This is to certify that the

thesis entitled

EFFECTS OF ZONE TILLAGE AND COMPACTION
ON GROWTH OF CARROTS AND ONIONS IN ORGANIC SOILS

presented by

Joseph A. Strzalka

has been accepted towards fulfillment
of the requirements for

M.S. degree in Crop and Soil Science

Darryl D. Warncke
Major professor

Date 9/13/90

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.

DATE DUE	DATE DUE	DATE DUE
11 0 2 07		

EFFECTS OF ZONE TILLAGE AND COMPACTION ON GROWTH OF CARROTS AND ONIONS IN ORGANIC SOILS

By

Joseph A. Strzalka

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Crop and Soil Science

1990

Abstract

EFFECTS OF ZONE TILLAGE AND COMPACTION

ON GROWTH OF CARROTS AND ONIONS IN ORGANIC SOILS.

by Joseph A. Strzalka

Soil strength and decreased aeration decreases root growth and can decrease crop yields. The effects of zone tillage, compaction and soil moistures of organic soils on carrot and onion growth were evaluated in field and greenhouse studies.

Zone tillage with a Bushhog-Rotill and Tye Paratill increased carrot length 4 cm and weight of marketable carrots by 12%. Total yield was unaffected. Carrot seedling emergence was reduced.

Compacting soil with a cement roller reduced total and marketable yields of carrots. Onion growth was reduced by compaction.

Carrot and onion seedlings, grown in the greenhouse, had decreased root growth with increased compaction. Increasing gravimetric moisture percent increased carrot growth 300% but decreased onion 60%.

Table of Contents

List of Tables

Introduction

Agricultural practices can detrimentally affect the soil. One of the most deliterious affects is soil compaction. Compaction has been shown to affect plant growth on a wide range of soil types. Compaction increases soil strength and affects drainage. Poor drainage can lead to aeration stress of roots. Poor aeration and high soil strength have been shown to reduce root growth (Gill and Miller, 1956).

The production of onions and carrots in Michigan necessitates field operations when the soil is susceptible to compaction. Soil compaction affects the quality and quantity of onions and carrots harvested.

Deep tillage has been used to improve soil conditions by breaking up compacted layers (Spoor and Godwin, 1978). Deep tillage can increase crop yield by lowering soil strength and improving water infiltration (Kaddah, 1975).

The paratillage equipment is a recent improvement in deep tillage treatments. It can be used for zone tillage where only the portion of the field under the row is loosened. It has been shown to lower bulk density, increase water infiltration and decrease soil strength (Erbach et. al., 1984 and Henry and Van Doren, 1975).

High soil strength affects roots by reducing root penetration and growth (Taylor et al. 1966). A study by Unger and Danielson (1965) indicated that a reduced supply of oxygen may be responsible for reduced growth of young corn plants under poorly aerated conditions. Asady et. al. (1985) found root lengths of edible bean seedlings declined with decreasing air filled porosity.

Carrot taproots reach marketable lengths within 24 days after germination. Many physical and biological factors that cause carrot defects act during this period of growth (White and Strandberg, 1978). Strandberg and White (1979) have also shown that soil strength can affect both growth of young taproots and the size, weight and shape of mature carrots. Carrots grown at higher soil strengths tended to be thicker, convoluted and more branched. Olymbios and Schwabe (1977) found a reduction in taproot growth was due to mechanical and aeration stresses.

Four experiments were done to explore the effects of the soil environment on carrot and onion growth. Three field studies were done on a Houghton muck and a fourth was done in the greenhouse with both muck and marl soils. One field study which was conducted for two years explored the effects of zone tillage on carrot and onion growth. Another field study involved growing carrots and onions on soils compacted with a cement roller. A greenhouse study involved growing onion and carrot seedlings in muck and marl soils under varying compacted and moisture conditions.

The hypothesis is that improving the soil environment will increase carrot and onion yields. The objectives of these studies were: 1) to measure the effects of zone tillage on carrot and onion growth and yields; 2) to measure the effect of zone tillage on soil physical properties; 3) to determine the response of carrots and onions to a compacted soil; 4) to measure the effects of compaction on soil physical properties; 5) to determine the response of onion and carrot seedlings to compacted layers; and 6) to determine the response of onion and carrot seedlings to different soil moisture contents.

LITERATURE REVIEW

Adverse physical properties of the soil inhibit plant growth. One of these conditions is compaction. Compaction is the compression of an unsaturated soil body resulting in the reduction of the fractional air volume by reducing the volumes and numbers of larger pores (Hillel, 1982). This review will cover the causes and affects of soil compaction and its alleviation.

CAUSES OF COMPACTION

Compaction results from a decrease in soil volume. According to Chancellor (1976), this change in soil volume can be brought on by natural consolidation during the soil formation processes, trampling by animals, including humans, natural shrinkage of soils upon drying and soil response to pressure and deformations imposed by wheels, tracks and soil engaging tools. An applied force can cause compaction by the compression of soil particles or of the liquid and gas within the pore spaces, a change in the liquid and gas contents in pore spaces or by the rearrangement of the soil particles. On nonsaturated soils, rearrangement of soil particles is the major factor contributing to compaction. Under saturated conditions, the rate at which liquid moves with and from the soil is the major compaction factor (Harris, 1971).

Soil structure is the controlling factor in the behavior of soil in response to an external force. The structure is a function of the gradation, shape, texture, and orientation of the soil particles and of the soil-water faces interaction (Harris, 1971). Soils having a wide range of primary particle sizes are more susceptible to compaction than soils with uniform sizes of primary particles (Chancellor, 1971).

In agricultural systems the primary cause of compaction is man. Man causes compaction by the weight of machinery and the use of implements. Work by Mulligan et al. (1985) showed that excessive traffic and secondary tillage treatments resulted in more compact soils with the greatest response occuring in the surface 25 to 30 cm. The bulk density of a Charity clay went from 1.16g/cm^3 with minimal tillage to 1.22 and 1.44 g/cm^3 with conventional and excessive tillage. The percent pore space decreased from 55.4 to 53.8 and 47.0. On a Belleville sandy loam the bulk density increased from 1.56 to 1.58 and 1.67 with a decrease in percent pore space from 40.7 to 40.0 and 36.9.

Implements which cause the soil to move tend to produce localized compaction. Blunt cutting edges, high coefficients of friction or adhesion at the soil-metal interface, and improper rake angles can produce compactive forces (Cohron 1971). Spoor and Godwin (1978), in a study on deep loosening of the soil by rigid tines, found that each tine has a maximum useful working depth. Below that depth soil compaction, rather than loosening, occurs and specific resistance increases. At shallow working depths the soil is displaced forwards, sideways and upwards (crecent failure).

Crecent failure continues until a critical depth where the soil at the base begins to flow forwards and sideways, creating compaction at that depth. The shape of the compacted zone depends on the tine shape.

The primary source of externally applied forces is vehicular traffic. Pressures from 20-50 psi are commonly applied to soil by agricultural tractor tires operating at nominal inflation pressures of 10 to 15 psi (Cohron, 1971). Wheel traffic associated with spring field operations, averaged over 5 years, increased the bulk density of the 0-15cm soil layer by 20 percent and the 15-30 cm layer by 10 percent over that of nontracked soil. Compaction effects were as deep as 30 cm or more (Voorhees et al. 1978).

The severity of compaction is related to soil moisture. The water acts as a lubricant allowing the soil particles to move more easily when pressure is applied. For a given soil the resultant bulk density from an applied force is a function of the soil's moisture content and the compactive force used. For a partially saturated condition, the higher the moisture content of the soil, the more it is compactible by a given force until it reaches a maximum bulk density near saturation (Saini and Chow, 1984). Soil increases in compactability to a point where the air-filled pores are nearly filled with water. At this point, the soil is not as compactable, and the compactability decreases with added water (Hillel, 1982). When subsoiling, the wetter and more plastic the soil, the shallower the depth at which compaction occurs (Spoor and Godwin, 1978).

The organic matter content of a soil may play a beneficial role in reducing the compactability of soils (Saini and Chow, 1984). On California forest and range soils, soils that had the least amount of organic carbon were shown to be the most susceptible to compaction (Howard, 1981). On a silty loam, soil compaction was greatest in the treatments that had the lowest amount of organic carbon (Pikul and Allmaras, 1986). Soils containing the highest amount of organic matter and at the same moisture level were compacted the least by a given force (Free et al., 1947). The addition of raw organic matter always reduces the bulk density of a soil because the bulk density of organic matter is less than the soil displaced by organic matter. Residual humus materials have densities of about 1.4 g/cm^3 while the specific densities of most mineral soils is 2.65 to 2.70 g/cm^3 (Bowen, 1981). However, organic soils and soils high in organic matter are not immune from compaction. Organic soils have been compacted to the point to where they affect plant growth. Strandberg and White (1979) have shown how increasing soil strength on organic soils decreased carrot size and increased the amount of culls (Strandberg and White, 1979).

Compaction causes a change in soil physical properties. The most important changes are in water retention, gas diffusion and strength of soils. Each of these will be discussed seperately.

WATER RETENTION

Pores are the area between solid particles filled with air and water. Pore sizes are determined by the size and distribution of the soil particles. Where aggregates are fairly distinct soil pores consist of macropores and micropores. Macropores are larger pores responsible for water infiltration, drainage and aeration. Micropores are smaller and are responsible for retention of water and solutes. There is no set size for macropores and micropores, and the dividing line between them is often arbitrary (Hillel, 1982). Cannell and Jackson (1981) divide pore size into three categories, the first being large pores that are air filled at field capacity. At water potentials of -5 to -10 kPa these pores would be greater than 60-30 um. In soils containing 30-40 percent clay the water potential is higher so that only pores larger than 100 to 300 um would be filled. The second class of pores are those that are small enough to hold water against gravity yet permit water to be extracted by roots down to a potential of about -1500 kPa; this corresponds to diameters between 60 um and 0.2 um. The third class, less than 0.2 um, are those pores so small that plants are unable to remove water from them.

The attraction of water for the soil is called suction (Warkentin, 1971). Soil suction increases as soil water decreases. The soil water potential determines the strength that water is held by the soil. It is the difference in energy between water in the soil and free water. Soil water usually has a lower free energy than free water and is always negative. As the water content decreases, soil water potential becomes more negative. The forces that determine the soil water potential are capillary and adsorptive forces. Capillarity results from the surface tension of water and its contact angle with the solid particles. It is defined by the capillary rise equation. Adsorptive forces are due to the adhesive attraction of water to the soil surfaces (Hillel, 1982).

The effect of compaction is to decrease total porosity, decrease the volume of macropores and increase the intermediate pores while the smallest micropores remain unaffected (Hillel, 1982). Capillarity determines the retention of water by soils at medium and low suctions. According to the capillary rise equation, as pore radius decreases, suction increases. Therefore, because of the change in pore sizes, compacted soils will retain less water at low suctions and more water at higher suctions. At very high suctions, the adsorptive forces determine water retention, and total water content between compacted and non compacted soils remain the same.

The exact response of a compactive force on soil pores and water retention varies with soil type. According to Hill and Sumner (1967) an increase in bulk density on sandy soils increased the water content at a given suction. On clays, the water content increased with suction with the increase being greater at higher suctions. Loams had a decrease in water content at low suctions and an increase at higher suctions.

A decrease in macropores will decrease the amount of water infiltration and drainage. Water will infiltrate more slowly, causing puddling and surface runoff.

GAS DIFFUSION

Plant roots and aerobic soil organisms respire. Respiration requires oxygen and produces carbon dioxide. To prevent anaerobic conditions and death of the roots, oxygen needs to be steadily supplied, and CO_2 needs to be removed. Thus, gas diffusion is an important part of the soil environment. Factors that affect gas diffusion will affect the growth of roots and the plant.

Gas diffuses through soils in both the gaseous and liquid phases but primarily through air filled pores (Grable, 1971). Compacting soils leads to a larger volume of soil comprised of small pores (Vomocil and Flocker, 1961). These smaller pores retain water at field capacity and restrict the diffusion of gases (Grable, 1971). An air porosity below 10 percent is considered inadequate for plant growth (Vomocil and Flocker, 1961). The solubility of oxygen is about 10^4 times lower in the water phase than the gaseous (Cannell and Jackson,1981). Therefore, water saturated soils are often under oxygen stress.

