Getting to the Root of Tree Stress along Highways©

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Soil compaction has been identified as a major contributor to urban tree failure. In order to develop criteria to increase rates of survival of outplanted trees in roadside environments this study investigated the influence of bulk density as an indicator of soil compaction on tree morphology and physiology. In 2012, four # 10 container-grown tree species were planted into a total of 37 quadrats at two highway interchanges in the Niagara Region, Ontario, Canada. Four data collection cycles were conducted and measurements included: tree height, caliper as well as chlorophyll content of leaves, soil moisture tension and stomatal conductance. The soil texture was mainly comprised of fine particles (clay and fine silt). Average soil bulk density for Site 1 was 1.45 g·cm^{-3} and was 1.55 g·cm^{-3} for the 0-10 and 20-30 cm depth respectively. For Site 2, the average soil bulk density was 1.49 g·cm^{-3} and 1.67 g·cm^{-3} for the 0-10 and 20-30 cm depth respectively. The results suggest soil bulk density was consistently above root limiting levels at both sites for samples collected at the 20-30 cm depth. These findings illustrate the importance of developing root systems with shallow structural roots that are radially oriented around the trunk in the nursery for trees that will be outplanted into urban soils.

INTRODUCTION

Many nursery growers are tasked with producing trees that will be transplanted into urban environments. In fact, in Canada, of the $644,677,730 total nursery sales reported in 2010 $73,344,000 (11%) were direct sales to the public, $158,838,795 (25%) were sales to landscape contractors, $40,960,970 (6.5%) were sales to government and public agencies, $86,570,130 (13%) were sales to mass retail stores (Statistics Canada, 2012). The lesson here is that trees produced in the nursery in Canada and elsewhere in North America will likely end up in an urban or residential setting where the soil has been subjected to construction practices that have altered the physical characteristics of the soil ecosystem. It is important for producers to understand the challenges that their material will face once outplanted into these types of environments in order to better condition the plant material for survival. One consideration that has been investigated is the influence that production-type (e.g. field-grown versus container-grown) has on survival of trees transplanted into urban soils, for instance work by Gilman and Anderson (2006) investigates how production methods influence growth post-transplant. Conversely, the soil that the trees will be transplanted into is another important consideration for growers that are marketing their products to locations that are heavily impacted by construction like an urban transportation corridor.

Overcoming the barriers that result in low rates of tree establishment after transplanting is critical for roadside ecosystem transplanting success (Haan et al., 2012). In fact, Nowak et al. (2004) found that tree mortality was higher in land types classified as "transportation" compared to other urban land classifications. Newly planted trees tend to die at a higher rate than established trees (Miller and Miller, 1991; Nowak et al., 2004) because the healthy soils that promote early vigorous growth are absent (Pavao-Zuckerman, 2008). Soil compaction at urban sites has been identified as a primary driver of tree mortality (Day et al., 2010; Haan et al., 2012; Oldfield et al., 2014). For instance, silty clay soils with bulk density values of 1.49 g·cm^{-3} are root limiting and 1.58 g·cm^{-3} and above are root restricting reducing the root and shoot growth of newly planted trees by 50% (Watson and Himmelick, 2013). During road construction the topsoil layer is removed and subsoil is returned to the site to be graded and compacted (Haan et al., 2012; Watson and Himmelick, 2013). In compacted soil, pore space is limited thereby limiting oxygen and water (Sinnett et al., 2008). Oldfield et al. (2014) found that sapling growth and survival was improved across time after site preparation, which resulted in reductions in bulk density from ~1.4 to 0.72 g·cm^{-3}.

Haan et al. (2012) illustrated that choosing appropriate plant species for roadside planting remains very challenging because of poor soil physical conditions and is exacerbated by the lack of post-transplant maintenance. Because safe access of highway planting sites requires preparation and planning and it becomes very expensive and the sheer volume of planted areas often makes it untenable. Death linked to transplant failure typically tapers off after 5 years (Koeser et al., 2013) but trees in poor site conditions begin dying in years 1-3 at higher rates (Nowak et al., 2004). In order to better understand the stress response of transplanted highway trees we designed a non-destructive study to mimic current practices in roadside tree planting contracts by planting the trees in to unprepared soil that tracks the transplanted trees for 5 years. So far we evaluated the survival and growth of four tree species at two sites from May to October of 2013 and again in June 2014. The aim of this study is to investigate the effects of soil compaction on bulk density and the potential influence of bulk density on: (1) growth, (2) soil moisture tension, (3) stomatal conductance and, (4) total chlorophyll content of leaves in Years 1-5 after transplanting.

