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CARROT SEEDLING EMERGENCE AND YIELD

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The effects of five tillage treatments on soil bulk density and mechanical impedance were examined on Newburg sandy loam soil in the Willamette Valley, Oregon, in 1987. Subsequent effects on seedling emergence and yield of carrots (Daucus carota L., cvs. Orlando Gold and Royal Chantenay) were also measured. Mechanical impedance was recorded on three dates at 2.5-cm intervals to a depth of 44 cm with a hydraulically driven penetrometer. A tillage pan often prevented penetration of the penetrometer beyond 35 cm. Soil cores were collected, on the days of penetrometer measurements, at three depths to measure bulk density and water content.

Early season mechanical impedance at soil depths less than 23 cm was less in reduced tillage treatments than in conventional or excessive tillage treatments. Subsoiling before tillage resulted in less mechanical impedance at depths between 23 and 35 cm. Differences in mechanical impedance between treatments diminished later in the season to the point of being nonsignificant. Because of soil

variability and the limited number of soil cores taken, bulk density differences between treatments were not significant for any of the dates.

In both carrot cultivars, total yields were not significantly affected by tillage. Size distribution of roots (by diameter) was affected, with reduced tillage producing smaller diameter carrots. This was most likely a result of the slightly higher, though nonsignificant, number of seedlings emerged in the reduced tillage treatment. Seedling emergence of both cultivars had a moderate negative correlation with soil mechanical impedance at 5 cm.

# EFFECTS OF TILLAGE-INDUCED SOIL COMPACTION ON CARROT SEEDLING EMERGENCE AND YIELD

by

James E. Thomasson

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Dean of Graduate School

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# EFFECTS OF TILLAGE-INDUCED SOIL COMPACTION ON CARROT SEEDLING EMERGENCE AND YIELD

## CHAPTER 1

## INTRODUCTION

The United States produced 326,574 metric tons of carrots (Daucus carota L.) for processing in 1986 with a total value of 22.6 million dollars. Oregon ranked fourth among the states in the production of processed carrots in 1986; the total production for the state was 17,786 metric tons with a value of 1.7 million dollars (USDA, 1987). The majority of carrots in Oregon are grown in sandy loam soil in the Willamette Valley.

In recent years soil compaction has been detected in some commercial carrot fields in the Willamette Valley. This compaction is suspected to be affecting the yield of carrots grown in those fields. Soil compaction has been shown to reduce the length and yield of carrot roots in organic (Strandberg and White, 1979), silt loam (Olymbios and Schwabe, 1977), and fine sandy soil (Taksdal, 1984).

Compaction in carrot fields is likely caused by spring tillage or fall harvest, two procedures that provide the majority of field traffic. Experiments in other areas have proven that excessive tillage has been commonly practiced by some farmers (McKibben, 1971), though it has not been documented specifically for carrot growers. Lovely et al. (1960) pointed out that excessive manipulation of soil became common when tractors became available to most farmers. They claimed that the attitude of many farmers has been, "If a little is good, then a lot should be better." The additional traffic of excessive tillage can cause increased soil compaction because of forces exerted on the soil by the tractor wheels and tillage implements. The question arises as to how much tillage is too much?

Deep chiseling (subsoiling) is a means of breaking up compact layers of soil that exist at the plow sole (Trouse, 1983; Vebraskas and Miner, 1986; Ross, 1986). Quantified compaction levels at which carrot root growth is restricted, however, have not been identified. Therefore, it is not known what degree of compaction justifies the added expense of subsoiling in commercial carrot fields.

The objectives of this study were (1) to examine the effects of different intensities of tillage on soil compaction, (2) to examine the effects of subsoiling on soil compaction, and (3) to determine the influence of the resultant differences in soil compaction on carrot seedling emergence and yield.

# CHAPTER 2

# LITERATURE REVIEW

## I. INTRODUCTION

Tillage has been used for thousands of years to break and stir the soil and improve crop yields. Though tillage implements have greatly evolved from the forked sticks and sharp stones used by early humans, the basic goal of tillage is still the same: to obtain optimum crop production. Proper tillage provides an ideal environment for seed germination, seedling emergence, root growth, weed control, soil moisture control, and soil erosion control. Tillage operations modify the soil environment by altering soil physical properties. For example, the soil is loosened by the parting and shearing actions of tillage implements. Concurrently, the force applied to the soil, and the soil's resistance to motion, result in compression of soil. Thus, tillage may result in an overall loosening of the soil while portions of the soil mass are made more compact (Cooper, 1971; Cohron, 1971). Another force acting upon the soil during tillage is the compacting pressure beneath the tractor wheels. The effects of wheel traffic on soil compaction have been well documented (Soane et al., 1981; Cohron, 1971) and are considered to be the primary cause of soil compaction.

Any tillage activity beyond what is required for an ideal soil environment is of questionable value and potentially detrimental to crop production. Excessive tillage can cause soil compaction, which may affect the germination, growth, development, and yield of many crops.

## II. METHODS OF MEASURING SOIL COMPACTION

Freitag (1971) described and discussed several methods of measuring soil compaction. The two methods most commonly used in agricultural research are bulk density and mechanical impedance.

### A. Bulk density

When soil is compacted there is a decrease in volume for a given mass of soil. Bulk density, the weight of dry solids per unit volume of soil, is a direct measurement of soil compaction. Bulk density data can also be converted to porosity, which may be more meaningful as far as crop growth is concerned (Vomocil and Flocker, 1961).

Soil core sampling is the traditional method of determining soil bulk density and is preferred by Blake (1965) and McIntyre (1974). The method consists of using a cylindrical metal sampler to remove a known volume of soil and drying and weighing the sample. Although this is referred to as taking an "undisturbed sample" the soil may often be compressed or shattered when the sampler is pressed or hammered into the soil (Blake and Hartge, 1986). This disturbance, along with spatial and temporal variability, can produce unreliable results if not compensated for. Vomocil (1957) points out that because of soil variability only a large number of bulk density samples will yield reliable information. Cassel (1982) notes that researchers usually take an insufficient number of samples to perform rigorous statistical analysis. The intense labor and time required to collect soil core samples often limits the number of samples collected. Also, it may not be feasible in some situations because it is a destructive sampling method. Erbach (1982) indicated there is no quick, easy accurate method for determining soil bulk density. A more thorough discussion of methods for determining bulk density can be found in Blake and Hartge (1986).

### B. Mechanical impedance

Mechanical impedance has recently gained popularity as a method of measuring soil compaction because many measurements can be made in a short time with relative ease. Mechanical impedance is the mechanical resistance of the soil to penetration. It is measured with a penetrometer, and the data reported as cone index: the ratio of the force required to push a metal cone into the soil vs. the basal area of the cone (Davidson, 1965). Mechanical impedance depends on soil physical properties such as those altered by tillage (bulk density, structure, and water content) as well as soil texture, clay minerology, and percent organic matter (Cassel, 1982). Therefore it can only be used as a relative measure of compactness under conditions where the other variables are kept constant or are accounted for.

Penetrometers of various types have been used as far back as the 1930's to measure compaction. Keen and Cashen (1932) designed an apparatus similar to a pile driver and based the mechanical impedance of the soil on the number of impacts required for a rod to reach a certain depth. Culpin (1936) designed a penetrometer which used springs to force a probe into the soil. His apparatus gave results similar to drawbar resistance results measured with a dynamometer when plowing. Culpin also demonstrated the use of firing a revolver into the soil and measuring the depth of penetration of the bullet as an indicator of the degree of compactness. The penetrability of the bullets is inversely proportional to the soil density and was used to illustrate the difference in compactness between gyrotilled and control plots.

Shaw et al. (1940) found soil moisture to be the dominant factor influencing the penetrability of the soil. Still, they were able to use a penetrometer to find zones of maximum compaction after using different intensities of tillage. They concluded that the penetrometer is a useful tool for field experiments. Chancellor (1976) discusses variations in cone index data that are attributable to water suction and suggests reducing the variability by measuring cone resistance when the soil is at field capacity. Jamison and Weaver (1951) defined a hardness function that took soil moisture and mechanical impedance into account in estimating soil porosity. The hardness function, $\log(\theta H^{1/2})$, where $\theta$ is field moisture percentage and H the number of blows required to cut a 470-cc soil core with a hammer sampler, was highly correlated with macroporosity in fine sandy loam and clay. They suggested use of this function in estimating soil porosity conditions.

Many current tillage and soil compaction studies employ the use of the penetrometer to determine the hardness of soils. Cassel (1982) justified the use of the penetrometer for assessing the effects of different tillage operations on soil hardness, despite obvious differences between a root and a metal penetrometer cone. He recommends that supporting data, such as soil moisture and bulk density, be made available for proper interpretation of cone index data. The use of penetrometers is more thoroughly discussed by Davidson (1965) and Bradford (1986).

