Effects of Four Compaction Remediation Methods for Landscape Trees on Soil Aeration, Mechanical Impedance and Tree Establishment[1]

S. D. Day[2], N. L. Bassuk[3] and H. van Es[4]
Urban Horticulture Institute, Cornell University
20 Plant Science, Ithaca, NY 14853

Abstract

Landscape trees are often planted in heavily compacted soils around newly constructed buildings or in urban areas. Under such conditions, trees frequently die, or decline prematurely. Four techniques for improving tree establishment on such sites were studied: peat-amended backfill; vertical drainage mat panels; radiating trenches filled with sandy loam soil; and vertical, gravel-filled sump drains. Sugar maple (*Acer saccharum* 'Seneca Chief'), a species sensitive to soil compaction, and the less sensitive Callery pear (*Pyrus calleryana* 'Redspire') were planted bare root into treatments in a compacted silty clay loam soil. Controls were backfilled with native soil. Shoot and root growth were measured over three growing seasons. Soil air oxygen content was monitored for one year. Effects of treatments on soil compaction were characterized using measurements of both soil strength and bulk density. Shoot growth of pears was greatest for treatments that alleviated mechanical impedance (soil trenches and amended backfill) and least for treatments that did not (controls and vertical drains). Drainage mats, which may alleviate mechanical impedance to a lesser degree, showed intermediate growth. Root growth was well correlated with shoot growth. Length of 2 to 5-mm diameter roots was greater for pears in soil trench treatments than for those with no treatment (controls) at the end of 3 growing seasons. Vertical drainage mats and vertical gravel-filled sump drains were shown to increase O_2 percent in surrounding soil. Regardless of treatment, all oxygen levels were usually close to atmospheric levels and never lower than 10%. Maple mortality was high and no treatment effects were shown.

Index words: bulk density, compacted soil, penetrometer, plant establishment, soil strength.

Species used in this study: sugar maple (*Acer saccharum* Marsh. 'Seneca Chief'); Callery pear (*Pyrus calleryana* Decne. 'Redspire').

Significance to the Nursery Industry

Landscapers are often faced with the intractable problem of planting into severely compacted soil. Soil at planting sites around new buildings as well as at most urban sites is often a heavily compacted mixture of dense subsoil and construction fill. When planting in compacted soil areas, even the highest quality plant material and most careful transplanting techniques cannot guarantee survival of trees and shrubs. At present, there are few satisfactory solutions for improving such poor planting sites, and contractors are often required to replace failed plant material at significant expense. Furthermore, as new plants are generally placed into the same inhospitable conditions, the entire planting can fail in the long term. This can be detrimental to customer satisfaction and landscaper and nursery reputations. This study evaluates several remedial techniques for improving tree establishment in compacted soil. Results indicate that efforts to improve planting sites where soil is compacted would best be directed towards reducing mechanical impedance caused by hard soil rather than installing aeration devices.

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[2]Former Graduate Research Assistant, Urban Horticulture Institute. Current address: Department of Horticulture, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.

[3]Professor, Urban Horticulture Institute.

[4]Associate Professor, Department of Soil, Crop and Atmospheric Sciences, Cornell University, Ithaca NY 14853.

Introduction

Establishing landscape trees successfully in modern urban and community environments is extremely problematic. A large number of trees do not survive their first two years, and the average street tree lifespan in city conditions has been estimated to be only 10 years (14). The poor rooting environment provided by many urban sites is thought to be a major contributor to this poor survival rate (8). Landscape plantings are most often around buildings, especially newly constructed ones, where subsoil and fill are generally mixed and compacted by heavy construction traffic and covered with a shallow layer of topsoil (2). Consequently compaction levels in developed areas are often extreme. Average bulk densities from 1.4 to 2.2 g/cm^3 (0.051 to 0.079 lb/in^3) have been recorded around new construction and in urban areas (2, 24). These are above levels of compaction shown to restrict root growth for many woody species (6, 22, 37). Restricted rooting space and poor aeration and drainage are also typically associated with compacted soil (8).

Low soil oxygen levels restrict plant growth (12, 30, 34). Because the smaller pores of compacted soil retain water longer and thereby restrict air diffusion (9), poor plant growth in such soils is in part attributed to the low soil oxygen levels considered to be associated with compaction (13, 23, 26, 32, 36). However, in soils compacted to bulk densities of 1.75 to 1.88 g/cm^3 (0.063 to 0.068 lb/in^3), researchers found numerous indications that poor aeration was not a factor in restricted root growth of cotton (29). Measurements of soil air in other studies indicate that compacted or heavy soils do not always result in low oxygen levels (5, 35). Nevertheless, because plant response to soil oxygen level has been shown to interact with mechanical impedance (15, 27), oxygen levels that would only moderately limit plant growth in uncompacted soils may more severely affect plants in compacted soils.