METHODS

Study Sites

Two sites were selected along Highway 406 (southern Ontario, near Niagara Falls) at St. Davids and Beaverdams Road (hereafter known as Site 1 and Site 2, respectively). These sites were selected as they have been undisturbed since ~1965 when they were developed and the soil was compacted. For the region, mean annual temperature for 2013 was ~9°C with an annual precipitation of ~1100 mm (Table 1). Soil chemical analysis revealed that both sites had calcareous, low organic matter soil with low total salt concentrations (identified using soil electrical conductivity; Table 2).

In the fall of 2012, four cultivars grown in #10 containers were planted at both sites which included Freeman maple (*Acer × freemanii* 'Jeffersred', Autumn Blaze® Freeman maple), common hackberry (*Celtis occidentalis* L.), honey locust (*Gleditsia triacanthos* L.), and eastern redbud (*Cercis canadensis* L.). At both sites, trees were randomly planted in set blocks of 15 trees. At Site 1, six blocks of *A. × freemanii* and five blocks of *C. occidentalis*, *G. triacanthos*, and *C. canadensis* were planted. At Site 2, four block of each species were planted.

Table 1. Mean monthly temperature (°C) and total monthly precipitation (mm) for the Niagara region. Climate normal data for mean annual temperature and mean annual precipitation is also included (1981-2010; <http://climate.weather.gc.ca/>).

Month	Temperature (°C) 2013	Precipitation (mm) 2013	Temperature (°C) 1981-2010	Precipitation (mm) 1981-2010
May	15.10	88.00	12.79	76.35
June	19.10	142.60	18.27	84.90
July	22.60	111.40[a]	20.85	100.66
August	21.00	61.50	19.95	79.16
September	16.70	76.40	15.83	81.85

[a]July 19th ~65 mm of precipitation fell.

Table 2. Soil chemical analysis for highway sites [N = 36 (Site 1) and 32 (Site 2)].

Properties	Units	Site 1	Site 2
pH		7.79	7.77
Organic matter	%	3.82	3.20
Total salt	mmhos·cm^{-1}	0.44	0.41
Phosphorus	mg·kg^{-1}	8.65	6.66
Potassium	mg·kg^{-1}	94.72	91.07
Calcium	mg·kg^{-1}	4571.21	4357.27
Magnesium	mg·kg^{-1}	308.62	297.56
CEC	meq·kg^{-1}	2.69	2.57

Field Sampling and Lab Analysis

1. Tree Response Analysis. Repeated growth and stress parameters on a sub-set (219 of the total 552) of the planted trees were conducted at the beginning of each month from June to September. Prior to the field assessment, six trees were randomly selected per quadrat for repeated measurements. From the selected trees three branches were flagged for analysis. Growth parameters included tree height and caliper (at 30 cm for determination of trunk cross sectional area [TCSA]). Growth rates were determined for tree height and TCSA by subtracting the initial season growth (June data) from the final growth measurement taken in September. Chlorophyll content (-9.9 to 199.9) was measured using an indexed reading chlorophyll meter (SPAD 502 Plus Chlorophyll Meter, Spectrum Technologies, Inc., Aurora, Illinois) for the first three shoots of each flagged branch. Leaves for chlorophyll measurements were randomly selected along each shoot. Stomatal conductance (g_s; mmol·m^{-2}·s^{-1}) was measured using a steady state porometer reading (Decagon SC-1 Leaf Porometer, Decagon Devices, Inc. Pullman, Washington) in the upper exterior portion of the canopy on a leaf exposed continuously to sunlight. Porometer readings were only conducted on clear sunny days between 11:45 to 14:15.

2. Soil Measurements and Analysis. Soil moisture tension (-kPa) was measured using a tensiometer (2900F1L 18 Quick Draw Moisture Probe, Soil Moisture Equipment Corp., Santa Barbara, California) for each of sub-sample trees.