SOIL STRENGTH

Soil strength is the resistance of an object moving through a soil and is measured in force/unit area. Chancellor (1971) defines soil strength as a measure of resistance that must be exceeded in order to physically deform a soil. The strength is affected by many factors including soil type, aggregate distribution and moisture content. The higher the moisture content, the lower the resistance to an applied pressure and the lower its soil strength. Compaction generally increases the soil strength. Soil strengths on an Amarillo fine sandy loam at field capacity in 10^6 dynes/cm^2 ranged from 2.8 on a noncompacted soil at the surface to 27.6 on a compacted soil at 15 cm (Taylor and Ratliff, 1964). Barley et al. (1965) reported soil strength values on a Harlington clay near 30 bars on soils at 25 percent moisture and a bulk density of 1.50 g/cm^3 to less than 10 bars for a saturated soil with a bulk density of 1.40 g/cm^3.

EFFECTS OF COMPACTION ON PLANT GROWTH

Compaction affects plant growth on a wide range of soil types. It has reduced the height of cotton and slowed the growth of sorghum (Taylor and Locke, 1964), decreased yield and quality of potatoes (Flocker et al., 1960) and impeded the growth of sunflower roots (Veihmeyer and Hendrickson, 1948). Compaction to the point that it affects plant growth occurs on clays, clay loams and loamy sand (Veimeyer and Hendrickson, 1948), medium to coarse textured soils (Taylor et al., 1966) and organic soils (Strandberg and White, 1979). Root growth is adversly affected by an increase in soil strength and a decrease in aeration. Gill and Miller (1956) found that the ability of the root to enlarge, despite mechanical restraint, was greatly impaired by reductions in oxygen content. The level at which oxygen inhibited root growth depended on the degree of mechanical impedence (Tacket and Pearson, 1964). Scott and Erickson (1964) found that sugarbeets and tomatoes were affected by both a high soil strength and decreased oxygen levels. Shallower rooting depths of corn were attributed to high bulk density and low aeration (Fehrenbacher and Rust, 1956). Bertrand and Kohnke (1957), found that mechanical impedance and a lack of oxygen may cause dense subsoils to act as a barrier to root penetration of young corn roots.

Root penetration is a function of soil strength, soil porosity, size, continuity and tortuosity of voids. On medium and coarse textured soils, mechanical impedance to root penetration and not aeration will be the limiting factor for root growth (Tacket and Pearson, 1964). Soil strength at the time root penetration occurred, not bulk density, was the critical impedance factor controlling root penetration through soil cores (Taylor and Gardner, 1963). Willat (1986) demonstrated that root length densities decrease with increasing soil strength. Parker and Taylor (1965), found a decrease in sorghum emergence with an increase in soil strength at the surface or crusting. As soil strength increases the primary root becomes more twisted and the root ratio of first order laterals to primary roots increases (Voorhees et al., 1975). Eavis (1972) found that root elongation is inversely proportional to mechanical resistance. On swelling clays root elongation rates of cotton and peas decreased with increases in soil strength, particularly for strengths greater than 10 bars (Gerard et al., 1972).

The reaction of root growth to soil strength varies with the type of plant grown. An increase in soil strength to 7.2 bars decreased cotton root elongation rates by 50 percent while an increase to 1.91 MPa decreased peanut root elongation rates the same amount (Taylor and Ratliff, 1969). Root growth was found to be prevented when soil strength reached 2.5 to 3.0 MPa (Taylor and Burnett, 1965). Taylor et al. (1966) found that root penetration was reduced drastically as soil strength increased to 25 bars. No taproots penetrated through cores with strengths greater than 25 bars regardless of soil material. The pressure at which root elongation stopped was found to be a function of percent clay. The critical strength ranged from 60-70 bars in coarse textured soils to 25 bars in clay loams (Gerard et al., 1982). Merideth and Patrick (1961) found a decrease in sudangrass root penetration as compaction increased. He concluded that the roots couldn't make the initial entry through the compacted zone. Wiersum (1957) found that roots can't enter pores smaller than themselves. Therefore, compaction can inhibit root growth by reducing the size of the pores smaller than the root diameter.

A higher moisture content lowers soil strength and increases root growth (Barley, 1963). Graecen and Oh (1972) found that in an otherwise uniform soil, roots proliferate in wetter zones because mechanical resistance is lower rather than because soil water potential is high. Under moist soil conditions, soil strength was shown to be the limiting factor for growth of roots of oats (Schuurman, 1965), wheat and peas (Barley et al., 1965), cotton, guar, sesbania, mung beans, cow peas and sorghum (Taylor and Burnett, 1965).

Plant roots are affected by both CO_2 and O_2 levels. Concentrations of CO_2 and O_2 in the soil atmosphere influence the respiration rate of roots. Reduction in respiration is the first step in growth limiting effects of insufficient aeration (Harris, 1957). Under water saturated conditions, the major detrimental effect is caused by the lack of O_2 (Williamson and Splinter, 1968). Unger and Danielson (1965) in a study of the influence of CO_2 and O_2 on the germination and seedling development of corn found that a reduced supply of O_2 rather than a buildup of CO_2 may be responsible for reduced growth of young plants under poorly aerated conditions.

High CO_2 levels decrease the uptake of some nutrient elements (Chang and Loomis, 1945). Soil atmosphere at 100% CO_2 decreases the extension of oat coleoptiles (Harrison, 1965). High concentrations of CO_2 for over 24 hours injure the root system of Vicia faba l. (Williamson, 1968). Absorption of water by wheat roots was reduced 14-15% by high CO_2 concentrations (Chang and Loomis, 1945). Concentrations of CO_2 in the field high enough to cause damage is rare. Air filled porosity must be reduced to about 1% before CO_2 levels affect roots (Van Bavel, 1951). CO_2 rarely accumulates to toxic levels (Harrison, 1965).

A study of low oxygen content on growth of roots and shoots by Letey et al. (1962), shows that low oxygen is most detrimental during early stages of growth. The roots stop growing and transpiration decreases at this stage. The number of days that the soil can be waterlogged without damage to the plant occuring is dependent upon the stage of plant and root development. There is a time lag in the recovery of root growth. Low oxygen levels in the soil reduce the rate of broad bean root cell division (Williamson, 1968). However, Eavis (1972) found that with peas, shorter thicker root development under low oxygen levels was not due to a decrease in cell division but rather a decrease in cell elongation and breadth. Soil oxygen levels of 1 percent cause wilting and reduced growth of tobacco (Williamson and Splinter, 1968). One of the first effects of poor aeration in tobacco is the increased resistance to water movement into the root

(Kramer, 1954). Low O_2 can be a limiting factor in the growth of sugar beets (Wiersma and Mortland, 1953), cotton (Leonard and Pinckard, 1946) and corn seedlings (Unger et al., 1965). It is the oxygen diffusion rate (ODR) not bulk density or soil strength that limits yield of potatoes (Saini, 1976). An ODR of $20 \times 10^{-8} g\ cm^{-2}\ min^{-1}$ is required for root growth of Newport bluegrass and the optimum is greater than 40 (Letey et al., 1964). An ODR of about $20 \times 10^{-8}\ g\ cm^{-2}\ min^{-1}$ can be used as an index where root growth will not occur (Stolzy et al., 1961).

The severity of O_2 limiting conditions depends on the plant. Plum roots are more sensitive than peach and apricot. The response to waterlogging depends on duration and temperature (Rowe and Catin, 1971). On tobacco, the severity of lack of oxygen was shown to be dependent on temperature and light intensity (Williamson, 1969). Shallow rooted species with a very fibrous root system are probably more efficient in O_2 uptake under conditions of poor aeration than are deeply rooted species (Williamson, 1964). For O_2 consumption, it is necessary to know the critical demand characteristics of the root. The rate of O_2 uptake varies with genetic background and physiological age of the tissue (Lemon and Wiegand, 1962). Plant root requirements and the O_2 supplying power of the soil need to be considered when studying aeration in soils (Lemon, 1962).

TILLAGE

Tillage is mechanical manipulation of the soil and is designed to improve soil conditions affecting crop growth (Hillel, 1982). Tillage affects the strength, aeration, water status and temperature of the soil (Soane and Pidgeon, 1975). These are all physical properties that affect the plant (Letey, 1985). Cooper (1971) states the reasons for tillage are to move soil for seed insertion, modify topography, manage crop residue, change the physical condition of the soil, reduce wind erosion, add soil amendments, and control insects, diseases and weeds. According to Pidgeon (1983) plowing originated as weed control. With chemical weed control and planters which can insert seed into an untilled soil, it is the physical properties of the soil that determine tillage requirements (Soane and Pidgeon, 1975).

Primary tillage in conventional tillage systems commonly consist of moldboard plowing in either the spring or the fall of each cropping season. The moldboard plow loosens the soil by shearing, lateral movement and inversion. The surface of the soil is left free of plant residues. Secondary tillage is then performed in the spring to create a uniform seed bed, increase the soil to seed contact and to break up loose clods. This system requires large inputs of time, labor and fuel yet and offers little protection against wind and water erosion (Soane and Pidgeon, 1975).

Deep tillage has been used to improve soil conditions by breaking up compacted layers. Soil below 30 cm is usually loosened by soil subsoiling operations which consist of shattering the soil using high draft rigid-tined implements referred to as subsoilers and deep chisels (Spoor and Godwin, 1978).

Significant increases in wheat yield and shoot and root growth have resulted from deep tillage. These increases are due to lowered soil strength and better water infiltration (Kaddah, 1975). Millet and sweet corn yields were increased by chisel plowing compacted soils. These soils had improved aeration when wet and increased soil water availability when dry (Doty et al., 1975). Deep tillage for maize was shown to decrease soil strength while increasing rooting length and yields (Chaudary et al., 1985). Chiseling of soil can reduce root impedance, increase water infiltration and increase rooting depth. The deeper root proliferation enables plants to extract water from a larger volume of soil which increases yields (Campbell et al., 1974). Yield increases in the southeast U.S. from under the row subsoiling were attributed to roots penetrating the plow pan in the Ap horizon and taking advantage of the water below (Trouse, 1983).

The attachment of wings to the tine foot of subsoilers and the use of shallow tines to loosen the surface layers in front of the tines increases soil disturbance. This disturbance reduces the specific resistance, increases the critical depth at which compaction occurs, and allows for a more effective soil arrangement. The greatest advantage of wings is their ability to significantly increase soil disturbance in the deeper layers (Spoor and Godwin, 1978). The paraplow is an instrument that takes advantage of this design. It loosens the soil down to 25-30 cm with no soil inversion. The paraplow has a tool bar with legs angled 45 degrees to the side. Behind each leg is an adjustable flap that enables the user to adjust the slant leg and alter the amount of lift and soil cracking to the desired amount (Pidgeon, 1983).

The paraplow has been shown to lower the bulk density, increase water infiltration and decrease the strength of soils (Erbach et al., 1984 and Henry and Van Doren, 1985). Comparing the moldboard plow, no-till and paraplowing, Muchtar et al. (1985) showed that the paraplow gave higher water infiltration rates. Similar bulk densities were observed between treatments while the no-till and paraplowing normally had higher soil moistures. Wilkens et al. (1986), on a silt loam, found no benefit of breaking the hardpan by the paraplow on wheat and pea yields or soil moisture but did find a decrease in soil strength. Pidgeon (1983) stated that the paraplow had the capability of greatly increased water infiltration while retaining surface residue. He also noted that there was no benefit in using it where soil conditions are not limiting.

CARROTS AND ONIONS

In Michigan, carrots and onions are primarily grown on organic soils. Organic soils are formed under saturated conditions and are subject to flooding and O_2 stress. The production of carrots and onions may necessitate field operations when soil conditions are ideal for compaction. This causes many soils to have compacted layers which affect crop growth.

Carrot taproots reach marketable lengths within 24 days after germination. All growth after this is enlargement of the root. Many physical and biological factors can cause defects during this period of growth (White and Strandberg, 1978). Exposure to water saturated conditions induces branching and discoloration of root tips (White and Strandberg, 1979). Carrot size has been shown to be affected by plant density (Robinson, 1969 and Thompson, 1969). Variation in root size at harvest has been shown to be associated with competition between early and late germinating seeds (Mann, 1949). Cracking but not forking had been shown to be associated with age of the carrot (Chipmen, 1959). Nutrition has been shown to affect carrot quality with medium amounts of nitrogen producing the highest yields of smooth carrots (Bienz, 1965).

