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Short communication

Stability of landscape trees in engineered and conventional urban soil mixes

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ABSTRACT

Urban trees are frequently exposed to unsuitable soil conditions that can hamper root system development, potentially affecting both tree health and stability. Engineered soil designs have been developed to increase soil volume for trees planted in confined spaces, and past research has shown that these designs improve growing conditions. However, tree stability in these engineered soils has received limited attention from researchers. In this study, we evaluated the stability of two tree species of contrasting soil quality tolerance (*Prunus serrulata* and *Ulmus parvifolia*) after 3 years growth in two skeletal soil mixes, in a suspended pavement design (uncompacted soil), and in a conventionally prepared soil pit. Tree stability was evaluated by measuring trunk resistance to a lateral deflecting force applied with a rope winch system under both ambient and near-saturated soil conditions. Although heavily irrigating the experimental soils had no effect on tree stability, species-specific responses to soil mixes were observed. *P. serrulata* grown in the gravel-based skeletal soil showed greater trunk deflection resistance than trees grown in the other soil treatments, yet the stability of *U. parvifolia* was unaffected by soil type. These species-specific responses were consistent with earlier observations of root development in which *P. serrulata* grew up to 60 times greater root length in gravel-based skeletal soil whereas *U. parvifolia* root growth was similar in all soil treatments. This research provides evidence that certain tree species planted in conventional tree pits may be more prone to uprooting due to poor root development and that root anchorage might be improved for these species by utilizing a skeletal soil mix.

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Introduction

Successfully integrating trees and grey infrastructure is a significant challenge for creating high-value urban forests. Situating trees among expansive paved areas such as parking lots, sidewalks, and plazas is desirable from both an ecological and architectural standpoint, but the design requirements for stable pavement and healthy trees are typically incompatible. As subsoil is compacted to support the weight of pavement and its anticipated traffic, macroporosity is decreased, diminishing the soil's capacity for hydration and aeration (Craul, 1985). Moreover, compaction increases soil strength, thereby limiting tree root penetration (Grabosky et al., 2002b) and exploration of the soil. As a result, landscape trees planted in soil volumes confined by pavement often suffer chronic water stress (Krizek and Dubik, 1987) and imbalanced nutrient ratios (Flueckiger and Braun, 1999), which can diminish their health and shorten their lifespan (Krizek and Dubik, 1987).

Over the past three decades, researchers and engineers have developed several urban infrastructure designs to meet the dual needs of pavement stability and tree health. There are two fundamental approaches to these designs: skeletal soils and suspended pavement. Skeletal or structural soils are composed of course stone mixed with fine-textured mineral soil to create a high-porosity matrix that can be compacted to engineering load-bearing standards yet retain physical properties conducive to aeration, hydration, and root elongation. One example is Davis soil, which comprises lava rock and mineral soil mixed in a ratio of 3:1 by volume (Xiao and McPherson, 2008). A similar application of porous stone in a skeletal soil incorporates Stalite (Carolina Stalite Company, Salisbury, NC USA) – a heat-expanded slate – that is mixed with sandy clay loam in a ratio of 4:1 (Costello and Jones, 2003). CU-Structural Soil® or CU-Soil™ (US Patent #5,849,069; produced and marketed by Amereq, Inc., New City, NY, USA) is a skeletal soil design that incorporates crushed stone and clay loam at a ratio of 4:1 by weight (Grabosky et al., 2002b). Suspended pavement designs, which typically are custom-engineered for specific projects, rely on rigid piers rather than compacted soil to support pavement and traffic loads. As a result, a large volume of uncompacted soil can be provided for landscape trees planted within or adjacent to the suspended pavement system. Recently, proprietary systems have come onto the market that permit modular construction of suspended pavement soil volumes, potentially improving the affordability and reliability of this infrastructure

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concept. Examples include Silva Cell™ (Deep Root Partners, San Francisco, CA, USA) and StormTank™ (Brentwood Industries, Inc., Reading, PA, USA).

