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Relationship of structural root depth on the formation of stem encircling roots and stem girdling roots: Implications on tree condition

Richard J. Hauer[a,*], Gary R. Johnson[b]

[a] College of Natural Resources, University of Wisconsin–Stevens Point, 800 Reserve Street, Stevens Point, WI 54481, United States

[b] Department of Forest Resources, University of Minnesota, 115 Green Hall, 1530 Cleveland Ave. N., St. Paul, MN 55108, United States

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ABSTRACT

The relationships of structural root depth, stem girdling roots, stem diameter, and boulevard width were studied on the condition of four tree species (*Acer saccharum* L., *Celtis occidentalis* L., *Fraxinus pennsylvanica* Marsh, and *Tilia cordata* Mill.) grown as street trees. The relationship between depth from the soil surface to the structural roots and development of stem encircling roots and stem girdling roots was also determined. Stem girdling roots, boulevard width, and root depth were significant predictors of tree condition. Tree condition was greater as boulevard width increased, but stem girdling roots and structural root depth had a negative relationship on tree condition. Depth to structural roots was positively related to the percentage of the tree stem circumference with stem encircling roots and also for stem girdling roots. For every cm the structural roots were below the soil surface, 3.3 % of the stem was encircled. Thus, a 10 cm root depth translates to approximately 1/3 of the stem with encircling roots. With stem girdling roots, an approximate 1 % of the stem was girdled for each cm that structural roots were below the surface. Results from the measurement of 398 trees that were approximately 10–20 years post planting provide additional justification for maintaining structural roots at the soil surface. Results also demonstrate the importance for planning tree planting locations with adequate boulevard widths to foster tree health. Findings have implications with nursery production, tree planting, and arboricultural treatments to remove soil away from tree stems and expose structural roots at planting and subsequently with established trees.

1. Introduction

Trees in urban and community forests have many abiotic and biotic factors that affect tree health (Rich and Walton, 1979; Berrang et al., 1985; Drilias et al., 1982; Costello et al., 1991; Bond, 2010; Clark and Matheny, 1991; Hauer et al., 2020). The depth that structural roots are below the soil surface (and subsequently the tree stems) and stem girdling roots are believed to be two important factors that affect tree health, tree growth, and longevity of landscape trees (d'Ambrosio, 1990; Johnson and Hauer, 2000; Wells et al., 2006; Day et al., 2009; Giblin et al., 2011). The belief that structural root depth affects the health and survival of trees is not new (Lawson, 1618; Evelyn, 1664; Ball, 1999). Lawson (1618) observed functioning roots near the soil surface and believed injury to trees may result from buried tree root systems. Evelyn (1664) wrote "… never to inter your stem deeper than you found it standing; for profound burying very frequently destroys a tree …" Girdling roots have been suggested since at least the 1930's as a factor that influences the decline and premature death of landscape trees (Van Wormer, 1940). Van Wormer (1937, 1940) observed nearly all declining *Acer saccharum* L. trees to have severe girdling roots. Girdling roots can be quite common and Tate (1980) quantified 82 % of *Acer platanoides* L. had at least one girdling root. However, most trees in that study had 37.5 % or less encirclement and overall tree canopies showed little impact from stem girdling. Maple species (*A. platanoides* L, *Acer rubrum* L, *and A. saccharum*) have been noted as common hosts of girdling roots, and at least in one study all three species were confirmed as chronically inflicted by the abnormality 3–10 years after transplanting (Watson et al., 1990). In contrast, the same study found that encircling or girdling roots on *Gleditsia triacanthos* L., *Fraxinus pennsylvanica* Marsh, and *Tilia cordata* Mill. were less common than with maple species. Girdling roots can be removed; however, if soil is backfilled in the excavated area post removal, they have the potential to grow back and in position as encircling or girdling roots (Watson and Clark, 1993).

A buried structural root system occurs through a variety of ways.

* Corresponding author.
E-mail addresses: rhauer@uwsp.edu (R.J. Hauer), johns054@umn.edu (G.R. Johnson).

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These include soil fill placed over existing trees, excessive organic mulch over the root system especially the zone of rapid taper, root systems buried deeply during tree planting, trees sinking into the landscape soil profile post planting, soil deposition from flooding, during nursery production, and nursery harvesting practices (Johnson and Hauer, 2000; Wells et al., 2006: Day et al., 2009; Gilman et al., 2010a). Several authors report a 5–28 cm depth from the soil surface to structural roots in B&B harvested trees planted in landscapes and as street trees in the northeastern USA (Smiley and Booth, 2000; Giblin et al., 2005; Smiley, 2005; Rathjens et al., 2007). Thus, standards (*e.g.*, Z60.1 and A300 Part 6) and best practice offer approaches to develop and maintain trees.

