Effect of Soil Compaction on Carrot Roots

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Abstract. Effects of soil compaction on early root growth of carrot (Daucus carota L.) growing in organic soil contained in specially constructed pots were studied under controlled environmental conditions. Screened and steamed mucky peat soil was artificially compacted with an applied pressure of 0.45—2.23 bars to produce soil densities of 0.7—1.1 g/cm³. Soil strength, measured as penetrometer resistance was directly related to applied compacting pressure. Highest soil strengths were produced when the soil contained 52-58% moisture. Taproot lengths 16 days after seeding were significantly shorter at each increase in soil strength produced by applying compacting pressures of 0.45, 1.12, 1.51, and 2.23 bars. Rates of early taproot growth measured at 2-day intervals for 18 days were similarly decreased with increasing soil strength. Young taproots grew normally through compaction zones produced by 0.45 bars but were severely impeded when compaction zones produced by 1.12, 1.51, and 2.23 bars were encountered. Roots impeded by high soil strength were frequently thickened and convoluted with increased branching but no significant differences between treatments could be detected. Effects of soil compaction on mature roots were evidenced by abnormally short, blunt, and abruptly tapered roots. Mature root weight, diameter, and length decreased with increasing soil compaction.

The physical effects of soil compaction on root growth have been well documented for various crop plants (15, 16, 17, 19, 21). Most measured effects have influenced root growth rate (13, 16, 17, 18), root mass (8, 11, 13, 15, 16, 18), fruit or biomass yield (8, 12), and seedling emergence (19). For carrot, especially those grown for fresh market, factors acting within the soil environment can directly influence root size, shape, and conformation, (2, 20, 22), and ultimately the yield and value of the harvested product (23, 24). Soil compaction has been implicated as one of these factors and more needs to be known of the quantitative aspects of the effects on carrot root growth. Thus, fresh market carrot cultural methods which avoid or minimize compacted soil in the taproot zone have been developed empirically, particularly for organic soils (22, 23, 24).

This study was designed to verify the importance and elucidate the key effects of soil compaction or soil strength on the early root growth and mature root conformation of carrots grown on organic soils.

Materials and Methods

Root growth of carrots was studied in a controlled environment using specially designed pots constructed of 10.1 cm outside diameter polyvinylchloride pipe sections 38 cm long. The pipe sections were split lengthwise and rejoined together with heavy-duty nylon filament tape. The pots were packed with an organic soil (Everglades Mucky Peat, about 90% organic matter, pH 6.7) which had been steamed for 2 hr and sieved through a 6.4 mm screen. Each pot held about 2140 cm³ of soil. Pots were placed on a hard, smooth surface and screened soil (50-55% moisture content) was added in 400 cm³ increments. Each soil increment was compacted to the desired level with a torque-regulated compacting device. Compacting pressure was applied to the surface of each increment of soil through a 66.7 cm² round, steel plate slightly smaller than the inside diameter of the pots. An automotive-type torque wrench was used to apply and regulate compacting pressure (CP) at the soil surface which ranged from 0.45 to 2.23 bars (0.46—2.23 kg/cm²). Compacted soils were checked with a soil penetrometer (Model CL-700, Soil Test, Inc.) for uniform compaction within treatments and these penetrometer resistance readings are presented as unconfined soil strength.

Physical properties of the organic soil used were established by measuring bulk density and unconfined soil strength after...
compaction at different water contents and applied compacting pressures. Samples of air-dry soil were mixed with calculated volumes of water to produce approximately the desired moisture levels on a weight/weight basis and known volumes compacted in special pipe sections (10.1 cm outside diameter × 12 cm in length). Compacted soil cores were removed from the pots, and densities were determined by weighing compacted cores before and after drying at 110°C for 24 hr. Soil strength was measured by averaging 6 penetrometer readings obtained with the CL-700 penetrometer as the force needed to press a 0.5 cm diameter rod (soil penetrometer probe) 0.5 cm deep.

Four levels of soil compaction were employed in various combinations and treatments. These were produced by an applied compacting pressure of 0.45, 1.12, 1.51, and 2.23 bars, respectively. Pots were filled and packed to within 2 cm of the top.

