Published in Urban Forestry & Urban Greening 4 (2006) 69-74

The impact of soil compaction on soil aeration and fine root density of *Quercus palustris*

Gary W. Watson[a,*], Patrick Kelsey[b]

[a]*The Morton Arboretum, Lisle, Illinois, USA*
[b]*Christopher B. Burke Engineering, Ltd, St. Charles, Illinois, USA*

Abstract

The soil around *Quercus palustris* trees, 30 cm (11.8 in) average diameter breast height (DBH) were treated by compaction (C) or C plus clay slurry (CS) treatments in November 1994 and repeated in May 1996. Soil oxygen diffusion rate (ODR), fine root density (FRD), DBH, twig growth, leaf area and dieback were monitored for 4 years beginning in 1996. Both compaction treatments significantly reduced ODR at 15 cm. Early each season, ODR was below the 0.20 g/cm^2/min threshold level reported to inhibit root growth in several species [Stolzy, L.H., Letey, J., 1964. Correlation of plant response to soil oxygen diffusion rates. Hilgardia 35, 567-576] for all treatments and depths. In summer each year, ODR was adequate in the shallow soils of all treatments, though often still significantly lower in compacted soils. At 30 cm, there were no consistent differences in ODR between compacted and uncompacted soil. Significant differences in FRD due to compaction treatments were inconsistent and limited to the upper 9 cm of soil in years 2 and 3. Reduced FRD in compacted soils may be a response to the reduced ODR in spring. There were no differences in DBH, twig growth, leaf area or dieback rating. Given the minimal difference in root growth, the lack of differences in top growth are understandable. This controlled study, and others preceding it, have failed to clearly show the underlying causes of tree decline and death commonly associated with soil compaction and addition of fill soil in real landscapes.

Keywords: Oxygen diffusion rate; Bulk density; Root growth

Introduction

Soil compaction (C) is common on construction sites (Lichter and Lindsay, 1994; Randrup, 1997). Decline and death of trees on construction sites is commonly attributed to soil compaction, and a resulting deterioration of the root environment. Compaction reduces total air-filled (noncapillary) pore space and reduces average pore size, increases mechanical resistance to root penetration, and can increase or decrease waterholding capacity, depending on the amount of compaction, and initial bulk density and pore size distribution. With the loss of macropore space, water infiltration and gas diffusion is reduced, soil oxygen concentration is decreased and carbon dioxide concentration can increase, possibly to toxic levels. This deterioration in quality of the soil environment renders the soil less favorable for root growth (Craul, 1992).Studies with tree seedlings in containers have shown that soil compaction reduces vertical root penetration (Zisa et al., 1980; Halverson and Zisa, 1982), but not total root weight of the seedlings (Halverson and Zisa, 1982). For newly planted *Gleditsia triacanthos* seedlings, compaction of field soils reduced vertical penetration and overall root development, but increased root length in the upper 2.5 cm of soil (Gilman et al., 1987). Root dry weight of *Forsythia ovata* was decreased by field soil compaction, but not root dry weight of *Cornus sericea* (Alberty et al., 1984). All of these studies used small, recently planted trees and shrubs and measured root growth into new soil. There have been no studies of the effects of soil compaction on the roots of existing large trees with already established root systems in urban landscapes.

Addition of compacted fill could produce some of the same effects as compaction. The fill layer would reduce air and water movement into the soil beneath. The equipment used to place the fill, as well as the weight of the fill itself, would result in some soil compaction, even if the existing soil was not deliberately compacted prior to adding the fill soil.

In a study of a limited number of sites in actual landscapes, Yelenosky (1963) reported that after nine months, oxygen content decreased and carbon dioxide content increased as depth of clay fill increased from 1 to 3 ft, but no measurements of root development were attempted. In controlled studies, reported effects of soil fill have generally been much less severe. Twenty centimeters of clayey subsoil fill over the root system of *Pinus strobus* for 2 years altered soil gas concentrations slightly, but not enough to damage root systems (Smith et al., 1995). Fill depth of 30 cm lowered oxygen diffusion rate (ODR) in the root zone of *Prunus mahaleb*, but effects were inconsistent, and no plant injury resulted (Tusler et al., 1998). Overlying compacted or uncompacted sandy loam construction fill 20 cm deep had no negative impact on *Quercus alba* and *Liquidambar stryraciflua* root density over 3 years (Day et al., 2001). Compacted fill 30 cm deep had no effect on 3 year old *Prunus* x *yedoensis* 'Afterglow' trees after on1 year (MacDonald et al., 2004).