Buried structural roots affect root system form, upward direction of root growth, and tree stability (Gilman et al., 2010a; Giblin et al., 2011; Gilman and Grabosky et al., 2011). The relationship of structural root depth on tree growth and survival is less clear. Reports include little to no relationship (Watson et al., 1990; Broschat, 1995; Gilman and Grobosky, 2004; Jarecki et al., 2005; Day et al., 2009) to reduced growth in tree height and diameter (Broschat, 1995; Arnold et al., 2005; Giblin et al., 2005; Wells 2006; Arnold et al., 2007; Day et al., 2009). The amount of time following when the burial of roots occurred, root depth, and contributing factors (*e.g.*, adventitious root formation, soil moisture, flooding, soil texture) appear as reasons for differences in reported relationship (Gilman and Grabosky, 2004; Arnold et al., 2005; Wells et al., 2006).

Stem tissue girdling by roots lead to anatomical changes in xylem (vessel elements, rays, and fiber tracheids) and phloem tissue through compression and distortion of normal tissue orientation (Hudler and Beale, 1981). The anatomical change from stem compression by roots likely leads to physiological change in tissue function and increased water stress (Johnson and Hauer, 2000). Tree growth and crown appearance are indirect evidence that girdling roots have a negative relationship on tree growth and condition, but study results have been inconsistent and do not always show indirect relationships through reduced tree growth and canopy dieback (Tate, 1980; Holmes, 1984; d'Ambrosio, 1990; Johnson and Hauer, 2000). In a study where phloem tissue of six year old Norway spruce (*Picea abies* (L.) H. Karst.) trees were physically girdled at bud break, during rapid shoot and caliper expansion, and post shoot growth, fine root biomass was significantly reduced compared to controls, and the starch content of coarse roots was likewise significantly reduced compared to controls (Rainer-Lethaus and Olberhuber, 2018). All trees girdled at bud break were dead within five months, and drought-stressed trees girdled during peak shoot and stem growth were dead within four months. Thus, girdling roots gradually reduce the size and efficiency of transport tissues leading to dysfunction.

The size of a tree at planting may determine if deep planting is to become detrimental. Small tree seedlings (*e.g.*, 1–3 years old planting stock) outplanted in forests are often planted deep on purpose with favorable results for tree survival, especially during dry periods of soil moisture (Slocum and Maki, 1956; Stroempl, 1990; VanderSchaaf and South, 2003; Dreesen and Fenchel, 2008; Pinto et al., 2011). Planting seedlings 5–10 cm deep on well-drained soil was also suggested to decrease tree mortality due to a lower incidence of heat damage to stem tissue at the root collar (Switzer, 1960; Stroempl, 1990). Adventitious roots may develop above the original root system in some tree species (Stroempl, 1990). In all, it appears seedlings might have an inherent recovery capacity when root systems are replanted at a greater depth (Van Eerden and Kinghorn, 1978). This relationship is apparently lost as seedlings transition towards a sapling stage (Gilman and Anderson, 2005).

The intent of this study was to 1) quantify the relationship of structural root depth and stem girdling roots on tree condition, and 2) quantify the relationship of structural root depth on encircling root and stem girdling root development. We hypothesized a relationship based on observations prior to designing this experiment that structural root depth is positively related to stem girdling root formation and a resultant negative relationship on tree condition. We also hypothesized that structural root depth is positively related to stem encircling root formation. Thus, we set out to test any relationships of structural root depth and stem girdling roots on tree condition. We also asked the question if structural root depth explained the percentage of the stem with stem encircling roots and/or stem girdling roots.

2. Methods

2.1. Study site and species studied

Four tree species were studied for the relationships of distance from the soil line mark on the tree trunks to structural roots on tree condition and any relationship(s) on the development of stem encircling roots and stem girdling roots (Appendix A). Three species, *Acer saccharum* Marshall (sugar maple), *Fraxinus pennsylvanica* Marshall (green ash), and *Tilia cordata* Mill. (littleleaf linden) were located in boulevards (i.e. the area between the curb and sidewalk) along street segments in Minneapolis, MN USA 44.9778 °N, 93.2650 °W. A fourth tree species, *Celtis occidentalis* L. (hackberry) was randomly selected from a boulevard tree population along street segments in Rochester, MN USA 44.0121 °N, 92.4802 °W. In both communities a street segment is a contiguous distance (approximately 100–200 m) between two street intersections (city block). The sites (i.e. boulevards) and species were chosen based on prior observations with diagnosing declining trees suggesting a relationship between tree condition and the development of stem encircling roots and stem girdling roots as a function of structural root depth.

The species selected were trees commonly planted within the urban forests of the study locations. Trees were initially identified within the study locations by selecting trees that were established post transplanting (at least two years after transplanting), approximately 10–20 years of age, and between 7.6 cm and 22.9 cm stem diameter at 1.37 m above the ground. The size and location (street segments) of the study population was obtained from tree inventories provided by the two communities and three times the number of trees by species were located and vetted for species identification and targeted size accuracy, resulting in approximately 300 eligible trees per species. Subsequently, every third tree by species along the street segments were included in the study.