'Dominator' carrot seeds were germinated on moist filter paper for 3 days at 24°C. Germinated seeds were placed on the compacted soil surface and covered with 1 cm of screened soil. Germinated seeds were handled gently with forceps to avoid root injury. The soil was gently packed and 50 ml of water added at planting and once daily thereafter. Carrots were grown in a warm greenhouse (ambient temperature range 22-28°C) or a 24°C controlled environment chamber as specified. In controlled environment chambers, the tops of the pots were placed 28 cm below six 25-watt (F25 T12 25W) cool-white fluorescent tubes supplemented by four 15-watt incandescent bulbs (measured total irradiance at soil surface of the pots: 40 W/m²). At specified intervals after seeding, roots were removed by washing with a gentle stream of water and evaluated as previously described (24). Root length was measured from the cotyledonary node to the root tip of the taproot. To evaluate effects of soil strength on mature carrot roots, germinated seeds were planted as previously described in pots prepared with 0.45, 1.12, 1.51, and 2.23 bars CP. Carrots were grown in a warm greenhouse (ambient temperature range 22-28°C), watered as needed, and washed free of soil and evaluated 78 days after seeding. Root length was measured as the length of the portion of root showing secondary thickening. Root diameter was measured at 2 and 10 cm below the hypocotyl area (crown). Shape index, a figure of merit for consumer acceptance was obtained by dividing the diameter 2 cm below the hypocotyl by the diameter 10 cm below the hypocotyl. A small index describes a gentle tapered root (desirable), and a larger index describes an abrupt taper (undesirable) (9).

**Results**

The bulk densities and unconfined soil strength (penetrometer resistance readings) of the soil were generally increased as a result of artificial compaction. Bulk densities ranged from 0.7 to 1.1 g/cm³ and were directly related to moisture content of soil and compacting pressure applied (Fig. 1). Unconfined soil strength increased with compacting pressure when applied to moderately moist soil (Fig. 2) containing 52-55% moisture. This was the usual moisture reading after field soil was screened and steamed for 2 hr. Unconfined strength also varied with compacting pressure and moisture content of the soil. The organic soil used in this experiment could be highly compacted as measured by soil strength over a moisture range of 50-60%. At the high soil moisture level of 62.5% and the low moisture of 43%, soil strength decreased rapidly with all applied compacting pressures (Fig. 3). Thus, soil moisture content of 50-55% was used in all subsequent experiments.

Artificially compacted soils greatly affected the rate of taproot growth of young carrots by 16 days after seeding (DAS) over the range of 0.45-2.23 bars applied compacting pressure. Taproot length at 18 DAS increased significantly with each increase in soil strength (Fig. 4). Root diameter measured 2 cm below the hypocotyl varied significantly, but root tip diameter did not (Table 1). However, root diameter and convolution of roots were extremely variable both within and among soil treatments. About 25% of the roots showed excessive thickening and a convoluted shape at 1.51 and 2.23 bars CP. Root system configuration also varied with soil strength.

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![Fig. 1](image1.png)  
**Fig. 1.** Soil densities produced by compacting a steamed and screened organic soil with 0.45 and 2.23 bars applied pressure at different soil moisture contents.

![Fig. 2](image2.png)  
**Fig. 2.** Relative soil strengths (soil penetrometer resistance readings) obtained at upper and lower surfaces of organic soil at 55% moisture compacted within 10.1 cm diameter PVC pots 38 cm high.
Fig. 3. Relative soil strengths (soil penetrometer resistance readings) obtained by compacting screened and steamed organic soil of 43, 55.1, 59.6, and 62.5% moisture content at 0.5, 1.1, 1.5, and 2.2 bars compacting pressure (CP).

At higher soil strengths, taproots tended to be thicker, convoluted, and more branched than roots grown at lower soil strengths. As for root diameter, these responses varied widely within and among the 2 higher soil compaction treatments. Representative roots are drawn to scale in Fig. 6.

Fig. 4. Taproot lengths of young carrots growing in 4 levels of soil strength at 24°C. Roots were measured at 2-day intervals.

Table 1. Effect of soil compaction on rate of carrot root growth and root diameter in an organic soil after 16 days at 24°C.