Soil chemical analysis was conducted on samples collected at a depth of 0-10 cm at both Site 1 (*n*=36) and Site 2 (*n*=32). Samples were sent to SGS Agrifood Laboratories <http://www.agtest.com/index.cfm> for chemical analysis; pH, organic matter percentage, total salt, phosphorus, potassium, calcium, zinc, magnesium, and cation exchange capacity (Table 2). Continuous (weekly) total salt content in the soil was also monitored during spring snow melt (monitoring period 17 Apr. to 1 May 2013) to access salt concentration and movement. However, we found that during spring melt, when highest concentrations of salt are entering the soil due to winter accumulation of de-icing agents (NaCl), total salt content (based on electrical conductivity) was low. Maximum conductivity was below 2 mS·cm^{-1}, which is an indication that salt content was not entering the soil column but mostly removed by surface runoff.

Bulk density (Bd) soil samples were collected at two depths; 0-10 cm and 20-30 cm, using a hammer corer (core height: 51 mm and width 50 mm) at Site 1 (*n*=96) and Site 2 (*n*=64). These depths were selected to represent soil from the A and top of the B horizons. Prior to analysis samples were stored at 4°C. Bulk density samples were weighed; to determine field moisture weight before drying at 105°C for 24 h. Once dried, samples were weighed to determine dry weight and then sieved using a 2-mm sieve to remove any coarse debris (i.e., roots, rocks). Coarse fragments (>2 mm) were removed and weighed and the density of the coarse fragments (per sample) were also determined by measuring the water displacement of the coarse material. On all Bd samples, loss-on-ignition (LOI) was preformed to estimate organic matter content of the soil. Soils were ignited at 375°C for 16 h (Ball, 1964).

Soil texture [percent sand (2000-60 µm), silt (60-8 µm), and clay (<2 µm)] was determined using a Horiba Partica LA-950 Laser Diffraction Particle Size Analyzer (Whitfield and Watmough, 2012). A higher range for clay size was used (<8 µm) based off the recommendations from Konert and Vandenberghe (1997). The soil was not pretreated before analysis due to the low organic matter content. Soil particle density was determined following a similar method to Klute (1986) and Rowell (1994). Particle density was determined by water displacement in a volumetric flask at constant water temperatures (30-35°C). Samples were heated to remove any air bubbles, which could influence the sample volume. Porosity was then estimated by using the particle density and soil Bd.

3. Statistical Analysis. The relationship between average block soil Bd and tree growth could not be assessed due to the fact that the majority of the Bd samples were over the root limiting levels. Similarly, average block Bd could not be assessed to total chlorophyll content or stomatal conductance.

Regression analysis was carried out between soil Bd and moisture (g [water]/g [dry soil]) percentage. Regression analysis was also conducted between soil Bd and moisture tension (-kPa). Prior to regression analysis, variables were tested for normality using the Shapiro-Wilt test ($p>0.05$). All statistical analysis was conducted using Systat 13.1 (Cranes Software International Ltd.).

RESULTS

Survival

Winter survival of *A. × freemanii*, *C. occidentalis,* and *G. triacanthos* was high after the Fall 2012 planting. In contrast, *C. canadensis* had a low winter survival rate (Site 1 – 64% and Site 2 – 25%; Table 3). From June to September, at both sites for *C. occidentalis* and *C. canadensis* a few trees were lost due to accumulated stress. The September 2013 survival percentages represent survival rates 1 year after planting. In June 2014, tree survival was again assessed to evaluate the rate of survival after a second winter period. Survival rates decreased for all species, including *A. × freemanii* that had a 100% survival rate prior to the 2014 winter.

Table 3. Sites 1 and 2 tree survival (%) from June 2013 to June 2014.

Species	Site 1			Site 2		
	June (2013)	September (2013)	June (2014)	June (2013)	September (2013)	June (2014)
	Survival (%)	Survival (%)	Survival (%)	Survival (%)	Survival (%)	Survival (%)
Acer × freemanii	100	100	90	100	100	90
Celtis occidentalis	96	93	79	97	90	86
Gleditsia triacanthos	99	99	84	98	98	86
Cercis canadensis	64	60	49	25	21	5

Tree Growth

Tree growth (height) was determined to be higher at Site 1 compared to Site 2 for all species (Table 4). *Acer × freemanii* was determined to have the highest growth rate, compared to *C. occidentalis*, *G. triacanthos*, and *C. canadensis*. A slight decrease in average height was observed at Site 2 for *G. triacanthos* and *C. canadensis*, this was due to tissue dieback on the tree during the summer months. Overall for TCSA, positive growth rates were determined for all species at both sites.

Table 4. Average site growth rates for tree height, shoot length and trunk cross sectional area (TCSA).

