Effect of Soil Compaction and Oxygen Content on Vertical and Horizontal Root Distribution[1]

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Abstract

Gleditsia triacanthos var. inermis seedlings were field planted in compacted and non-compacted soil in both normal oxygen and reduced oxygen soil atmosphere. Entire root systems were excavated and mapped. Compaction caused significantly shallower roots in normal and reduced oxygen areas. Roots in the reduced oxygen area were not significantly shallower than in normal oxygen areas. Root spread was correlated with stem diameter and branch spread. Lateral roots extended three times as far from the trunk as did the branches.

Index words: Root excavation, root spread, branch spread, trunk diameter, soil aeration, bulk density

Introduction

Root growth is restricted by low soil oxygen (O_2) supply (6, 12, 17) and mechanical impedance due to soil compaction (3, 10, 11). Container studies have shown that woody plants respond to compacted soil by producing a shallow root system (7, 13, 18, 23). Root growth is generally restricted at soil bulk densities between 1.25 and 1.6 g/cc (24). Critical bulk density values are subjected to wide variation because of strong interactions between bulk density, soil type and moisture content (24). One of the most extensive documentations of urban soil compaction showed that in soil tree pits in Washington, D.C. bulk density ranged from 1.7 g/cc to 2.2 g/cc (14), far above the levels known to affect root growth. As a comparison, brick has a bulk density ranging from 1.4–2.3 g/cc (15).

Roots which develop in well-aerated soil are long and light in color with many root hairs. Those with insufficient O_2 are thicker, twisted, shorter, darker in color and have few root hairs (16). Soil aeration affects root distribution by restricting deeper penetration at low O_2 concentrations (4, 9, 11). Frequently in low O_2 environments, a dense mat of roots develops within the top several cm of soil (2, 5).

Factors affecting horizontal root spread in woody perennial plants are not as well understood. Of the limited number of published studies, most present evidence suggesting that root spread may be predicted from above-ground measurements. Trunk diameter and tree height of oak and maple species in a closed forest stand were positively correlated with root area (19). Root-system radius of isolated *Pinus palustris* trees in the forest was 2 or more times the branch crown radii (8). Watson and Himelick (21) presented a model of a typical nursery-grown tree showing the root radius as 3 times the branch-crown radius.

This study was designed to 1) investigate the impact of reduced soil oxygen content and soil compaction on vertical root distribution and 2) predict horizontal root spread from above-ground growth parameters.

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Materials and Methods

Soils over former refuse landfills contain from 1% to 21% O_2 (5), making them ideal for studying plant response to reduced soil O_2.

A plot, several hectares in area on a 9 m (30 ft) deep former refuse landfill near New Brunswick, N.J., was sampled for soil O_2 and CO_2 content at a depth of 20 cm (8 in). Measurements were made using a gas chromatograph with a thermal conductivity detector (4). Compacted and non-compacted treatments were established in a normal-oxygen area ($O_2 > 19\%$) and a reduced-oxygen area ($O_2 < 15\%$). Gas measurements were collected with gas tight syringes bi-monthly during the experimental period from two 20 cm (8 in) deep in-ground samplers at each tree located 30 cm (12 in) north and 30 cm (12 in) south of the trunk. This totaled 86 sampling dates during the 3-year study. On each date, 4 samples were collected from each of 4 treatments totaling 1,376 gas analyses during the study period. Compression in the compacted treatment area was obtained by driving a large 4-wheeled front-end loader over each successive 15 cm (6 in) layer of soil until the full 75 cm (30 in) depth was spread. Six undisturbed 300 cc soil cores were collected from each treatment area, dried at 85°C for 24 hours and weighed to establish a bulk density for each area. Bulk density in this area at the 0–15 cm (0–6 in) depth ranged from 1.72–1.79 g/cm (Table 1). In the non-compacted treatment, 75 cm (30 in) of soil was placed by the loader and spread by hand. Bulk density here ranged from 1.21–1.30 g/cm. Sassafus sandy loam soil was used for all treatments. Each of the 4 treatment areas measured 4 m × 5 m.

Two 2-year-old *Gleditsia triacanthos* var. inermis seedlings were planted in 60 cm (24 in) diameter holes in March of 1978 in each area for a total of 8 trees. Weeds colonizing the plots were mowed weekly during the summer. Weeds were hand pulled periodically from a 60 cm (24 in) diameter circle around each plant. Plants were irrigated to receive a total of 2.5 cm (1 in) of water each week from rain and irrigation during the first growing season. No water was supplied after the first year. Each experimental area received 2.7 kg N/93 square m (6 lb. N/1000 square ft) from urea-formaldehyde each year in one spring application. In August of 1980, the entire root system of each tree was excavated with a shovel, small hand trowel and paint brush from the point of emergence closest to the trunk to the root tips. All intact roots larger than 1 mm (0.04 in) in diameter were mapped. After an individual root had been exposed, the distance from the soil surface to the root center was measured at 30 cm (12 in) intervals for the entire root length. A root map was constructed for each plant. Root excavation and mapping required from 8–22 hours per plant, depending on size of the root system and soil compaction.