<table>
<thead>
<tr>
<th>Applied compacting pressure (bars)</th>
<th>Root length (cm) 2 cm below hypocotyl tip</th>
<th>Root diameter (mm) at root tip</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>19.6</td>
<td>1.88</td>
</tr>
<tr>
<td>1.12</td>
<td>16.8</td>
<td>2.49</td>
</tr>
<tr>
<td>1.51</td>
<td>12.1</td>
<td>1.62</td>
</tr>
<tr>
<td>2.23</td>
<td>10.0</td>
<td>1.63</td>
</tr>
<tr>
<td>F value</td>
<td>24.83*</td>
<td>5.20**</td>
</tr>
</tbody>
</table>

Values are averages for 10 replicates with 5 plants per replicate. *, ** Significant different at 5% (*) and 1% (**) level by t-test; NS = not significant.

To more closely simulate field conditions, pots were prepared with soil layers of varying combinations of soil strengths. Again, rates of taproot growth decreased with increasing soil strength (Table 2). Young carrot taproots (evaluated at 18 DAS)
Fig. 6. Early carrot root growth in compacted soils produced by 0.5, 1.5, and 2.3 bars compacting pressure. Roots were measured 16 days after seeding.

Carrots grew well in layers of low soil strength (0.45 bars CP), but growth rate decreased when root tips encountered soil strengths produced by 1.12 bars or greater CP (Table 2, Fig. 5). Taproot lengths were generally related to the depth of the low soil strength layer (i.e. 0.45 bars CP) and penetrated high soil strength zones (1.12 bars CP) only a short distance (Fig. 4).

In this series of experiments, no differences were detected in biomass of leaves (tops) or roots as measured by dry weight (Table 2).

Carrots grown to maturity (78 DAS) in soils of different soil strengths demonstrated that the effects of soil strength

Table 2. Effect of uniform and layered soil compaction on early carrot root growth after 18 days at 24°C.

<table>
<thead>
<tr>
<th>Applied compacting pressure (bars)</th>
<th>Root length (cm)</th>
<th>Avg dry wt^z per plant (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper layer</td>
<td>Lower layer</td>
<td>Root length</td>
</tr>
<tr>
<td>0.45 uniform</td>
<td>--</td>
<td>35.0</td>
</tr>
<tr>
<td>1.12</td>
<td>--</td>
<td>26.4</td>
</tr>
<tr>
<td>1.51</td>
<td>--</td>
<td>8.7</td>
</tr>
<tr>
<td>2.23</td>
<td>--</td>
<td>7.2</td>
</tr>
<tr>
<td>0.45 (21 cm)</td>
<td>1.12 (16 cm)</td>
<td>32.1</td>
</tr>
<tr>
<td>0.45 (11 cm)</td>
<td>1.12 (26 cm)</td>
<td>19.1</td>
</tr>
<tr>
<td>0.51 (21 cm)</td>
<td>1.51 (16 cm)</td>
<td>25.5</td>
</tr>
<tr>
<td>0.45 (11 cm)</td>
<td>1.51 (26 cm)</td>
<td>14.8</td>
</tr>
<tr>
<td>0.45 (21 cm)</td>
<td>2.23 (16 cm)</td>
<td>19.1</td>
</tr>
<tr>
<td>0.45 (11 cm)</td>
<td>2.23 (26 cm)</td>
<td>15.1</td>
</tr>
</tbody>
</table>

F value 16.25** 0.70 NS 1.07 NS

zAverage for 5 replicates with 5 plants per replicate.

**Significantly different at 1% level by t-test.

Table 3. Effects of soil compaction (soil strength) on mature carrot root conformation 78 days after seeding.

<table>
<thead>
<tr>
<th>Applied compacting pressure (bars)</th>
<th>Root length (cm)</th>
<th>Root wt^z (g)</th>
<th>A 2 cm below crown</th>
<th>B 10 cm below crown</th>
<th>Shape^y index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>12.7</td>
<td>1.14</td>
<td>1.15</td>
<td>0.36</td>
<td>3.2</td>
</tr>
<tr>
<td>1.12</td>
<td>12.3</td>
<td>1.65</td>
<td>1.26</td>
<td>0.36</td>
<td>3.5</td>
</tr>
<tr>
<td>1.51</td>
<td>7.4</td>
<td>0.96</td>
<td>1.10</td>
<td>0.17</td>
<td>6.5</td>
</tr>
<tr>
<td>2.23</td>
<td>5.3</td>
<td>0.58</td>
<td>0.68</td>
<td>0.10</td>
<td>6.8</td>
</tr>
</tbody>
</table>

F value 9.05** 8.83** 4.29** 9.66**

^yShape index: lower values indicate a gentle taper from crown to root tip; higher values indicate an undesirable abrupt taper. Shape index = diameter 2 cm below crown / diameter 10 cm below crown.