The marketable portion of the carrot, the tap root, is most affected by compaction. A reduction in taproot growth is due to mechanical and aeration stresses (Olymbios and

Schwabe, 1977). Rates of taproot growth have been shown to decrease with high soil strength. Increased traffic reduces the size and grades of number one carrots and the shape of the roots (Taksdal, 1984). Carrots grown in loose soil tend to be cylindrical while those in compacted soils tend to be conical (Olymbios, 1977). Strandberg and White (1979) have shown that soil strength can affect both the growth of young taproots and the size, weight and shape of mature carrots. Carrots grown at higher soil strengths tended to be thicker, convoluted and more branched.

The growth of onion roots is different from that of carrots in that they have no taproot and are shallower rooted. All roots are initiated from the bulb and exhibit minimal branching. The maturity of onions has been shown to be controlled more by moisture than nitrogen supply. High soil moisture can delay maturity (Riekels, 1977) It is hypothesized that compaction on organic soils inhibits onion root growth. The plant will allocate more carbon to the roots that could be used for shoot and bulb growth. This reallocation of carbon can reduce top growth and reduce total yields. Plants would be more susceptible to water stress with decreased rooting with high soil strength. Compacted layers can reduce drainage causing aeration stress. It is possible to get delayed maturities due to higher soil moistures caused by reduced drainage.

SUMMARY

Compaction changes soil physical properties. Compacted soils have higher soil strengths and smaller pores. A decrease in pore radius results in higher moisture contents at given tensions. Higher moisture contents reduce oxygen diffusion and lower oxygen levels below that of noncompacted soils.

Roots grown in compacted soils are often twisted and stunted, and have an increase in secondary growth. These symptoms are caused by physical and aeration stresses. Increasing soil strength, by increasing the amount of energy required for root expansion , reduces root growth. Low oxygen levels in the soil atmosphere combined with high soil strengths is detrimental to root growth. Roots require even more oxygen to overcome physical stress. Plants grown under compacted conditions often exhibit smaller top growth and reduced yields. This is due partly to a larger amount of energy being spent by the plant to overcome the root stress that could otherwise be used on top growth. Other causes of reduced growth are reduced nutrient and water uptake due to a smaller rooting zone.

Organic soils used for carrot and onion production are susceptable to compaction which in turn affects yield. Carrot growth has been shown to be affected by high soil strengths and low oxygen contents. Lower yields and an increase in unmarketable carrots have been shown to be due to compaction.

Tillage is used to alter soil physical conditions. Deep tillage is often used to alleviate compaction. The paraplow has been shown to effectively decrease soil strength and increase water infiltration. Zone tillage with the use of the paraplow on organic soils will improve drainage, aeration and soil strength. Reducing oxygen stress, improving drainage and decreasing soil strength will encourage maximum root growth. Improving root growth will enhance plant growth and increase the yield and quality of carrots and onions.

Lower yields reduce total return to the grower. Alleviating compaction once it has occured increases grower costs by increased wear and tear of machinery, labor and fuel. Zone tillage can reduce inputs by only alleviating the compaction in the zone that the crop is grown. While an energy and labor efficient tillage system can be developed with zone tillage, Chancellor (1982) states that energy used for tillage and planting is but 3 percent of total energy use and that almost any energy intense tillage practice that increases crop yields without increasing irrigation or fertilizer inputs can be justified.

LITERATURE CITED

Asady, G. H., A. J. M. Smucker, and M. W. Adams. 1985. Seedling test for the quantitative measurement of root tolerances to compacted soil. Crop Sci. 25:802-806.

Barley, K.P. 1963. Influencee of soil strength on the growth of roots. Soil Sci. 96:175-180.

Barley, K. P., D. A. Farrell and E. L. Greacen. 1965. The influence of soil strength on the penetration of a loam by plant roots. Aust. J. Soil Res. 3:69-79.

Bertrand, A. R. and H. Kohnke. 1957. Subsoil conditions and their effects on oxygen supply and the growth of corn roots. Soil Sci. Amer. Proc. 21:135-140.

Bienz, D. R. 1965. Carrot splitting and second growth in central Washingtom as influenced by spacing, time of sidedressing and other cultural practices. Proc. Amer. Soc. Hort. Sci. 86:406-410.

Bowen, H. D. 1981. Alleviating mechanical impedance. p.p. 21-60 In G. F. Arkin and H. M. Taylor (ed.). Modifying the Environment to Reduce Crop Stress. Am. Soc. Agric. Eng., St. Joseph, MI.

Campbell, R. B., D. C. Reicosky and C. W. Doty. 1974. Physical properties and tillage of Paleudalts in the southeastern coastal plains. J. Soil Water Conserv. 29:220-224.

Cannell, R. Q., and M. B. Jackson. 1981. Alleviating aeration stresses. p. 141-194. In G. F. Arkin and H. M. Taylor (ed.) Modifying the Root Environment to Reduce Crop Stress. Am. Soc. Agric. Eng., St. Joseph, MI

Chancellor, W. J. 1971. Effects of compaction on soil strength. p. 190-212. In K. K. Barnes, W. M. Carleton, H. M. Taylor, P. I. Throckmorton and G. E. Vandenberg. Compaction of agricultural soils. Am. Soc. Agric. Eng., St. Joseph, MI

Chancellor, W. J. 1976. Compaction of soil by agricultural equiptment. Division of Agri. Sci. Univ. of California Bulletin 1881. 53 pp.

Chancellor, William J. 1982. Energy efficiency of tillage systems. J. Soil Water Conserv. 37:105-108.

Chang, H. T. and W. E. Loomis. 1945. Effect of carbon dioxide on absorption of water and nutrients of roots. Plant Physiol. 20:221-232.

Chaudhary, A. R., P.R. Gajri, S. S. Rrihar and Romesh Khera. 1985. Effect of deep tillage on soil physical properties and maize yields on coarse textured soils. Soil and Tillage Res. 6:31-34.

Chipmen, E. W. 1959. The influence of length of growing season on root type of carrot varieties. Proc. Amer. Soc. Hort. Sci. 74:583-586.

Cohron, G. T. 1971. Forces causing soil compaction. p. 106-124. In K. K. Barnes et al. Compaction of Agricultural Soils. Am Soc. Agric. Eng., St. Joseph, MI

Cooper, A. W. 1971. Effects of Tillage on Soil Compaction. p. 315-366. In K. K. Barnes et al. Compaction of Agricultural Soils. Am. Soc. Agric. Eng., St. Joseph, MI

Doty, Coy W., Robert B. Campbell and Donald C. Reicosky. 1975. Crop response to chiseling and irrigation in soils with a compact A 2 horizon. Trans. Am. Soc. Agric. Eng. 18:668-672.

Eavis, B. W. 1972. Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam. Plant and Soil 36:613-622.

Eavis, B. W. 1972. Soil physical conditions affecting seedling root growth III. Comparisons between root growth in poorly aerated soil and at different oxygen partial pressures. Plant and Soil 37:151-158.

Erbach, D. C., R.M. Cruse, M. A. Elamin, S. Mukhatar, J. G. Benjamin and C. H. Choi. 1984. Soil Condition and corn growth response to paraplowing. A.S.A.E. Paper No. 84-1013. A.S.A.E. St. Joseph, Mi.

Fehrenbacher, J. B., and R. H. Rust. 1956. Corn root penetration in soils derived from various textures of Wisconsin age glacial till. Soil Sci. 82:369-378.

Flocker, W.J., H. Timm and J. A. Vomocil. 1960. Effect of soil compaction on tomato and potato yields. Agron. J. 52:345-348.

Free, George R., John Lamb and Everett Carleton. 1947. Compactability of certain soils as related to organic matter and erosion. Journal of the American Society of Agron. 39:1068-1076.

Gerard, C. J., P. Sexton and G. Shaw. 1982. Physical factors influencing soil strength and root growth. Agron. J. 74:875-879.

Gerard, C. J., H. C. Mehta and E. Hinojosa. 1972. Root growth in a clay soil. Soil Sci. 114:37-49.

Gill, W. R. and R. D. A. Miller. 1956. A method for study of the influence of mechanical impedance and aeration on the growth of seedling roots. Soil Sci. Amer. Proc. 20:154-157.

Grable, A. R. 1971. Effects of compaction on content and transmission of air in soils. p. 154-164. In K. K. Barnes et al. Compaction of Agricultural Soils. Am. Soc. of Agric. Eng., St Joseph, MI.

Greacen, E. L. and J. S. Oh. 1972. Physics of root growth. Nature, New Biol. 235:24-25.

Harris, D. G. and C. H. M. Van Bavel. 1957. Root respiration of tobacco, corn and cotton plants. Agron. J. 49:182-184.

Harris, W. L. 1971. The soil compaction process. p. 9-46. In K. K. Barnes et al. Compaction of Agricultural Soils. Am. Soc. Agric. Eng., St. Joseph, MI

Harrison, A. 1965. Auxanometer experiments on extension growth of <u>Avena</u> coleoptiles in different CO_2 concentration. Physiol. Plant 18:321-328.

Harrison, Alan. 1965. Carbon dioxide effects on the extension in length of <u>Avena</u> coleoptiles. Physiol. Plant. 18:208-218.

Henry, J. E. and D. M. Van Doren. 1985. Progress report on the use of the paraplow. A.S.A.E. Paper No. 85-1011.

Hill, J. N. S. and M. E. Sumner. 1967. Effect of bulk density on moisture characteristics of soils. Soil Sci. 103:234-238.

Hillel, Daniel. 1982. Introduction to Soil Physics. Academic Press, Inc. N.Y. pp. 177, 200.

Howard, Richard F., Michael J. Singer and Gregory A. Frantz. 1981. Effects of soil properties, water content and compactive effort on the compaction of selected California soils. Soil Sci. Soc. Am. J. 45:231-236.

Kaddah. 1975. Subsoil chiseling and strip plowing effects on soil properties and wheat grown on a stratified fine sandy soil. Agron. J. 68:36-39.

Kramer, Paul J. and William T. Jackson. 1954. Causes of injury to flooded tobacco plants. Plant Physiol. 29:241-245.

Lemon, E. R. 1962. Soil aeration and plant root relations I. Theory. Agron. J. 54:167-170.

Lemon, E. R. and C. L. Wiegand. 1962. Soil aeration and plant root relations II. Root respiration. Agron. J. 54:171-175.

Leonard, D. A. and J. A. Pinckard. 1946. Effect of various oxygen and carbon dioxide concentrations on cotton root development. Plant Physiol. 21:18-36.

Letey, J., L. H. Stolzy and G. B. Blank. 1962. Effect of duration and timing of low soil oxygen content on shoot and root growth. Agron. J. 54:34-37.

Letey, J., L. H. Stolzy, O. R. Lunt and V. B. Younger. 1964. Growth and nutrient uptake of newport bluegrass as affected by soil oxygen. Plant and Soil. 20:143-148.

Letey, 1985. Relationship between soil physical properties and crop production. p. 227-294. In B. A. Stewart. Advances in Soil Sci. Vol. I. Springer-Verlog, New York, New York.

Mann, L. K., and J. H. MacGilliuray. 1949. Some factors affecting the size of carrot roots. Proc. Amer. Soc. Hort. Sci. 54:311-318.

Merideth, H. L. and W. H. Patrick Jr. 1961. Effects of soil compaction on subsoil root penetration and physical properties of three soils in Louisiana. Agron. J. 53:163-167.

Mulligan, M. F., A. J. M. Smucker and G. F. Safir. 1985. Tillage modifications of dry edible bean root colonization by VAM fungi. Agron. J. 77:140-144.

Mukhtar, S., J. L. Baker, R. Horton and D. C. Erbach. 1985. Soil water infiltration as affected by the use of the paraplow. ASAE 28(6):1811-1816.

Olymbios, C. M. and W. W. Schwabe. 1977. Effects of aeration and soil compaction on growth of the carrot, Daucus carota l. J. of Hort. Sci. 52:485-500.

Parker, J. J. and H. M. Taylor, 1965. Soil strength and seedling emergence relations. I. Soil type, moisture tension, temperature and planting depth effects. Agron. J. 57:289-291.

Pidgeon, J. D. 1983. Paraplow- A new approach to soil loosening. ASAE Paper No. 83-2136; St. Joseph, MI.

