and only occasional (and marginally significant) differences in yearly diameter growth in *Acer rubrum* L. (red maple) over the course of ten growing seasons.

Similarly, we failed to find differences in tree height. This is contrary to findings by Arnold et al. (2007), who found deep planting reduced total height in four of five species assessed over a three-year period. Bryan et al. (2010) also noted that deep planting negatively impacted relative height growth in *Platanus occidentalis* L., though deeply planted *Taxodium distichum* L. fared no worse than those planted at grade and better than those planted above grade with regard to height growth in the first year after planting. Our findings are more in line with work by Gilman and Grabosky (2011), who found no difference in height for *Q. virginiana* trees after five growing seasons. While our study spanned nine growing seasons (longer than any of the aforementioned studies), trees are very long-lived organisms that can hide the effects of environmental stresses or management activities for years. Efforts should be made to identify older populations of trees where planting depth is known for future study.

Root Defects

The two deep planting treatments had more ascending roots than trees planted at grade. While deeply planted trees had more kinked, tangential, and circling roots than trees planted at grade, the difference was of marginal significance (*P* = 0.058), likely due to the low number of replicates in this study. These results are in partial agreement with Wells et al. (2006), Day and Harris (2008), and Gilman and Grabosky (2011), who found that deeply planted trees had a greater proportion of their trunks impacted or potentially impacted by girdling and circling roots. However, we found no difference in stem girdling roots among the three treatments, which is not surprising given the relatively young age of the trees in this study. Future research investigating long-term effects of planting depth on root characteristics and stability as trees mature would be beneficial to urban tree managers.

Tree Stability

Despite our efforts to maintain saturated soil conditions for this experiment, we did find that soil moisture impacted our observed measures of bending moment. This is similar to the impacts noted by Kamimura et al. (2012) in their assessment of root anchorage in hinoki (*Chamaecyparis obtuse*). Average soil moisture around the bases of our trees ranged from 27.2% to 42.6%, with an overall average of 37.6%. Irrigation of the site occurred in the hours leading up to the experiment, but timing between irrigation and pull tests varied. Soil drying likely occurred as the day progressed, accounting for much of the differences noted in our moisture data. While we were able to account for some of this variation in our model, maintaining uniform, saturated conditions may best approximate actual storm conditions (Gilman et al. 2013). That noted, our findings run contrary to more recent work by Harris et al. (2016), who found no correlation between soil moisture content and likelihood of failure.

Our findings suggest that root architecture played a significant role in stability, with windward surface root volumes (0 to 10 cm) and windward deep root volumes (40.1 to 50 cm and greater than 60.1 cm) having the largest impact on resistance to overturning. These findings are in partial agreement with Gilman and Grabosky (2011), who found positive correlations between bending stress and root cross-sectional area 20 to 30 cm and 40 to 50 cm below the soil surface for *Q. virginiana* trees planted in sandy soils. Mickovski and Ennos (2003) reported that sinker and tap roots, and not lateral roots, provided much of anchorage of mature *Pinus peuce* trees, and Nicoll et al. (2006) found that it took 10 to 15% more force to overturn

Picea sitchensis (Bong.) Carr. trees with a rootable depth greater than 80 cm than those with less than 80 cm. Similarly, utilizing finite element modelling of root systems, Dupuy et al. (2005) found that heart root systems and tap root systems had a higher resistance to overturning than herringbone and plate root systems. Furthermore, Peltola et al. (2006) found that root depth was positively correlated with maximum resistive bending moment. Unfortunately, urban soils (as currently constructed) may not support root growth and development, especially deep into the soil profile (Watson et al. 2014). Ow et al. (2010) investigated if planting trees in topsoil or structural soils with stone:soil ratios of 80:20 and 50:50 affected bending moment, but results were inconclusive. However, they did report that root plate size was positively correlated with bending moment, which is similar to our findings. Increasing the depth of favorable soil for root growth through processes such as soil profile rebuilding (Layman et al. 2016) might prove to be an effective management strategy for improving tree stability, especially in locations where lateral root growth is impeded. Future research should consider investigating soil improvements on tree stability.