## III. TILLAGE AND SOIL COMPACTION EFFECTS ON CROP DEVELOPMENT

Cassel (1982) reviewed much of the published data that describe tillage effects on soil bulk density and mechanical impedance. He also discussed problems with measurement techniques and presents recommendations for measurements and data interpretation. Cooper (1971) discussed the effects of tillage on soil compaction, including the physical reaction of the soil to specific tillage implements. Soane et al. (1981) reviewed soil and wheel characteristics which influence compaction resulting from the passage of agricultural vehicles. Later, a second review (Soane et al., 1982) noted the extent of soil compaction occurring on agricultural soils and its subsequent effects on crop production. In general, the above reviews point out that tillage and compaction studies are worthwhile endeavors. Among the important points discussed are the following: (1) Soil compaction is widespread under modern systems of crop production because of a trend toward increasing the weight and number of passes of agricultural vehicles. (2) There is increasing evidence for widespread harmful effects of field traffic on crop production. (3) The wide and confusing variety of methods, units and expressions used in compaction studies should be standardised. (4) Because experimental site and tillage equipment impose an important influence on the results obtained, it is recommended that detailed descriptions of soil tillage operations, sampling scheme and statistical methods be reported. (5) Attention should be paid to vertical and horizontal distribution of soil properties during compaction of soils. (6) Further quantitative cost and benefit information in adopting different practices and equipment for compaction reduction is needed.

Soil compaction affects yields of several crops, including cucumbers (Smittle and Williamson, 1977), potatoes (Flocker et al., 1960), maize (Kayombo and Lal, 1986; Boone et al., 1987), sugar beets, and field beans (Brereton et al., 1986). Smittle and Williamson (1977) reported root growth of cucumbers grown in loamy sand to be inhibited 80% at a soil strength of 850 kPa. Nitrogen uptake was reduced by soil compaction and attributed to shallow root growth and leaching of $NO_3$ below the rhizosphere. They reported that the effects of soil compaction could be partially alleviated by increasing the rate of nitrogen fertilization. Kayombo and Lal (1986) found a 63% reduction in maize yields grown in soil compacted by heavy traffic. Yield reductions were attributed to "adverse soil conditions" which reduced root growth. They reported correlation of maize yields with the following soil properties: dry bulk density ($r=-.80$), porosity ($r=.79$), infiltration rate ($r=.82$), penetrometer resistance ($r=-.59$).

Flocker et al. (1960) found that fine sandy loam soil compacted by passes with a loaded truck reduced yields of potatoes but not tomatoes. They concluded that the different yield response was because of differences in the extent and vigor of the root systems. Brereton et al. (1986) reported that compaction induced by tractor wheelings on coarse gravelly sandy loam reduced yields of sugar beets by 59% and field beans by 26% but did not affect spring barley yields.

In agreement with Flocker et al., they suggest that the different responses of crops to soil compaction is related to inherent root density of the species. They disagree with the common suggestion that change in crop water status is a major factor affecting crop growth as a result of tillage operations, as their results showed no effect of compaction on the diurnal and seasonal variation of leaf water potential, osmotic potential or leaf turgor in beans, beets or barley.

Cone index data have been negatively correlated with tobacco root concentrations at soil depths of 0.15 to 0.30 m (Vepraskas and Miner, 1986). Because of high correlation coefficients found in their study relating cone index with root concentrations (-.79 to -.88), Vepraskas and Miner concluded that cone index was a major factor affecting root concentrations between the soil surface and tillage pan. Boone et al. (1987) concluded that insufficient soil aeration was the major factor reducing maize yields in soil compacted by tractor passes. As evidence they noted oxygen concentrations in the soil and the shifting of roots toward soil layers with more adequate oxygen. In controlled environments, Asady et al. (1984) found dry-bean xylem accumulation of anaerobic metabolites to be correlated with soil bulk density and inversely related to oxygen diffusion rates in the soil. Crop responses to modification of soil physical properties by tillage and traffic can be quite complex. As shown by the studies cited here, yield decreases may be the result of compaction effects on factors such as oxygen deficiency, mechanical impedance, water relations, nutrient uptake and their interactions.

Studies have shown that compact tillage pans reduce subsoil root development and that subsoiling reduces the mechanical impedance of tillage pans, allowing increased root growth below the pan (Vapraskas and Miner, 1986; Taylor et al., 1966). Vepraskas and Miner identified a tillage-pan cone-index value of 2.8 MPa or greater, at which subsoiling can effectively increase the number of roots below the depth of the tillage pan. They caution the reader in using this value for quantitative comparisons, however, because of possible differences in soil structural cracks, soil moisture and penetrometer types.

For a given bulk density, greater root penetration can occur in moist soil than dry soil, because mechanical impedance is moisture dependent (Vepraskas et al., 1986). Ross (1986) reported subsoiling increased potato yields only under very dry conditions, suggesting that problems caused by tillage pans may be overcome by appropriate irrigation management.

The practice of subsoiling is thoroughly described and reviewed by Swain (1975).

Intensive tillage can increase compaction and cause deterioration of soil structure. The result may be severe crusting and seedling emergence problems. Hegarty and Royle (1978) showed that soil crust strength is dependent on compaction and the amount of rainfall after compaction. They reported a 20% reduction in calabrese (broccoli) seedling emergence due to crust formation in compacted soil. In a review on soil crusting by Awadhwal and Thierstein (1985) conditions are listed under which harder and less permeable soil crusts develop. They include (1) compact top soil; (2) small soil aggregates at the surface; (3) high water content in the top layer maintained for a long time; and (4) low organic matter and high clay content.

Awadhwal and Thierstein point out that seedling emergence is lowest through a crusted soil when the moisture is the lowest. The wetter the soil, however, the greater the influence of crust on the diffusion of air through the soil. Therefore, the low porosity and highly-orientated soil particles of a crust can limit the supply of oxygen to germinating seeds when the soil is wet. A study by Braunack and Dexter (1988) indicated smaller aggregates result in a delay of wheat seedling emergence in wet years, while in drier years smaller aggregates result in less time to emergence. This is possibly explained by a limited oxygen supply in fine soil when the pores are occupied by water. Braunack and Dexter also report percentage emergence of wheat seedlings is highest when soil aggregates are 2-4 mm in size, compared with both smaller and larger aggregates. This coincides with the aggregate sizes that had the weakest crust formations.

Some researchers have reported negative inverse relationships between mechanical impedance and seedling emergence. Parker and Taylor (1965) measured the force required to push a cylindrical-tipped penetrometer 5 mm into six different soil types. In all soil types, emergence of sorghum was progressively decreased by increases in soil strength above 3 bars. Royle and Hegarty (1977) used a 2-mm diameter flat-ended penetrometer to measure soil impedance of sandy loam soil to a depth of 15 mm. The area under the curve of force against distance was calculated as "integral impedance" and was found to have a high negative correlation with the percentage emergence of calabrese. In crusted soils the "peak force" required to penetrate the crust also had a high negative correlation with percentage emergence.

# IV. SOIL FACTORS AFFECTING CARROT PRODUCTION

## A. Stand Establishment

The sowing rate for carrots should be adjusted according to the state of the soil, with different rates chosen for "cold soil and poor tilth", "average conditions", "good conditions", or "ideal conditions" (Moore as cited in Hegarty, 1976). Hegarty (1976) reports carrot (cv. Red Cored Chantenay) stand establishment is primarily dependent on soil tilth, soil nutrient status, seed or soil infection, seed drill performance and seed vigor, while soil temperature and moisture are less influential. Soil temperature is an important factor, as Hagerty (1973) found that 19 out of 50 Chantenay carrot seed lots had a significant reduction in germination at 10 degrees C compared with 20 degrees C. Both Gray (1979) and Hagerty (1978) report the rate of carrot seedling emergence is dominantly related to soil temperature. Several researchers have shown that the time of harvesting the carrot seed crop (Hawthorn et al., 1962; Gray, 1979) and the position of the seed on the umble (Borthwick, 1931; Hawthorn, 1962; Gray, 1979) affect germination. In general, the more mature seeds (e.g. harvested late and from primary umbles) have a faster rate and higher percentage of germination.

In wet soil conditions, lack of oxygen has been implicated as a factor affecting carrot germination and emergence. Reduction in the availability of oxygen has been shown to inhibit seed germination in many plants (Koller and Hadas, 1982). Heydecker (1962) compared carrot seedling emergence after applying three watering treatments and allowing two levels of soil evaporative water loss. He observed that field capacity is not as favorable for germination as a less wet condition, and attributed this to differences in aeration.

Reduction of seedling emergence by soil crusting can also be a problem in carrot production. Many researchers have tried soil additives to maintain proper soil aggregation or to reduce resistance to emergence (Hemphill, 1982; Page and Quick, 1979; Robbins et al., 1972). Hemphill found that vermiculite is an effective anticrustant, reducing mechanical resistance of the soil surface five-fold and increasing early carrot stands by three times over those of the check plots.