The four techniques evaluated in this study have been thought to improve plant growth in compacted soil by increasing soil aeration, reducing mechanical impedance, or both; but research determining their effectiveness is limited. Two years after vertical, perforated, PVC pipe sump drains backfilled with gravel (a treatment intended to alleviate the detrimental effects of compaction by aerating the soil) were installed around established Chinese wingnut trees (*Pterocarya stenoptera*), no improvement in shoot growth was found (25). Trees had been established for 10 years and showed reasonably good vigor and therefore might not have responded as measurably as more stressed trees. Vertical, fibercloth-covered Enkadrain drainage mat panels (BASF Corporation, Fibers Div., Enka, NC) placed around London plane trees (*Platanus* x *acerifolia*) elevated oxygen diffusion rate 3 cm (1.2 in) from the drainage mat for one day after irrigation. However, no effect on tree growth was shown (19). Other techniques, such as radially arranged trenches filled with a friable soil extending outwards from the root ball zone, have been used in practice, but no controlled evaluation conducted. Research with another type of trenching, however, indicates that such a method might provide favorable rooting space for plants. When trenches were dug in dense subsoil in rows of cotton and filled with less dense material such as vermiculite and loose soil, rooting depth of cotton planted on top of the trenched row increased as roots took full advantage of the looser soil below (16).

Several studies have focused on the effects of amending planting hole backfill with organic material (7, 17, 18). Amended backfill resulted in little or no benefit for container-grown woody plants in Florida (17, 18). Similar, although more variable, results were found with container-grown plants transplanted into a heavy clay soil (7). Bare root and balled and burlapped trees transplanted into compacted clay soil benefited from amended backfill (33% pine bark by volume) when well irrigated, but amended backfill was detrimental under minimal irrigation (7).

Contractors continue to be faced with the dilemma of planting trees into compacted soil, yet proposed solutions to this problem are often based on anecdotal and incomplete evidence. The aim of this study is to evaluate some current practices intended to alleviate the detrimental effects of compacted soil, especially as it relates to their ability to reduce the effects of low soil oxygen and high soil strength. Of special interest are treatments that can also be installed *after* a tree has been planted, where it is suspected that poor establishment is a result of compacted soil.

Materials and Methods

Tree planting. Acer saccharum 'Seneca Chief' (sugar maple), and *Pyrus calleryana* 'Redspire' (Callery pear), were dug bare root in late fall 1990 and kept in cold storage until they were planted out in Ithaca, NY on June 4 and 5, 1991. Pears averaged 2.75 m (9 ft 2 in) in height and 3.7 cm (1.5 in) in trunk diameter at the graft union (approximately 12 cm (5 in) up from the root collar). Maples averaged 2.58 m (8 ft 7 in) tall and 1.8 cm (0.75 in) in diameter at the graft union (also approximately 12 cm (5 in) up from the root collar). Pears were well branched, with an average of 19 major branches per tree. Maples averaged 5 branches. Roots systems were uniform for each species and met the standards of the American Association of Nurserymen (1). The field soil, a silty clay loam (Table 1), was compacted before planting by driving a 3,630 kg (8,000 lb) tractor with a 450 kg (1,000 lb) compactor-roller implement over the field when gravimetric soil moisture averaged 20.1% at 5 to 20 cm (2 to 8 in) deep. The tractor tires passed over every portion of the field twice, and the compactor-roller twelve times. Trees were planted in a randomized complete block design: 2 species × 5 treatments × 12 blocks = 120 trees. Three maples died and were replaced within one month of the original planting.

Trees were planted on 2.4 m (8 ft) centers into one of five treatments. *Amended backfill*: Fifty percent (by vol) milled sphagnum peat moss was mixed with native soil and backfilled into the planting hole. *Drainage mat*: Four panels of Enkadrain fibercloth-covered drainage mat were inserted vertically into the soil in a spoke pattern around the tree and planting hole backfilled with native soil. Each panel was 2 cm (0.75 in) thick, 60 cm (2 ft) long and 45 cm (1.5 ft) deep. In order not to disturb the compaction level of the surrounding soil, panels were inserted into the narrowest possible trenches created with a chain-saw-mounted trencher. Panels were placed so that one edge protruded into the planting hole. *Soil trenches*: Four trenches, also radiating out from the planting hole, were dug using a mechanical trencher and then filled with Arkport sandy loam soil (Table 1). Each trench was 12 cm (5 in) wide, 30 cm (1 ft) deep and 60 cm (2 ft) long. The planting hole was backfilled with native soil. *Vertical drains*: The planting hole was backfilled with native soil and four sump drains were placed around the tree 80 cm (2 ft 8 in) from the trunk. Drains were constructed of corrugated, perforated 10 cm (4 in) ADS piping placed vertically in the ground extending from the surface to a depth of 70 cm (2 ft 4 in) and filled with gravel (2 to 4 cm (0.75 to 1.5 in) diameter size range). A 23 cm (9 in) diameter auger was used to drill holes for installation. Soil was backfilled around the drain and tamped with a hand compactor. *Control*: Planting holes were backfilled with native soil (Table 1). For this and for all other treatments, planting holes were dug to a uniform size with a backhoe when soil moisture was low. Small adjustments to the planting hole (less than 7.5 cm (3 in)) were made by hand with a shovel at planting time to accommodate each tree as necessary. Backhoe-dug holes were approximately 45 cm (1.5 ft) deep for pears and 30 cm (1 ft) deep for maples and 65 cm (2 ft 2 in) wide for both species. Planting hole sides were slightly sloped and not 'glazed.'