2.2. Condition rating system

A rating system was used to determine an overall tree condition ranking based on the visual appearance of the tree stem, tree canopy, and leaf condition (Johnson and Fallon, 2009). Each of the three tree locations (stem, canopy, leaf) were ranked 0 (poor), 1 (fair), 2 (good), and 3 (excellent). Ranking guidelines were:

3 - No obvious problems or defects; tree appears healthy and normal as evidenced by other like species in the communities.

2 - Minor problems and/or defects which are recoverable and/or repairable; tree has noticeable abnormal condition determined to be minor and that the tree will most likely recover.

1 - Significant problems which may be difficult to recover and/or repair; tree is in advanced decline and requires immediate attention to decrease possibility of irrecoverable defects.

0 - Irrecoverable defects and/or problems; the tree has major problems and recovery is not expected.

For leaves, characteristics such as unusual leaf color (*e.g.* chlorotic), leaf size smaller than normal for the species, scorched leaves, and early or unusual leaf drop were used in ranking (Johnson and Fallon, 2009). In the canopy we used early autumn color, branch/twig dieback, canopy thinning, and stagheading (i.e. death of large, structural branches) with the ranking assignment. Stem condition included cracking, cambial dieback, and abnormal lean to rank trees (Fig. 1). The 12-point ranking system that used equal weighting for each of the three tree locations (*e.g.*, leaf, canopy, and stem) was further adjusted to a 0–100 % scale. The tree condition ranking was conducted "blind," prior to the

Fig. 1. *Acer platanoides* with significant stem compression from stem girdling roots and extensive sapwood decay as evidenced by the fungal fruiting structures.

determination of the depth to structural roots and the assessment of the tree root system. The root system was excluded from the condition rating since it was a study variable of interest as either a dependent or independent variable depending on the research questions presented later. The "blind" above-ground condition ratings were conducted by the same principle investigators for each species.

2.3. Field root examination method and measurements

Tree roots were non-destructively exposed by hand removal of soil, with vacuum extraction of soil to a distance of 10–15 cm from the tree stems as needed. Soil removal was done to ascertain the depth (cm) from the soil surface to the structural roots (aka, first-order roots, primary roots, skeletal roots, scaffold roots) and to visually examine for the presence of stem encircling roots and stem girdling roots (Table 1). The presence or absence of stem encircling roots and stem girdling roots was noted for all trees in the study (Fig. 2). The total percentage of the stem circumference with stem encircling roots and stem girdling roots was calculated for *C. occidentalis* (n = 96), *F. pennsylvanica* (n = 101), and *T. cordata* (n = 101) by measuring the total length of stem encircling roots and stem girdling roots, the buried stem circumference above the flare at the root-stem transition zone, and dividing total length by circumference (Fig. 3). In cases that the length was greater than the stem circumference due to multiple encircling and/or girdling roots, the product was set at 100 % for a totally encircled or girdled tree. *A. saccharum* (n = 100) only had the presence or absence of stem encircling roots or stem girdling roots recorded. Boulevard width, stem diameter (at 1.37 m), and tree species were recorded (Table 1). All measurements and assessments occurred during the growing season after full leaf development and prior to normal fall leaf color change and leaf drop (mid-May to late September).

2.4. Research models and statistical approach

Structural root depth and the incidence of stem girdling roots was tested for significance on tree condition *a priori* through two different linear regression models. The first full model was tree condition = stem diameter + boulevard width + % stem girdling root + root depth +

Table 1
Data variables and definitions used in this study.

Variable	Definition
Bouelvard Width	The distance in m between a street curb back edge and the sidewalk
Condition	A 12 point rating of the tree condition/health from above-ground plant parts of stem, canopy, and leaf with each assigned a score of 0 (poor), 1 (fair), 2 (good), or 3 (excellent) for 0–9 total points used to scale 0–100%
Encircling Root	Presence or absence of encircling/tangential roots within 15.2 cm (6 inches) of stem, but not yet causing compression of tissue, recorded as yes/no and total length in cm
Percent Encircled	Percent encircling root = total encircing root length / total stem circumferance
Percent Girdled	Percent stem girdling root = total stem girdling root length / total stem circumferance
Root Depth	Distance between the soil surface and the top of the structural root system in cm
Stem Circumferance	The total distance around the stem above the root flare at the root-stem transition zone
Stem Diameter	Diameter in cm of the tree trunk at 1.37 m above the soil surface
Stem Girdling Root	Presence or absence of roots causing stem compression, recorded as yes/no and total length
Street Segment	A contiguous distance (approximately 100–200 m) between two street intersections (city block)
Tree Number	Unigue record of each tree and study location
Tree Species	One of four tree species (*Acer saccharum*, *Celtis occidentalis*, *Fraxinus pennsylvanica*, and *Tilia cordata*) in this study

Fig. 2. A root examination of this *Tilia cordata* revealed a single stem girdling root (SGR), identified by the compression of the tree trunk that had resulted from the SGR placement. Visual confirmation of stem compression was a requirement for a root to be identified as a SGR.