## B. Soil Compaction Studies in Carrots

Experiments involving soil compaction and carrots have been performed in the field and under controlled environmental conditions. Five of those studies are discussed here.

Olymbios and Schwabe (1977) applied piston pressure to silt loam soil in pots to create four different levels of compaction (bulk densities of 1.02, 1.21, 1.31, 1.46 $g/cm^3$). They found that 'Royal Chantenay' carrots grown in the 1.46 $g/cm^3$ soil had tap root weights 32% less than those grown in 1.31 $g/cm^3$. Tap roots in the 1.02 $g/cm^3$ soil also weighed considerably less than those of the 1.31 $g/cm^3$ soil, indicating that an optimal degree of compaction exists. Although both loose and compact soil result in smaller carrots, the compact treatment had a lower root/shoot ratio: 0.91 compared to 1.14 of the loose soil. The authors attribute this to greater cambial activity of roots in well-aerated soil, which might increase the "sink strength" of the root. The shape of the carrots are affected by compaction, with those grown in loose soil tending to be cylindrical while those in compacted soil, conical. Olymbios and Schwabe attribute the differences in root size and shape to differences in aeration and mechanical impedance. The decreased aeration conclusion is partially based on results from their water culture experiment, which showed dry matter accumulation and growth of carrots are severely affected by a lack of aeration.

Strandberg and White (1979) applied four different compacting pressures to organic soil in pots and produced bulk densities ranging from 0.7 to 1.1 g/cm$^3$. They found that compaction causes a decrease in the growth rate of young carrot tap roots and in the size and weight of mature carrots. They also reported compact soils result in an abrupt taper rather than the gentle taper found in the less compact soil. Unlike Olymbios and Schwabe, Strandberg and White concluded, based on the healthy appearance of carrot root tips, that oxygen stress was not a factor in their results. They attribute their results to the inability of the roots to penetrate pore spaces at higher soil strengths.

In a field study on fine sandy soil, Taksdal (1984) created three different levels of compaction in a bed system with 0, 2, and 4 tractor passes ("wheelings") before tillage. He showed that penetration resistance of the soil at depths 10 to 35 cm increases with an increase in the number of wheelings. The increased penetration resistance resulted in reduced carrot (cv. Nantes Duke) root lengths. In support of Olymbios and Schwabe's results, Taksdal found the percentages of distinctly conical roots were doubled by each additional two wheelings. Total yields were reduced by wheelings in 1982 but not in 1983, although the yield of grade I carrots (according to the Norwegian standard rules for carrot quality) was significantly reduced by wheelings in both years.

White (1978) reported, in a field study, that rolling organic soil with a drum roller after tillage contributed to soil compaction and resulted in lower marketable yields and more forks in 'Hicolor 9' and 'Dominator' carrots. He found a linear relationship between marketable yield and the soil depth at which compaction, measured by a penetrometer, reached 4.5 $kg/cm^2$.

In another field study, using tractor wheelings across beds, Harrison et al. (1985) found that wheelings increased soil bulk density and penetrometer resistance. However, the compaction was not great enough to affect carrot yield or quality. They attribute this to dry soil conditions at the time the wheelings were imposed and to good soil structure due to grass and clover grown in the two previous years.

# CHAPTER 3

# MATERIALS AND METHODS

A field experiment was conducted in 1987 on Newburg sandy loam soil at the Oregon State University Vegetable Research Farm, Corvallis, Oregon. A randomized-block design was used with 5 treatments and 4 replicates, creating 20 plots, each measuring 10.6 by 10.6 meters. A conventional tillage treatment was established based on current cultural methods used in the Willamette Valley. One treatment with reduced and one with excessive tillage were added, as well as two subsoiling treatments (Table 1). A moldboard plow, cultimulcher, and roterra with roller were used in all treatments and were operated parallel to the carrot rows. The tillage implements that were not common to all treatments were operated perpendicular to the carrot rows. The implements, the tractors that pulled them, and the depths of tillage are listed in Table 2.

The gravimetric water content at the time of tillage was 15.4% at a soil depth of 5 to 10 cm. Fertilizer was broadcast over all plots at 90 kg N, 118 kg P, and 75 kg K per hectare. Trifluralin was applied for weed control and diazinon for wireworm control; both were incorporated, along with the fertilizer, by the roterra and roller. 'Royal Chantenay' carrots were planted on one side of each block and 'Orlando Gold' carrots on the other. A hand-pushed Planet Jr. with a scatter shoe was used to plant the carrots on May 21, at 61-cm row spacings. All plots were irrigated daily until emergence; then a schedule was maintained at which 33 mm of water was applied about every 10 days.

Penetrometer measurements were made with the soil moisture near "field capacity" on June 9 and August 19 and under dry soil conditions (one day before irrigation) on July 7. Measurements were taken at 6 positions evenly spaced along a transect parallel to the carrot rows. A 90-degree cone, with a 2.54-cm diameter base, at the tip of the penetrometer rod was hydraulically pushed into the ground. The force required was sensed at the top of the rod by a load cell, while a displacement transducer sensed the depth of soil penetration. The signals were then transmitted to a CX86805 signal conditioner, an ADC71A analog to digital converter, and finally to a HP71B computer. As the cone was pushed into the soil the computer recorded the force applied, at 2.5-cm intervals. The penetrometer assembly was mounted on a small trailer with balloon tires and pulled by a lightweight Allis Chalmers G-model tractor for the June 9 measurements. On July 8 and August 19 the penetrometer and trailer, with wheels removed, were mounted on a three-point hitch behind a Kubota tractor. Soil cores, 3.47 cm in diameter and 6.35 cm in length, were collected with a Mederra soil probe at three depths (center of core at 5, 15, and 25 cm) between the two most central penetrometer measurements in each plot, on the same day that penetrometer measurements were taken. The soil cores were weighed, oven-dried at 35 degrees C for 24 hours, and reweighed to provide bulk density and water-content data.

On June 19, the number of carrots emerged were counted in 0.91 m of row at four random locations in each plot. Carrot roots were harvested from 6 m of row in each plot on October 6 and separated into five shoulder diameter size grades (<25, 25-38, 38-51, 51-64, and >64 mm). Each grade was weighed separately and carrots in each grade were counted. Forked, cracked, and crooked carrots were classified as culls and counted. Twenty-five carrots were randomly selected from the 38-51 mm grade for root-length measurements. A single-factor randomized block design was used for the separate analyses of variance of total yield, root length, emergence, percentage culls, and harvest density. Analyses of variance were also performed for the percentage of yield in each size grade and for the percentage of yield less than 38 mm.

Cassel (1982) recommends that penetrometer data be reported using cone index values: the ratio of the force required to push a metal cone into the soil vs. the basal area of the cone (Davidson, 1965). Cone index values in my study, however, did not have homogeneous variability, a necessary assumption when using analysis of variance. To correct the nonhomogeneity, all cone index data were transformed to common logarithms (base 10). A two-factor randomized block design was then used for the separate analyses of variance of log cone index and soil bulk densities, using tillage treatment and soil-depth as factors. Correlation coefficients were calculated using the June 9 cone index at 5 cm and the June 19 emergence data.

Table 1--Tillage treatments with implements listed chronologically

| Treatment | Tillage implements |
|---|---|
| Reduced tillage | Moldboard plow |
| | Cultimulcher |
| | Roterra with roller |
| Conventional tillage | Moldboard plow |
| | Cultimulcher |
| | Disk with roller (2 passes) |
| | Roterra with roller |
| Excessive tillage | Moldboard plow |
| | Cultimulcher |
| | Kongskilde harrow (3 passes) |
| | Disk with roller (5 passes) |
| | Roterra with roller |
| Subsoil before tillage | Chisel subsoiler |
| | Moldboard plow |
| | Cultimulcher |
| | Roterra with roller |
| Subsoil after tillage | Moldboard plow |
| | Cultimulcher |
| | Chisel subsoiler |
| | Spike-toothed harrow |
| | Roterra with roller |

Table 2-- Tillage details

| Tillage implement | Tillage depth (cm) | Tractor |
|---|---|---|
| Single-shank chisel subsoiler | 50 | John Deere 2640 |
| Moldboard plow (3-bottom) | 32 | John Deere 2640 |
| John Deere 950 cultimulcher | 21 | Ford TW-10 |
| Tandem disk and roller | 15 | Massey Ferguson diesel 135 |
| Kongskilde Triple-K harrow | 15 | Massey Ferguson diesel 135 |
| Spike-toothed harrow | 7 | Massey Ferguson 135 |
| Lely roterra and roller | 10 | John Deere 2640 |

# CHAPTER 4

# RESULTS

## Soil Mechanical Impedance

The analysis of variance of log cone-index data indicated that tillage-treatment and soil-depth main effects and their interaction were significant on June 9. The highest cone index (CI) in soil depths up to 18 cm occurred in excessive tillage and the lowest in reduced tillage (Figure 1). Though not statistically significant, subsoiling after tillage resulted in slightly higher CI than all other treatments except excessive tillage. Throughout the 35-cm soil profile, subsoiling after tillage resulted in higher CI than subsoiling before tillage. Furthermore, the lowest CI that persisted over several depths occurred in the subsoil-before-tillage treatment at 20-28 cm depths, and at 28-33 cm were less than half of the CI of the nearest treatment.