Engineered soils, such as CU-Structural Soil®, can improve tree root development, which has been found to result in larger, healthier trees (Grabosky and Bassuk, 1995, 1996) compared to conventional plantings. Grabosky et al. (2002a) as well as Grabosky and Bassuk (2008) compared trees growing in structural soil to those in conventional tree lawns in Brooklyn and Ithaca, NY and found equal and in some cases increased tree growth. Smiley et al. (2006) evaluated trees grown in several engineered soils overlain with pavement – including three skeletal soils and a suspended pavement soil – and found that trees grew better in the engineered soils than in conventionally prepared tree pits during the first 14 months after establishment. Growth enhancements were most pronounced in the suspended pavement treatment. Similarly, Loh et al. (2003) compared the development of *Ficus benjamina* L. grown 15 months in two volumes (0.01 m^3 and 0.05 m^3 containers) of structural soil and uncompacted loam and found that trees in loam had greater shoot and root growth than those in equivalent volumes of structural soil regardless of container size.

While there is mounting evidence that trees grow better and are healthier when planted in engineered soils rather than conventional tree pits, there is a dearth of literature on the structural stability of trees grown in engineered soils. Anecdotal evidence suggests that trees grown in conventional tree pits are at greater risk of uprooting because the depth and spread of their root systems are constrained by hardscape, underground utilities, and compacted soil, but there are no research reports to our knowledge that confirm or refute this belief. Risk of such tree failures could be exacerbated in areas subject to severe weather such as heavy rain and high winds, which are known to predispose trees to uprooting. Tree failures have been evaluated for various storm events with wind speeds of up to 265 km/h, during which up to 40% of surveyed trees have uprooted or snapped (Duryea et al., 1996; Jim and Liu, 1997; Duryea et al., 2007). Some researchers attributed these tree failures to shallow soil and poor rooting properties and surmised that planting these tree species in deeper soils or on more protected sites would increase their survival (Duryea et al., 1996). Nicoll et al. (2006) investigated the stability of *Picea sitchensis* (Bong.) Carrière via pulling tests and found that significantly greater force was required to overturn trees with rooting depths of more than 80 cm compared to trees of similar mass rooted at less than 80 cm. Limited root spread can also impact tree stability. Smiley (2008) found that immature *Quercus phellos* L. with roots severed at a horizontal distance less than three times their trunk diameter required significantly less pulling force to deflect their trunks than trees with roots severed at greater distances.

Because engineered soils can promote deeper, more extensive root systems, trees planted in these systems may also exhibit greater structural stability. Rahardjo et al. (2009) used theoretical modeling to investigate the stability of a mature tropical tree with a plate-root system grown in four soil types including pure top soil, pure granite chips, and two mixes containing both. Their models showed that a 1:4 mixture of topsoil to granite chips (by dry mass) required the highest wind force to uproot the tree and that uprooting wind force decreased as root length was shortened. The researchers attributed the superior modeling performance of the topsoil/granite chip mix to its enhanced shear strength relative to the other soil types. These theoretical findings suggest that utilizing engineered soil mixes in lieu of conventional tree pits might enhance severe weather tolerance of the urban forest, which could prove beneficial in conserving tree canopy cover, reducing debris cleanup costs, and protecting people and property from uprooted trees. However, there is no empirical research, to our knowledge, that has investigated tree stability in engineered soils.

The purpose of our study was to empirically investigate the biomechanics of trees grown in a range of urban soil mixes. Our first objective was to evaluate the stability of two landscape tree species of contrasting soil quality tolerance grown in two engineered soils compared to those grown in conventional tree pits using stem pulling tests. Our second objective was to determine whether tree stability in these urban soil mixes differed under drained versus near-saturated soil moisture conditions.

Methods

Study site and experimental design

The study was conducted on the grounds of the Bartlett Tree Research Laboratory in Charlotte, NC, USA. During the spring of 2004, three parallel trenches (6 m wide × 24 m long) spaced 3 m apart were excavated to a depth of 0.6 m in native sandy clay loam soil. The trenches were lined with geotextile (Typar Style 3801g, BBA Fiberweb, Old Hickory, TN, USA) to contain root growth and segregate soil treatments. Each row was then subdivided into four 6 m × 6 m sections (one section for each soil treatment) and then further subdivided into four 3 m × 3 m sub-sections (two sub-sections for each tree species), which were partitioned with Biobarrier (BBA Fiberweb) to segregate roots of adjacent trees.