**Significantly different at 1% level by t-test.

This and all values are averages for 6 replicates with 4-5 roots per replicate.

Fig. 7. Frequency distribution of carrot root lengths 78 days after seeding in soil strengths produced by 0.5, 1.1, 1.5, and 2.2 bars compacting pressure.
on taproots measured at 16-18 DAS were reflected by the length, shape, and weights of mature carrot roots grown within the same system. Mature carrot root weight, length, and diameter decreased with increasing soil strengths and the shape index increased indicating an undesirable ratio of root diameter and root taper (Table 3).

Since root shape and length are determinants of consumer acceptability, root lengths were plotted by discrete frequency classes of mature root length (Fig. 7). Considering relative root length, a large proportion of roots grown in soil strengths produced by 1.51 and 2.23 bars were culls due to insufficient root length (24); 83% of these cull roots were abruptly tapered or had blunted tips rather than the gentle taper characteristics of fresh market cultivars (9). The percentage of roots in short length classes increased with soil strength.

Discussion

Our results demonstrate 2 important effects of soil strength on carrot taproot growth and validates field observations made by carrot growers. Additionally, a sound basis is provided for the practice of deep tillage or preparation of raised beds in fresh market carrot production. We have shown that soil strength can affect both rate of growth of young taproots and the size, weight, and shape of mature carrots.

Several reports have emphasized the inhibitory effects of high soil density on root growth for field crop plants where high densities were created by cultural or by natural conditions (11, 12, 18, 20). Soil compactability has been shown to increase with organic matter content (4, 5). Taylor, et al. (14, 15, 16, 17, 18), and others (3, 4) demonstrated that soil strength and root density was the important factor which affects root growth through compacted soils. Our results with carrot root growth are in good agreement with conclusions previously reported for cotton, peas, and peanuts whose root elongation rates were also decreased with increasing soil strength (16, 17).

The soil densities produced by compaction levels employed in our experiments are within the range encountered in the field for similar soil types. Soil penetrometer readings have been justified as a satisfactory method of measuring relative soil strength (3, 6, 16, 17, 19), and the range of soil strengths among the treatments employed were also similar to those encountered under field conditions (23). Soil strength readings which varied with different moisture and applied CP's in this study (Fig. 4) indicate that complex soil strength relationships may prevail in organic soils in the field and that favorable soil strength environments for carrot root growth may be created by various combinations of moisture and compaction. For example, soil strength did not increase greatly after compaction at either higher or lower than normal moisture levels in the organic soil used. Soil strengths of other soil types are similarly affected by soil moisture (4, 10) and may explain why long, slender carrots can be grown on what appear to be hard, dense soils if favorable moisture levels are maintained.

The healthy appearance of carrot root tips impeded by high soil strengths as well as lack of differences in weight of young root systems indicates that oxygen stress was not present, or other essentials for growth were not lacking in highly compacted soil treatments. It is more likely that roots were unable to penetrate pore spaces at higher soil strengths or only penetrate them with great difficulty. Wiersum (25) has demonstrated that small pore size coupled with structural rigidity of the soil can prevent root penetration of soil pores smaller than the root diameter. He described proliferation of branching behind the impeded root tip, enlarged root diameter, and root tip deformity as results of the inability of roots to move soil particles or penetrate rigid pores smaller than the root diameter. Others have intensively investigated the mechanisms of root tip growth and provide probable explanation for these phenomenon (1, 6, 7, 16). Our results for carrot root growth are in agreement with and are adequately explained by these reported general studies of root growth (6, 7, 16), including growth of roots through high soil strengths and layered soil compaction zones (1, 10, 21).

A complicating factor which we observed in many experiments was the variability in response to treatments within an expected uniform population of hybrid carrots. Such variability prevented statistical identification of root tip thickening as reported by others (18) and in some experiments, differences in root length. Individual roots often partly penetrated compacted layers whereas their cohorts did not. Taylor and Burnett (16) also noted this response in cotton and peanut roots and suggested that plant breeders exploit this variability.