The general trend of all treatments was for CI to increase with depth to a slightly compact layer near 8 cm and then decrease to a minimum at 20-25 cm. A sharp increase began beyond 25 cm and continued to the last valid measurement at 35 cm. The penetrometer was often unable to penetrate past 35 cm because of the high mechanical impedance at this depth. A tillage pan had apparently developed from years of tillage at the experimental site.

On July 7 and August 19 there was no significant CI difference between treatments and no treatment-by-depth interaction. All three dates had significantly different CI between depths. The CI values

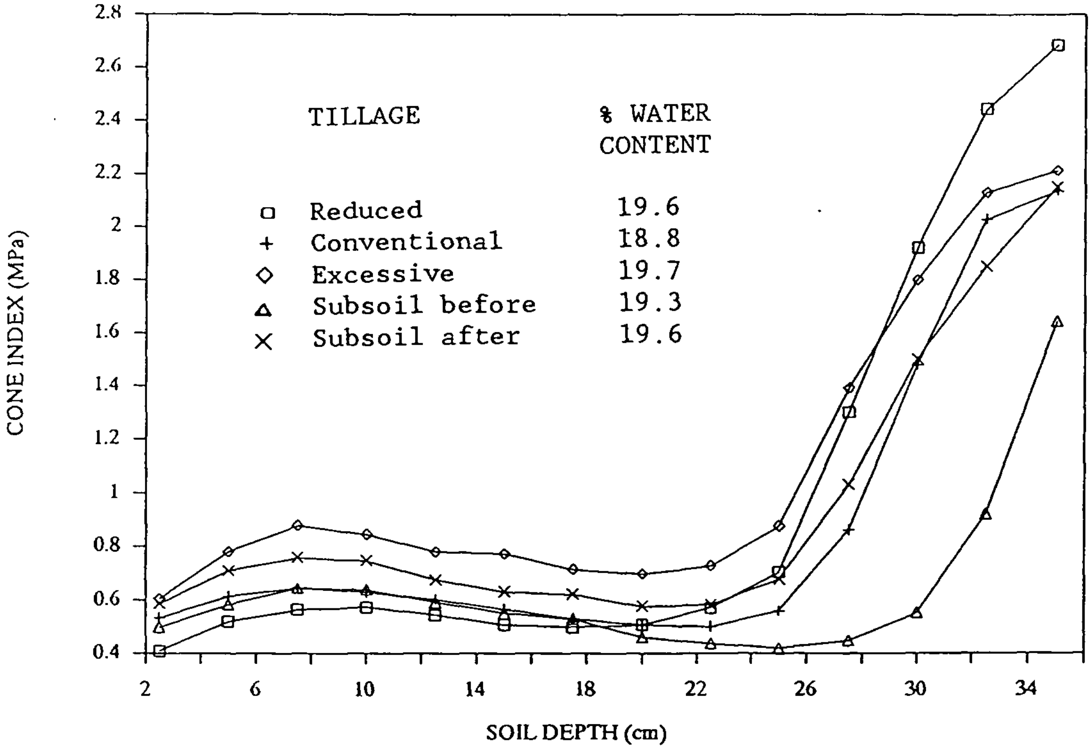

Figure 1--June 9 depth profile of mechanical impedance for five tillage treatments (% water content is an average of 5, 15 and 25 cm soil depths). Statistical comparisons are shown in Table 9 in the appendix.

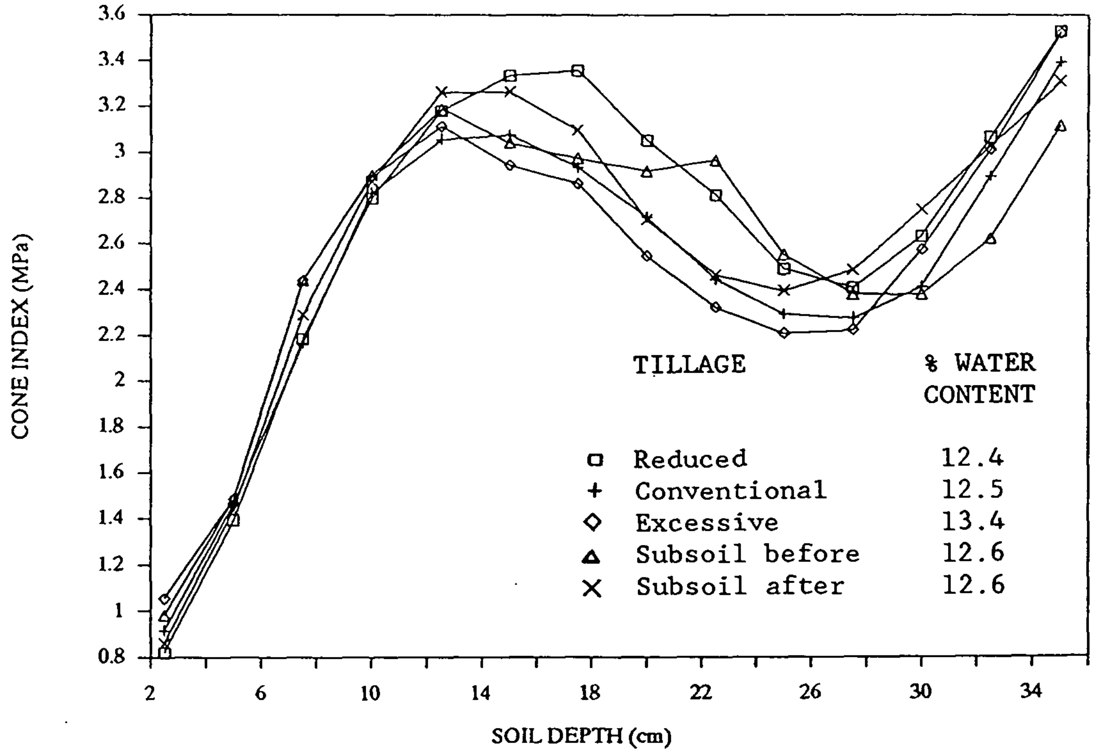

Figure 2--July 7 depth profile of mechanical impedance for five tillage treatments (% water content is an average of 5, 15 and 25 cm soil depths). Statistical comparisons between depths are shown in Table 10 in the appendix.

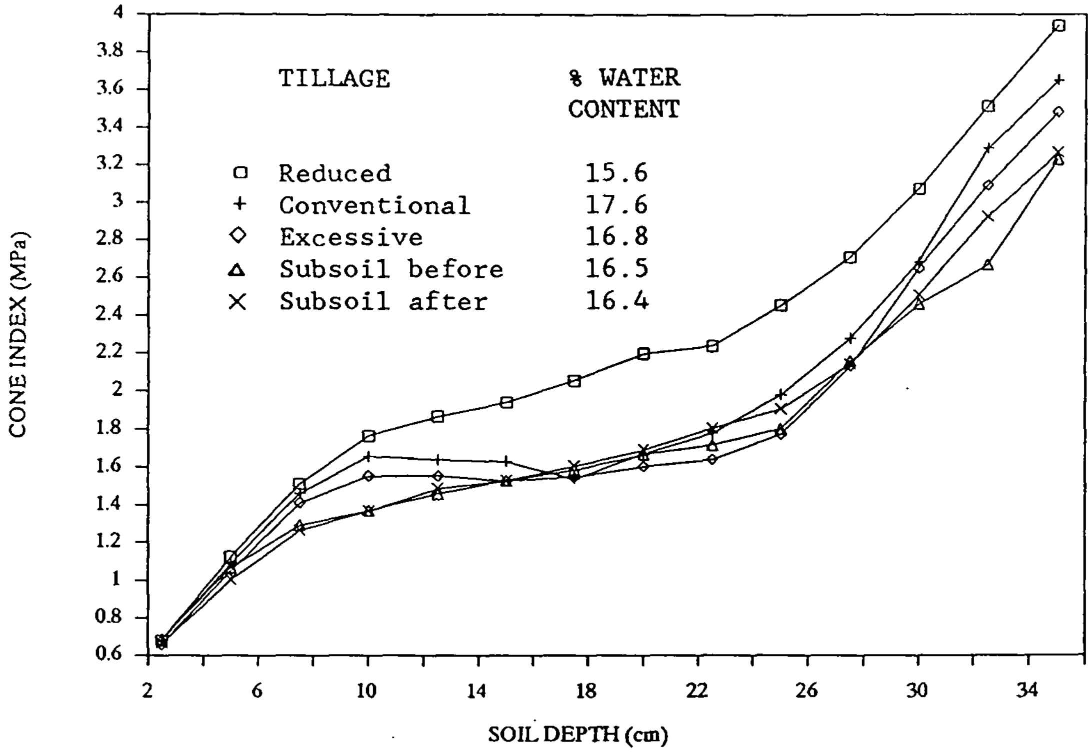

Figure 3--August 19 depth profile of mechanical impedance for five tillage treatments (% water content is an average of 5, 15 and 25 cm soil depths). Statistical comparisons between depths are shown in Table 11 in the appendix.

on July 7 and August 19 were generally higher than those on June 9. The dry measurements taken on July 7 had a dramatic peak CI at the 10-18 cm soil depth (Figure 2). Cone index on August 19 generally increased with increasing depth (Figure 3). At depths greater than 2.5 cm, the reduced-tillage treatment appeared to have slightly higher CI than other treatments, though not significantly so. There was no significant treatment difference in percent water content for any of the three dates. Water content was averaged over three depths and presented in figures 1, 2 and 3.