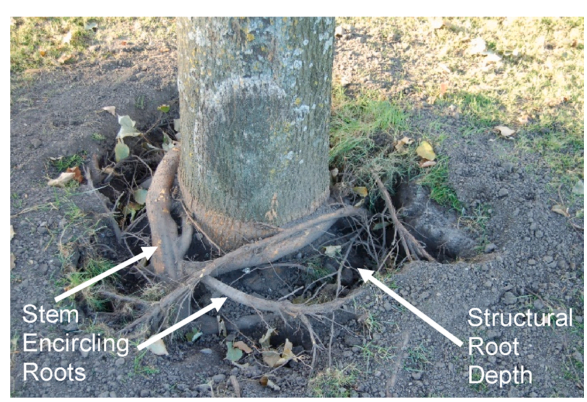

Fig. 3. A non-destructive root examination of a *Tilia cordata* revealing multiple layers of stem encircling roots, and no evidence of the original structural roots at this depth.

species. This model was tested with *F. pennsylvanica*, and *T. cordata* which both had % stem girdling root quantified, and boulevard width measured. A second full model tested tree condition = stem diameter + presence of stem girdling root + root depth + species. Presence of stem girdling root was coded as 0 or 1 for presence and included all four tree species. A relationship between root depth and percentage of stem surrounded by stem encircling roots was tested as encircling root = stem diameter + root depth + species. A similar full model was tested for stem girdling root = stem diameter + root depth + species. The species coefficient was coded as 0 or 1 for each species and each added individually into all full models. Tests for independence, homoscedasticity, and normality used residual plots and no violations observed. SPSS version 25 (IBM Corp. Armonk, NY: IBM Corp.) was used for all statistical analyses with $\alpha = 0.05$ as a test for significance with final model inclusion of study variables.

3. Results

Stem diameter ranged between 7.6 and 22.9 cm with a mean 16.4 (0.22 SE) (Table 2). As a percent of stem circumference, stem encircling roots averaged 64.3 % (2.3 SE) and stem girdling roots averaged 7.2 % (0.89 SE), with both ranging between 0 % and 100 % (Table 2, Fig. 4). Trees with structural roots at the surface averaged 6 % encircling and no stem girdling roots were observed. Stem encircling roots increased to 53 % with just 1–3 cm of soil over the uppermost structural surface and stem girdling roots average 4 % at this depth. Trees with structural roots 26 cm or more below the surface had 100 % stem encircling roots and a mean 38 % stem girdling roots. Overall tree condition ranged between 16.7 % and 100.0 % with a mean 75.6 % (0.91 SE). Root depth to structural roots varied between 0.0 and 29.2 cm and a mean 8.5 cm (0.33 SE) found.

3.1. Models predicting tree condition

Both tree condition models differed with variables that predicted tree condition (Tables 2,3). The first model with stem girdling roots on a percentage basis showed boulevard width ($p < 0.001$) and stem girdling roots ($p = 0.012$) as significant predictors of tree condition ($F = 12.495$, df = 2,196, $p < 0.0001$, Adj $R^2 = 0.10$). All tree species were not significant ($p > 0.25$) and stem diameter ($p = 0.24$) and root depth ($p = 0.14$) were not significant, thus these were not retained in the final model (Table 3). A second model treating stem girdling roots as a bivariate (1 = presence) showed *T. cordata* ($p = 0.19$) and stem diameter ($p = 0.26$) as not significant in the initial model. The final model ($F = 44.274$, df = 5,392, $p < 0.0001$, Adj $R^2 = 0.35$) showed stem girdling roots ($p = 0.004$), root depth ($p = 0.002$), *F. pennsylvanica* ($p = 0.048$), *A saccharum* ($p = 0.034$), and *C. occidentalis* ($p < 0.001$) as significant predictors of tree condition (Table 4). Tree condition declined as the percent of the stem circumference with stem girdling roots increased (Fig. 1). Boulevard width was positively related to tree condition. Root depth was not significant in model 1, but in model 2 it negatively affected tree condition. Trees with a greater depth to structural roots were thus lower in condition.

Table 2
Study sample descriptive findings.