Experimental results seem to conflict with experience in the landscape. More research is needed to understand the relationship between alterations to the soil environment, such as compaction and fill, and fine root development and tree health. Fine roots are responsible for the majority of absorption of water and nutrients supplied to the crown**.** The purpose of this study is to determine if soil compaction can reduce fine root development of existing large trees with already established root systems in urban landscapes to the point of causing crown decline often associated with compaction after construction around existing trees.

Materials and Methods

An existing plantation of *Quercus palustris*, 30 cm (11.8 in) average diameter breast height (DBH) was available for the experiment. This species naturally occurs in moist soils of floodplains and edges of streams and ponds (Mohlenbrock, 1986), the type of habitat from which many of the best urban trees in the Midwest United States originate. *Q. palustris* is commonly used in urban landscapes that do not have alkaline soils and is probably more tolerant of low soil oxygen than other species. A second, less tolerant species was not available for comparison. The trees were growing in closely spaced linear groups of 2-5 trees, with less than 2 m between trees, and 15 m between groups of trees.

The soil was a Beecher silt loam. This is a nearly level, somewhat poorly drained soil. The surface layer is a very dark gray silt loam about 18 cm thick, with a dark grayish brown silty loam subsurface layer about 10 cm thick. The subsoil is about 70 cm thick transitioning from dark grayish brown firm silty clay to light olive brown silty clay loam. The water table is at a depth of 30-90 cm during wet seasons. Root development is restricted below 86 cm by the compact, moderately fine glacial till. Reaction in the surface layer is slightly acid. Reaction in the subsurface layer ranges from midly acid in the upper part to mildly alkaline in the lower part (Mapes, 1979).

Compaction treatments were applied around the groups of trees because of the intermingled root systems of each group of trees, and the need for access by the large equipment used to compact the soil. Uncompacted space between individual trees was less than 0.5% of the total plot area. Each treatment was applied to two groups of trees, with the end trees of each linear group used for sampling (four trees per treatment). The size of the compacted area was based on industry consensus for construction root protection zone (Harris, 1992). It was equivalent to the surface area of a circle 12 cm radius for each 1 cm (1ft/in) of DBH, converted to a large rectangle around each group of trees.

Two types of compaction treatments were implemented. The simple compaction (C) treatment was implemented by driving a Ford F800, 15,000 kg (33,000 pound) gross vehicle weight, single axle dump truck with 11R22.5 tires at 105 psi, loaded to capacity, back and forth across each plot multiple times when soil moisture was near field capacity, until there was visible evidence of compaction in the soil structure of sample soil cores. An additional clay slurry (CS) treatment was applied to half of the compacted plots to simulate the type of CS that is sometimes pumped out of flooded foundation excavations and over the surrounding, already compacted, soil. The clay particles could fill the pore space that has already been reduced by compaction, further reducing movement of oxygen. A hole was dug 2 m deep, filled with 1 m of water and agitated with the backhoe bucket for several minutes, creating a slurry with the light olive brown calcareous clay loam underlying soil. The slurry was pumped onto half of the compacted plots until it began to puddle and run off. Controls received no C or CS.

The C and CS treatments were applied in November 1994. No soil oxygen or root system sampling was planned for 1995, in order to allow one full season for treatment effects to develop after the treatments were applied. The treatments had to be repeated in late-May 1996, because multiple freeze-thaw cycles in the first two winters had begun to reverse the compaction more rapidly than expected. All plots, including the uncompacted control, were maintained in bare soil condition by occasional hand weeding and spot treatment with glyphosate herbicide, not more than once per growing season. Sampling began in June 1996, after the second compaction (C) and clay slurry (CS) treatments.

Soil ODR, root growth and top growth were monitored for 4 years. ODR was measured weekly during the growing season at 15 cm (6 in) and 30 cm (12 in) below the surface using the platinum electrode method (Phene, 1982). The platinum electrodes were left in place for the entire season. Measurement locations were chosen in areas of the plots where water drainage was typical (no water pooling), where the soil was shaded by the canopy, and within 3 m (10 ft) of the trunks to assure good fine root development and water uptake, while maintaining adequate separation from the other sampling location. The measurement locations were on opposite sides of the groups of trees (four replications per treatment).

Root sampling was done at the ends of the rows of trees where there would be few, if any, roots of other trees from the group also growing. These end trees were also the largest trees. There were four replications (individual trees) for each treatment and controls. Root core samples were taken each year in early summer, when soils are both warm and moist, for optimum root growth and ease of core sampling. In June of each year, two core samples were taken from the root zone of each tree for analysis of root density. All core holes were refilled with other soil to minimize the impact of disturbance. The 30 cm (12 in) deep and 7 cm (2.7 in) diameter soil cores were divided into 3 cm (1.5 in) segments. Roots were washed from the soil and length of fine roots (<2 mm diameter) was measured and converted to fine root density (FRD) with a WinRhizo system (Regent Instruments, Quebec).