Maintenance. Irrigation was supplied as needed via drip hose during 1991. No irrigation was supplied in 1992, as frequent rainfall made it unnecessary, or in 1993. The field was kept free of weeds with Roundup (glyphosate), granular Ronstar (oxadiazon) and occasional hand pulling.

Table 1. Soil pH, organic matter content and texture of field soil and soil used to fill trenches.

			Mineral separates		
Soil area	pH	% O.M.	% Sand	% Silt	% Clay
Field soil	6.6	3.2	19.0	44.5	36.5
Trench treatment soil	6.8	3.0	59.8	24.0	16.2

Shoot measurements. Shoot growth was measured July 3, 1992 and July 23, 1993 after terminal buds had set for that growing season. For maples, the uppermost 5 shoots were measured and averaged. For pears, we measured the most dominant 4 shoots including the leader plus one shoot from the most dominant co-leader. This system was adopted so that the degree of branching of the leader would not unduly affect shoot measurements.

Root measurements. Root growth of pears in control, amended backfill and soil trench treatments only was measured in 7 blocks in August 1993 via partial excavation. Three rectangular areas approximately 35 cm (14 in) wide and 70 cm (2 ft 4 in) long were excavated to 30 cm (1 ft) depth from one side of each tree using a backhoe such that the center rectangle would encompass the soil trench on trees with this treatment. Each excavated area began 30 cm (1 ft) from the trunk. Roots were sifted from the excavated soil manually. Roots were soaked for 30 min in water and separated into 3 diameter classes (0 to ≤ 2 mm, > 2 to ≤ 5 mm, and > 5 mm (0 to ≤ .08 in, .08 to ≤ .20 in, and > .20 in)) using a microcaliper. Root volume for each class was then determined using water displacement. Root length was estimated by considering the root volume to be the volume of a cylinder of the average diameter for each root diameter class and then calculating length. Roots were then oven dried at 75C (167F) to a constant mass and weighed.

Soil oxygen measurements. Soil air oxygen content was measured using a soil air sampling chamber technique (34) with some modifications. Sampling chambers were constructed of 3.8 cm (1.5 in) schedule 40 PVC pipe, sealed at the top with a PVC cap using PVC glue. The bottom was left open. The volume of each chamber was 200 ml (6.8 oz). A hole was drilled in the cap and a 30 cm (1 ft) long Nalgene tube was inserted, and capped with a 7 mm (0.25 in) septum. Chambers were buried upright in the soil with the bottom at 30 cm (1 ft) depth and a portion of the tubing remaining above ground so that gas samples could be withdrawn through the septum. An auger of the same diameter as the chambers was used for installation so as not to disturb the adjacent soil. Loose soil was carefully removed from the bottom of the augered hole with a spoon so as to obtain as undisturbed an interface as possible.

Chambers were installed in 3 blocks, 3 chambers at each tree in the following patterns: *Control and amended backfill*: one chamber in the planting hole, one 8 cm (3.3 in) from the edge of the hole, one 20 cm (8 in) away; *Vertical drains and drainage mat*: one chamber flush against mat or drain, one 8 cm (3.3 in) away and one 20 cm (8 in) away; and *Soil trenches*: one chamber in trench, one 8 cm (3.3 in) away and one 20 cm (8 in) away.

A Servomex 574A oxygen analyzer (Servomex Co., Norwood, MA), was used to measure soil air oxygen content. At each sampling, two 6 ml (0.2 oz) samples were drawn from the chamber through a syringe needle on the probe attachment of the analyzer and the O_2 concentration was determined for each sample. The first sample cleared air trapped in the tubing or probe attachment and was discarded. At least monthly in July, August and September, 1991 and in April, May and June, 1992, measurements were taken on 3 consecutive days immediately after a rainfall or irrigation. Additional single-day measurements were occasionally made to determine if soil O_2 was at limiting levels.

Water table measurements. Water table depth was measured in the center of each block using 70 cm (27.5 in) deep observation wells made of 3.8 cm (1.5 in) schedule 40 PVC pipe with numerous holes drilled in the lower 15 cm (6 in) to allow free water movement. Additional wells, of the same depth as the treatments, were installed in, or flush against, treatment areas in 3 blocks.

Soil measurements. Temperature: Soil temperature at 30 cm (1 ft) was measured with a thermocouple in 1992 on days when soil air oxygen levels were measured. Bulk density: Soil bulk density was measured in 8 sites distributed throughout the field centered at three depths (5, 15, and 20 cm (2, 6, and 8 in) in November 1991, using a hand-operated undisturbed core sampler. Cores (volume 347 cm^3 (21 in^3)) were oven dried at 30C (86F) to a constant weight and bulk density calculated. Bulk density was again measured in 1992 and 1993 in conjunction with soil strength measurements. In 1992, a trailer-mounted Giddings Hydraulic Probe (Giddings Machine Co., Fort Collins, CO) was used to extract cores at 3 field locations, at the upper, middle and lower part of the site. At one location, cores were taken at 3 depths (15, 30 and 45 cm (8 in, 1 ft and 1 ft 8 in)). Bulk densities at 30 (1 ft) and 45 cm (1 ft 8 in) depths were similar, therefore cores were taken only at the first two depths for the remaining sites. In 1993, cores were taken manually at 9 and 23 cm (3.5 and 9 in) depths inside the soil trenches, in the amended planting hole and in the planting hole of control trees in 3 blocks. Cores were oven dried at 75C (167F)

Table 2. Mean new shoot growth[z] of pears after budset for 2nd and 3rd year after planting.