Total root length of 8 trees was measured. Mean root-system radius was calculated by averaging the distance from the trunk base to the furthest root tip in the N, E, S and W compass directions. The percentage of the total root length which grew downward, upward toward the soil surface and parallel to the soil surface was determined. The proportion of total root length in specified depth intervals was also determined for each tree.

Trunk diameter was taken at 20 cm (8 in) above soil line as the average of the NS diameter and EW diameter. Mean canopy radius was computed as the average of the N, E, S and W branch radii.

Results and Discussion

Vertical Root Distribution—Compaction significantly ($P < .01$) influenced the root distribution. More roots were growing through the upper soil layers in the compacted soil than in the uncompacted soil (Table 1). This effect was more pronounced in the normal O_2 area than in reduced O_2 area. In compacted soil treatments 70% or more of the total root length was in the upper 12 cm (5 in) of soil compared to 40% or less in uncompacted soil.

Reduced soil oxygen (14.4–14.9%) concentration was correlated with elevated CO_2 (6.2–8.1%) ($r = -.94$) and was associated with a shallower root system although the effect was not statistically significant ($P > .10$) (Table 1). This effect was more pronounced in the non-compacted area. Attributing root response to low soil O_2 or elevated CO_2 is frequently not possible nor desirable in field studies since soil carbon dioxide and O_2 concentrations are generally inversely correlated with each other (5, 23). Others have described similar root responses to soil aeration and compaction in agronomic (3, 11) and forest sites (2, 9) but in depth studies related to urban landscape sites have only recently begun (1, 14).

Roots in compacted areas were significantly ($P < .01$) redirected up toward the soil surface from deeper layers (Table 2). Those roots originating from the 12–18 cm (5–7 in) depth grew to the surface along the bottom and sides of the original planting hole (Fig. 1). Apparently, roots were unable to penetrate the undisturbed compacted soil outside of the loose, disturbed soil in the planting area until they reached within several cm of the surface. Roots in the non-compacted area were not redirected up toward the soil surface and grew freely into the original soil at any depth (Table 2, Fig. 1).

Greater number of shallow adventitious roots, increased branching of the deeper roots and no tap root development were noted in the compacted soils and the reduced O_2 non-compacted soil (Fig. 1). These adventitious roots were longer, straighter and larger in diameter than deeper roots, indicating vigorous growth. In the non-compacted normal O_2 area, tap roots were well developed and the deeper roots penetrated further than in the other 3 areas. In all trees excavated, the smaller feeder-like roots were not recorded because they were 1 mm (0.04 in) or less in diameter and grew more or less vertically toward the soil surface. Therefore, the zone of maximum nutrient and water absorbtion was somewhat shallower than these data indicate. Most of these smaller roots originated from laterals within the top 5 cm (2 in) of soil and could be exposed by simply brushing

Table 1. Percent of root length in each root depth class, total root length, trunk diameter, oxygen and carbon dioxide concentrations and soil bulk density in the 4 treatment areas.

Root Depth Class, cm. (in)	Treatment Area: No Compaction Normal Oxygen	No Compaction Reduced Oxygen	Compaction Normal Oxygen	Compaction Reduced Oxygen
		%[u]		
0–2.5 (0–1)	0 a[v]	3 a	25 b	34 b
2.5–12 (1–5)	26	37	53	36
12–25 (5–10)	16	21	22	28
25–38 (10–15)	34	32	0	2
38–51 (15–20)	14	7	0	0
51–64 (20–25)	6	0	0	0
> 64 (> 25)	4	0	0	0
Total Root Length (m)[w]	36 a	30.8 ab	25.5 b	14.5 c
Trunk diameter (cm)[xw]	4.1 a	3.5 b	3.2 b	1.8 c
O_2 (%)[yw]	19.9 a (1.1)	14.4 b (3.2)	19.8 a (1.1)	14.9 b (3.0)
CO_2 (%)[yw]	1.4 a (0.3)	6.2 c (0.6)	2.1 b (0.5)	8.1 d (0.8)
Bulk Density (g/cm)[zw]	1.21 a	1.30 a	1.79 b	1.72 b

[z]Means, each from 6 points within each treatment area at the 0–15 cm (0–6 in) depth.

[y]Means, each from bi-monthly readings April, 1978–August, 1980 at the 20 cm (8 in) depth from 2 samples at each tree. Number in ( ) is one standard deviation.

[x]Means, each from the average of the NS diameter and EW diameter at 20 cm (8 in) above soil line.

[w]Means followed by different letters are significantly different at $P < .01$.

[v]Values within a row followed by a different letter have significantly different root distribution at $P < .01$ by Chi-Square Analysis.

[u]Percents are averages from 2 trees per treatment.