In late August of each year, terminal twig growth was measured on two lateral braches per tree, in the midpoint of the crown on opposite sides of the tree. Three undamaged fully-expanded leaves from the same branches were collected to measure leaf area on a Delta-T (video) Area Meter. DBH was also measured annually at a mark painted on the trunk.

Dieback was rated on a scale from 0 to 3. No dieback was rated 0. Minor dieback of small lateral branches not affecting the form of the tree was rated 1. Dieback of lateral branches to the extent that the shape of the tree was slightly disfigured was rated 2. Extensive dieback of the laterals or central leader substantially reducing the amenity value of the tree was rated 3.

One-way ANOVA ($P \leq 0.05$), with separation of means by the Tukey Method (SigmaStat 3.0, SPSS Science) was used to compare twig growth, leaf area, dieback ratings, ODR for each period and soil depth, and FRD at each depth.

Results and Discussion

After treatment, the surface soil bulk density exceeded the 1.46 g/cm^3 threshold value considered to be restrictive to root development in a fine-textured soil (Craul, 1992). The compaction treatment created a platy soil structure typical of compacted soil. At 15 cm, an increase of bulk density resulted from the compaction treatment. Bulk density was unchanged at 30 cm (Table 1). The compaction treatment apparently did not penetrate deep enough to change bulk density at 30 cm, which already was above 1.46 g/cm^3 naturally.

The first season after the second compaction, there were no treatment differences in root density, or in ODR, throughout the upper 30 cm of soil. ODRs were lower than in subsequent years, probably related to the 60% above normal rainfall throughout the summer months, and 18% above normal in the fall. Data for this year is not shown.

Beginning in the second year, ODR was affected by time of year and compaction treatment. A perched water table was present each year until mid-June when it dissipated rapidly. As a result ODR measurements also changed rapidly at that time. The data were grouped by date, before and after June 15, and will be referred to as spring and summer, respectively (Table 2).

Each spring, ODR was significantly reduced by both compaction treatments compared to controls at 15 cm. At 30 cm, ODR was lower for treated and control plots, and significantly different only in the second year. This difference was due primarily to an unusually high value for the control plots, compared to the other years (Table 2).

Table 1. Bulk density (g/cm³) and standard deviation (in parenthesis) of control, compaction (C), compaction and slurry (CS) treatment plots

Soil depth (cm)	Control	C	CS
Surface (1-8)	1.27 (0.10)	1.55 (0.10)	1.58 (0.04)
15-22 cm	1.53 (0.05)	1.63 (0.09)	1.59 (0.04)
30-38 cm	1.53 (0.06)	1.63 (0.11)	1.56 (0.15)

Depth measurements indicate top and bottom of bulk density core.

Table 2. Average soil oxygen diffusion rate (g/cm^2/min) in spring and summer after soil compaction treatment

	Spring		Summer	
	15 cm	30 cm	15 cm	30 cm
1997				
Control	0.32	0.13	0.46	0.23
C[a]	0.16*	0.07	0.26*	0.18
CS[b]	0.12*	0.06	0.27*	0.14
1998				
Control	0.31	0.18	0.45	0.26
C	0.20*	0.12*	0.32*	0.2
CS	0.14*	0.10*	0.27*	0.18
1999				
Control	0.26	0.12	0.48	0.25
C	0.13*	0.16	0.37	0.28
CS	0.15*	0.1	0.39	0.23

* Indicates difference from control at the same time of year ($P < 0.05$)

[a] Compaction treatment

[b] Compaction plus slurry treatment

In summer, ODR was higher for all treatments at both depths. Both compaction treatments significantly reduced ODR at 15 cm for the first 2 years. ODR was not affected by treatment at 30 cm depth in any year in summer (Table 2).

Significant differences in FRD due to compaction treatments were inconsistent and occurred most often in the upper 9 cm of soil in years 2 and 3 (Figs. 1 and 2), the depth at which the bulk density was most noticeably increased. In the fourth year, the difference between compaction and control at 6 cm depth appears to be even greater than the other years (Fig. 3). The lack of statistical difference is due to very high variation in the control data for that year (68% coefficient of variation). In all years, there were a few FRD differences in soils 15-21 cm deep where bulk density was slightly increased, but a clear relationship could not be established. FRD in the upper 3 cm of soil was consistently lower than at 3-6 cm. This is common in bare soil, or when grass competition is present (Watson, 1988).