Treatment	2nd year growth (cm) (n = 11)	3rd year growth (cm) (n = 5)
Soil trenches	36.38a[y]	50.56a
Amended backfill	35.40a	44.40ab
Drainage mat	31.80ab	43.24ab
Control	21.16bc	26.84b
Vertical drains	16.89c	28.56b

[z]Average of 5 shoots per tree.

[y]Mean separation within columns by Duncan's new multiple range test, α =.05.

Table 3. Cumulative tree mortality by treatment in 2nd and 3rd growing seasons. Note that data for 1993 is for remaining 7 blocks after 5 blocks were harvested for root data.

	% Dead as of July 3 1992		% Dead as of July 23 1993	
	(n = 12)		(n = 7)	
Treatment*	Maples	Pears	Maples	Pears
Soil trenches	33	0	57	0
Amended backfill	42	0	29	14
Drainage mat	42	0	100	0
Unamended backfill (control)	50	0	71	29
Vertical drains	58	8	57	29

*No significant difference among treatments.

Table 4. Average root length by diameter class in total excavated area for surviving pears planted into unamended backfill (control), amended backfill and soil trench treatments. Measurements were taken after 3 growing seasons.

	Root diameter range (mm)	
	> 0 ≤ 2	> 2 ≤ 5
Treatment	Average root length (m)	
Soil trench	744a[z]	43.9a
Amended backfill	627a	23.5b
Unamended backfill (control)	385a	16.0b

[z]Mean separation within columns by Duncan's new multiple range test, α = .05

Table 5. Average percent of harvested root length in center section of excavated area for surviving pears by treatment and diameter class. In the soil trench treatment, the center section encompassed the trench.

	Root diameter range (mm)	
	> 0 ≤ 2	> 2 ≤ 5
Treatment	Average percent root length in center section	
Soil trench	41.96 (2.85)[z]	40.22 (6.44)
Amended backfill	34.57 (2.28)	40.50 (9.00)
Unamended backfill (control)	35.68 (2.33)	33.40 (11.90)

[z]Standard error of the mean in parentheses.

to a constant weight and bulk density calculated. Soil strength: Soil strength was measured with a Bush Recording Soil Penetrometer (Findlay Irvine, Ltd., Penicuik, Scotland) at 3 field locations (upper, middle and lower part of the site) on July 9, August 25 and August 27, 1992, and inside soil trenches and planting holes, each on 2 different occasions in October and November, 1993. This penetrometer measures resistance at 3.5 cm (1.4 in) depth intervals to a depth of 49 cm (19 in). It has a 30° cone 12.8 mm (.5 in) in diameter with a recessed shaft and corresponds to the standard of the American Society of Agricultural Engineers (4). In 1992, four, and in 1993, eight penetrations were made each time at each location. Gravimetric soil water content was measured at penetration sites and converted to volumetric soil water content using soil bulk density data obtained earlier.

Statistical analysis. The data were analyzed using t-tests, analysis of variance or, when data were unbalanced, a general linear models procedure. If treatment effects were significant, differences between means were tested using Duncan's new multiple range test (21). Mortality data were analyzed using the non-parametric Cochran's Q test (10). Regression analysis was used for soil strength and soil moisture data. Outliers were identified by Cook's distance and discarded as appropriate (20).

Results and Discussion

Shoot growth. Shoot growth in pears was significantly affected by treatments (Table 2). Soil trenches and amended backfill treatments produced 82% and 73% more second-season growth, respectively, than controls. Third-season shoot growth of pear trees in soil trench treatments was 88% greater than that of controls. Second-year data suggest that drainage mats increased, and vertical drains decreased, shoot growth, although both effects were statistically insignificant. Pear mortality was generally low and was not associated with treatments (Table 3).

For sugar maples, mortality was high, and no differences in shoot growth were found among treatments. Surviving maples generally showed very poor vigor with shoot extension averaging only 5 to 6 cm (2 to 2.5 in). The stress of transplanting into unfavorable soil conditions apparently dominated any effect that treatment might have had on maples. Maple mortality was not associated with any particular treatment (Table 3).

Root growth. In the soil areas excavated in 1993, root length in the 2 to 5-mm diameter range was greater for pears with soil trenches than for those in amended backfill or unamended backfill (control) (Table 4). Roots from other treatments were not measured. Root length of the 2 to 5-mm diameter class was a better predictor of shoot growth than root length of the 0 to 2-mm class (Fig. 1 A and B). Almost no roots greater than 5 mm in diameter were harvested from any trees. There was considerable variation in the 0 to 2-mm diameter range and although average root length was again highest for trees with soil trenches, differences between treatments were not statistically significant. This large variation among trees in the same treatment may be due to one or a combination of the following factors: Smaller roots may have been more easily overlooked in the hand-sifting process, resulting in greater error; or smaller roots may die and grow more frequently than larger roots, thus resulting in more variation among trees depending upon what stage of root growth they were in when harvested. Nonetheless, root length in the smaller diameter class for each tree was strongly related to root length in the larger diameter class (Fig. 1C). After a certain point, however, an increase in 2 to 5-mm root length was not accompanied by an increase in 0 to 2-mm root length.