Within each row, one of four soil treatments was randomly assigned to each 6 m × 6 m trench section, which constituted an experimental unit. One of the soil treatments proved unsuitable for tree growth, resulting in the death of several experimental trees, and has been excluded from this report. A fourth soil treatment (suspended pavement) was installed in a fourth trench excavated adjacent to the other three rows. Due to the complexity of constructing the suspended pavement, the treatment was not randomized within the other rows. Instead, all four sections of the fourth row were dedicated to the suspended pavement treatment. In summary, the evaluated soil treatments (Smiley et al., 2006) included:

1. Gravel/soil mixture – composed of 80% gravel (2.5 to 3.5 cm diameter) and 20% sandy clay loam soil. A hydrogel (Terra-Sorb® Fine, Plant Health Care Inc., Pittsburgh, PA, USA) was sprayed on the gravel before mixing with soil. Lifts were 20.3 cm thick and were compacted with an impact compactor to 95% Proctor density.
2. Expanded Slate/soil mixture – composed of 80% expanded slate (Stalite [2–3.5 cm diameter], Carolina Stalite Company, Salisbury, NC, USA) mixed with 20% sandy clay loam. The expanded slate was wetted before mixing with soil. Lifts were 30.5 cm thick and compacted with a vibratory plate compactor to the manufacturer's specifications.
3. Compacted soil – sandy clay loam installed in 20.3 cm lifts and compacted with an impact compactor to 95% Proctor density.
4. Suspended pavement – native sandy clay loam was decompacted using the method proposed by Rolf (1994) and 15.2 cm diameter holes were augered to 61 cm depth within the soil and filled with concrete to serve as pillars for the suspended concrete slab.

Two landscape tree species of contrasting soil quality tolerance were evaluated in the soil treatments: flowering cherry (*Prunus serrulata* Lindl. 'Snow Goose') and Chinese elm (*Ulmus parvifolia* Jacq. 'Bosque'). Wire baskets and burlap were removed from the tops of root balls prior to planting the 5 cm caliper nursery stock into the experimental soil pits. Two trees of each species were randomly assigned to each soil treatment section and planted in the center of the four adjacent 3 m × 3 m pits, giving each tree approximately 5.4 m^3 total soil volume. A continuous concrete slab underlain with 5 cm of gravel was poured over the surface of each row, leaving an

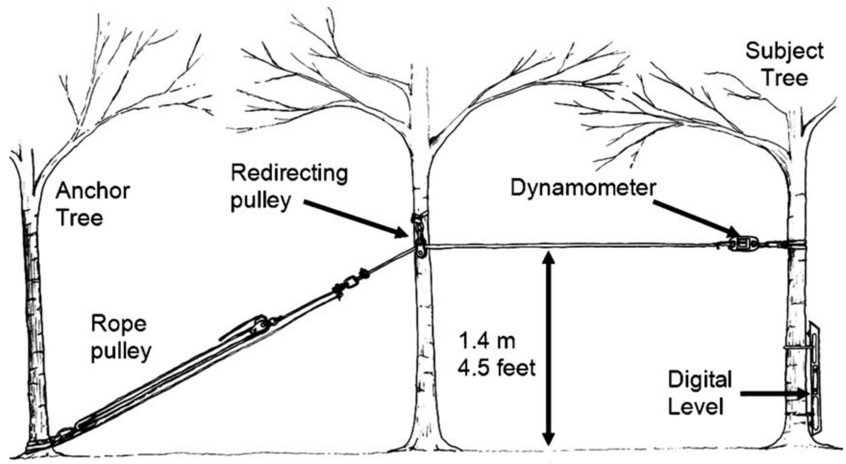

Fig. 1. Schematic drawing of the rigging system used to apply and measure force required to deflect the trunks of experimental (subject) trees growing in the engineered soil mixes. In the drawing, the proximity of the anchor, redirect, and subject trees is not drawn to scale. For subject trees at the end of planting rows, the winch system was anchored to a tow hook on the bumper of a vehicle positioned in the same manner as an anchor tree.
Drawing adapted from Smiley (2008).

80 cm diameter hole centered on each tree trunk. Two irrigation bubblers were installed above the root ball of each tree on opposite sides of the trunk. During transplant establishment, trees in the gravel-based and expanded slate-based treatments were irrigated at a rate of 1.9 L min^{-1} whereas trees in the compacted soil and suspended pavement treatments were irrigated with 0.95 L min^{-1}. Water content of the root ball soil was monitored with one tensiometer (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) per soil treatment and automated irrigation was applied when readings fell below 50 kPa of vacuum.