Pikul, J. L. Jr. and R. R. Allmaras. 1986. Physical and chemical properties of a Hapluxeroll after fifty years of residue management. Soil Sci. Soc. Am. J. 50:214-219.

Riekels, Jeral W. 1977. Nitrogen-water relationships of onions grown on organic soil. J. Amer. Soc. Hort. Sci. 102(2):139-142.

Robinson, Frank E. 1969. Carrot population density and yield in an arid environment. Agron. J. 61:499-500.

Rowe, R. N. and P. B. Catin. 1971. Differential sensitivity to water logging and cyanogenesis by peach, apricot and plum roots. J. Amer. Soc. Hort. Sci. 96:305-308.

Saini, G. R. and T. L. Chow. 1984. Compactibility indexes of some agricultural soils of New Brunswick, Canada. Soil Sci. 137:33-38.

Saini, G. R. 1976. Relationship between potato yield and oxygen diffusion rate of subsoil. Agron. J. 68:823-825.

Schuurman, J. J. 1965. Influence of soil density on root development and growth of oats. Plant and Soil 22:352-374.

Scott, T. W. and A. E. Erickson. 1964. Effect of aeration and mechanical impedance on the root development of alfalfa, sugar beets and tomatoes. Agron. J. 56:575-576.

Soane and J. D. Pidgeon, 1975. Tillage requirement in relation to soil physical properties. Soil Sci. 119:376-383.

Spoor, G. and R. J. Godwin. 1978. An experimental investigation into the deep loosening of soil by rigid tines. J. Agric. Eng. Res. 23:243-258.

Stolzy, L. H., J. Letey, T. G. Szoszkiewicz and O. R. Lunt. 1961. Root growth and diffusion rates as functions of oxygen concentration. Soil Sci. Soc. Am. Proc. 25:463-467.

Strandberg, J. O. and J. M. White. 1979. Effect of soil compaction on carrot roots. J. Amer. Soc. Hort. Sci. 104(3):344-349.

Tackett, J. L. and R. W. Pearson. 1964. Effect of carbon dioxide on cotton seedling root penetration of compacted soil cores. Soil Sci. Amer. Proc. 28:741-743.

Taksdal, G. 1984. Effects of tractor wheelings on carrot quality. Acta Hort. 163:255-260.

Taylor, Howard M. and Earl Burnett. 1965. Influence of soil strength on the root growth habits of plants. Soil Sci. 98:174-180.

Taylor, H. M., L.F. Locke, and J. E. Box. 1964. Pans in southern Great Plains soils: III. Their effects on yield of cotton and grain sorghum. Agron. J. 56:542-545.

Taylor, Howard M. and Herbert R. Gardner. 1963. Penetration of cotton seedling tap roots as influenced by bulk density, moisture content and strength of soil. Soil Sci. 96:153-156.

Taylor, Howard M. and Larry F. Ratliff. 1964. Root growth pressures of cotton, peas and peanuts. Agron. J. 61:398-402.

Taylor, Howard M. and Larry F. Ratliff. 1969. Root elongation rates of cotton and peanuts as a result of soil strength and water content. Soil Sci. 108:113-119.

Taylor, Howard M., Gene M. Roberson, Jesse J. Parker Jr. 1966. Soil strength-root penetration relations for medium to coarse textured soils. Soil Sci. 102:18-22.

Thompson, R. 1969. Some factors affecting carrot root shape and size. Euphytica 18:277-285.

Trouse, Albert C. Jr. 1983. Observations on under-the-row subsoiling after conventional tillage. Soil and Tillage Res. 3:67-81.

Unger, Paul W. and Robert E. Danielson. 1965. Influence of Oxygen and Carbon Dioxide on germination and seedling development of corn (Zea mays L.). Agron. J. 57:56-58.

Van Bavel, C.H.M. 1951. A soil aeration theory based on diffusion. Soil Sci. 72:73:33-46.

Veihmeyer, F. J. and A. H. Hendrickson. 1948. Soil density and root penetration. Soil Sci. 65:487-493.

Vomocil, J. A. and W. J. Flocker. 1961. Effect of soil compaction on storage and movement of soil air and water. ASAE Trans.4:242-245.

Voorhees, W. B., C. G. Senst and W. W. Nelson. 1978. Compaction and soil structure modification by wheel traffic in the northern corn belt. Soil Sci. Soc. Am. J. 42:344-349.

Voorhees, W. B., D. A. Farrel, and W. E. Lason. 1975. Soil strength and aeration effects on root elongation. Soil Sci. Soc. Am. J. 39:948-953.

Warkentin, B. P. 1971. Effects of compaction on control and transmission of water in soils. p. 126-153. In K. K. Barnes et al. Compaction of Agricultural Soils. Am. Soc. Agric. Eng., St. Joseph, MI.

White, J. M. and J. O. Strandberg. 1978. Early root growth of carrots in organic soil. J. Amer. Soc. Hort. Sci. 103(3):344-347.

White, J. M. and J. O. Strandberg. 1979. Physical factors affecting carrot root growth: Water saturation of soil. J. Amer. Soc. Hort. Sci. 104(3):414-416.

Wiersma, D. and M. M. Mortland. 1953. Response of sugar beets to peroxide fertilization and its relationship to oxygen diffusion. Soil Sci. 75:355-360.

Wiersum, L. K. 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant and Soil 9:75-85.

Wilkens, D. E., J. M. Kraft, and P. E. Rasmussen. 1986. Effect of paraplowing on wheat and fresh pea yields. ASAE Paper No. 86-1516. St. Joseph, MI.

Willat, S. T. 1986. Root growth of winter barley in a soil compacted by the passage of tractors. Soils and Tillage Res. 7:41-50.

Williamson, R. E. and W. E. Splinter. 1968. Effect of gaseous composition of root environment upon root development and growth of Nicotiana tabacum. Agron. J. 60:365-368.

Williamson, R. E. and W. E. Splinter. 1969. Effects of light intensity, temperature and root gaseous environment on growth of Nicotiana tabacum L.. Agron. J. 61:285-288.

Williamson, R. E. 1964. The effect of root aeration on plant growth. Soil Sci. Amer. Proc. 28:86-90.

Williamson, R. E. 1968. Influence of gas mixtures on cell division and root elongation of broad bean, vicia faba L.. Agron J. 60:317-321.

FIELD TILLAGE STUDIES

Introduction

The production of onions and carrots in Michigan sometimes results in field operations when the soil is moist and susceptible to compaction. Many Michigan fields have a compacted layer below the plow layer which has been developed durin previous tillage and traffic operations. Soil compaction is believed to affect the quality and quantity of onions and carrots harvested.

Deep tillage has been used to improve soil conditions by breaking up compacted layers (Spoor and Godwin, 1978). Deep tillage increases crop yield by lowering soil strength and improving soil aeration by increasing water infiltration (Kaddah, 1975).

The paratill is a recent improvement in tillage instruments for deep tillage. It is used for zone tillage where only the portion of the field under the row is loosened. It has been shown to lower bulk density, increase water infiltration and decrease soil strength (Erbach et. al., 1984 and Henry and Van Doren, 1975).

High soil strength affects roots by reducing root penetration and growth (Taylor et al. 1966). Strandberg and White (1979) have shown that soil strength can affect both growth of young taproots and the size, weight and shape of mature carrots. Carrots grown at higher soil strengths tended to be thicker, convoluted and more branched. Olymbios and

Schwabe (1977) found a reduction in taproot growth was due to mechanical and aeration stresses.

Onions are more shallow rooted than carrots and have no taproot. Shallow rooted crops are more susceptible to water stress. A compacted layer prevents soil moisture from moving up and the roots from growing deep during dry conditions.

In this study, carrots and onions were grown on a Houghton muck (Euic, Mesic, Typic medisaprist) comparing conventional and zone tillage. Zone tillage was done using a Tye paratill and Bushhog rotill. The objectives of this study were to: 1) measure the effects of zone tillage on soil physical properties; and 2) Quantify the improvements of zone tillage on carrot and onion development and yields.

MATERIALS AND METHODS

Experiments were conducted in 1988 and 1989 on research plots at the M.S.U. Muck Research Center located in Laingsburg, MI. The soil is a tile drained Houghton muck (Euic, Mesic, Typic Medisaprist).

Prior to establishing the tillage treatments in 1988 the entire study area was moldboard plowed to a depth of 30 cm in early April. Fertilizer was drilled on April 26 in accordance with soil test recommendations. In two replications barley was seeded to simulate the seeding of a cover crop for wind erosion control. The four tillage treatments done before seeding were: 1) Disking and rolling with a light weight roll (PDR), (in the two replicates with barley no secondary tillage was done); 2) A Bushhog-Rotill unit pulled through 35 cm deep (Rt); 3) A Tye paratill unit pulled through 35 cm deep (Pt); and 4) A Tye paratill unit pulled through 35 cm deep, followed by rolling with a light weight firming roller (P+R). The barley was allowed to grow 12-14 inches before being killed with Fusilade. Ramrod was used as a pre-emergence herbicide on the onions followed by post-emergence applications of Fusilade, Goal, Dual, and Furloe-chloro IPC at the recommended rates. Lorox and Furloe were used pre-emergence on the carrots followed by post-emergence applications of Mineral Spirits, Fusilade, Caparol and Lorox DF as needed at recommended rates. The onions were side dressed in mid June with nitrogen in the form of urea at 80 pounds N per acre. Carrots (<u>Daucus carota</u>, var Six Pak II.) and onions (<u>Allium cepa</u>, var. Northern Oak) were seeded May 12. Both were seeded using a Gaspardo seeder. The carrots and onions were grown in three row beds 50 feet long with 18 inches (45.7 cm) between rows. In the zone tillage plots, the soil under the 42 inch (106.7 cm) beds was loosened with the rotill or paratill units while the wheel track between the beds was left undisturbed. The tops of the rotill and paratill shanks were 34 and 28 inches apart, respectively.

In 1989 five tillage systems were used. They were: 1) Plow, disk and roll (PDR); 2) Plow, disk and roll followed by the Bushhog-Rotill unit pulled through 35 cm deep (R+P); 3) Plow, disk and roll followed by the Tye paratill unit pulled through 35 cm deep (P+P); 4) Rotill only 35 cm deep (RO); and 5) Paratill only 35 cm deep (PO). Prowl and Ramrod was used pre-emergence on the onions followed by post-emergence applications of Goal, Fusilade, Furloe, Buctril, and Dual as needed at recommended rates. Furloe and Buctril were used pre-emergence on carrots with post-emergence applications of Fusilade, Stoddard Solvent and Lorox at recommended rates as needed. The onions were sidedressed in mid June with urea at 80 pounds per acre. Onions var. Northern Oak were seeded May 9. Carrots var. Vitagold were seeded May 17.

An Eijeklamp recording cone penetrometer was used to measure soil strength (Suaze Technical Products Corp., 345 Cornelia Street, Plattsburgh, NY 12901). The largest of tips

1, 2, 3 and 4 (1 cm^2, 2 cm^2, 3.5 cm^2 and 5 cm^2) were used depending on which tip allowed for the probe to be pushed through the soil with even amounts of pressure. Six samples were taken per plot for all treatments. In the zone tillage treatments, the penetrometer readings were taken in the loosened zone 5cm to the side of the row. The 1988 soil strength measurements were taken August 17 for the onions and carrots. The 1989 measurements were taken in the rotill and paratill plots before zone tillage May 4 in the onions and May 5 in the carrots to measure the effect of plowing an untilled soil. Measurements were taken again August 10 in the carrots and August 28 in the onions. Soil moisture samples were taken at depths of 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm for each plot. Moisture contents were also measured on all plots for the onions in 1989 on May 25 and in the carrots on June 26. These samples were oven dried at 90 C for 48 hours and the gravimetric moisture contents were determined. The soil strength measurements were made at depths of 5, 10, 15, 20, 25, 30, 35, and 40 cm.

Plant populations of carrots were evaluated 24 days after seeding in 1989 by counting the plants per 3 meters of row for each plot.

Roots were sampled in 1989 adjacent to the plant with an open ended, 10.16cm square box, at depths of 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm. Prior to separation the roots were soaked in a solution of 5% Calgon and 0.8% NaOH for 24 hours.