Table 2. **Distribution frequency of total root length in root growth direction class.**

Root Growth Direction Class	Treatment Area: No Compaction Normal Oxygen	No Compaction Reduced Oxygen	Compaction Normal Oxygen	Compaction Reduced Oxygen
	%[y]			
Percent of total root length which grew up toward soil surface	14.8 a[z]	22.6 a	32.2 b	36.4 b
Percent of total root length which grew parallel to soil surface	32.1	16.1	35.2	38.6
Percent of total root length which grew downward	53.1	61.3	32.2	25.0

[z]Values within a row followed by a different letter have significantly different root distributions at $P < .01$ by Chi-Square Analysis.
[y]Percents are averages from 2 trees per treatment.

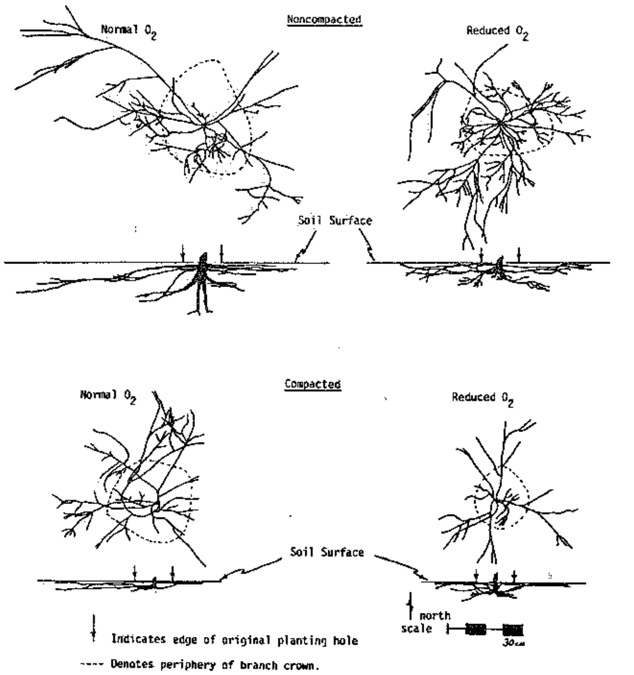

Fig. 1. Plan and elevation view of one root system in each treatment area.

the soil from the surface. This phenomenon is characteristic of several hardwood species (19).

Well-documented morphological responses to periods of low soil O_2 include increased branching of roots and formation of adventitious roots (9). More recently Gilman and others (4) showed that whereas a number of trees survived periods of reduced soil O_2, only those capable of producing a shallow root system grew well. These data support the hypothesis that revised landscape planting practices need to be identified in order to encourage quick establishment of shallow roots in compacted, reduced-oxygen soil (20).

Horizontal Root Distribution—Root systems were more or less symmetrical around the tree stems forming a circular or oval outline (Fig. 1). There was no tendency toward increased growth in the northern quadrant as previously reported for nursery grown plants (21). There was no relationship between shapes of the branch crown and root system. Increased shoot branching on one side of the tree did not correspond to a proliferation of roots on that side.

Both stem diameter and mean canopy radius were significantly correlated with mean root radius (Fig. 2). Root radius was more than twice the branch spread (Fig. 1) which is similar to reported values for a closed canopy forest (19), an open forest stand (8) and a nursery site (21). Stem diameter has been previously correlated with root spread (8) and with root area (19) for a number of forest grown tree species.

Significance to the Nursery Industry

Tree roots respond to the stress brought about in compacted soil and low O_2 soil by growing closer to the soil surface. Roots placed lower than about 12 cm (5 in) below soil line at planting grew toward the soil surface and only proliferated upon reaching the top several cm. This suggests that by planting at a shallow depth in compacted soil, trees may establish themselves quicker because more roots will be placed at a depth where they will ultimately grow best i.e. just beneath the soil surface. Maintenance practices such as fertilization and irrigation should be amended to account for shallow rooting in compacted soil.

The planting hole in compacted soil should be wider than in non-compacted soil to allow for lateral root growth until freeze/thaw cycles, insect activities, cultivation, etc. break up the surface several cm of original soil to allow for continued root growth. These and other alternate planting practices need to be tested to determine how to quickly encourage shallow root systems in compacted soils.

Root spread for young trees three growing seasons after planting was predicted reliably from stem diameter measurements. This type of relationship needs to be described

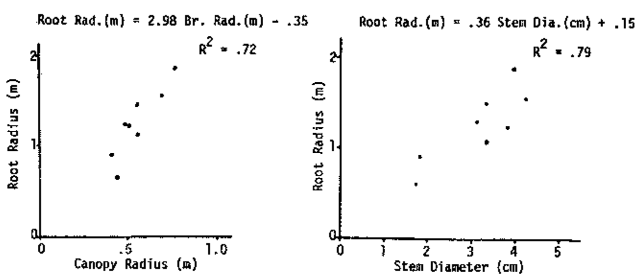

Fig. 2. Branch radius and stem diameter related to root radius. Each point represents data from one tree.

for a number of species and ages under a variety of environmental and cultural conditions.

Roots extended an average of slightly less than three times the distance from the trunk to the drip line. However, roots of other tree species with different crown shapes, e.g. narrow columnar, may extend well beyond three times the drip line. Since studies on landscape root systems are just beginning, it is too early to set these relationships as standards.

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