Because the suspended pavement treatment was not randomized amongst the other soil treatments, it was not included in statistical comparisons; however, data are reported as a point of reference for the reader. Therefore, the experimental design for the study was a complete randomized block consisting of three blocks (rows), three soil treatments per block (compacted soil, expanded slate mix, and gravel-based skeletal soil), two tree species per treatment, and two trees (sub-samples) per treatment × species combination. Refer to Smiley et al. (2006) for further details on the design and installation of the experimental plot.

Measurement procedure

Tree stability evaluations were conducted during December 2007 using the tree-pulling procedure of Smiley (2008). The procedure entailed applying a lateral force to each experimental tree utilizing a system of ropes and pulleys until its trunk deflected 2° from its ambient vertical position while simultaneously measuring the applied force (Fig. 1). Smiley (2008) found a high correlation (R^2 = 0.76) between the pull-to-failure force and the force required to mildly deflect the trunks of similar sized *Q. phellos* grown in the same native soil. As such, the mild deflection pulling procedure was deemed suitable for evaluating tree stability in the current study.

Tree-pulling tests were conducted under ambient soil moisture conditions on 5–6 December 2007 and then repeated on 18 December 2007 following 12 h of continuous irrigation at a rate 3.8 L min^{-1} via irrigation bubblers positioned near the trunk of each tree. To prepare for tree pulling, a 61 cm long digital level (Craftsman LaserTrac®, Sears LLC, Hoffman Estates, IL, USA) with 0.1° accuracy was first attached vertically to the trunk of the subject tree using elastic straps and then tared to 0°. Next, a 12 mm diameter arborist rope was secured to the tree trunk at 1.4 m above ground line, passed through a pulley attached at the same height to an adjacent tree, and secured to the base of another nearby tree using a manual winch system. A digital dynamometer (Dillon 5000LB ED-JUNIOR, Dillon Quality Inc., Kansas City, MO, USA) placed in-line with the pull rope system was used to measure the force required to deflect the trunk of the subject tree 2° from vertical. Each tree was pulled three consecutive times and the deflection force re-measured, allowing the tension to relax and the tree to return to vertical between pulls. Trunk diameter at 1.2 m above ground line was also recorded for each tree.

Statistical analysis

Main effects of tree species, soil treatment, and soil moisture (along with independent variable interactions) on trunk deflection force were analyzed using the MIXED procedure in SAS 9.0 (SAS Institute Inc., Cary, NC, USA). Trunk deflection force was log transformed to meet the analysis assumptions of normality and homogeneity of variance. Trunk diameter was found to be a significant (p < 0.0001) covariate of trunk deflection force. To control for the influential effect of trunk diameter on the response variable, treatment means for each tree species were adjusted prior to performing pairwise comparisons of the treatments. Adjusted treatment means were calculated using the formula

$$\hat{\mu}_{ia} = \bar{y}_{i.} - \hat{\beta}(\bar{x}_{i.} - \bar{x}_{..})$$

where μ_{ia} is the adjusted mean of the response variable for the ith treatment, $y_{i.}$ is the observed mean of the response variable for the ith treatment, β is the pooled slope of the linear regression between the response variable and the covariate, $x_{i.}$ is the observed mean of the covariate for the ith treatment, and $x_{..}$ is the observed mean of the covariate across all treatments. A cubic transformation was first applied to trunk diameter values as bending stress is inversely proportional to cubic trunk diameter (Pavlis et al., 2008). Following adjustment of treatment means, pairwise comparisons of the soil treatments were performed using Tukey's HSD procedure in SAS at the α = 0.05 significance level. Since the suspended pavement (uncompacted) treatment could not be properly randomized into the block experimental design due to installation restraints, this treatment was excluded from the statistical analysis and is only discussed descriptively hereafter.

Table 1
Soil water potential measured at 15 cm and 45 cm below grade in four engineered urban soil profiles during tree stability evaluations. Ambient condition evaluation was conducted on 5–6 December 2007 after prevailing weather whereas irrigated condition evaluation was conducted on 18 December 2007 after heavily irrigating each tree for 12 h. Measurements were recorded with automated tensiometers placed in one tree pit per soil treatment.