Species	Site 1		Site 2	
	Height (cm)	TCSA (mm^2)	Height (cm)	TCSA (mm^2)
Acer × freemanii	18.84	87.27	11.96	126.00
Celtis occidentalis	8.12	48.58	0.62	65.08
Gleditsia triacanthos	2.99	39.58	-3.23	49.44
Cercis canadensis	3.78	32.14	-9.31	23.43

Soil Physical Analysis

Average Bd was significantly higher ($p<0.05$) at Site 2 for the sub-soil (20-30 cm; Table 5). No significant difference was observed with the topsoil (0-10 cm). A wide range for soil Bd was observed at Site 1 (min – 1.16 $g \cdot cm^{-3}$ and max – 1.81 $g \cdot cm^{-3}$), compared to Site 2 (min – 1.34 $g \cdot cm^{-3}$ and max – 1.83 $g \cdot cm^{-3}$) at a depth of 0-10 cm. In contrast, at a depth of 20-30 cm, smaller ranges between min and max variables were observed. Overall, average Bd at both sites was 1.47 $g \cdot cm^{-3}$ (0-10 cm) and 1.60 $g \cdot cm^{-3}$ (20-30 cm). Based on the samples collected, 40 and 81% were above the root limiting levels for Bd (limit 1.49 $g \cdot cm^{-3}$) and 15 and 56% were above the root restriction level (>1.58 $g \cdot cm^{-3}$) for the 0-10 and 20-30 cm depth respectively. Soils collected for Bd were analyzed for coarse debris (rocks, roots, etc.), which has the potential to drastically influence soil density. Overall, the majority of soil samples collected contained no coarse debris.

Table 5. Minimum, maximum and average bulk density for Sites 1 and 2 soil at two depths (0-10 and 20-30 cm).

Site	Depth	Bulk density		
		Minimum	Maximum	Average
1	0-10	1.16	1.81	1.45
1	20-30	1.30	1.77	1.55
2	0-10	1.34	1.83	1.49
2	20-30	1.49	1.94	1.67

Soil Moisture and Tension

Two snap-shot methods to assess soil moisture were used; soil collection with oven drying and using a soil tensiometer. A significant negative relationship was determined between soil percent moisture (g [water]/g [dry soil]) and Bd (Fig. 1). Similar significant relationships were observed with LOI and porosity. In contrast no relationship was observed between clay content and moisture. Based on visual inspection of the data, soils that contained a Bd less than 1.49 $g \cdot cm^{-3}$ were more likely to have higher but more variable percent moisture. Soils with a Bd of 1.49 $g \cdot cm^{-3}$ or greater had a steady decrease in percent moisture. Soil tension measurements were taken monthly (from June to September). Values from the tensiometer were typically over the tension capabilities for the meter (> 80 centibars of soil suction), which made it impossible to determine if a relationship existed between the soil characteristics and moisture tension.

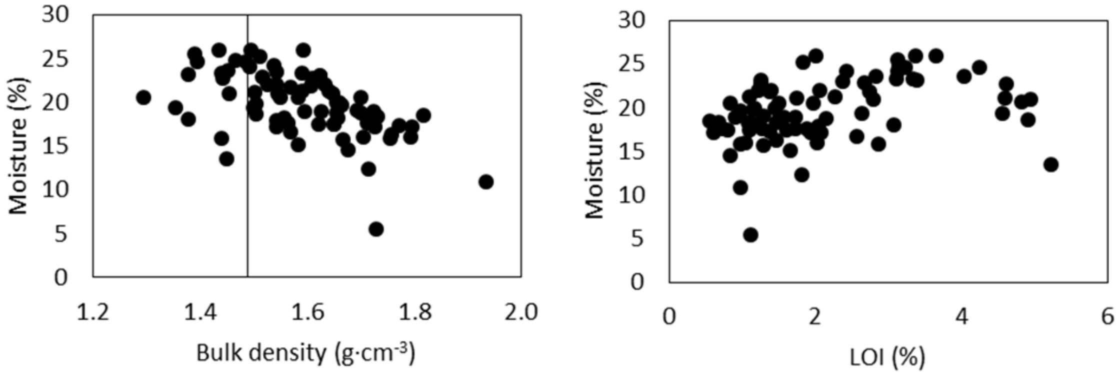

Fig. 1. Response of soil moisture to bulk density (left; g·cm^{-3}) and organic matter content (loss on ignition %; right). The solid vertical line (left) indicate soil bulk density at 1.49 g·cm$^{-3.}$

Stomatal Conductance and Total Chlorophyll Content of Leaves

Although no regression analysis was performed patterns based on monthly observations emerged in the dataset. In July, all of the tested species were considered the most stressed which was observed with the low stomatal conductance (Table 5). The highest values for stomatal conductance (least stressed) were observed in September. Peak chlorophyll content for each tree species was determined in the month of July (Table 6). Overall, a gradual decrease in chlorophyll content was observed in August and then again in September (data not shown).