The ODR value of soils in which roots of many plants will not grow has been reported as 0.20 g/cm^2/min. ODR between 0.2 and 0.3 g/cm^2/min retards root growth. Species for which data is available include avocado, citrus, corn, wheat, barley, sugar beets, sunflowers, cotton, snapdragons and bluegrass (Stolzy and Letey, 1964). No data is available for *Q. palustris*. As a species that naturally occurs in floodplains (Mohlenbrock, 1986), it may be somewhat more tolerant of low ODR.

The reduction of ODR in the top 15 cm of the compacted plots is likely responsible for the occasional reduction in FRD. In spring, for all treatments and

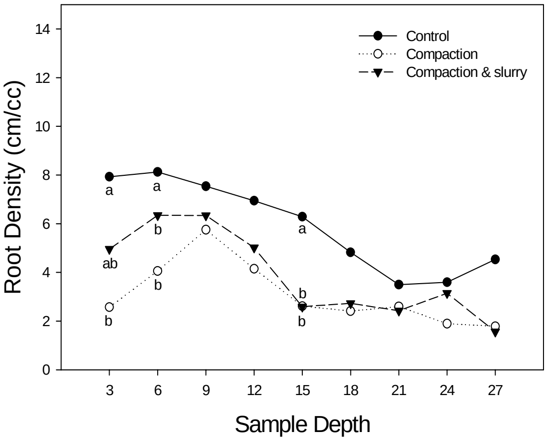

Fig. 1. Fine root density profile of *Quercus palustris* 2 years after compaction treatments (1997). For each soil depth different letters indicate a difference in fine root density between treatments. No letters indicate no difference between treatments at that soil depth.

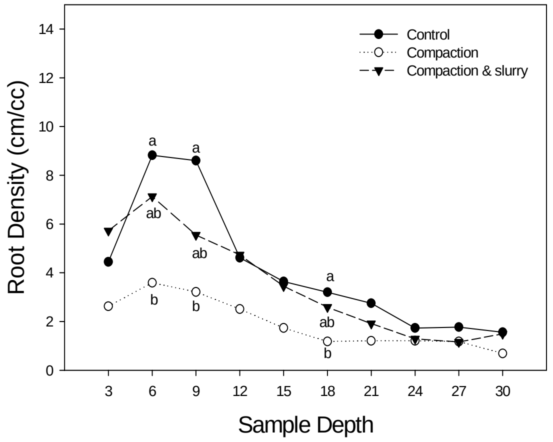

Fig. 2. Fine root density profile of Quercus palustris 3 years after compaction treatments (1998). For each soil depth different letters indicate a difference in fine root density between treatments. No letters indicate no difference between treatments at that soil depth.

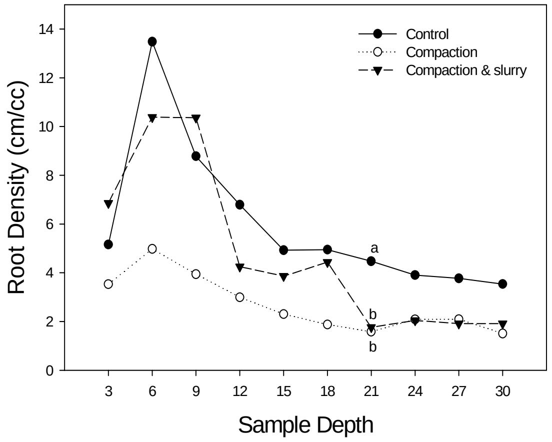

Fig. 3. Fine root density profile of *Quercus palustris* 4 years after compaction treatments (1999). For each soil depth different letters indicate a difference in fine root density between treatments. No letters indicate no difference between treatments at that soil depth.

years, except the compaction only treatment in 1998, the ODR levels were 20-40% below the 0.2 g/cm^2/min. Root growth must have been reduced even in this bottomland species, if not stopped altogether. In summer, ODRs at 15 cm were higher than in spring, but only slightly below the possibly restrictive 0.30 g/cm^2/min level in the treated plots, and only for the first 2 years.

FRD differences resulting from the compaction treatment would not be expected at 30 cm since there was no difference in ODR resulting from the compaction treatments except in spring of 1998. The higher natural bulk density, above the 1.46 g/cm^3 threshold value considered to be restrictive to root development in a fine-textured soil (Craul, 1992), would be expected to reduce fine root development, and FRD did decrease with depth on all plots.