Soil treatment	Soil water potential (kPa)					
	Ambient condition			Irrigated condition		
	Min.[a]	Mean[b]	Max.[c]	Min.	Mean	Max.
15 cm depth						
Compacted soil	28	30	33	12	12	13
Gravel/soil mix	111	116	120	35	42	46
Stalite/soil mix[d]	–	–	–	–	–	–
Suspended pavement	127	132	137	95	97	99
45 cm depth						
Compacted soil	6	9	12	3	4	6
Gravel/soil mix	8	9	10	12	12	13
Stalite/soil mix	7	8	10	5	6	7
Suspended pavement	5	6	6	4	5	5

[a] Minimum hourly soil water potential value recorded during the evaluation period.
[b] Mean hourly soil water potential for the evaluation period.
[c] Maximum hourly soil water potential value recorded during the evaluation period.
[d] Instrument data not available.

Results and discussion

Soil moisture effects

Since tensiometers were originally installed in the experimental plots to monitor irrigation regimes, only one tensiometer was installed per treatment, which precluded statistical comparisons of soil moisture before and after irrigating the plots. However, qualitative comparisons suggest that soil mixes were appreciably wetter after 12-h irrigation (Table 1). In the compacted soil treatment, moisture content of surface soil was near field capacity (−30 kPa) under ambient conditions, but much wetter (−12 kPa) following irrigation, and soil deeper in the profile was near saturation (−4 kPa). In contrast, the gravel-based skeletal soil and uncompacted soil appeared dryer near the soil surface than the compacted soil under both ambient and heavily-irrigated conditions, presumably due to higher macroporosity and thus higher infiltration rate and lower water holding capacity. Despite these changes in soil moisture, no significant differences in tree stability were detected regardless of tree species or soil type (Table 2).

It is well understood that higher soil water content of non-skeletal soils decreases soil shear strength. Tensile strength and other soil physical properties are closely related to soil moisture (Greacen and Sands, 1980), and soil cohesion in particular has been shown to heavily influence the theoretical stability of trees to wind forces (Rahardjo et al., 2009). One would expect that trees in heavily-irrigated soils would tolerate less destabilization force than those in drier soil conditions due to moisture effects on root slippage and soil shearing, but our results did not support this hypothesis.

The absence of soil saturation effects on tree stability in the expanded slate/soil mix and gravel/soil mix was contrary to our initial hypothesis. Because the mineral soil component in each mix is rather small (20%, v/v), the stability of the substrate may be more so dictated by macrostructure of the stone matrix rather than microstructure of the fine-earth fraction. Therefore, moisture-induced reduction of shear strength in the mineral soil component might minimally affect the stability of the substrate mix. However, using mathematical modeling, Rahardjo et al. (2009) found that failure force for a tropical tree growing in a 4:1 topsoil:granite chip mixture doubled as the soil water potential dropped from 0 to −60 kPa, suggesting that trees would be less stable in a saturated skeletal soil. To our knowledge, this theoretical model has not been validated with empirical data, and the limitations of our experimental design may not have permitted detection of a moisture effect. There is also the possibility that the overlain concrete pad in our study further stabilized the trees, which may have further obscured otherwise detectible effects of soil moisture on tree stability. As such, there remains insufficient evidence to support or refute the hypothesis that landscape trees are less stable in satu-

Table 2
Trunk diameter and trunk deflection force measured for two landscape tree species 4 years after transplanting to four engineered urban soil mixes. Standard error of the mean shown in parentheses.

Species	Soil treatment	Trunk diameter (cm)[a]	Trunk deflection force (N) – Ambient soil[b]	Trunk deflection force (N) – Irrigated soil[c]	Adjusted trunk Deflection force (N)[d]
Prunus serrulata	Compacted soil	10.4 (0.1)	661 (20)	677 (23)	600 b
	Gravel/soil mix	10.8 (0.2)	1111 (73)	1074 (65)	1102 a
	Stalite/soil mix	10.2 (0.4)	706 (73)	699 (69)	673 b
	Suspended pavement	11.5 (0.3)	1243 (86)	1265 (60)	–
Ulmus parvifolia	Compacted soil	11.3 (0.4)	1695 (128)	1695 (111)	1221 a
	Gravel/soil mix	9.5 (0.2)	985 (81)	1016 (77)	1092 a
	Stalite/soil mix	8.1 (0.2)	465 (41)	479 (39)	1189 a
	Suspended pavement	11.6 (0.4)	1799 (138)	1724 (127)	–