Variable (unit)	N	Mean	Std. Error of Mean	Standard Deviation	Minimum	Maximum
Boulevard Width (m)	199	1.55	0.02	0.28	0.76	2.13
Condition (%)	398	75.65	0.91	18.16	16.70	100.0
Encircling Root (%)	298	64.34	2.23	38.41	0.00	100.0
Structural Root Depth (cm)	398	8.45	0.33	6.50	0.00	29.21
Stem Diameter (cm)	398	16.36	0.22	4.34	7.60	22.90
Stem Girdling Root (%)	298	7.20	0.89	15.39	0.00	100.0

3.2. Models predicting development of stem encircling roots and stem girdling roots

Several parameters explained root encircling of tree stems (Tables 5,6). Root depth was a significant predictor of root encircling ($p < 0.001$) and stem girdling roots ($P < 0.001$). As root depth increased, the percentage of the stem with encircling or girdling roots increased. Stem diameter was also a significant predictor of stem encircling roots ($p = 0.004$) and stem girdling roots ($p < 0.001$). With stem encircling roots, a negative relationship was found, thus as stem diameter increased the percentage of stem with stem encircling roots decreased. In contrast, the relationship was positive with stem girdling roots and larger trees had a greater stem percentage compressed by root tissue. The finding is intuitive in that as the diameters of tree stems and roots increase through growth stem compression may occur. And then by definition an encircling root becomes a stem girdling root. Likewise, smaller diameter trees have a greater stem encircling roots abundance as roots are in proximity but not yet causing stem girdling. No species were significant predictors (all $P > 0.10$) and boulevard width was also not significant ($p > 0.10$) in stem girdling root development. The models also showed *T. cordata* trees were more likely to have stem encircling roots and *C. occidentalis* less likely to have stem encircling roots.

4. Discussion

This study tested the relationships of structural root depth on the development of abnormal root systems (*e.g.*, stem encircling roots and stem girdling roots) and tree condition. We found that depth to structural roots was a strong predictor of trees developing stem encircling roots and stem girdling roots. Both root depth and stem girdling roots combined were associated with relationships on tree condition. The significance with these findings and other published results follows.

4.1. Structural root depth

Structural root depth occurs both naturally (*e.g.*, soil deposition from flooding) and artificially (*e.g.*, soil added on top or tree planting depth). Adventitious root development in riparian species is a natural survival adaptation to soil burying of tree roots, and trees buried in riparian areas have a uniform cylindrical shape rather than a flare at the soil surface (Sigafoos, 1964; Wilford et al., 2004). This same cylindrical shape has been found for planted landscape and street trees (Tate, 1981a,b; Johnson and Hauer, 2000; Gilman et al., 2010a). Species vary in response to burying with Dech and Maun (2006) finding adventitious root development stimulated by burying in *Salix cordata* Michx. and *Populus balsamifera* L., both riparian species. Two upland conifers, *Pinus strobus* L. and *Picea glauca* (Moench) Voss, lacked burial tolerance. *Taxodium distichum* (L.) Rich., a riparian species, was also found to develop adventitious roots, which was surmised as a survival strategy (Tremmel and Martin, 2000). What is unclear, however, is even if a species is an effective adventitious root developer, is there a minimum soil moisture content necessary for adventitious root development? The riparian species in nature grow in a bottomland situation and more likely will have access to soil moisture. Species ability to develop adventitious roots may change with age, with *Quercus virginiana* Mill showing limited to no development in larger saplings (Gilman and Anderson, 2005).

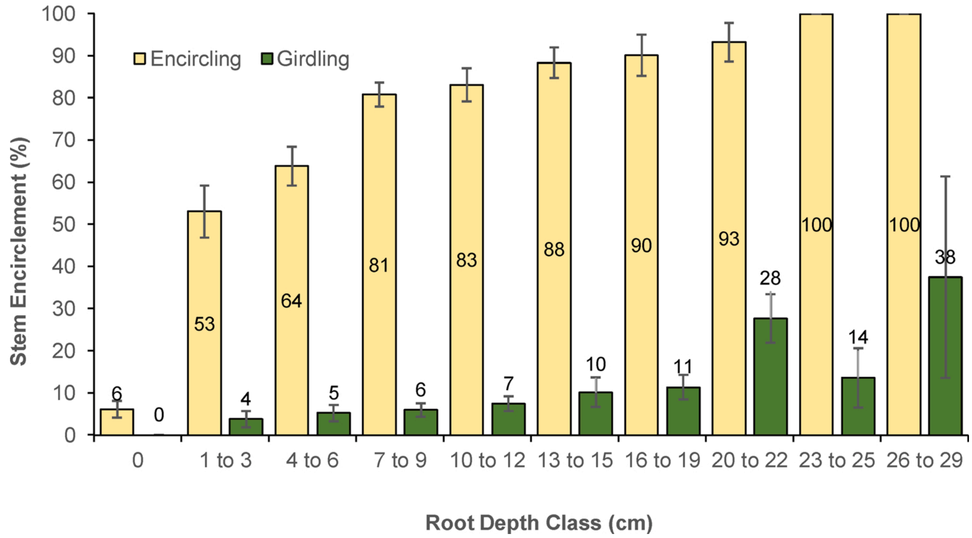

Fig. 4. Relationship of depth from soil surface to structural roots on percentage encircling roots (within 15 cm and no stem compression) and stem girdling roots (causing stem compression) of stem circumference. (Bars are standard errors).