Excessive soil strength caused by a variety of soil conditions can indirectly affect yield and fruit quality in other vegetable crops through effects on root growth (8, 12). For fresh market carrots, these effects can be expected to directly influence root yield and quality. Attempts to improve yields, quality and crop efficiency must consider optimum soil strengths and adequate cultural methods to create them. Carrot varietal improvement should also consider the ability of rapid, early root growth in compacted soils as a desirable trait. Finally, excessive soil strength caused by natural processes or production practices can also explain many root defects encountered by carrot producers.

Literature Cited


Differential Response of Lycopersicon and Solanum Species to Salinity


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Additional index words: tomato, Lycopersicon esculentum, L. Peruvianum, Solanum lycopersicoides, S. pennellii, NaCl tolerance

Abstract. Lycopersicon and Solanum species and an F1 hybrid of L. esculentum × S. lycopersicoides differed in growth and concentration of elements in leaves in response to levels of NaCl in outdoor sand culture. S. lycopersicoides and its hybrid with the tomato were more sensitive to NaCl on the basis of reduction in dry matter accumulation than L. esculentum, L. peruvianum, or S. pennellii. The dry weights of S. lycopersicoides and the F1 grown without NaCl in the rooting medium were 6 times greater than the average of L. esculentum, L. peruvianum, and S. pennellii, but only 2 times greater when the plants were grown with 294 meq NaCl/liter of rooting medium nutrient solution. S. lycopersicoides and the F1 were fruitless. The average tops without fruit of all species had 10.9% dry weight when grown without NaCl while tops of plants grown with 294 meq NaCl/liter nutrient solution had 14.0% dry weight. NaCl in the rooting medium increased the concentration of Na less in the leaves of S. lycopersicoides and the F1 than the other species and increased the Cl concentration in the leaves of all species. S. lycopersicoides and the F1 had higher concentration of K, and lower Ca in the leaves than the other species. S. pennellii had higher concentrations of Fe and Mn in the leaves than other species.

Tomato cultivars vary in elemental composition and respond differently to element nutrition (1,4,7,10,11,12,24). Genetic diversity in response to elements may increase in the future, since interspecific hybridization is being increasingly used in tomato breeding (19). Tal (21) concluded that Lycopersicon cheesmanii Riley, although not tolerant per se of high NaCl levels, has genes that interact with those of L. esculentum Mill. to make possible development of cultivars with high salt tolerance. Rick (17, 18) reported finding another biotype of L. cheesmanii with extraordinary salt tolerance, being adapted to a seacoast habitat. Rush and Epstein (20) reported that biotypes of L. cheesmanii differed in salinity tolerance, but all were more salt tolerant than the tomato. Tal and Gavish (22) found that L. peruvianum Mill. is more tolerant than the tomato to high salt and differs in several factors, including transpiration, stomatal density and opening, and abscisic acid level, that influence response to high NaCl.

Since large genetic variation can result from interspecific crosses with the tomato, perhaps even greater genetic variation in element composition and response to NaCl might result from intergeneric crosses with the tomato. Rick (15, 16) showed that S. lycopersicoides Dun. and S. pennellii Corr. can be crossed with the tomato, L. esculentum. The purpose of this work was to compare these Solanum species with the tomato and L. peruvianum for plant growth and leaf concentration of elements in response to different levels of NaCl in the rooting medium.

Materials and Methods

L. esculentum cv. Pelican, L. peruvianum, S. pennellii PI 246502, S. lycopersicoides PI 365378, and the F1 of L. esculentum cv. New York × S. lycopersicoides PI 365378 were transplanted at equilateral spacing of 48 cm into 4 outdoor sand nutrient culture systems on June 3, 1976. Seed of the self-compatible accession of L. peruvianum was kindly provided by N. G. Hogenboom, Institute for Horticultural Plant Breeding, Wageningen, Holland, and the Solanum species by the USDA Plant Introduction Stations at Geneva, NY, and Sturgeon Bay, Wisc. The L. esculentum × S. lycopersicoides F1 plants were clones of a single plant obtained by embryo culture.

A Latin square design with 5 replications of the 5 taxa was used in each nutrient bed, and each of the 4 nutrient beds was randomly designated for a different NaCl treatment. The planting area in each bed was 5.8 m² and was filled to a depth of 30.5 cm with inert quartz sand, size 4Q-Rok, obtained from the Pennsylvania Glass Sand Corp. Nutrient solution was pumped 4 times daily into each bed to 5 cm below the surface of the sand, and then drained back to underground storage tanks. Water depth recorders were used to measure daily water...