[a] Measured 137 cm above ground line ($n = 6$ for each species × soil treatment combination).
[b] Force applied to deflect trunk angle 2° from vertical under ambient soil moisture conditions ($n = 18$ for each species × soil treatment combination).
[c] Force applied to deflect trunk angle 2° from vertical following 12 hours of tree irrigation ($n = 18$ for each species × soil treatment combination).
[d] Mean trunk deflection force (average of ambient and irrigated values) adjusted for trunk diameter ($n = 36$ for each species × soil treatment combination). For each species, soil treatment means followed by different letters are significantly different ($\alpha = 0.05$) using Tukey's HSD (excluding the uncompacted treatment).

rated urban soil mixes. The effects of soil moisture content on tree stability in skeletal soil warrants further empirical research.

Soil treatment effects

Trunk diameter was a significant covariate ($p < 0.0001$) of trunk deflection force in the presence of other independent variables in the statistical model; therefore, all treatment means were adjusted for trunk diameter prior to statistical comparison. Both soil treatment and tree species significantly affected trunk deflection force ($p = 0.0009$ and $p = 0.0011$, respectively). In addition, there was a significant interaction between these two independent variables ($p = 0.0004$), indicating that stability of the two tree species responded differently to the soil treatments.

Looking at species-specific responses, trunk deflection force of *U. parvifolia* was unaffected by soil type whereas *P. serrulata* in the gravel/soil mix was more stable than in either the expanded slate/soil mix or the compacted soil (Table 2). *P. serrulata* grown in the gravel/soil mix withstood nearly two times the trunk deflection force of trees in the other soil treatments. These patterns in species-specific stability were consistent with earlier observations of root system development in these trees. Root growth analysis of these same trees in summer 2005 revealed no soil treatment related differences in root growth for *U. parvifolia*; in contrast, *P. serrulata* grown in the gravel/soil mix produced total root length 40–60 times greater than in the expanded slate/soil mix and the compacted soil, resulting in greater root spread (Smiley et al., 2006). *P. serrulata* is generally regarded as less adaptive to urban soil extremes, particularly poor drainage (Rhodus, 2002), and would therefore be expected to be more responsive to improvements in experimental soil quality. This suggests that the gravel/soil mix provides soil conditions more favorable for root growth, which affirms previous findings of Grabosky et al. (2001). *U. parvifolia* on the other hand is generally regarded as tolerant of poor soil, particularly dry soils (Yiesla, 2010), and would be expected to show more consistent root growth across a range of soil quality. Based on these findings, it appears that enhanced root development of *P. serrulata* in the gravel/soil mix was contributing to its greater stability. However, the physical characteristics of the gravel-based skeletal soil might also contribute to tree stability because the stones are denser and are highly angular (allowing them to interlock more effectively) compared to the expanded slate aggregates.

Conclusion

U. parvifolia and *P. serrulata* were evaluated 3.5 years after planting to several urban soil designs to examine the effects of substrate, soil moisture, and species on tree stability. Our data showed no significant influence of soil saturation on tree stability, but the experimental design did not allow us to fully evaluate this relationship. Controlling for trunk diameter, *P. serrulata* showed greater stability in the gravel/soil mix compared to the other two treatments, which supports our hypothesis that trees in the gravel/soil mix are more resistant to destabilization due to their enhanced rooting. In contrast, stability of *U. parvifolia* was similar in all soil treatments, which likely reflects the species' ability to effectively root in a range of soil media constrained by density or moisture content. Our findings indicate that sensitive tree species planted in conventional tree pits may be more prone to uprooting due to poor root development and that root anchorage could be improved for these species by utilizing a skeletal soil mix that enhances aeration, hydration, and root elongation.

However, this study had some limitations that merit consideration in future research. First, the study was conducted using small-diameter, juvenile trees evaluated with a pulling procedure; large trees exposed to dynamic wind forces may not respond in the same manner. Future research should focus on larger trees and subject trees to dynamic loads that better replicate wind gust conditions. In addition, the trunk pulling procedure employed was non-destructive and instead relied on resistance to mild trunk deflection as measure of tree stability. Although this method was based on empirical data showing a strong relationship between deflection resistance and full uprooting force, differences in species and soil conditions warrant caution in extrapolating the results of this study. Further research employing destructive sampling techniques may be necessary to validate our observations of substrate effects on tree stability.

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