Table 3
Model 1 testing the relationship of stem diameter, percent stem girdling root, boulevard width, and root depth on tree condition of *Fraxinus pennsylvanica* and *Tilia cordata*.

	Unstandardized Coefficients		Standardized Coefficients	*t*-test Statistics		Correlations	
Model Variables	B	Std. Error	Beta	*t*-value	Sig.	Zero-order	Partial
Initial full Model (R^2 =.127 R^2_{adj} =.109, std. error of est. = 11.245, F(4,194) =7.095, p < .0001)							
(Intercept)	57.353	5.778		9.926	0.000		
Stem Diameter (cm)	−0.215	0.182	−0.081	−1.176	0.241	−0.094	−0.084
Stem Girdling Root (%)	−0.124	0.069	−0.130	−1.807	0.072	−0.140	−0.129
Boulevard Width (m)	12.581	2.848	0.299	4.417	0.000	0.290	0.302
Root Depth (cm)	−0.217	0.145	−0.107	−1.498	0.136	−0.136	−0.107
Final a priori Model (R^2 =.113, R^2_{adj} =.104, std. error of est. = 11.277, F(2,196) = 12.495, p < .0001)							
(Intercept)	51.546	4.469		11.534	0.000		
Stem Girdling Root (%)	−0.164	0.065	−0.171	−2.527	0.012	−0.140	−0.178
Boulevard Width (m)	12.935	2.847	0.307	4.543	0.000	0.290	0.309

Table 4
Model 2 testing the relationship of stem diameter, presence of stem girdling root, boulevard width, and root depth on tree condition of *Acer saccharum*, *Celtis occidentalis, Fraxinus pennsylvanica*, and *Tilia cordata*.

	Unstandardized Coefficients		Standardized Coefficients	*t*-test Statistics		Correlations	
Model Variables	B	Std. Error	Beta	*t*-value	Sig.	Zero-order	Partial
Initial full Model (R^2 =.363 R^2_{adj} =.353, std. error of est.=14.606, F(6,391)=37.13, p<.0001)							
(Intercept)	81.145	3.352	24.207	0.000			
Stem Girdling Root[a]	−4.625	1.700	−0.119	−2.720	0.007	−0.265	−0.136
Root Depth (cm)	−0.398	0.121	−0.144	−3.281	0.001	−0.252	−0.164
Stem Diameter (cm)	−0.194	0.172	−0.046	−1.126	0.261	−0.033	−0.057
F. pennsylvanica[a]	−3.924	2.068	−0.094	−1.898	0.058	−0.214	−0.096
A. saccharum[a]	−4.245	2.084	−0.102	−2.037	0.042	−0.225	−0.102
C. occidentalis[a]	19.036	2.145	0.449	8.876	0.000	0.558	0.410
Final a priori Model (R^2 =.361 R^2_{adj} =.353, std. error of est.=14.611, F(5,392)=44.27, p<.0001)							
(Intercept)	78.024	1.884		41.425	0.000		
Stem Girdling Root[a]	−4.875	1.686	−0.126	−2.892	0.004	−0.265	−0.145
Root Depth (cm)	−0.379	0.120	−0.137	−3.152	0.002	−0.252	−0.157
F. pennsylvanica[a]	−4.090	2.064	−0.098	−1.982	0.048	−0.214	−0.100
A. saccharum[a]	−4.417	2.079	−0.106	−2.124	0.034	−0.225	−0.107
C. occidentalis[a]	18.865	2.140	0.445	8.815	0.000	0.558	0.407

[a] Bivariate indicator with 1 = presence.

In terms of the relationship of depth to structural roots and the frequency of stem encircling and girdling roots, findings from this study were largely consistent with several similar studies despite the variety of species and sizes investigated (Wells et al., 2006; Day and Harris, 2008; Gilman et al., 2010a, 2010b). Having stated that, not all studies found that relationship. Watson et al. (1990) were unable to discern a

Table 5
Relationship of stem diameter and root depth on percentage of stem circumference with root encircling in *Celtis occidentalis, Fraxinus pennsylvanica*, and *Tilia cordata*.

	Unstandardized Coefficients		Standardized Coefficients	*t*-test Statistics		Correlations	
Model Variables	B	Std. Error	Beta	*t*-value	Sig.	Zero-order	Partial
Final a priori Model (R^2 =.629 R^2_{adj} =.624 std. error of est.=23.542, F(4,293)=124.40, p<.0001)							
(Constant)	52.648	6.071		8.672	0.000		
Stem Diameter	−0.908	0.309	−0.106	−2.941	0.004	−0.206	−0.169
Root Depth (cm)	3.275	0.208	0.579	15.782	0.000	0.680	0.678
T. cordata[a]	15.518	3.329	0.192	4.662	0.000	0.428	0.263
C. occidentalis[a]	−22.031	3.396	−0.268	−6.487	0.000	−0.492	−0.354

[a] Bivariate indicator with 1 = presence.