Table 5. Average stomatal conductance (mmol·m^{-2}·s^{-1}) for each tree species for July, August and September.

Species	July	August	September
Acer × freemanii	70.66	171.50	199.14
Celtis occidentalis	65.20	165.53	257.27
Gleditsia triacanthos	76.38	195.95	197.35

Table 6. Minimum, maximum and average chlorophyll (SPAD) content for each tree species in July.

Species	Min	Max	Average
Acer × freemanii	24.41	29.05	26.73
Celtis occidentalis	21.13	26.74	23.36
Gleditsia triacanthos	25.65	39.87	35.05

DISCUSSION

The bulk density samples that were collected across both sites were above root limiting ranges for the soil type (40% [0-10 cm] and 81% [20-30 cm] were above 1.49 g·cm^{-3} for silty clay soils) if not above root restricting values (15% [0-10 cm] and 56% [20-30 cm] were above 1.58 g·cm^{-3}) (Watson and Himmelick, 2013). Even after ~45 years for potential recovery, compaction impacts were still observed at levels that influence tree roots and survival.

Day et al. (2009) argues that when trees leave the nursery and have developed deep structural roots and roots that are not radially oriented, establishment in the landscape is more difficult. This is particularly a problem when weak or deep primary roots encounter the compacted or poorly drained soils close to the surface in urban environments. When the conditions in the lower soil profile are less favourable than those near the surface structural roots, and as a result tree establishment, can be inhibited. Arnold et al. (2007) found that planting small [9.3 L (3 gal)] container-grown trees as little as 7.5 cm below grade decreased survival and growth of all but one of five taxa, as the trees were planted into a sandy-loam soil (15-30 cm) over a hard-pan clay.

Tree roots respond to the stress that results from being transplanted into compacted soils and low O_2 by concentration of root growth closer to the soil surface. Gilman et al. (1987) found that roots that are lower than 12 cm below the soil line at planting grew toward the soil surface and were most prevalent in the topmost centimeters of the soil volume. Managing root growth during production, especially of root distribution and depth in the nursery is vital for woody species that will be transplanted into compact soils in the urban environment. Gilman et al. (1987) found that *G. triacanathos* var. *inermis* seedlings had significantly shallower roots in compacted soils with more of the roots distributed into the upper soil layers. Additionally, many of the roots were directed up towards the soil surface from the deeper soil layers. Our findings regarding the influence on tree growth corroborate the findings from other tree studies that have investigated urban tree survival in compacted soils (e.g., Gilman et al., 1987; Arnold et al., 2007; Day et al., 2009). The growth of primary roots slows when it encounters denser, less aerated conditions of deeper soil conditions, which according to our findings can actually occur in the 0-10 cm range of compacted soils.

Dirr (1998) classifies woody vegetation as slow (less than 30 cm growth annually) medium (30-60 cm), and fast growing (more than 60 cm annually). *Cercis canadensis* is considered to have a medium growth rate (Dirr, 1998) but average growth was 0.04 cm at Site 1 and -0.09 cm at Site 2 (the negative value is an artefact of tissue dieback during the season). The average vertical growth of *G. triacanthos* planted in the USA was 49 cm per year during the first 7 years and when well established the annual diameter growth is 8 to 13 mm (Blair, 1990). *Celtis occidentalis* growth can be as much as 8 mm in diameter annually on alluvial soils (Krajicek and Williams, 1990) and slow growth and dwarfing is an indicator of poor soil conditions. *Acer* × *freemanii* performed the best in terms of growth for the first season after transplant. Fair et al. (2012) found *A.* × *freemanii* 'Celzam', Celebration® maple was not affected by soil compaction and put on significantly more caliper than all other cultivars despite compaction. Different cultivars responded differently to soil compaction; some cultivars of *A.* × *freemanii* are more capable of increasing caliper growth in high bulk density soils. Even for *A.* × *freemanii* cultivars however, high density soils have been reported to result in significantly smaller aboveground biomass, than those growing in non-compacted plots (Fair et al., 2012). For instance, for some cultivars growing in non-compacted plots increased caliper on average 83% more than trees growing in the compacted plots. Commonly, the effects of soil compaction on root growth of woody species precede the effects on shoot and diameter growth (Tardieu et al., 1991; Kozlowski, 1999). Our hypothesis that the suboptimal vegetative growth recorded during this study is a result of the consistently high bulk density is corroborated by Arnold et al. (2007); they found that planting below-grade into hard-pan clay significantly reduced the height growth and trunk cross-sectional area of four of five taxa. Additionally, Amoroso et al. (2010) reported that container-produced trees with root deformations from production exhibit higher levels of stress and reduced growth when compared to trees without root deformations. Height, caliper, and shoot growth in Year 2 could be decreased as vegetation growth outstrips root mass accumulation.