In an early iteration of our analysis, we assessed the impact of planting depth (i.e., depth to topmost root only) on bending moment and found no statistical significance. Though we eventually adopted the analysis reported above (which takes into consideration the architecture of the whole root system), these early results were similar to the findings of Gilman and Grabosky (2011), who found that planting depth had no impact on bending stress of *Q. virginiana* trees planted in sandy soils. Similarly, Gilman and Wiese (2012) found no difference in stability between *Q. virginiana* 'Highrise' trees planted deeply in containers during nursery production and those with the root flare at grade throughout production. More recently, Harris et al. (2016) reported that *Acer rubrum* L. 'Franksred' planted with the root flare 30 cm deep were more resistant to uprooting (i.e., had greater bending moment and bending stress) than those planted at grade. Every tree in this study had several large structural roots growing horizontally as well as vertically, well beyond 60.1 cm deep (Figure 2). Given the favorable growing conditions for roots deep within the soil profile at our research site, it is not surprising that planting depth (a somewhat coarse metric given the complexities of root systems) was not a significant predictor of bending moment.

It is important to note the limitations of this research. The root volume that was measured only included those roots contained within the 244 cm diameter root ball. In reality, root systems of the trees in this study extended well beyond the width of the hydraulic tree spade used to excavate the root systems. That said, utilizing 3D models to measure total volume of all structural roots within the root ball gives a similar, but more complete, picture than measuring root cross-sectional area of the main structural roots. Another limitation is that although fine root (< 1 cm diameter) dry mass was measured, we did not consider the overall impact of fine roots on stability in our model of bending moment. All fine roots for each tree were combined in the field and weighed as one measure, preventing us from sectioning them as we were able to for the larger root volumes.

Despite the above-mentioned limitations, we feel the methods outlined in this paper have the potential to advance tree biomechanics research. Once our whole root system models were generated, we were able to measure them several different ways to address questions that occurred during analysis. For example, while our interest in the presence of defects among the treatments (Table 1) was spurred by observations made in the field, logistical considerations made it impossible to investigate further onsite. Having a digital copy of our trees preserved this data and allowed us to go back and tally root defects and other conditions like adventitious rooting (Table 1).

CONCLUSION

Deep planting continues to be a complex issue that varies in its impact on tree health and stability. In our nine-year study, neither tree height nor trunk diameter were affected by rooting depth. Bending moment varied based on the volume of roots (opposite the pulling direction) located both at the soil surface (0 to 10 cm) and deeper in the ground (i.e., 40.1 to 50 cm and greater than 60.1 cm). Connecting this back to our original research questions, the depth of roots (as measured by root volume) was impacted by our original planting treatments. Given that many urban trees are initially planted too deep, creating environments that are favorable for roots to grow deeply in urban soils may increase rooting stability beyond initial establishment if the species, nursery production method, and planting conditions are such that health is not impacted or the root system is not predisposed to significant root defects.

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Résumé. Les arbres sont souvent plantés profondément, conséquence de pratiques en pépinière et en aménagement paysager. Bien que plusieurs recherches antérieures aient examiné l’impact d’une plantation profonde sur la croissance et la survie des arbres, son impact sur la stabilité des arbres n’est pas solidement documenté. Des frênes rouges Patmore (*Fraxinus pennsylvanica* ‘Patmore’) furent plantés à trois profondeurs différentes dans des parcelles d’essai et laissés ainsi pendant neuf ans. Sur le plan de la croissance aérienne, la profondeur de plantation n’eut aucun effet sur la croissance en diamètre des tiges (mesuré au dhp) (P-valeur = 0.421; $n = 32$) ou sur le hauteur des arbres (P-valeur = 0.501; $n = 32$). Des essais statiques à l’arrachement furent menés afin d’évaluer les conséquences d’une plantation profonde sur la stabilité des arbres. Ayant recours à des modèles informatiques dérivés de la photogrammétrie de type structure à partir du mouvement, afin d’évaluer l’architecture racinaire, nous constatâmes que les facteurs les plus significatifs affectant la stabilité des arbres étaient: 1) le volume des racines dans les premiers dix centimètres de sol d’une pointe de 90° située du côté opposé à la direction de traction; 2) le volume des racines entre les profondeurs de 40.1 à 50 centimètres de sol d’une pointe de 90° située du côté opposé à la direction de traction; et 3) le volume des racines plus profondes que 60.1 centimètres de sol d’une pointe de 90° située du côté opposé à la direction de traction (version finale : P-valeur < 0.001; $n = 30$; R^2 ajusté = 0.852). L’importance de la morphologie structurale des racines dans l’ensemble des profils de sol et les implications pour les relations sol-racines urbaines sur la stabilité des arbres sont examinées.