## Soil Bulk Density

An analysis of variance of soil bulk densities for all three dates indicated that the treatment main effect and the treatment-by-depth interaction were not significant. The soil-depth main effect was significant for all dates at $p<0.05$ (Tables 3, 4, and 5). Generally, of the three depths sampled, the greatest bulk density occurred at 15 cm and the least at 5 cm. On June 9 the treatment differences at 15 cm deep, though not statistically significant, nearly match the order of CI treatment-differences at the same depth; excessive tillage had the greatest bulk density while reduced tillage had the lowest. Calculation of the correlation coefficient for bulk density and CI at 15 cm, however, showed no correlation ($r = -.08$).

## Carrots

No significant effect of tillage treatment was found on emergence, total yield, density at harvest, percentage culls, or root length for either carrot cultivar (Table 6). There are some trends,

Table 3--June 9 soil bulk density (g/cm$^3$) as a function of tillage treatment and soil depth

| Treatment | Soil depth (cm) | | | Treatment |
|---|---|---|---|---|
| | 5 | 15 | 25 | mean |
| Reduced tillage | 1.38 | 1.43 | 1.38 | 1.40 |
| Conventional tillage | 1.38 | 1.45 | 1.42 | 1.41 |
| Excessive tillage | 1.34 | 1.56 | 1.40 | 1.43 |
| Subsoil before tillage | 1.33 | 1.48 | 1.41 | 1.40 |
| Subsoil after tillage | 1.38 | 1.51 | 1.40 | 1.43 |
| Mean | 1.36<br>b | 1.48<br>a | 1.40<br>b | |

Multiple comparison by the Waller-Duncan k-ratio t test, 5% level

Table 4--July 7 soil bulk density (g/cm$^3$) as a function of tillage treatment and soil depth.

| Treatment | Soil depth (cm) | | | Treatment |
|---|---|---|---|---|
| | 5 | 15 | 25 | mean |
| Reduced tillage | 1.32 | 1.41 | 1.40 | 1.37 |
| Conventional tillage | 1.34 | 1.39 | 1.43 | 1.38 |
| Excessive tillage | 1.35 | 1.42 | 1.40 | 1.39 |
| Subsoil before tillage | 1.32 | 1.54 | 1.49 | 1.45 |
| Subsoil after tillage | 1.30 | 1.39 | 1.34 | 1.35 |
| Mean | 1.33<br>a | 1.43<br>b | 1.41<br>b | |

Multiple comparison by the Waller-Duncan k-ratio t test, 5% level

Table 5--August 19 soil bulk density (g/cm$^3$) as a function of tillage treatment and soil depth.

| Treatment | Soil depth (cm) | | | Treatment |
|---|---|---|---|---|
| | 5 | 15 | 25 | mean |
| Reduced tillage | 1.40 | 1.54 | 1.46 | 1.47 |
| Conventional tillage | 1.39 | 1.46 | 1.47 | 1.44 |
| Excessive tillage | 1.37 | 1.52 | 1.44 | 1.45 |
| Subsoil before tillage | 1.39 | 1.49 | 1.45 | 1.44 |
| Subsoil after tillage | 1.39 | 1.51 | 1.44 | 1.44 |
| Mean | 1.39<br>a | 1.50<br>b | 1.45<br>c | |

Multiple comparison by the Waller-Duncan k-ratio t test, 5% level

Table 6--Effects of tillage treatment on carrot development

| Tillage Treatment | Emergence June 19 (plants/m) | Total yield (Mg/ha) | Harvest density (plants/m) | Percent culls | Length (mm) of 38-51 mm diam roots |
|---|---|---|---|---|---|
| | cultivar: Orlando Gold | | | | |
| Reduced | 64.4 | 79.3 | 54.9 | 19.8 | 96 |
| Conventional | 57.7 | 82.3 | 53.3 | 21.0 | 90 |
| Excessive | 58.7 | 77.0 | 49.4 | 19.8 | 84 |
| Subsoil before | 58.7 | 75.7 | 52.9 | 18.1 | 90 |
| Subsoil after | 56.4 | 78.6 | 47.0 | 20.3 | 86 |
| | cultivar: Royal Chantenay | | | | |
| Reduced | 61.1 | 102.8 | 49.2 | 8.9 | 48 |
| Conventional | 56.9 | 104.1 | 50.3 | 6.2 | 47 |
| Excessive | 52.9 | 101.2 | 47.5 | 7.5 | 46 |
| Subsoil before | 56.0 | 103.5 | 47.2 | 10.6 | 46 |
| Subsoil after | 57.7 | 104.9 | 49.9 | 8.0 | 46 |

Differences between tillage treatments are not statistically significant.

however, that should be noted: Orlando Gold carrots were slightly longer in the reduced tillage treatment than other treatments and; in both cultivars, the reduced tillage treatment had the greatest number of carrots emerged 29 days after planting. Emergence of carrot seedlings had a moderate negative correlation with 5-cm CI data of June 9; as cone index values increased, the number of seedlings that emerged decreased. The scatter plot for Orlando Gold is given in Figure 4 and for Royal Chantenay in Figure 5.

Tillage treatment significantly affected size distribution in both 'Orlando Gold' and 'Royal Chantenay' (Table 7). Size distribution data are simplified in Table 8, using 38 mm as a cut-off diameter because Oregon carrot processors use this size to divide the smaller (Grade 1) and larger (Grade 2) carrots into seperate grades. Reduced tillage, in both cultivars, resulted in a higher percentage of small carrots than other treatments.

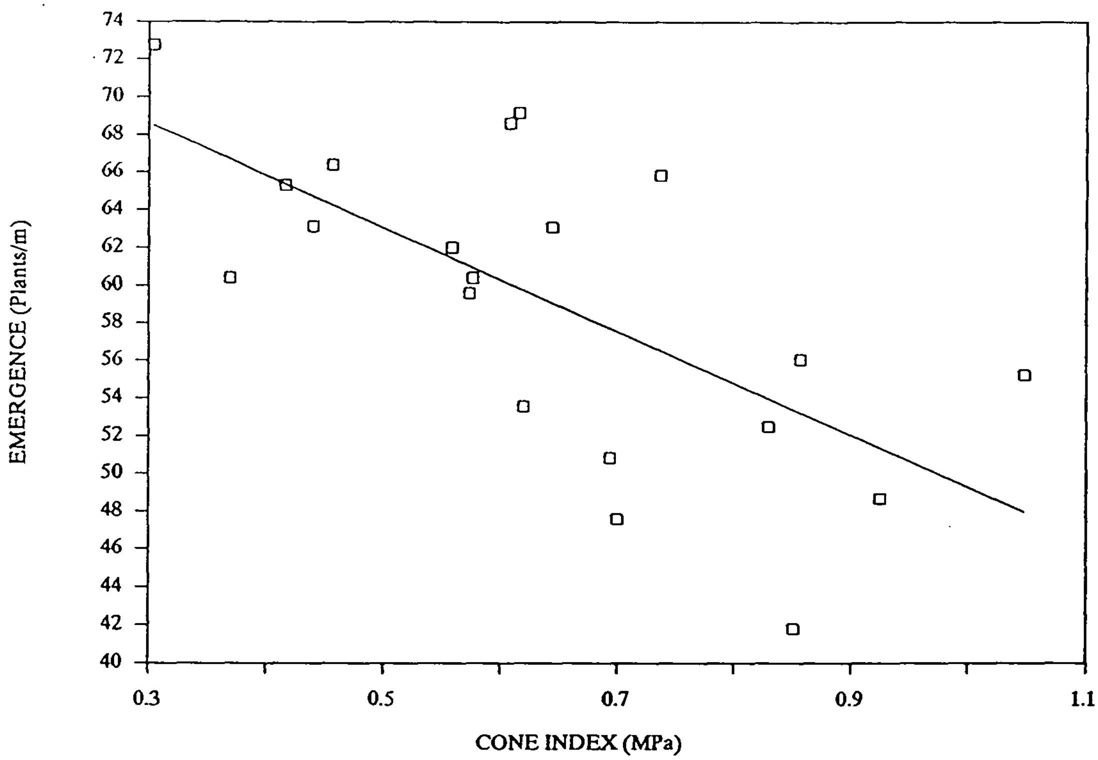

Figure 4--Relationship between Orlando Gold carrot emergence (stand count on June 19) and mechanical impedance (June 9 cone index at 5 cm). r=-.66