Table 6
Relationship of stem diameter and root depth on percentage of stem circumference with stem girdling roots of *Celtis occidentalis, Fraxinus pennsylvanica*, and *Tilia cordata*.

	Unstandardized Coefficients		Standardized Coefficients	*t*-test Statistics		Correlations	
Model Variables	B	Std. Error	Beta	*t*-value	Sig.	Zero-order	Partial
Final a priori Model (R^2 =.194 R^2_{adj} =.189 std. error of est.=13.857, F(2,295)=35.61, p<.0001)							
(Constant)	−11.118	3.323		−3.346	0.001		
Stem Diameter	0.618	0.181	0.180	3.412	0.001	0.130	0.195
Root Depth (cm)	0.962	0.119	0.424	8.066	0.000	0.403	0.425

significant relationship between planting depth and the number of stem encircling or girdling roots, despite the fact that their study included three of the four species in this study with similar sizes. However, the numbers of sampled trees per species may have contributed to those differences. The Watson et al. (1990) study included 15 *Acer saccharum*, 10 *Fraxinus pennsylvanica*, and 10 *Tilia cordata*, whereas this study included 100 *Acer saccharum*, 101 *Fraxinus pennsylvanica*, and 101 *Tilia cordata*.

Most root depth studies have been with Angiospermous deciduous trees. In palms, deep planting is regularly done for perceived stability post planting. *Phoenix roebelenii* O'Brien planted at their original depth had greater root development than those planted 15–90 cm deep. The deepest treatment had 40 % survival after 15 months post-transplanting. Thus, the relationships of buried roots systems occur from both monocots and dicots. Monocots such as palms also regularly develop adventitious roots which could aid survival from deep planting.

Root systems are opportunistic and grow in areas suitable for growth. Wagar (1985) observed that trees planted deeply had roots that grew to the surface. Horizontal root growth then resumed at the surface, however the direction (*e.g.*, towards or away from stem) was not reported. In this study we observed *Tilia cordata* and *Acer saccharum* had roots that grew vertically to the surface and did not always radiate away from the stem upon resumption of horizontal growth. A "random like" horizontal direction occurred with some roots growing towards the stem (Johnson and Hauer, 2000).

When horizontally growing lateral roots are deflected up to 30° from the original plane of growth, they tend to radiate in the original horizontal direction after growing beyond the deflecting barrier (Wilson, 1967). If the deflection was greater than 30°, however, the root did not fully return to the original plane of growth. When the barrier was 60° to 90°, the angle of deflection was approximately 35° to 45°. This raises an interesting question with deep structural roots: "what direction do lateral roots proceed after returning to a horizontal direction from a vertical ascent?" Thus, if the lateral roots radiate toward rather than away from the stem, this could result in a stem girdling root situation. The horizontal direction that the roots follow after a vertical ascent is uncertain and was not ascertained in this study.

Soil oxygen concentration affects root growth. As depth from the soil surface increases, soil oxygen levels are likely to decrease to levels that affect root respiration. Lemon and Erickson (1952) measured oxygen diffusion rates (ODR) of three different soil textures (fine to coarse) at depths to 20 cm. For each 2.5 cm in depth, soil ODR declined at significant rates, especially with fine textured soil such as a clay. At 20 cm, the ODR in a clay soil approached zero. MacDonald et al. (1993) found a correlation between soil ODR and the relative health of oaks in a California landscape, to wit, the lower ODR was associated with declining mature oaks, higher ODR was associated with healthy mature oaks. Both research studies noted that ODR is a function of soil texture, soil bulk density (compaction), and soil moisture. Oxygen diffusion rates decline the fastest with depth when the soil is a compacted, more so with fine textured soil with a higher moisture content. Thus, opportunistic root growth into soil closer to the surface may explain root growth from lower soil depths towards the surface and later growth towards a buried stem and lead to stem encircling or stem girdling roots.

4.2. Tree lawn width and stem girdling root development

We found no relationship between the distance between the curb and sidewalk and stem girding root development. This finding is consistent with Tate (1980, 1981b) who also found no relationship between tree lawn width and girdling root development. Regardless, space to grow street trees is important and a predictor for tree health (Hauer et al., 2020; Hilbert et al., 2020).