Héroult et al. (2013) found that stomatal conductance for *Eucalyptus* spp. was distinctly lower during a drought event compared with later in the season. Zwack et al. (1998) reported measurements of 43 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ during the fourth drought cycle for *A.* × *freemanii* cultivars which is consistent with the low average stomatal conductance values we observed in July for all species (65.20, 76.38, and 70.66 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for *C. occidentalis*, *G. triacanthos*, and *A.* × *freemanii*, respectively). Precipitation for July

(2013) was ~110 mm (climate normal ~100 mm [1981-2010]; Table 1). July precipitation was inflated with a one-day heavy rainfall event (~65 mm fell). With the elimination of that extreme event, July was a warm, dry month with ~45 mm of rain. The values for stomatal conductance are high (values for species increased in August and again in September). Additionally, Zwack et al. (1998) reported stomatal conductance as 255 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at container capacity for *A.* × *freemanii* cultivars. The averages for September for *A.* × *freemanii*, *C. occidentalis*, and *G. triancanthos* (199.14, 257.27 and 197.35 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively) therefore appear high. However, a more in depth, multi-year study that includes various treatments for soil Bd levels would help to better explain this relationship for the species tested.

The values from the tensiometer were typically over the tension capabilities for the meter (>80 centibars of soil suction), making it impossible to determine if a relationship existed between the soil characteristics and moisture tension. However, Fair et al. (2012) found that compacted soils held water more tightly at the higher tension and less water is available for trees. Day et al. (2000) found *Acer saccharinum*'s (L.) roots were capable of penetrating compacted soils at saturation but *Cornus florida* (L.) was not. During heavy inundation of precipitation the voids in the soil may completely be occupied by water and air would be absent (Jim, 1998; Watson and Himmelick, 2013). This may explain why bottomland species like *A. saccharinum* and *C. occidentalis* are more adaptable in compacted urban soils. In the clay-based soils in the study by Fair et al. (2012) the authors report that hydraulic conductivity was significantly reduced due to compaction, and the higher density soils led to a reduction in above ground biomass for the majority of the samples that were tested.

Although survival after Year 1 was high, after the second winter, survival was reduced for all species. Miller and Miller (1991) found that much of the mortality associated with newly planted street trees (4-5 cm caliper) occurs 1 to 2 years after installation. The generally poor survival rate of *C. canadensis* may be attributed to the source of the propagative material. For instance, *C. canadensis* plants of southern origin were slower to enter dormancy under shorter days (Donselman et al., 1982). We can also attribute the low survival of *C. canadensis* to the fact it does not grow well on flooded sites and cannot survive in poorly aerated soils (Dickson, 1990).

We conclude that high bulk density is a limiting factor for tree establishment in highway roadside plantings. It is particularly of concern because of the high bulk density observed at all of the soil sampling locations tested. Although this paper avoids discussion of specific root management practices in the nursery and instead focuses on root ecological interactions with the environment it is important for the nursery industry to understand the types of environments into which their products will be planted in order to better understand how to produce plants that are better equipped to deal with the conditions of urban soils. In particular, based on the soil conditions we have encountered practices that ensure shallow structural roots that are radially oriented around the trunk are better situated to make contact with the least compact volume of soil and begin accruing resources post-transplant and would increase survival.

ACKNOWLEDGEMENTS

Funding came from the Ontario Ministry of Transportation, Walker Industries Holdings Ltd., and Landscape Ontario. We thank Michael Brownbridge for his hard work getting the project running. We also thank A. Krzywdzinski for her work in the field and laboratory. A special thanks to P. Berketo and the Landscape Ontario Growers Group for all their help and advice.

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