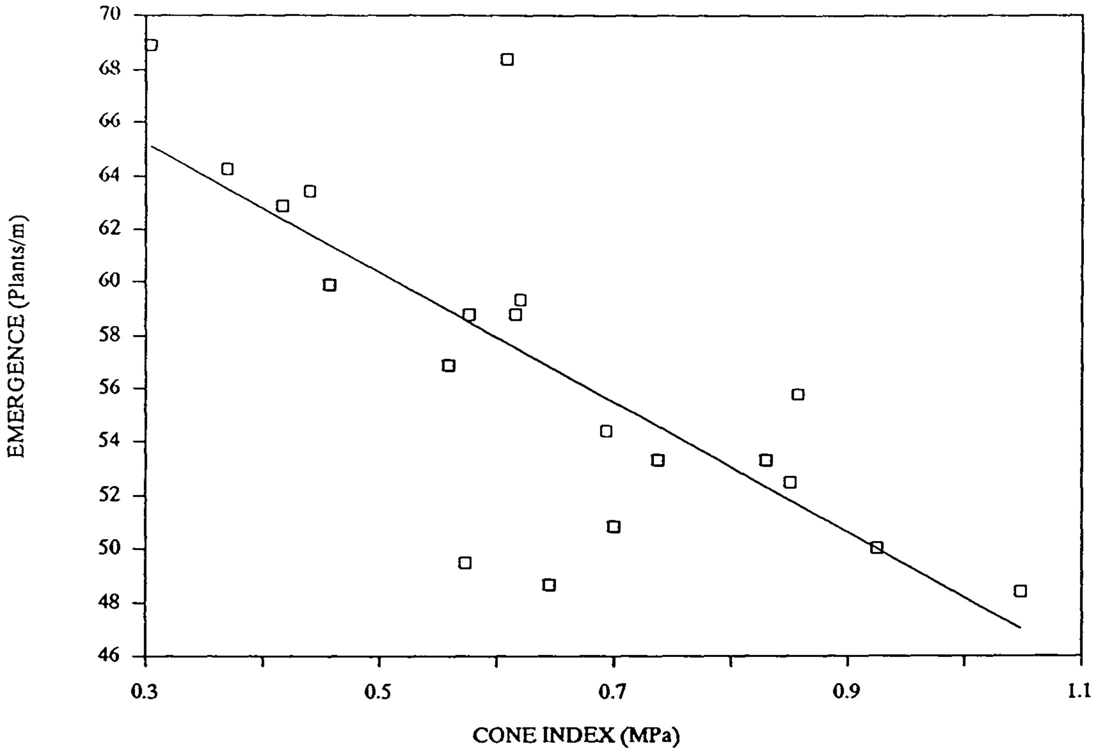

Figure 5--Relationship between Royal Chantenay carrot emergence (stand count on June 19) and mechanical impedance (June 9 cone index at 5 cm). r=-.75

Table 7--Effect of tillage on carrot root diameter size distribution (percent of total yield).

cv: Orlando Gold

| | diameter (mm) | | | |
|---|---|---|---|---|
| Treatment | < 25 | 25-38 | 38-51 | > 51 |
| Reduced tillage | 13.8 a | 47.4 a | 33.5 bc | 5.4 b |
| Conventional tillage | 9.2 ab | 41.2 ab | 40.1 ab | 12.0 ab |
| Excessive tillage | 8.9 ab | 35.1 b | 44.0 a | 12.0 ab |
| Subsoil before tillage | 13.0 a | 45.2 a | 30.7 c | 11.1 ab |
| Subsoil after tillage | 7.3 b | 38.4 ab | 41.4 a | 13.1 a |

cv: Royal Chantenay

| | diameter (mm) | | | | |
|---|---|---|---|---|---|
| Treatment | < 25 | 25-38 | 38-51 | 51-64 | > 64 |
| Reduced tillage | 1.9 | 21.2 a | 33.9 | 28.0 | 15.0 |
| Conventional tillage | 1.0 | 12.6 b | 36.6 | 30.8 | 19.1 |
| Excessive tillage | 1.0 | 13.4 b | 32.4 | 34.3 | 18.9 |
| Subsoil before tillage | .9 | 10.9 b | 32.9 | 34.1 | 21.2 |
| Subsoil after tillage | 1.2 | 12.1 b | 33.7 | 34.3 | 18.8 |
| | ns | | ns | ns | ns |

Multiple comparison by the Waller-Duncan k-ratio t test, 5% level

Table 8--Percentage of carrot root yield less than 38 mm in diameter.

| Treatment | Orlando Gold | Royal Chantenay |
|---|---|---|
| Reduced tillage | 61.1 a | 23.1 a |
| Conventional tillage | 50.4 abc | 13.6 b |
| Excessive tillage | 44.0 c | 14.4 b |
| Subsoil before tillage | 58.2 ab | 11.8 b |
| Subsoil after tillage | 45.6 bc | 13.3 b |

Multiple comparison by Waller-Duncan k-ratio t test, 5% level

# CHAPTER 5

# DISCUSSION

## Soil bulk density and mechanical impedance

As the amount of tillage in dry sandy-loam soil increased (reduced < conventional < excessive), so did the amount of mechanical impedance in the top 20 cm of soil, according to June 9 CI data (Figure 1). This effect was expected because each tillage pass broke up soil aggregates, allowing soil particles to be pressed closer together, and compaction pressure was added with each pass of the implement and tractor. Mechanical impedance is also greatly affected by soil moisture (Shaw et al., 1940; Taylor and Gardner, 1963). Because moisture content was fairly uniform among treatments, it was not a likely factor in CI treatment differences. It appears, by the noncorrelation beween CI and bulk density and by the nonsignificance of bulk density treatment differences, that bulk density was not the factor causing CI differences. Bulk density of any given soil normally has a large amount of spatial variability, requiring a large number of samples to get an accurate estimate of the mean bulk density (Vomocil, 1957). Because only one soil core sample per plot was collected in the present study and the core was relatively small, the bulk density data are probably not an accurate assessment of the mean bulk density of each treatment. With this in mind and the other factors that affect mechanical impedance such as texture, water content, and percent organic matter being relatively constant, the CI differences were most likely a result of differences in bulk density.

The maximum mechanical impedance of June 9 for each treatment

(Figure 1) corresponds to the approximate depth at which the soil was moldboard plowed (Table 2). The mechanical impedance of this plow pan was reduced by subsoiling before tillage. In fact, the mechanical impedance at all depths below the tillage depth of the cultimulcher (21 cm) was reduced by subsoiling before tillage. It is interesting that subsoiling after tillage did not give the same results. A possible explanation for this is that the soil near the surface had been broken into small particles before subsoiling, enabling more of them to fall into voids created by the subsoiler. The high mechanical impedance of the soil up to 20 cm in the subsoil-after-tillage treatment was likely a result of soil aggregates being broken up and then passed over with the large, heavy tractor used for subsoiling.

A comparison of Figures 1, 2, and 3 shows the dramatic effect soil moisture had on mechanical impedance. Although some of the increased mechanical impedance later in the season may be from soil settling and water drop impact, the differences in mechanical impedance appear to be more closely related to differences in moisture content. Moisture content differences explained 54% of the CI variability (Figure 6) in linear regression. Including bulk density in multiple linear regression explained only 14% more of the variability in CI. The CI at 5 cm on July 7 were not as high as expected from the CI/moisture regression curve, probably because of the excessive dryness on that date and the tilth of the soil near the surface. If those five anomalous points are excluded from the data, 81% of the variability in CI can be explained by moisture content in linear regression (Figure 7), or 85% using nonlinear regression ($Y = -3.6 + .83/X$).

The dry conditions on July 7 required considerably more force to penetrate the soil, and a compact zone at 10-18 cm became evident. Because this zone occurred in all treatments and was just below 10 cm, it was probably due to the action of the roterra. The 10-18 cm compact zone was less evident when wet penetrometer readings were made on August 19, giving evidence that zones impeding root penetration may be overcome by sufficient irrigation. The soil moisture content was less on August 19 than on June 9, and is the most likely cause for the higher CI of August 19. The apparent high mechanical impedance for the reduced tillage treatment on August 19 is not fully understood but may be partially explained by the lower soil moisture content in that treatment.

Differences in mechanical impedance between treatments on June 9 did not show up on July 7 or August 19. This could be due to settling of the loose soil in response to alternate wetting and drying. Cassel and Nelson (1985) reported a smaller change in bulk density with time in compact soil than in noncompact soil. The lack of treatment differences also could be due to variability caused by differential soil water content influenced by plant water uptake. On June 9, the carrots had just emerged and were taking very little water from the soil. By July 7 root systems were well established and on August 19 the tap roots were approaching maturity.