Because the center excavation encompassed the trench in the soil trench treatments, root length in this excavated section was analyzed as a percent of total harvested roots to determine if root growth was concentrated in the soil trenches (Table 5). The data did not show that roots proliferated in the center excavation. However, root proliferation within the soil trench could have been obscured because the soil trench made up less than a third of the center excavation. Also, during harvesting we noted that a large number of relatively straight, rope-like roots were growing in the soil trenches. Such straighter roots may have less total length than the excessively branched roots typical in a more compacted soil (31). Regardless, the soil trenches apparently allowed more rapid establishment of the pears, as evidenced by overall greater root and shoot growth.

Soil aeration. Soil air oxygen measurements were analyzed for each treatment to determine if the mean oxygen content increased as the distance between the sample chamber and the treatment area decreased (Fig. 2). Only drainage mats and vertical drains (maples only) had such an aerating effect, and this was limited. Only samples from immediately next to the mat or drain, had average oxygen levels

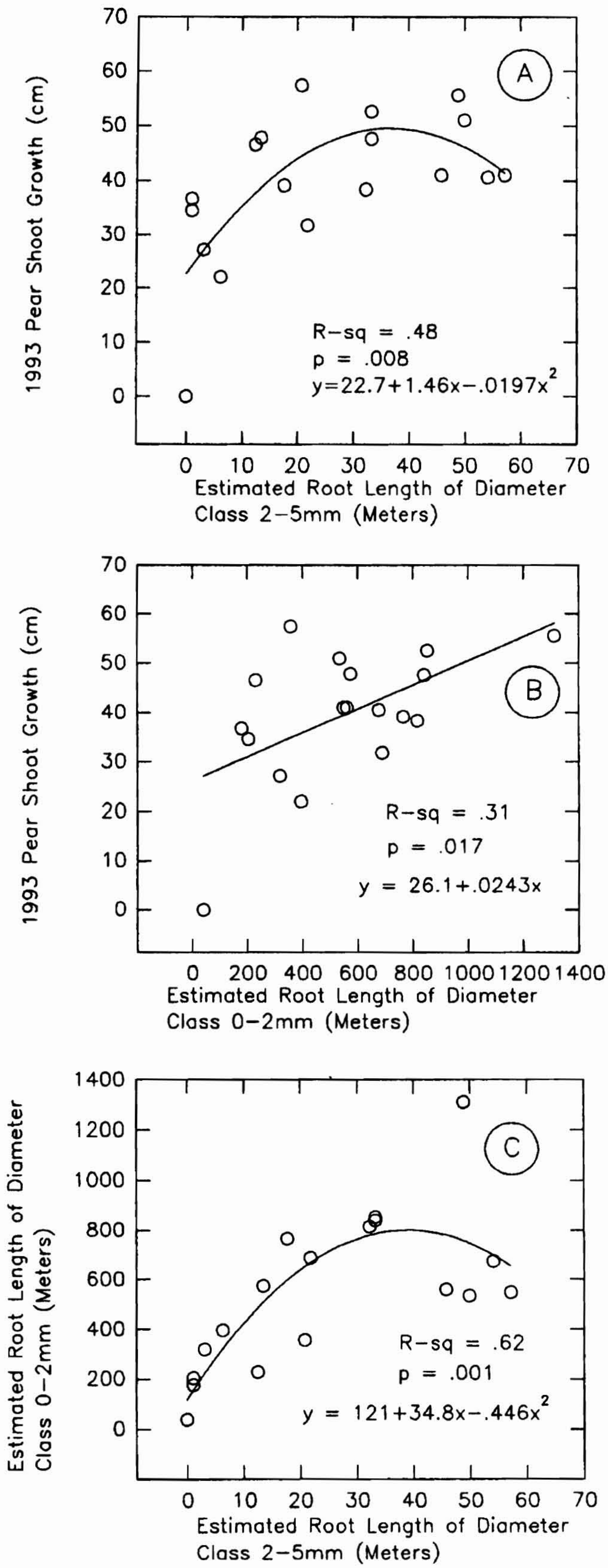

Fig. 1. 1993 root and shoot growth relations for Callery pears. a) Regression of length of excavated roots in > 2 ≤ 5mm diameter class and shoot growth. b) Regression of length of excavated roots in > 0 ≤ 2mm diameter class and shoot growth. c) Regression of length of excavated roots of > 0 ≤ 2mm and those of > 2 ≤ 5mm.

greater than those from the chamber 20 cm (8 in) away from the mat or drain. The aerating effect had therefore dissipated before the middle sample location, 8 cm (3 in) from the treatment. Furthermore, the increase in mean oxygen percent was less than one, which, though statistically significant, likely has no effect on tree growth. Vertical drains in pear plots showed no aerating effect, but the reason for this species × oxygen level interaction is unclear. Also of interest is that the limited aeration effect achieved by the drainage mat seemed to be reduced when oxygen levels were lowered after a rain, although the decrease in oxygen level did not vary significantly with distance (data not shown). Presumably this occurred because the soil was more uniformly wet after a rain.