Most reports of root responses to compaction have used small seedlings with expanding root systems as subjects. Compaction can affect the soil environment and also penetration resistance. Existing roots and fine roots being gradually replaced by the turnover process would be less affected by increased penetration resistance than roots penetrating into new soil volumes. Therefore, roots of established trees may be less affected by compaction treatments than roots of seedlings. Since the compaction was limited to the surface soils, deeper roots were not directly affected.

The CS treatment FRD values were consistently intermediate between compaction (C) and Control in the top 15 cm of soil. It was expected that the CS would further reduce the pore space over compaction (C) alone, reducing aeration and affecting root growth. ODR values of the C and CS treatments were never significantly different, yet root growth was at times. No explanation could be found.

There were no differences in DBH, twig growth, leaf area and dieback rating between compaction treatments and controls in any year (data not shown). Given the minimal difference in FRD, lack of differences in top growth are understandable.

Conclusions

Compaction treatments produced changes in ODR that affected root growth only near the surface in the spring. Similar to previous studies showing little or no damage to root systems from adding fill soil, this study showed only a minor reduction in FRD following compaction. Tree decline and death is commonly associated with soil compaction and addition of fill soil in real landscapes, but this and other studies have failed to show similar results. Perhaps the same conditions are not being reproduced experimentally. More study is needed to fully understand the impact of soil damage on tree root systems and tree health.

Acknowledgements

Partial funding for this project was received from The Care of Trees, Wheeling, Illinois and the Tree Research and Education Endowment Fund.

References

Alberty, C.A., Pellett, H.M., Taylor, D.H., 1984. Characterization of soil compaction at construction sites and woody plant response. Journal of Environmental Horticulture 2, 48-53.

Craul, P.J., 1992. Urban Soil in Landscape Design. Wiley, New York.

Day, S.D., Seiler, J.R., Smith, D.W., Kreh, R.E., 2001. Overlaying compacted or uncompacted construction fill has no negative impact on white oak and sweetgum growth and physiology. Canadian Journal of Forest Research 31, 100-109.

Gilman, E.F., Leone, I.A., Flower, F.B., 1987. Effect of soil compaction and oxygen content on vertical and horizontal root distribution. Journal of Environmental Horticulture 5, 33-36.

Halverson, H.G., Zisa, R.P., 1982. Measuring the response of conifer seedlings to soil compaction stress. Forest Service Research Paper NE-509.

Harris, R.W., 1992. Arboriculture: Integrated Management of Landscape Trees, Shrubs and Vines. second ed. Prentice Hall, Englewood Cliffs, NJ.

Lichter, J.M., Lindsey, P.A., 1994. Soil compaction and site construction: assessment and case studies. In: Watson, G.W., Neely, D. (Eds.), The Landscape Below Ground. International Society of Arboriculture, Savoy, IL, pp. 126-131.

MacDonald, J.D., Costello, L.R., Lichter, J.M., Quickert, D., 2004. Fill soil effects on soil aeration and tree growth. Journal of Arboriculture 30, 19-26.

Mapes, D.R., 1979. Soil Survey of Du Page and Part of Cook Counties, Illinois. University of Illinois Agricultural Experiment Station Soil Report No. 108.

Mohlenbrock, R.H., 1986. Forest Trees of Illinois . Illinois Department of Conservation

Phene, C.J., 1982. Oxygen electrode measurement. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. American Society of Agronomy & Soil Science Society of America, Madison, WI, pp. 1137-1160.

Randrup, T.B., 1997. Soil compaction on construction sites. Journal of Arboriculture 23, 207-210.

Smith, K., Ham, D., Miller, A., Chestnut, T., 1995. Soil aeration systems: Do they work? In: Watson, G., Neely, N. (Eds.), Trees and Building Sites Conference Proceedings. International Society of Arboriculture, Savoy, IL, pp. 17-21.

Stolzy, L.H., Letey, J., 1964. Correlation of plant response to soil oxygen diffusion rates. Hilgardia 35, 567-576.

Tusler, P.E., MacDonald, J.D., Costello, L.R., 1998. Fill soil effects on soil aeration. In: Watson, G., Nelly, N.

(Eds.), Landscape Below Ground II. International Society of Arboriculture, Champaign, IL, pp. 97-104.

Watson, G.W., 1988. Organic surface mulch and grass competition influence root development. Journal of Arboriculture 14, 200-203.

Yelenosky, G., 1963. Soil aeration and tree growth. International Shade Tree Conference Proceedings 40, 127-147.

Zisa, H.P., Halverson, H.G., Stout, B.B., 1980. Establishment and early growth of conifers on compact soils in urban areas. Forest Service Research Paper NE-451.