### Carrot emergence and diameter

Size distribution was the only carrot parameter studied that was significantly affected by tillage treatment. Treatments with the least amount of compaction near the surface (Figure 1) tended to have a higher percentage of small carrots (Table 8). This contrasts with the results of Strandberg and White (1979), which showed a decrease in diameter with increasing soil compaction. My results were not a direct result of soil compaction, but were indirectly related via stand establishment. Emergence means of June 19 (Table 6) showed the greatest number of plants in the reduced tillage treatment, corresponding to the treatment with the highest percentage of small carrots. The lack of significant differences in the emergence data can be partially explained by the large amount of variability, inherent in the germination of carrot seeds harvested from different umbels (Gray, 1979). This germination variability is even greater at low temperatures (Hegarty, 1971) which were experienced in the present study for several days after planting. Even so, emergence of both cultivars was negatively correlated with CI at 5 cm (Figures 4 and 5). Thus, in less compact soil more carrots emerged, creating more competition and smaller carrots. Studies by Mack (1980) and Salter et al. (1979) have shown that high plant densities of carrots result in higher proportions of smaller size grades. The negative effect of compaction on emergence is in agreement with results found in other crops. Royle and Hegarty (1977) reported a negative correlation between mechanical impedance and percentage emergence of calabrese seedlings. Parker and Taylor (1965) showed that emergence of sorghum was progressively decreased by increases in soil strength of the surface 5 cm.

What are possible reasons for the negative relationship between soil compaction and carrot seedling emergence? The seedlings were not likely to have been impeded physically by the hard soil because the soil was kept wet after planting, enabling easy penetration. Likewise, impedance of the seedlings by soil crusting was prevented because crust strength gets lower as soil moisture increases (Holder and Brown, 1974). It is possible that the planter rode higher on the compact soil and did not get the seed deep enough for adequate moisture and seed-soil contact. This, however, was not observed during planting. The most likely reason for the relationship between compaction and emergence was soil anaerobic conditions. Although air space was not measured, it is known that soil with higher bulk density has less pore space and the pores are smaller. Small pores are slower to drain than large pores because of the adhesive forces of the soil particles. Thus, the more compact soil not only had less space for air movement in the soil, but the space that was there was occupied by water longer than non-compact soil. In the wet conditions after planting, the carrot seeds in more compact areas may have been without oxygen, preventing respiration thus preventing germination and seedling growth. This explanation is supported by the results of Flocker et al. (1959) who measured air space of differentially compacted soil and found a marked reduction in tomato seed germination in soils with low air space.

Plant population at harvest was lower in all treatments for both cultivars than the population at emergence, suggesting that self-thinning as reported by Salter et al. (1980), Bussell (1978) and Rubens (1969) had occurred. Salter et al. (1980) found that self-thinning progressively increased as plant density increased. This may explain why the higher density of the reduced tillage treatment at emergence was not higher than other treatments at the time of harvest.

## Carrot yields

Although previous studies have shown soil compaction reduces carrot yields (Olymbios and Schwabe, 1977; Strandberg and White, 1979; Taksdal, 1984; White, 1978), tillage methods used in this experiment did not result in severe enough compaction to affect carrot yields. Eleven tillage passes in the excessive tillage treatment did not affect yields, even when compared to reduced tillage which had only three passes. It appears, from this, that carrot growers need not be concerned with the number of tillage passes when working the soil at moisture levels comparable to those in the present study (15.4%). Tillage under more moist conditions, however, could have much more of an effect on compaction. Soane et al (1981) cited a thesis study by Blackwell that compared compaction by a tractor tire in soil with different moisture contents. "When the soil water content was 23% (w/w) the increase in bulk density at a depth of 150 mm was four times larger than when the water content was 14% (w/w)." Therefore, the same tillage treatments used in the present study would produce considerably more compaction on wet soil, possibly having yield effects similar to the previously cited compaction experiments.

## Practical implications

Subsoiling before tillage to ameliorate the tillage pan at 35 cm did not improve carrot yields even though compaction was considerably reduced beyond 25 cm. Subsoiling after tillage to negate the compaction effects of the current year's tillage also did not improve carrot yields and had little effect on compaction beyond 25 cm. The high mechanical impedance of the soil was apparently deep enough to not interfere with carrot elongation. Thus, the use of subsoiling in the production of processing-type carrots does not appear to be warranted by a tillage pan such as that found in this experiment (2.3 MPa cone index at 35 cm).

Because tillage treatment had no effect on total yield, carrot growers could apparently reduce their costs by reducing the amount of tillage performed. In the experiment, however, the soil was dry and plant residue cover was minimal during tillage, which is not always true in commercial carrot fields. Also, growers are reluctant to reduce tillage because germinating and emerging carrots are very susceptible to environmental conditions. Thorough tillage assures good seed-soil contact, proper planting-depth, and uniform seeding. To growers, an extra tillage pass is cheap insurance compared to the cost of replanting. However, according to results of the present study, excessive tillage can cause soil compaction that may reduce carrot seedling emergence under cold, wet conditions. It is common in springtime in Oregon's Willamette Valley to have wet conditions after planting, not unlike those induced by sprinkler irrigation in this experiment. Accordingly, growers may want to avoid compacting the soil near the surface when these conditions are expected, in order to get the desired carrot stand.

Another implication of this study is that carrot yield reductions by soil compaction in the Willamette Valley are unlikely to be the result of dry-soil tillage in the spring. Other causes of soil compaction include heavy truck traffic during fall harvest (especially in wet conditions) and spring tillage when the soil is too moist. Further studies to investigate these causes are necessary to assess effects of soil compaction in the Willamette Valley. Because soil compaction can accrue over several years, a multi-year study including experiments in commercial carrot fields would give the most realistic results.

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# APPENDIX

Table 9-- June 9 soil mechanical impedance (MPa) as a function of treatment and soil depth. Each datum is the mean of 24 measurements. Mean separation was calculated with log-transformed data, using Duncan's multiple-range test (5% level). Means with the same letter, within any given depth, are not significantly different.

| Tillage Treatment | Soil Depth (cm) | | | | | | | | | | | | | | Treatment Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2.5 | 5.0 | 7.5 | 10.0 | 12.5 | 15.0 | 17.5 | 20.0 | 22.5 | 25.0 | 27.5 | 30.0 | 32.5 | 35.0 | |
| Minimum | .410 b | .519 b | .564 b | .572 b | .544 b | .506 b | .498 b | .506a | .570ab | .703ab | 1.304ab | 1.923a | 2.447a | 2.686a | 1.362 |
| Conventional | .533ab | .613ab | .646ab | .628ab | .602ab | .567ab | .531ab | .506a | .500 b | .559cb | .863 b | 1.480a | 2.027a | 2.135a | 1.154 |
| Excessive | .603a | .782a | .879a | .845a | .782a | .775a | .716a | .698a | .727a | .876a | 1.393a | 1.802a | 2.129a | 2.211a | 1.383 |
| Subsoil Before | .497ab | .583ab | .646ab | .639ab | .592ab | .551ab | .528ab | .461a | .438 b | .419c | .449c | .553 b | .923 b | 1.640 b | 1.028 |
| Subsoil After | .586ab | .710ab | .758ab | .747ab | .676ab | .632ab | .622ab | .577a | .582ab | .677 b | 1.033 b | 1.503a | 1.850a | 2.147a | 1.311 |
| Mean | .526 | .641 | .698 | .686 | .639 | .606 | .579 | .550 | .563 | .647 | 1.009 | 1.452 | 1.875 | 2.164 | |

Table 10--Effects of tillage on July 7 cone index at 14 soil depths. Multiple comparison performed on log-transformed data by the Waller-Duncan k-ratio t test, 5% level.

| Depth (cm) | Mean cone index (MPa) | Waller-Duncan grouping | |
|---|---|---|---|
| 35 | 3.377 | | A |
| | | | A |
| 12.5 | 3.160 | B | A |
| | | B | A |
| 15 | 3.132 | B | A |
| | | B | |
| 17.5 | 3.046 | B | C |
| | | B | C |
| 32.5 | 2.931 | B | C |
| | | B | C |
| 10 | 2.858 | B | C |
| | | | C |
| 20 | 2.789 | D | C |
| | | D | |
| 22.5 | 2.604 | D | E |
| | | D | E |
| 30 | 2.553 | D | E |
| | | | E |
| 25 | 2.390 | | E |
| | | | E |
| 7.5 | 2.305 | | E |
| | | | E |
| 27.5 | 2.355 | | E |
| 5 | 1.455 | | F |
| 2.5 | 0.927 | | G |

Table 11--Effects of tillage on August 19 cone index at 14 soil depths. Multiple comparison performed on log-transformed data by the Waller-Duncan k-ratio t test, 5% level.