To seperate the roots the soil solution was poured onto a no. 80 sieve and was gently rinsed with water. After the soil remaining on the seive was rinsed, it was washed back into a beaker. The roots along with some debris floated and this was decanted onto a 710 mesh screen. The debris was gently rinsed leaving the roots and a small quantity of debris. This process was repeated several times until all the roots were extracted from the sample. Root length was approximated by use of the line intercept method of Newman (1966), revised by Tennant (1975).

The carrots were harvested on August 24 in 1988. Since over 25% were under marketable size they were harvested again on September 1. Onions were harvested September 28. The 1989 carrots were harvested September 11 to September 13 with 20 feet of bed (3 rows) and 2 beds per treatment harvested for all 6 replications. The weight and number of total, number 1 (shoulder width between 0.5 and 1.5 inches, length > 5 inches), jumbo (shoulder width 1.5 inches), small (shoulder width < 0/5 inches, length less than 5 inches) and cull carrots (forks, stubs and splits) were recorded. The length and diameter of 20 number 1 carrots were measured for each treatment. The onions were harvested on October 3 with 24 feet of row per plot harvested.

There were great differences in growing conditions between the two years. 1988 was a drought year with hot, dry conditions prevailing until the middle of July. Thrips severely damaged the onion crop resulting in small bulbs. June of 1989 was very wet, with many of the plots being underwater for days at a time. A seeding problem decreased the onion stand which was compounded by heavy rains and flooding at germination. While these two contrasting years make it difficult to predict what would happen under more "normal" conditions it did provide information under extreme conditions.

The experimental design was a randomized complete block and the treatments were replicated 6 times. Analysis of variance was used to detect significant differences between tillage treatments. Duncan's multiple range test was used to separate and rank the treatment means.

RESULTS

Carrot Tillage, 1988

Soil Strength

The Rt, Pt and P+R treatments all significantly lowered soil strength when averaged over all depths (Table 1). The PDR had an average soil strength of 4.53 MPa. The Pt and P+R treatments were nearly the same at 2.49 and 2.46 MPa. Average soil strength in the Rt was higher than the paratill treatments at 3.34 MPa although the increase was not significant.

There were no significant differences in soil strength between treatments at 40cm (Table 1). The P+R significantly lowered soil strength at all other depths compared to PDR. The Pt was significantly less than conventional tillage at all other depths except 30 and 35cm. The Rt significantly decreased soil strength over PDR in the 5 to 20 cm zone. Below 20 cm Rt was not significantly lower than PDR. The P+R significantly lowered soil strengths compared with the Rt at depths of 20, 25, and 30 cm. Soil strength with Pt was significantly less than the Rt only at 35cm. At all other depths there were no significant differences in soil strength between the Rt and Pt.

Rolling after paratilling did not significantly increase soil strength (Table 1). The P+R did produce a higher soil strength in the top 20 cm but it was not significantly higher than paratill alone.

Table 1. Effect of tillage on soil strength of a Houghton muck used for carrot production. August 17, 1988.

Depth (cm)	Tillage treatment[y] PDR	Rt	Pt	P+R	CV
	- - - - - -	- - - - MPa	- - - -	- - - - - -	
5	4.25 a[z]	2.04 b	1.73 b	2.57 b	35
10	6.18 a	3.43 b	2.63 b	3.46 b	20
15	6.20 a	4.17 b	3.21 b	3.47 b	18
20	5.68 a	4.16 b	3.16 bc	2.62 c	21
25	4.88 a	3.88 ab	2.81 bc	2.12 c	25
30	3.68 a	3.48 a	2.56 ab	1.89 b	23
35	2.96 ab	3.12 a	2.14 bc	1.87 c	22
40	2.40 a	2.47 a	1.70 a	1.66 a	24
Average	4.53 a	3.34 b	2.49 b	2.46 b	24

[y] PDR = plow-disk-roll; Rt = rotill; Pt = paratill; P+R = paratill plus roll.
[z] Values within a line followed by different letters are significant (P = 0.05).

There were no significant differences in soil moisture content between treatments at all depths analyzed on 8-17-88 (Table 2).

Table 2. Effect of tillage on soil moisture, 8-17-88

Tillage treatment[y]	Depth 0-10 cm	10-20 cm	20-30 cm	30-40 cm
	- - - - - - - -	% moisture	- - - -	- - - -
PDR	168.5 a[z]	178.0 a	209.2 a	341.5 a
Rt	165.2 a	179.5 a	241.2 a	355.5 a
Pt	175.2 a	181.2 a	211.7 a	279.7 a
P+R	163.5 a	181.2 a	211.7 a	314.7 a
CV	5	6	20	19

y PDR = plow-disk-roll; RO = rotill; PO = paratill; P+R = paratill plus roll.
[z] Values within a column followed by different letters are significant (P = 0.05).

YIELD

There were significantly fewer carrots harvested from the Pt and P+R treatments August 24 than in PDR (Table 3) but total weight was the same (Table 4). The zone tillage treatments left the soil too loose to get the good seed soil contact required for germination. Rotilling reduced the number and weight of carrots but the reduction was not significant. Rolling after paratilling increased the number and weight of carrots in the paratill treatment but the increase was not significant. No differences in the number or weight of jumbo carrots and cull carrots were detected between treatments.

The number of marketable carrots harvested on 8/24/88 was unaffected by treatment (Table 3). The P+R significantly increased the weight harvested over PDR (Table 4). The other treatments tended to increase the weight of marketable carrots but the increase was not significant.

The number and weight of small carrots was significantly reduced by the Rt, Pt and P+R treatments on August 24 (Tables 3 and 4). The PDR had 6.1 Mg/Ha of small carrots harvested while the Rt, Pt and P+R had 4.8, 4.3 and 4.0 Mg respectively. Significantly more small carrots were harvested from the Rt and Pt plots than P+R (Table 3). The weight of small carrots however was not significantly reduced. Therefore the small paratill carrots must have been larger than those under conventional tillage. No significant difference was detected between the two paratill treatments in size or weight of small carrots.

The weight of number one carrots in the Rt and P+R plots was significantly different from PDR on September 1, 1988 (Table 6). The weight increase came in the last week of growth. Rotilling and P+R significantly increased the total weight of carrots harvested September 1 (Table 6) but Pt without rolling decreased total number (Table 5). There were no changes in significant differences between treatments for the jumbo, small and cull carrots between August 24 and September 1.

Table 3. Effect of tillage on numbers of carrots harvested 8-24-88.

Tillage treatment[y]	Yield				
	Total	#1	Jumbo	Small	Culls
	carrots/3 meters				
PDR	91 a[z]	45 a	0.6 a	33 a	12 a
Rt	89 a	50 a	0.6 a	27 b	11 a
Pt	79 b	46 a	0.6 a	22 b	10 a
P+R	82 b	49 a	1.0 a	21 c	9 a
CV	6	10	61	12	23

[y] PDR = plow-disk-roll; Rt = rotill; Pt = paratill; P+R = paratill plus roll.
[z] Values within a column followed by different letters are significant (P = 0.05).

Table 4. Effect of tillage weight of carrots, 8-24-88.

Tillage treatment[y]	Yield Total	#1	Jumbo	Small	Culls
	Mg/Ha				
PDR	31.0 a[z]	19.8 b	0.8 a	6.1 a	4.2 a
Rt	32.7 a	22.7 ab	0.7 a	4.8 b	4.4 a
Pt	30.9 a	21.5 ab	0.8 a	4.3 b	4.2 a
P+R	33.8 a	24.1 a	1.4 a	4.0 b	4.3 a
CV	12	13	60	15	23

[y] PDR = plow-disk-roll; Rt = rotill; Pt = paratill; P+R = paratill plus roll.
[z] Values within a column followed by different letters are significant (P = 0.05).

Table 5. Effect of tillage on number of carrots harvested 9-1-88.

Tillage treatment[y]	Yield Total	#1	Jumbo	Small	Culls
	carrots/3 meters				
PDR	100 a[z]	45 a	3 a	41 a	8 a
Rt	91 ab	57 a	2 a	23 b	8 a
Pt	85 b	52 a	4 a	20 b	8 a
P+R	87 ab	53 a	3 a	20 b	10 a
CV	7	11	40	21	20

[y] PDR = plow-disk-roll; Rt = rotill; Pt = paratill; P+R = paratill plus roll.
[z] Values within a column followed by different letters are significant (P = 0.05).

Table 6. Effect of tillage on weight of carrots, 9-1-88.

Tillage treatment[y]	Yield				
	Total	#1	Jumbo	Small	Culls
	Mg/Ha				
PDR	36.4 b[z]	20.7 b	3.3 a	8.3 a	4.1 a
Rt	40.8 a	28.3 a	2.9 a	5.0 b	4.6 a
Pt	39.0 ab	26.0 ab	4.9 a	3.8 b	4.1 a
P+R	40.9 a	27.1 ab	4.1 a	4.4 b	5.2 a
CV	5	11	37	18	23

[y] PDR = plow-disk-roll; Rt = rotill; Pt = paratill; P+R = paratill plus roll.
[z] Values within a column followed by different letters are significant (P = 0.05).

Paratilling significantly increased carrot tap root length over PDR (Table 7). Rotilling and P+R also increased carrot length to 20.3 and 20.5 cm but the increase was not significant.

Table 7. Effect of tillage on carrot root lengths 9-1-88.

Tillage treatment[x]	Carrot length[y]
	cm
PDR	17.9 b[z]
Rt	20.3 ab
Pt	22.0 a
P+R	20.5 ab
CV	4

[x] PDR = plow-disk-roll; Rt = rotill; Pt = paratill; P+R = paratill plus roll
[y] Average for 20 carrots.
[z] Values within a column followed by different letters are significant (P = 0.05).

1989 Carrot Tillage Study

Soil Strength and Moisture

Averaged over all depths, zone tillage significantly lowered soil strength (Table 8). There were no significant differences between either of the rotill and paratill treatments. Strength with the PO was significantly less than with the R+P and the P+P was significantly less than both rotill treatments.

The use of the paratill significantly reduced soil strength over all depths (Table 8). There were no significant differences between the two paratill treatments in decrease of soil strength at any depth. Rotill only reduced soil strength at all depths except 40cm. Rotill plus plow did not reduce soil strength at any depth analyzed. At depths greater than 5 cm, P+P was significantly lower than the R+P. Soil strength with paratill only was significantly lower than R+P at all depths except 5 and 30 cm. Plowing increased soil strength in the rotill treatments with the R+P being significantly greater than the RO at depths of 15, 20, and 35cm. Paratill plus plow was significantly lower than RO at depths of 15, 20, and 25 cm. Paratill only tended to be lower than RO with significantly lower soil strengths at depths of 15 and 20cm.

Plowing significantly decreased soil strength relative to the non plowed plots prior to using the rotill and paratill at all depths analyzed May 5, 1989 (Table 9).

Table 8 Effect of tillage on soil strength August 10, 1989, depths 0 to 40cm.

Depth	Tillage treatment[y] PDR	R+P	P+P	RO	PO	CV
cm	MPa					
5	4.56 a[z]	3.56 ab	2.67 b	3.15 b	2.70 b	22
10	6.01 a	5.07 ab	3.27 c	4.12 bc	3.30 c	14
15	6.06 a	5.43 a	3.10 b	4.41 b	3.21 c	12
20	5.90 a	5.47 a	3.28 c	4.70 b	3.75 c	10
25	5.82 a	5.27 ab	3.57 d	4.82 bc	4.11 cd	13
30	5.41 a	5.09 ab	3.73 c	4.29 bc	4.21 bc	14
35	5.50 a	5.40 a	4.22 b	4.41 b	4.52 b	9
40	5.75 a	5.60 ab	4.74 b	5.00 ab	4.85 b	10
Avg.	5.61 a	4.77 b	3.57 d	4.36 bc	3.83 cd	11

y PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
z Values within a line followed by different letters are significant (P = 0.05).

Table 9 Effect of plowing on soil strength 5-5-89.

Depth	Plowed	Rotill prior to plowing	Paratill prior to plowing	CV
cm	MPa			
5	3.79 b[z]	7.71 a	9.29 a	22
10	4.80 b	10.42 a	11.39 a	21
15	5.11 b	10.36 a	10.68 a	26
20	5.23 b	10.01 a	10.75 a	18
25	5.13 b	11.24 a	12.22 a	15
30	5.71 b	14.60 a	15.49 a	20
35	6.17 b	17.68 a	18.93 a	14
40	6.47 b	18.90 a	19.60 a	9

z Values within a line followed by different letters are significant (P = 0.05).