4.3. Tree condition, growth, and stability

Tree survival and tree condition are factors associated with stem girdling roots and root depth. We found trees with stem girdling roots to have a 10 % lower tree condition rating and all things considered would likely be a stress factor, leading to secondary (opportunistic) biotic agents and tree decline (Clark and Matheny, 1991). And we also found as the percentage of the stem with stem girdling roots increased, tree condition decreased. Stem and collar cankers were associated as secondary decline factors with *Acer saccharum* in deeply planted (15–25 cm) street trees (Drilias et al., 1982). Soil against trees stems can also lead to pathogen colonization in landscape trees with deep structural roots (Smiley, 2005).

Reduced tree survival was found with *Prunus* × *yedoensis* Matsum. with 50 % of deeply planted trees dead after 2 years compared to no mortality with at grade planted trees (Wells et al., 2006). Day and Harris (2008) found greater mortality (40 %) in *Corylus colurna* L. after 8 years in trees planted 30 cm deep compared to 0 % for those at grade and 15 cm. Reduce growth was also found for trees 7.6 cm planted deep *Fraxinus pennsylvanica* and *Platanus occidentalis* L., *Lagerstroemia indica* ×

Lagerstroemia fauriei, and *Nerium oleander* L. versus trees above 7.6 cm) grade or above (Arnold et al., 2007). Results were varied by planting depth with trees planted 5.0 and 7.6 cm deep having greater survivability than trees planted at grade or 15.2 cm deep (Browne and Tilt, 1992)

Tree growth provides a mechanism to indirectly assess tree health with the premise growth is an end result of carbon assimilation (Pallardy, 2008). Studies vary in the relationship of planting depth on growth difference with no difference (Gilman and Anderson, 2005; Gilman et al., 2010a) versus reduced growth (Arnold et al., 2005; Gilman et al., 2010a; Gilman and Grabosky, 2011). Differences seem to relate to the length of the study and species used. For example, Arnold et al. (2005) found *Koelreuteria bipinnata* A.R. Franchet (a hypoxia intolerant species) had greater mortality than *Fraxinus pennsylvanica* (a hypoxia tolerant species), however, both species had less growth than trees planted at or above grade (7.6 cm) than planted deep (7.6 cm).

While not a part of this study, tree stability may be impacted by planting depth. Deeply planted (20 cm) *Malus domestica* Borkh. were more prone to wind shaking trees loose than trees planted at the grade from the nursery (Lyons et al., 1983). Deeply planted peach trees were less stable than those with the first main-order root system at grade (Lyons and Yoder, 1981). Thus, deep planting may affect tree stability (Lyons et al., 1987; Arnold et al., 2005, 2007).

4.4. Study limitations

This investigation used trees that were approximately one to two decades old. This age class was selected based on preliminary observations suggesting a relationship with structural root depth and tree condition, stem encircling roots, and stem girdling roots. It is possible that trees as they become older could compensate for stem compression by adaptive growth of stem tissue in another location. While possible, we found that as a tree grows, stem encircling roots become girdling roots and the percent of stem tissue compressed increases with an approximate 10 % greater stem compression for the largest versus smallest trees in the study. Trees with stem girdling roots had a lower overall condition rating (68.7 %) versus those without (79.0 %).

We defined a stem girdling root as one causing some degree of stem compression including bark and functional sapwood. At the initial stage of stem contact, compression might only consist of minimal tissue dysfunction. With time, compression becomes more severe and acute relationships on tree health and condition become a potential end result. Thus, the actual relationship of stem girdling roots changes over time. An absolute examination of tissue compression was beyond the scope of this study.

Finally, trees typically have multiple stress factors (*e.g.*, soil compaction, water deficits, de-icing salts, insects, disease, root damage, stem damage) at any one time or over the course of time that affect tree health (Clark and Matheny, 1991). While being able to quantify all factors affecting tree condition would likely increase the overall predictive nature of a model, this was beyond the scope of this paper. None-the-less, results from this study suggest that planting depth and presence of girdling roots should be considered in models that test and predict the decline of trees in urban and suburban landscapes.

5. Conclusion

In situ studies are always confounded by unintentional and sometime unseen variables. However, the data collected from this study combined with the robustness of the sample size, and the analysis of said data presents a conclusion that is unlikely to be coincidental and is supported by past research. Incremental additions of soil over the structural root systems of younger trees (approximately 20 years or less) did affect the condition of these four species, did increase the frequency of stem encircling roots, and did increase the frequency of stem girdling roots. How tree root systems come to be excessively buried by soil is varied and a challenge to correct. Many of the problems with deeply buried structural roots and tree stems can be corrected or avoided at planting time, but only addressing planting practices is a very limited management perspective. Sound management practices should include regular monitoring and correction of any situations that place additional depths of soil or pre-soil (aka, organic mulches) against the stems and over the structural roots of trees, especially those trees in their first two decades of life and service to the landscapes.

CRediT authorship contribution statement

Richard J. Hauer: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Gary R. Johnson:** Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

We have no conflict of interest in the reporting of our research results.

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Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2021.127031.

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