| Depth (cm) | Mean cone index (MPa) | Waller-Duncan grouping | |
|---|---|---|---|
| 35 | 3.516 | | A |
| 32.5 | 3.098 | | B |
| 30 | 2.675 | | C |
| 27.5 | 2.287 | | D |
| 25 | 1.987 | | E |
| | | | E |
| 22.5 | 1.836 | F | E |
| | | F | E |
| 20 | 1.766 | F | E |
| | | F | |
| 17.5 | 1.675 | F | |
| | | F | |
| 15 | 1.633 | F | |
| | | F | |
| 12.5 | 1.600 | F | |
| | | F | |
| 10 | 1.536 | F | G |
| | | | G |
| 7.5 | 1.384 | | G |
| 5 | 1.068 | | H |
| 2.5 | 0.674 | | I |

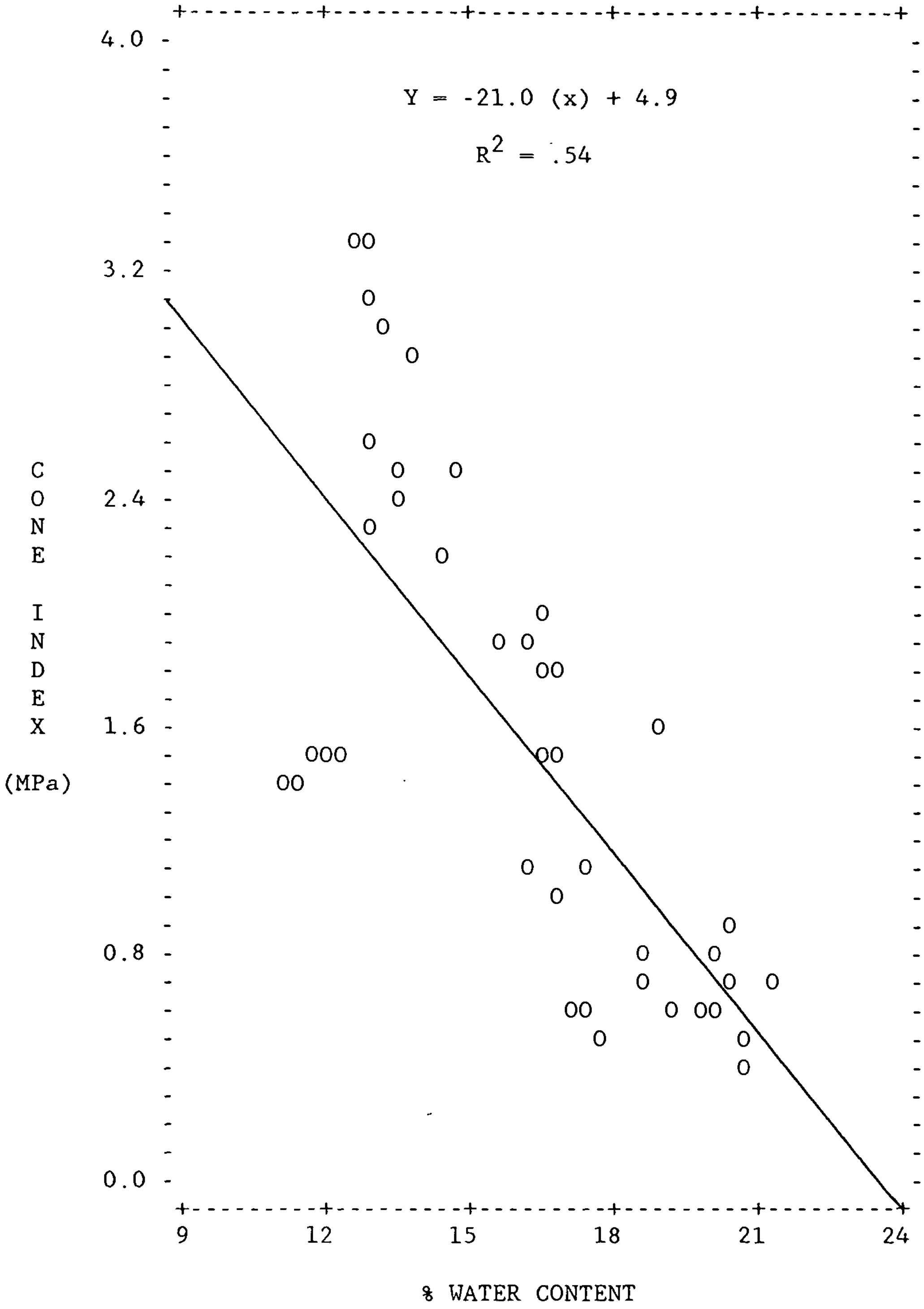

Figure 6--Relationship between soil moisture content and mechanical impedance. Combined data from June 9, July 7 and August 19 for all five treatments at 5, 15 and 25 cm.

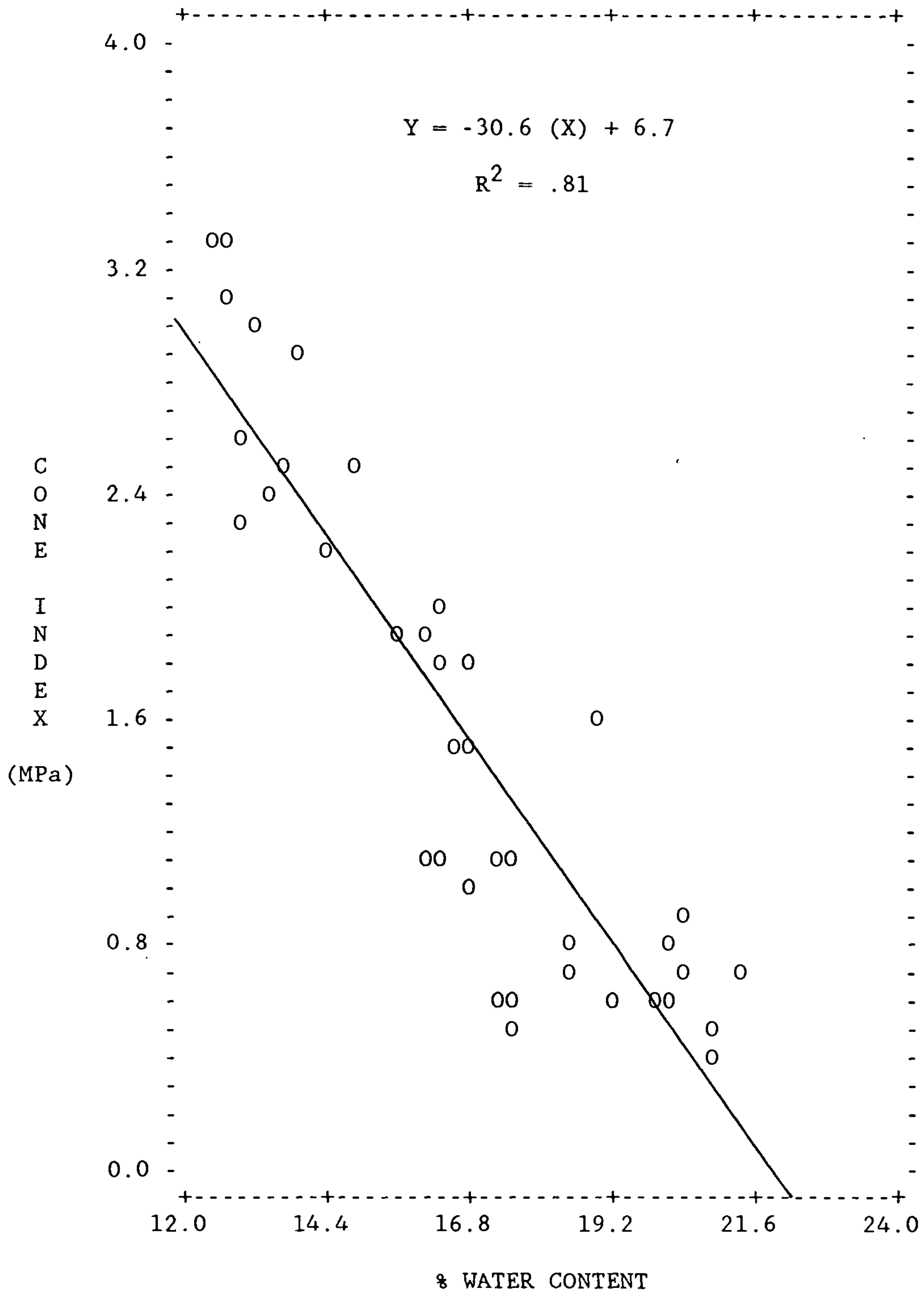

Figure 7--Relationship between soil moisture content and mechanical impedance. Data combined from June 9, July 7 and August 19 for all five treatments at 5, 15 and 25 cm (5-cm data on July 7 excluded).