Because shoot growth was greater in pears with amended backfill than in those with unamended backfill (controls), oxygen levels in the planting hole were compared for these two treatments to determine if this may have influenced shoot growth. Mean oxygen level in amended backfill planting holes was lower than in controls by 0.7%. The lowest oxygen level found in amended backfill was 12.6%, while the lowest in unamended planting holes was only 16.7%. These slightly lower oxygen levels in amended planting holes were apparently not detrimental to plant growth.

When considering poor aeration as a possible limiting factor to root growth, it is necessary to focus on the lowest oxygen levels, as well as seasonal means. The lowest oxygen level measured for all treatments in all locations was 10%, but oxygen levels were more usually 19 to 20.9% (Fig. 2), and thus not a serious limitation to root growth. Because measurements were taken over several days after rainfall or irrigation and throughout the growing season, including when the soil was warm, these measurements are expected to have encompassed any seasonal lows. This method of sampling soil air, however, does not allow samples to be withdrawn under flooded conditions when the chamber is filled with water. Such conditions were occasionally present for this experiment in March and early April. Consequently, oxygen levels may possibly have been limiting during such times. At all other times water table levels, as monitored by observation wells, were well below oxygen chambers and planting holes.

Poor soil aeration is frequently cited as a major reason why root growth is poor in compacted soil (13, 23, 26, 32, 36). These conclusions are primarily based on the understanding that poor soil structure reduces gas exchange and drainage, or on indirect measurements such as soil air-filled porosity, rather than on actual measurements of soil oxygen. When drainage is adequate, however, compacted soil may not necessarily result in poor soil aeration. In this experiment, oxygen levels, both means and low points, did not differ significantly between uncompacted areas, such as soil trenches and planting hole backfill, and compacted areas. It could be suggested that increased root growth in uncompacted areas depleted soil oxygen in what would otherwise be a better aerated zone. Oxygen measurements in soil trenches of a dead tree, however, were not higher and therefore do not support this view. The relative diffusion coefficient of oxygen through a compacted soil has been shown to be less than that through an uncompacted soil (9). Nonetheless, in the present study, compaction did not appear to limit oxygen replenishment of the soil to a biologically significant degree.

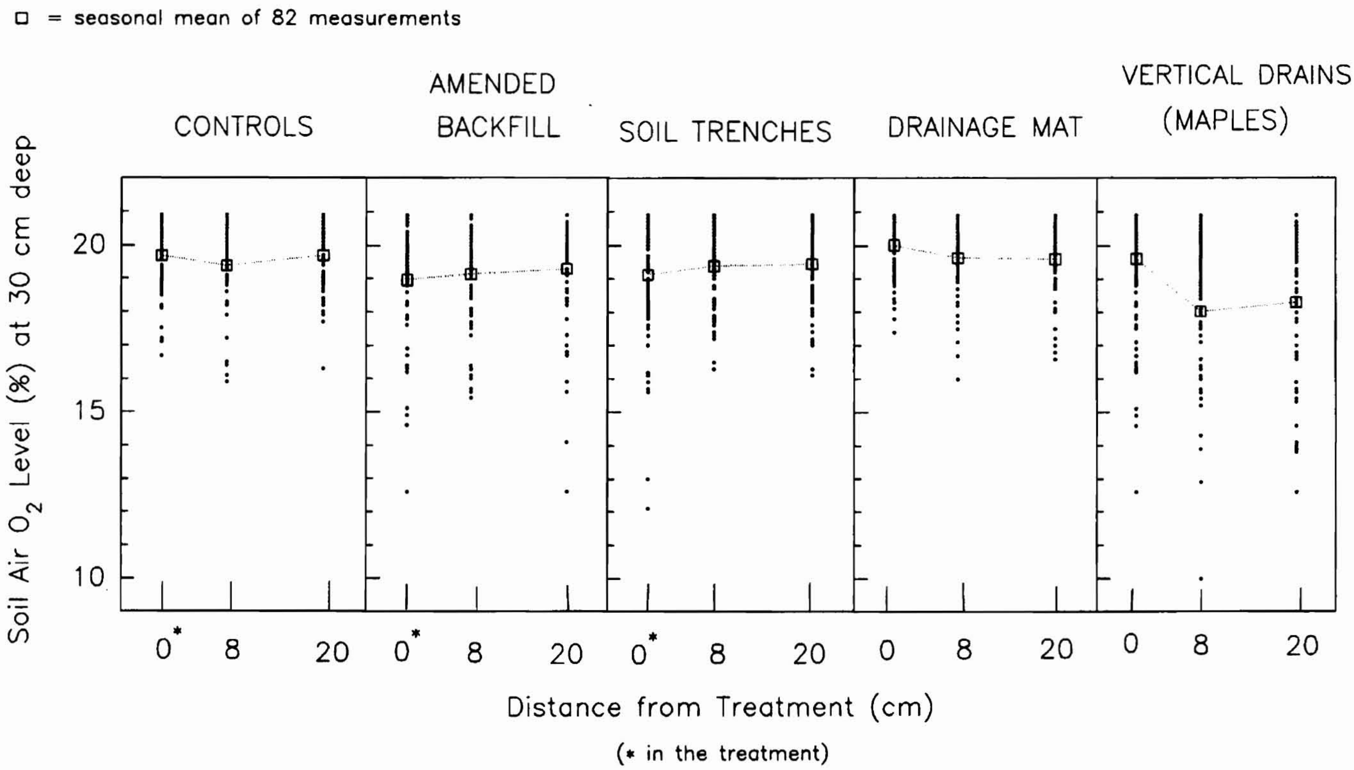

Fig. 2. Soil air oxygen levels measured during 1991 and 1992.