On June 26, 1989 the soil moisture content for the P+P was significantly greater than the PO at the 20-30cm depth (Table 10). Soil moisture contents were unaffected at all other depths sampled. On August 10, 1989 the P+P had a significantly higher soil moisture content than R+P at the 0-

10 depth (Table 10). There were no other significant differences between treatments at any other depths analyzed.

Table 10 Effect of tillage on gravimetric moisture content.

Depth	Tillage treatment[y]	moisture 6-26-89	moisture 8-10-89
cm		%	%
0-10	PDR	191.3 a[z]	162.7 ab
	R+P	185.3 a	157.7 b
	P+P	196.3 a	183.5 a
	RO	191.3 a	169.2 ab
	PO	174.6 a	167.0 ab
	CV	8	7
10-20	PDR	207.6 a	177.7 a
	R+P	201.3 a	173.5 a
	P+P	210.0 a	177.7 a
	RO	202.3 a	184.5 a
	PO	198.6 a	172.5 a
	CV	4	6
20-30	PDR	206.6 ab	182.2 a
	R+P	210.0 ab	187.0 a
	P+P	212.6 a	187.0 a
	RO	203.0 ab	183.2 a
	PO	196.6 b	180.7 a
	CV	4	5
30-40	PDR	207.3 a	217.7 a
	R+P	233.6 a	210.0 a
	P+P	216.0 a	212.2 a
	RO	258.3 a	221.7 a
	PO	210.0 a	224.5 a
	CV	16	10

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

Carrot Growth and Yield, 1989

Plant populations on June 9, 1989 revealed zone tillage significantly decreased the number of established carrots 3 meters of row (Table 11). Stands were decreased over the

PDR in the R+P and RO from 121 to 100 and 99 per 3 meters of row. Stands in the P+P and PO plots were lower than the rotill treatments with 92 and 93 carrots but this difference was not significant.

Table 11 Effect of tillage on carrot stand, 6-9-89.

Tillage treatment[y]	Stand
	carrots/3 meters
PDR	121 a[z]
R+P	100 b
P+P	92 b
RO	99 b
PO	93 b
CV	9

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

The fresh and dry weight of tops and roots sampled 7-10-89 was unaffected by treatment (Table 12). There were no significant differences due to large variability but the weights were appreciably lower with PO. Weights were higher in the plowed plots.

Table 12 Effect of tillage on plant growth 7-10-89.

Tillage treatment[y]	Fr. wt tops	Dry wt tops	Fr. wt roots	Dry wt roots
	- - - - - -	grams/10 plants	- - - - - -	
PDR	44.6 a[z]	7.1 a	18.9 a	2.1 a
R+P	41.6 a	7.3 a	22.4 a	2.4 a
P+P	38.3 a	6.5 a	17.9 a	2.0 a
RO	37.5 a	6.3 a	15.4 a	1.8 a
PO	25.8 a	4.4 a	8.6 a	1.0 a
CV	43	44	72	67

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

No significant differences in root length density were measured at the 0-10, 10-20, and 20-30cm depths (Table 13). At 30-40cm depths, the PO had a significantly lower root length density than PDR. No other significant differences were detected in root length density.

Table 13 Effect of tillage on carrot root length densities, September 7, 1989.

Tillage treatment[y]	Depth (cm) 0-10	10-20	20-30	30-40
	- - - - - -	cm/cm^3	- - - - - -	
PDR	0.74 a[z]	0.77 a	0.08 a	0.06 a
R+P	1.07 a	0.63 a	0.09 a	0.04 ab
P+P	1.42 a	0.33 a	0.06 a	0.05 ab
RO	0.97 a	0.39 a	0.07 a	0.05 ab
PO	1.67 a	0.58 a	0.10 a	0.01 b
CV	46	73	64	53

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

The P+P significantly decreased the total number of carrots harvested (Table 14). No other differences in number of carrots harvested were detected between treatments. No difference in total weight of carrots harvested was detected between treatments (Table 15).

No significant differences were detected between treatments in amount of U.S. number one carrots harvested. The PO significantly increased the weight of number one carrots harvested from 3.6 Mg for PDR to 7.0 Mg (Table 15). No significant increases were detected between PDR, P+P, R+P and RO nor between any of the zone tillage treatments.

No significant differences were detected between treatments in number of jumbos harvested. Paratill plus plow significantly increased the weight of jumbo carrots harvested. There were no significant differences detected between the PDR, R+P, RO and PO nor between any of the zone tillage treatments in weight of jumbo carrots. The number and weight of small carrots was unaffected by treatment.

All zone tillage treatments significantly decreased the number of cull carrots harvested (Table 14). No significant differences were detected between zone tillage treatments in number of culls (Table 14). The weight of culls was reduced by P+P and PO (Table 15). No significant differences in cull weights were detected between the PDR, R+P and RO or between any of the zone tillage treatments.

Percent culls by number was reduced by zone tillage but not significantly (Table 16). The PO had a significantly lower percent culls by weight than conventional tillage (Table 17). The farm was flooded in June when the carrots were in a critical stage of growth. Zone tillage apparently had better drainage during this time causing a decrease in cull carrots harvested.

Table 14. Effect of tillage on number of carrots harvested per 3 meters of row, September 13, 1989.

Tillage treatment[y]	Yield				
	Total	#1	Jumbo	Small	Culls
	-carrots/ 3 meters				
PDR	77 a[z]	5 a	0.3 a	3 a	67 a
R+P	64 a	10 a	1.0 a	3 a	49 bc
P+P	49 b	5 a	1.3 a	2 a	40 c
RO	65 a	9 a	1.1 a	3 a	51 b
PO	69 aa	12 a	1.1 a	4 a	51 b
CV	14	58	87	54	16

y PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
z Values within a column followed by different letters are significant (P = 0.05).

Table 15. Effect of tillage on weight of carrots, September 13,1989.

Tillage treatment[y]	Yield				
	Total	#1	Jumbo	Small	Culls
	Mg/Ha				
PDR	32.4 a[z]	3.6 a	0.6 b	1.3 a	26.9 a
R+P	32.3 a	5.7 a	1.2 ab	1.4 a	24.0 ab
P+P	29.5 a	3.8 a	2.0 a	0.9 a	22.8 b
RO	32.8 a	5.4 a	1.5 ab	1.3 a	24.6 ab
PO	32.6 a	7.0 a	1.4 ab	1.5 a	22.7 b
CV	11	54	82	45	9

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

Table 16. Effect of tillage on carrot percent count, September 13, 1989.

Tillage treatment[y]	Yield			
	#1	Jumbo	Small	Culls
	Percent			
PDR	7.9 a[z]	0.5 b	4.8 a	86.6 a
R+P	15.1 a	1.4 ab	5.7 a	77.5 a
P+P	10.7 a	2.9 a	4.1 a	82.1 a
RO	12.9 a	1.6 ab	5.2 a	80.1 a
PO	16.4 a	1.6 ab	6.1 a	75.7 a
CV	52	84	48	12

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

Table 17. Effect of tillage on carrot percent weight, September 13, 1989.

Tillage treatment[y]	Yield			
	#1	Jumbo	Small	Culls
	- - - - - - - - Percent - - - - - - - -			
PDR	10.7 a[z]	1.7 b	4.0 b	83.4 a
R+P	16.8 a	3.4 b	4.1 b	75.5 a
P+P	11.8 a	6.2 a	2.9 d	78.9 a
RO	15.2 a	4.2 ab	3.8 c	76.7 a
PO	20.6 a	4.1 ab	4.5 a	70.6 a
CV	47	75	39	13

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

Zone tillage significantly increased the average length of U.S. number one carrot (Table 18). The average length for PDR was 18.3 cm while for the R+P, P+P, RO and PO lengths were 21.2, 21.3, 20.8, and 21.5 cm respectively. There were no significant differences in width of U.S. number one carrots harvested nor in width to length ratio.

Table 18. Effect of tillage on length and diameter of number one carrots.

Tillage treatment[y]	Carrot length (cm)	Carrot width (cm)	Carrot length/width
	cm	cm	cm
PDR	18.3 b[z]	3.2 a	5.6 a
R+P	21.2 a	3.3 a	6.4 a
P+P	21.3 a	3.4 a	6.2 a
RO	20.8 a	3.2 a	6.6 a
PO	21.5 a	3.3 a	6.5 a
CV	6	9	11

y PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

Onion Tillage, 1988

Soil Strength and Moisture

Paratill and P+R significantly reduced soil strength averaged over all depths (Table 19). The PDR had a soil strength of 4.03 MPa. No significant differences within zone tillage treatments was detected. Rotill decreased soil strength to 2.49 MPa. There was a non significant increase in soil strength by rolling the paratill treatment from 1.88 to 2.24 MPa.

Paratill only significantly lowered soil strength at all depths (Table 19). The paratill plus roll treatment significantly decreased soil strengths relative to PDR at all depths except 40cm. Rotill only significantly decreased soil strengths from 0 to 30 cm. Paratill only was significantly lower than the RO at depths of 25 and 30 cm. The P+R significantly decreased soil strength over the RO only at the 35cm depth. There was a trend of increased soil strength in rolling the paratill treatment, especially in the top 15 cm.

Table 19. Effect of tillage on soil strength in onions, depths 0 to 40 cm, August 28, 1988.

Depth (cm)	Tillage treatment[y] PDR	Rt	Pt	P+R	CV
	MPa				
5	3.64 a[z]	1.30 b	1.34 b	1.87 b	43
10	5.05 a	1.93 b	1.63 b	2.32 b	25
15	5.20 a	2.59 b	1.87 b	2.47 b	24
20	4.98 a	2.97 b	2.05 b	2.37 b	24
25	4.59 a	3.11 b	1.91 c	2.27 bc	26
30	3.65 a	2.96 b	2.15 c	2.37 bc	19
35	2.84 a	2.85 a	2.21 b	2.28 b	13
40	2.28 a	2.23 a	1.85 b	1.96 ab	14
Avg.	4.03 a	2.49 b	1.88 b	2.24 b	83

[y] PDR = plow-disk-roll; Rt = rotill; Pt = paratill; P+R = paratill plus roll.
[z] Values within a line followed by different letters are significant (P = 0.05).

On August 17, 1988 there were no significant differences in soil moisture between any treatment at any depth analyzed (Table 20).

Table 20. Effect of tillage on gravimetric moisture content in onions.

Depth	Tillage treatment[x]	moisture 8-17-88	Tillage treatment[y]	moisture 8-28-89
cm		%		%
0-10	PDR	157.3 a[z]	PDR	129.0 b
	Rt	197.0 a	R+P	141.3 ab
	Pt	161.3 a	P+P	136.0 ab
	P+R	163.3 a	RO	147.0 a
			PO	139.6 ab
	CV	21		6
10-20	PDR	161.0 a	PDR	143.3 b
	Rt	183.0 a	R+P	156.6 a
	Pt	174.6 a	P+P	144.0 b
	P+R	166.3 a	RO	155.0 a
			PO	142.3 b
	CV	13		4
20-30	PDR	197.0 a	PDR	149.6 a
	Rt	202.6 a	R+P	150.3 a
	Pt	248.6 a	P+P	141.6 a
	P+R	229.6 a	RO	149.6 a
			PO	150.0 a
	CV	30		7
30-40	PDR	271.6 a	PDR	271.6 a
	Rt	338.3 a	R+P	173.0 bc
	Pt	296.6 a	P+P	187.6 ab
	P+R	331.6 a	RO	187.3 ab
			PO	198.6 a
	CV	24		6

[x] PDR = plow-disk-roll; Rt = rotill; Pt = paratill; P+R = paratill plus roll

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO = paratill only.

[z] Values within a column followed by different letters are significant (P = 0.05).

Yield

The Rt and P+R had more onions harvested than the PDR but the difference was not significant (Table 21). Rotill only and P+R significantly increased the total number of onions harvested over the Pt (Table 21). The Pt treatment had the fewest number of onions harvested with 104/3 meters but was not significantly lower than the PDR with 108.

Rotill only significantly increased total weight of onions harvested to 39.2 Mg/Ha over the PDR with 40.4 Mg (Table 22). No significant difference was detected between zone tillage treatments or the PDR, Pt and P+R were detected.