Zusammenfassung. Bäume werden als Resultat gängiger Baumschulpraktiken häufig tief gepflanzt. Während vergangene Forschung die Auswirkungen von tiefem Pflanzen auf Baumwachstum und Überleben untersucht hat, sind die Auswirkungen auf die gesamte Baumstabilität nicht gut dokumentiert. *Fraxinus pennsylvanica* ‘Patmore’ Bäume wurden in Forschungsbeeten mit drei verschiedenen Tiefen gepflanzt und für neun Jahre zur Etablierung stehengelassen. Bei der Untersuchung des oberirdischen Wuchses hatte die Pflanztiefe keinen Effekt auf den Stammdurchmesser (gemessen als bhd) (P-Wert = 0.421; $n = 32$), oder Baumhöhe (P-Wert = 0.501; $n = 32$). Statische Zugversuche wurden durchführt, um die Konsequenzen des tiefen Pflanzens auf die Stabilität zu evaluieren. Unter Verwendung von Struktur aus Bewegung, eine photogrammetrische Entfernungsbildgebungstechnik (SfM) zur Untersuchung der Wurzelarchitektur, fanden wir die meist signifikanten Faktoren, die die Stabilität beeinflussen: 1) Wurzelvolumen in den oberen 10 cm Boden in einem 90° Winkel auf der gegenüberliegenden Seite zur Zugrichtung; 2) Wurzelvolumen in 40.1 bis 50 cm Tiefe in einem 90° Winkel auf der gegenüberliegenden Seite zur Zugrichtung; und 3) Wurzelvolumen tiefer als 60.1 cm in einem 90° Winkel auf der gegenüberliegenden Seite zur Zugrichtung (finales Modell: P-Wert < 0.001; $n = 30$; angepasst $R^2 = 0.852$). Die Wichtigkeit von struktureller Wurzelmorphologie über das gesamte Bodenprofil und die Implikationen für urbane Wurzel-Boden-Relationen auf die Baumstabilität werden hier diskutiert.

Resumen. Los árboles a menudo se plantan profundamente como resultado de las prácticas de vivero y paisaje. Si bien investigaciones anteriores han investigado el impacto de la plantación profunda en el crecimiento y la supervivencia de los árboles, su impacto en la estabilidad del árbol no está bien documentado. Árboles de fresno verde (*Fraxinus pennsylvanica* ‘Patmore’) se plantaron a tres diferentes profundidades en parcelas de investigación y se establecieron durante nueve años. Al evaluar el crecimiento, la profundidad de plantación no tuvo efecto sobre el crecimiento del diámetro del tallo (medido como dap) (valor $P = 0.421$; $n = 32$), o la altura del árbol (valor $P = 0.501$; $n = 32$). Se realizaron pruebas de tracción estática para evaluar las consecuencias de la plantación profunda en la estabilidad de los árboles. Utilizando modelos de computadora derivados de la fotogrametría de la estructura del movimiento (SfM) para evaluar la arquitectura de la raíz, encontramos que los factores más importantes que afectan la estabilidad de los árboles fueron: 1) los volúmenes de la raíz en los 10 cm superiores del suelo en una cuña de 90° en el lado opuesto de la dirección de arrastre; 2) volúmenes de raíz de 40.1 a 50 cm de profundidad en una cuña de 90° en el lado opuesto a la dirección de extracción; y 3) volúmenes de raíz más profundos que 60.1 cm en una cuña de 90° en el lado opuesto a la dirección de extracción (modelo final: valor $P < 0.001$; $n = 30$; R^2 ajustado = 0.852). Se discute la importancia de la morfología estructural de la raíz en todo el perfil del suelo y las implicaciones para las relaciones urbanas de la raíz del suelo en la estabilidad de los árboles.