Mechanical impedance. Bulk density and soil penetrometer measurements indicated that the field soil was compacted to a degree to be restrictive to root growth. Bulk densities of 1.21 g/cm^3 and higher have been demonstrated to significantly restrict root growth depending on soil texture and species (2, 6, 37). Bulk densities of our individual samples of the compacted field soil ranged from 1.29 to 1.56 g/cm^3, generally above levels reported to restrict root growth in this texture soil. Yet even when soil texture is taken into account, bulk density gives only limited information regarding the resistance encountered by roots. Soil moisture also affects soil resistance. Thus penetrometer measurements may be expected to be better correlated with root growth because they integrate many of the factors affecting resistance, including texture and soil moisture. For penetrometer measurements, 2.3 MPa can tentatively be considered as a critical soil resistance level above which root growth is severely restricted for woody species (11). Soil resistance to penetration in the compacted field soil was nearly always greater than this critical level except in the upper 9 cm (3.5 in) of soil when volumetric soil water contents were greater than approximately 30 to 35% (Fig. 3). In contrast, resistance to penetration in soil trenches, amended backfill and backfill of loosened field soil in control trees 2.5 years after installation was consistently lower at all measured moisture levels (Fig. 4). Unfortunately, measurements in these last three areas were made in the fall when there was not sufficient variation in soil moisture levels to establish a regression relation between soil moisture and resistance for these soils.

Soil moisture plays an important role in compacted soils beyond supplying water to roots. For this fine-textured glaciolacustrine soil, the effect of soil moisture on soil strength is quite large at the 23 cm (9 in) and 9 cm (3.6 in) depths. At the 40 cm (1 ft 4 in) depth, soil moisture did not vary enough for the relationship between soil strength and moisture to be well characterized (Fig. 3).

The root growth data discussed earlier supports the finding that mechanical impedance restricted root growth. Furthermore, treatments that primarily alleviated mechanical impedance (soil trench and amended backfill) resulted in 97% more second-year shoot growth in pear trees than other treatments that did not alleviate mechanical impedance (vertical drains and controls). Root growth in these trees after three growing seasons was also 79% greater than for control trees. The increased growth of pears in soil trench treatments may be attributed in part to the greater volume of less resistant soil. The four soil trenches plus the planting hole provided .143 m^3 (5.14 ft^3) of soil volume, while the planting hole alone provided .057 m^3 (2.05 ft^3). Although other factors may have influenced these differences, this indicates that mechanical impedance, and not aeration, is the primary restricting factor for trees growing in compacted soil.

Mechanical impedance appears to play the primary role in root restriction in compacted soil. In contrast, compacted soil does not necessarily mean that aeration is limiting. Two years after being planted, pear trees demonstrated increased shoot growth in response to soil trenches and amended backfill. Both of these treatments provide uncompacted soil areas for root exploration, although the soil trench treatment also provides a greater volume of loosened soil. After 3 years, pear trees in the soil trench treatment showed statistically greater shoot growth than controls, while trees in amended backfill did not.

A soil-loosening effect may also have been achieved to some extent by the drainage mat treatment. Roots have been demonstrated to proliferate in cracks and other limited ar-