Paratill plus roll significantly increased the weight of onions in the less than 2 inch range compared to paratill only (Table 22).

The Rt significantly increased the weight and number of onions in the 2-3 inch range from 230 mg/Ha and 43 onions to 27.0 Mg and 48 onions (Tables 21 and 22). No significant differences were detected between the PDR, Pt and P+R or the Rt, Pt and P+R.

Table 21. Effect of tillage on number of harvested onions, September 28, 1988.

Tillage treatment[y]	Yield		
	Total	<2"	2-3"
	- - - onions/3 meters - - - -		
PDR	108 ab	65 a	43 b
Rotill	114 a	65 a	48 a
Paratill	104 b	58 b	45 ab
Paratill+Roll	114 a	70 a	44 ab
CV	6	8	5

[y] PDR = plow-disk-roll.
[z] Values within a column followed by different letters are significant (P = 0.05).

Table 22. Effect of tillage on onion yield 9-28-88.

Tillage treatment[y]	Yield		
	Total	<2"	2-3"
	- - - - - - - Mg/Ha - - - - - -		
PDR	40.4 b[z]	17.3 ab	23.0 b
Rotill	39.2 a	17.3 ab	27.0 a
Paratill	40.9 ab	16.0 b	24.9 ab
Paratill+Roll	43.0 ab	19.2 a	24.0 ab
CV	9	8	12

[y] PDR = plow-disk-roll.
[z] Values within a column followed by different letters are significant (P = 0.05).

Onion Tillage, 1989

Soil Strength and Moisture

The soil strength was significantly lowered by all zone tillage treatments averaged over all depths (Table 23). Paratilling was more effective in lowering soil strength than R+P. Plowing before rotilling significantly increased the average profile soil strength. Plowing did not significantly affect the paratill treatments. There were no significant differences between PO, P+P and RO.

Paratilling and rotill only significantly lowered soil strengths at all depths analyzed relative to conventional tillage (Table 23). Rotill plus plow significantly decreased the soil strength only at depths of 10, 15, 20 and 25cm. Soil strengths in the P+P, RO and PO plots were significantly less than R+P at depths greater than 5cm. Plowing did not affect the effectiveness of paratilling at any depth. Paratill plus plow tended to be lower than RO with the only significant difference at 15 cm. Paratill only was significantly lower than RO at depths of 15, 20 and 25 cm.

Plowing significantly lowered soil strengths at depths of 15-40 cm over nontilled soil prior to rotilling and paratilling (Table 24).

Table 23. Effect of tillage on soil strength in onions, August 28, 1989.

Depth	PDR	Tillage treatment[y] R+P	P+P	RO	PO	CV
cm	MPa					
5	3.18 a[z]	2.49 ab	2.01 b	2.04 b	1.83 b	21
10	4.41 a	3.31 b	2.37 c	2.59 c	2.11 c	10
15	4.38 a	3.43 b	2.40 d	2.87 c	2.08 d	10
20	4.26 a	3.41 b	2.31 cd	2.74 c	2.12 d	10
25	3.86 a	3.28 b	2.26 cd	2.67 c	2.15 d	11
30	3.24 a	3.06 a	2.15 b	2.47 b	2.26 b	11
35	2.88 a	2.79 a	2.24 b	2.31 b	2.37 b	6
40	2.63 a	2.66 a	2.16 b	2.29 b	2.30 b	6
Avg.	3.60 a	3.05 b	2.24 cd	2.50 c	2.15 c	8

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO + paratill only.
[z] Values within a line followed by different letters are significant (P = 0.05).

Table 24. Effect of plowing on soil strength May 4, 1989.

Depth	Plowed	Rotill prior to plowing	Paratill prior to plowing	CV
cm	MPa			
5	3.78 a[z]	7.28 a	6.85 a	27
10	5.24 a	9.15 a	8.76 a	24
15	5.65 b	10.15 a	9.79 a	19
20	5.85 b	10.15 a	10.11 a	15
25	5.73 b	10.55 a	11.95 a	22
30	6.22 b	13.16 a	14.68 a	19
35	7.63 b	17.02 a	17.00 a	13
40	9.04 b	17.69 a	17.95 a	17

[z] Values within a line followed by different letters are significant (P = 0.05).

Temperature readings taken May 24, 1989 showed a significantly lower soil temperature in the P+R than the RO and PO (Table 25). Temperatures tended to be lowest in the nonplowed zone tillage treatments.

Table 25 Effect of tillage on soil temperature 5-24-89.

Tillage treatment[y]	Temperature
	(C)
PDR	25 a[z]
R+P	25 ab
P+P	25 a
RO	24 b
PO	24 ab
CV	2

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO + paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

Plowing had no effect on soil moisture at any depth analyzed (Table 26). On August 28, 1989 the RO had a significantly higher soil moisture than the PDR at the 0-10cm range (Table 20). At 10-20cm the R+P and RO were significantly higher than the other treatments. There were no significant differences between treatments at the 20-30cm range. The soil moisture at 30-40cm was significantly greater in the PO plot than the PDR and R+P.

Table 26. Effect of plowing on gravimetric soil moisture content in onions, May 4, 1989.

Depth	Plow	Nonplowed rotill	Nonplowed paratill	CV
cm	%	%	%	
0-10	191.3 a[z]	182.3 a	186.0 a	3
10-20	199.3 a	196.3 a	201.3 a	6
20-30	216.3 a	216.3 a	246.6 a	1
30-40	256.0 a	258.6 a	276.0 a	19

[z] Values within a line followed by the same letter are not significant (P = 0.05).

Yield

Plow, disk and roll had the largest number of harvested onions with 39 per 3 meters (Table 27). Paratill plus plow and R+P significantly reduced the number harvested to 33 and 32. There were no significant differences among PDR, RO and PO; P+P, PO and RO; or R+P, P+P and PO. Total weight of harvested onions in PO with 18.8 Mg/Ha was significantly lower than PDR with 32.5 Mg (Table 28). There were no significant differences in total harvest weights among PDR, R+P, P+P, and RO or P+P, RO and PO.

Number and weight of jumbos was reduced by PO. There were no significant differences between PDR, R+P, P+P, and RO or any of the zone tillage treatments in number and weight of jumbos.

The number of harvested onions in the 2-3" range was significantly reduced by the RO and PO treatments relative to PDR. No differences in the number of onions in the 2-3" range were detected between the PDR, R+P and P+P; R+P, P+P and RO;

or between RO and PO. The weight of 2-3" onions with PO was significantly reduced over all other treatments. No differences between the other treatments was detected.

The number and weight in the <2" category was significantly increased by PO relative to conventional tillage. Plowing before zone tillage decreased the number and weight of small onions in both the rotill and paratill treatments. There were no significant differences between PDR, R+P, P+P and RO; or RO and PO.

Table 27. Effect of tillage on number of harvested onions, October 3, 1989.

Tillage treatment[y]	Yield			
	Total	Jumbo	2-3"	<2"
	----- onions/3 meters -----			
PDR	39 a[z]	3.3 a	22 a	13 b
R+P	32 c	2.9 ab	19 ab	10 b
P+P	33 bc	2.0 ab	17 bc	14 b
RO	36 ab	0.8 ab	20 ab	16 ab
PO	35 abc	0.1 b	13 c	22 a
CV	7	91	16	26

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO + paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

Table 28. Effect of tillage on onion yield, October 3, 1989.

Tillage treatment[y]	Yield Total	Jumbo	2-3"	<2"
	- - - - - - - - - Mg/Ha	- - - - - - - - - -		
PDR	32.5 a[z]	6.4 a	20.9 a	5.2 bc
R+P	27.0 a	5.5 ab	17.8 a	3.6 c
P+P	25.8 ab	4.2 ab	16.3 a	5.3 bc
RO	24.4 ab	1.9 ab	16.4 a	6.0 ab
PO	18.8 b	0.5 b	10.6 b	7.8 a
CV	21	83	22	21

[y] PDR = plow-disk-roll; R+P = rotill plus plow; P+P = paratill plus plow; RO = rotill only; PO + paratill only.
[z] Values within a column followed by different letters are significant (P = 0.05).

Discussion

Zone tillage reduced soil strength both years in onions and carrots. This agrees with the findings of Erbach et al. (1984) and Henry and Van Doren (1985) who found a decrease in soil strength with the use of the paratill. Erbach also reported lower bulk densities and higher water infiltration rates with the paratill.

Emergence in the carrot tillage studies was reduced by the use of zone tillage. Reduced germination due to poor seed soil contact is the probable cause of decreased emergence in the zone tilled treatments. There are four environmental factors that affect seed germination: water, temperature, oxygen and light (Meyer, 1960). Of these factors, water availability is the most important and most variable between tillage treatments. The seed must imbibe water from the soil in either the liquid or vapor form in order to germinate. The rate of water movement to the seed depends on the soil pore structure and amount of seed soil contact (Hartmann and Kester, 1975). Good contact between seed and moist soil aids moisture transfer to the seed. Compressing a soil improves this contact (Trouse, 1971). Rolling after paratilling in 1988 tended to increase carrot stand which would imply that the reduced germination is due to a loose seed bed. Zone tillage can reduce germination by reducing seed soil contact and affecting the pore distribution. Loosening the soil increases the size of pores and reduces the matrix potential. This will reduce the amount of water that can flow to the seed and reduce germination. Another possibility for reduced stands in the zone tillage treatments is movement of the seed to deeper depths after planting. A loose soil allows seeds to fall into voids or to be washed by rain or irrigations to greater depths (Trouse, 1972).

The number of marketable carrots was unchanged by zone tillage but the weight was increased. Therefore the number one carrots in the zone tillage treatments must weigh more than those under conventional tillage. The increased weight came from an increase in length of carrot. Previous research has shown a decrease in root growth with an increase in soil strength (Eavis, 1972; Taylor, 1964). Work on cotton by Taylor (1966) showed a decrease in tap root penetration of the soil with increasing soil strength. The increase in carrot length in the zone tillage treatments can be attributed to a decrease in soil strength. These findings are similar to those of Strandberg and White (1979) that found thicker more branched and convoluted carrot taproots with higher soil strengths. They determined that taproot growth decreased because of high soil strength and not oxygen stress.

An increase in cull carrots in 1989 was due to flooded conditions early in root growth. The water was not injurous to the roots but rather the oxygen deficiency that accompanies it (Williamson and Kriz, 1970). Low oxygen affects root growth by reducing respiration of the root (Harris and Van Bavel, 1957). The severity of anoxic conditions depends on the plant (Williamson, 1964). Long term exposure to oxygen limiting conditions can result in death of cells and roots (Williamson and Kriz, 1970). The increase in cull carrots under flooded conditions is similar to the results of White and Strandberg (1979). They found that early tap root growth can be severely reduced by short periods of exposure to a saturated environment. Exposure to water saturated conditions induced branching and discoloration of root tips as soon as 6 days after germination with as little as 12 hours of saturated conditions. Height of carrot tops was unaffected. They determined that the branching was due to low oxygen contents brought on by saturated conditions. Since marketable carrot yields were increased by the use of zone tillage the zone tillage treatments must have had better Ksat. The better drainage allowed for a higher oxygen diffusion rate which allowed for better tap root growth.

Onion tillage yield in 1988 tended to increase with decreasing soil strength. There was no significant reduction in stand count with decreasing soil strength in 1988. This would suggest that a decreased soil strength makes for a more favorable rooting environment that increases yield. Due to heavy thrip damage in 1988 and floods in 1989 it is difficult to determine the effects of zone tillage on onion growth.

Summary

Soil Strength

Zone tillage decreased soil strength over all depths. The Tye Paratill tends to lower soil strengths more than the Bushhog Rotill but the differences are not always statistically significant. Plowing reduced the effectiveness of rotilling in reducing soil strength. Rotilling was not as effective in reducing soil strengths throughout the 0-40 cm profile after plowing as in non-plowed soil. Plowing before the use of the paratill did not affect reduction in soil strength. Rolling after paratilling gave a non significant increase in soil strength and increased emergence and plant population.

Plowing reduced soil strength throughout the soil profile relative to non tilled soil prior to paratilling and rotilling. In general, zone tillage gave some differences among the soil moisture contents at specific depths, however no trend developed.