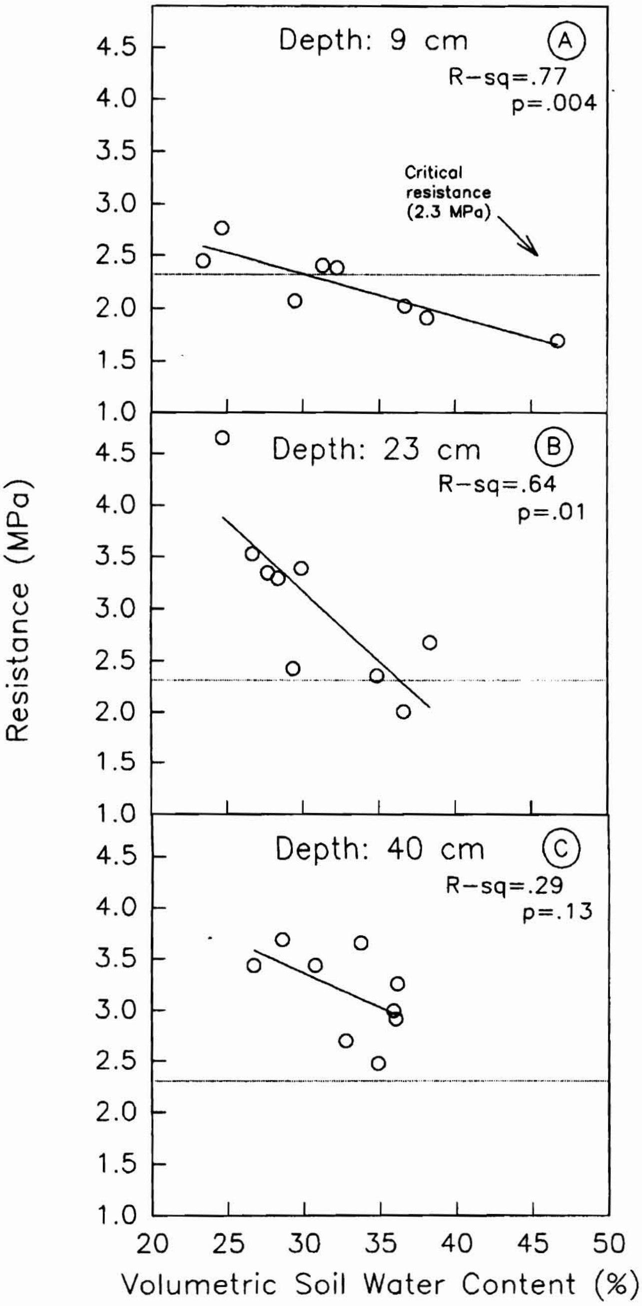

Fig. 3. Resistance to penetration of compacted field soil at three depths.

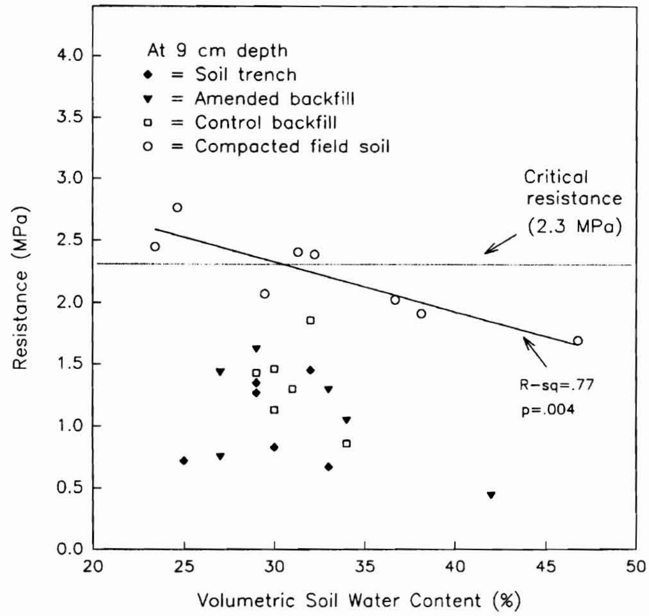

Fig. 4. Resistance to penetration at 9 cm depth of soils in treatment areas compared with compacted field soil.

eas of least resistance (28, 33). In a previous study, tree roots grew along and through this type of drainage mat (19). In the present study, however, although a number of panels were excavated and inspected, this was not observed. This treatment has a distinct advantage over soil trenches, however, in that the material is rigid and will not be subject to recompaction, and can be installed in small, difficult-to-maneuver-in areas such as city tree pits. By the end of this experiment, however, some mats were pushed out of the soil as much as 50% by frost heave. In practice, this could create a maintenance problem.

Maple establishment was not aided by treatments. The poor establishment of sugar maples in comparison to callery pears in all treatments might in part be due to differing genetic abilities for penetrating dense soils. One hypothesis is that pears were better able than maples to take advantage of periods of low soil strength. When the soil was wet, and its strength low, root growth of maples may have been slowed because of temporary limiting oxygen levels. Callery pears, reportedly tolerant of anoxia (3), could potentially be less affected by these lower oxygen levels. In ordinary soil, maples could resume growth after the soil dried and oxygen became available. However, compacted soil becomes impenetrable when dry. Consequently, continued root growth when soil is very wet would be critical to survival. Under this hypothesis, soil aeration plays an important role in restricting root growth in compacted soil, but aeration and drainage devices would not alleviate the problem. As, aided by the aeration device, soil pores filled with air (i.e. as the soil dries), soil strength would increase and root growth would still be restricted.

Research elucidating reasons for species differences would greatly improve our ability to make decisions regarding planting practices and remedial treatments for trees in compacted soils. Based on the results of this study, however, some recommendations regarding planting practices may be made:

- When considering planting or remedial techniques for compacted soil, primary consideration should be given to reducing mechanical impedance rather than improving aeration. Drainage should be installed where necessary.

- Soil trenches as described in this study may be helpful as a remedial treatment for trees showing poor establishment where compacted soil is the suspected cause. For that matter, any practice which increases the volume of easily penetrable soil would be expected to yield improved tree establishment and growth.

- The practice of amending backfill with sphagnum peat may be useful under conditions such as those in this study (i.e. compacted, inhospitable native soil with adequate moisture and drainage).

- The installation of surface vertical sump drains away from the planting hole for aeration purposes does not warrant the expense. At best they offer no benefit, and may, in fact, be detrimental to tree growth.

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