Carrot Yields

Carrot emergence is decreased by the use of zone tillage. The paratill has lower germination than the rotill. Rolling after use of the paratill increased the stand slightly but the increase was not significant. The trend of fewer carrots continued through harvesting with fewer carrots harvested in the zone tillage treatments.

The total weight of carrots harvested was not significantly affected by zone tillage. Over two years the zone tillage tended to increase the total weight of harvested carrots. Only on September 1, 1988 however was the increase significant for the Rotill and Paratill plus roll treatments.

The weight of U.S. number one carrots harvested was increased with the zone tillage treatments both years. The number of number one carrots in 1988 was unaffected by treatment but more number one carrots were produced in 1989.

The amount and weight of small carrots produced can be affected by the tillage treatments. In 1989 there were no differences detected between treatments. In 1988 the number and weight of small carrots was reduced by zone tillage over the conventional tillage, plow plus disk plus rolling.

Tillage can affect carrot quality with differences in amount of culls between treatments. In 1988 there were no differences in the number or weight of culls produced although there was a trend for less produced by the use of the paratill. In 1989 the amount and weight of culls was significantly reduced by the use of zone tillage. Plowing before zone tillage reduced the amount of culls over zone tillage alone. The paratill+plow and rotill+plow produced the least amount of culls with the paratill+plow treatment being significantly lower than the conventional tillage and the unplowed zone tillage treatments.

Carrot length was increased by zone tillage. Significant differences were detected both years. This increase in length is responsible for maintaining the weight of carrots harvested while the number of carrots harvested was reduced.

Onion Yields

Results from the onion study are variable due to factors other than tillage severely affecting onion growth in both 1988 and 1989.

Yield data from 1988 shows a trend of increased onion stands and weight with rotilling and paratilling followed by rolling relative to conventional tillage. Paratill alone had a detrimental affect on onion stands although weights were about the same. Rotill only produced a higher number and weight of onions than the other treatments. Fewer onions per row foot usually results in larger onions but in this case a higher population produced a larger onion yield. Paratill plus rolling had the most onions in the <2" range. Weights of onions in the paratill only plots were increased although the stand was reduced. The lack of weight reduction could be due to larger onions from spacing or zone tillage.

1989 yield data showed decreasing weight and number of onions with decreasing soil strength. Plowing before zone tillage gave a larger reduction in weight and number of onions harvested. Heavy rains and flooding at germination is assumed to have contributed to this trend.

Conclusions

Zone tillage with the paratill and rotill units, of organic soil reduces soil strength over conventional tillage. The average soil strength from 0 to 40 cm is reduced as is soil strength at all depths. The paratill tends to be more effective in reducing soil strength although the reduction is not always significant. Zone tillage had no significant effect on soil moisture content.

Zone tillage did reduce the number of established carrots per foot of row. The loose soil provided for poor seed soil contact that decreased germination. The loose soil also has voids and cracks that may result in non-uniform depth of seed placement which reduces emergence.

The total weight of carrots harvested was unchanged by the use of zone tillage. The weight of marketable carrots was increased. The weight of cull carrots harvested can be reduced in a wet year but remains unchanged under normal conditions. Zone tillage allows for better drainage and aeration which reduces the effects of flooding.

The length of marketable carrots is increased with zone tillage. The decreased soil strength resulting from tillage allows for a longer carrot tap root.

Onion yield tended to increase with zone tillage in 1988. Due to heavy thrip damage in 1988 and flooding in 1989 few conclusions can be drawn on the effects of zone tillage on onion growth.

Literature cited

Eavis, B. W. 1972. Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam. Plant and Soil 36:613-622.

Erbach, D. C., R.M. Cruse, M. A. Elamin, S. Mukhatar, J. G. Benjamin and C. H. Choi. 1984. Soil Condition and corn growth response to paraplowing. A.S.A.E. Paper No. 84-1013. A.S.A.E. St. Joseph, Mi.

Harris, D. G. and C. H. M. Van Bavel. 1957. Root respiration of tobacco, corn and cotton plants. Agron. J. 49:182-184.

Hartmann, Hudson T. and Dale E. Kester. 1975. Plant Propogation, Principles and Practices. Third edition. Prentice Hall, Inc. Englewood Cliffs, N.J. p. 170.

Henry, J. E. and D. M. Van Doren. 1985. Progress report on the use of the paraplow. A.S.A.E. Paper No. 85-1011.

Kaddah. 1975. Subsoil chiseling and strip plowing effects on soil properties and wheat grown on a stratified fine sandy soil. Agron. J. 68:36-39.

Meyer, Bernard S., Donald B. Anderson and Richard H. Bohning. 1960. Introduction to Plant Physiology. D. Van Nostrand Company, Inc. Princeton, N.J. pp. 510-529.

Newman, E. I. 1966. A method of estimating the total length of a root sample. J. appl. Ecol. 3:139-145.

Olymbios, C. M. and W. W. Schwabe. 1977. Effects of aeration and soil compaction on growth of the carrot, Daucus carota l. J. of Hort. Sci. 52:485-500.

Strandberg, J. O. and J. M. White. 1979. Effect of soil compaction on carrot roots. J. Amer. Soc. Hort. Sci. 104(3):344-349.

Taylor, H. M., L.F. Locke, and J. E. Box. 1964. Pans in southern Great Plains soils: III. Their effects on yield of cotton and grain sorghum. Agron. J. 56:542-545.

Taylor, Howard M., Gene M. Roberson, Jesse J. Parker Jr. 1966. Soil strength-root penetration relations for medium to coarse textured soils. Soil Sci. 102:18-22.

Tennant, D. 1975. A test of a modified line intersect method of estimating root length. J. of Ecol. 63:995-1001

Trouse, A. C. 1972. In K.K. Barnes et. al. Compaction of Agricultural Soils. Am. Soc. Agric. Eng., St. Joseph, MI. pp. 244-249

White, J. M. and J. O. Strandberg. 1979. Physical factors affecting carrot root growth: Water saturation of soil. J. Amer. Soc. Hort. Sci. 104(3):414-416.

Williamson, R. E. 1964. The effect of root aeration on plant growth. Soil Sci. Amer. Proc. 28:86-90.

Williamson, R. E. and George J. Kriz. 1970. Response of agricultural crops to flooding, depth of water table and soil gaseous composition. Trans. of the ASAE 13(2):216-220.

CARROT AND ONION COMPACTION STUDIES

Introduction

Compaction has been shown to affect plant growth and occur on a wide range of soil types. It has been shown to reduce the height of cotton and slow the growth of sorghum (Taylor and Locke, 1964), decrease yield and quality of potatoes (Flocker et al., 1960) and impede the growth of sunflower roots (Veihmeyer and Hendrickson, 1948). Compaction to the point that it affects plant growth has been shown to occur on clays, clay loams and loamy sand (Veimeyer and Hendrickson, 1948), medium to coarse textured soils (Taylor et al., 1966) and organic soils (Strandberg and White, 1979).

High soil strength affects roots by reducing root penetration and growth (Taylor et al. 1966). Strandberg and White (1979) have shown that soil strength can affect both growth of young taproots and the size, weight and shape of mature carrots. Carrots grown at higher soil strengths tended to be thicker, convoluted and more branched. Taksdal (1984) showed that increasing compaction of a mineral soil reduced yield of marketable carrots. Reducing root growth would affect growth of onions. Onions are shallow rooted and have no taproot. Reduced root growth would limit the plants ability to withstand moisture stress.

In this study a cement roller was used to artificially compact a Houghton muck. Carrot and onions were grown with increasing levels of compaction. The purpose of this study was to 1) measure the effects of compaction on onion and carrot growth and 2) measure the effects of compaction on soil physical properties.

Materials and Methods

This experiment was conducted in 1989 at the M.S.U. Muck Research Center located in Bath, MI. The soil at the experimental site is a Houghton muck (Euic, Mesic, Typic, Medisaprist) and is tiled drained.

The four treatments used for carrots and onions were 1) moldboard plowing followed by disking and rolling with a light weight roller (PDR). 2) moldboard plowing, disking and 2 passes with a heavy cement roller (2R). 3) moldboard plowing, disking and 5 passes with a cement roller (5R) and 4) a previously heavily trafficked alleyway which was plowed, disked and rolled (AW). Fertilizer was drilled in accordance to soil test recommendations. Prowl and Ramrod were used pre-emergence on the onions followed by post-emergence applications of Goal, Fusilade, Furloe, Buctril, and Dual as needed at recommended rates. Furloe and Lorox were used pre-emergence on carrots with post-emergence applications of Fusilade, Stoddard Solvent and Lorox at recommended rates as needed. <u>Daucus carota</u> var. Vitagold and <u>Allium cepa</u> var. Northern Oak were seeded with a Gaspardo seeder in 3 row groupings 42 inches (106.7 cm) wide and 18 inches (45.7 cm) between rows on May 22, 1989.

The experimental design was a completely randomized design with each treatment repeated three times. Analysis of variance was used to detect significant differences between treatments. Duncan's multiple range test was used to separate the treatment means.

An Eijeklamp recording cone penetrometer was used to measure soil strength (Suaze Technical Products Corp., 345 Cornelia Street, Plattsburgh, NY 12901). The largest of tips 1, 2, 3 and 4 (1 cm^2, 2 cm^2, 3.5 cm^2 and 5 cm^2) were used depending on which tip allowed for the probe to be pushed through the soil with even amounts of pressure. Soil strength was measured on May 24 and August 8 for the onions and August 11 for the carrots. Four readings per treatment were taken for all treatments. Moisture samples were taken at depths of 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm for each plot. Moisture contents, in addition to the soil penetrometer samples, were measured on all treatments for the carrots on 6/26. These samples were oven dried at 90 C for 48 hours and the gravimetric moisture contents were determined. The soil strengths were analyzed for 5, 10, 15, 20, 25, 30, 35, and 40 cm depths.

Carrot roots were sampled in September 1989 with a square 10.16 cm by 10.16 cm at depths of 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm. The soil was soaked in a 5% Calgon and 0.8% NaOH solution to disperse the organic matter prior to the extraction of the roots. To separate the roots the soil solution was poured onto a no. 80 sieve and was gently rinsed with water. After the soil was rinsed it was washed back into a beaker. The roots along with some debris floated and was decanted onto a 425 mesh screen. The debris was gently rinsed leaving the roots and a small quantity of debris on the screen. This process was repeated several times until all the roots were extracted from the sample. The root length was estimated using the line intercept method of Newman (1966) revised by Tennant (1975).

Ten onion plants per plot were harvested July 18. Plant measurements of top fresh and dry weights and leaf area were taken. The roots were removed with the plant and those still attached were gently washed off and the length was determined using the Tennant method.

Carrots were harvested September 13 (45 feet of row). The weight and number of total, number 1 (shoulder width between 0.5 and 1.5 inches, length > 5 inches), jumbo (shoulder width 1.5 inches), small (shoulder width < 0/5 inches, length less than 5 inches) and cull carrots (forks, stubs and splits) were recorded. The length and diameter of 20 number one carrots for each treatment was measured.

Results

Carrots

Soil Strength and Moisture

Averaged over all depths, treatment did not have any affect on soil strength (Table 29). The AW treatment had the highest average soil strength with 12.65 MPa but this was not significantly greater than the other treatments.

Although soil strength tended to increase with the number of passes with the roller, there were no other significant differences between treatments at all depths analyzed (Table 29).

Table 29. Effect of compaction treatment on soil strength 8-11-89.

	Compaction treatment[y]				
Depth	PDR	2R	5R	AW	CV
cm	MPa				
5	8.26 a[z]	7.76 a	10.83 a	10.46 a	23
10	9.68 a	11.71 a	12.39 a	12.12 a	20
15	9.28 a	11.43 a	11.79 a	11.28 a	20
20	8.89 a	11.48 a	10.71 a	10.40 a	20
25	9.07 a	9.78 a	9.90 a	11.45 a	18
30	10.87 b	11.17 ab	10.91 ab	14.18 a	15
35	13.19 a	15.54 a	13.16 a	15.24 a	16
40	13.94 a	16.21 a	14.90 a	16.05 a	15
Avg.	10.40 a	11.89 a	11.85 a	12.65 a	15

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a line followed by the same letter are not significant (P = 0.05).

There were no significant differences in soil moisture content between treatments at any of the depths analyzed on June 26 and August 11 (Table 30).

Table 30. Effect of compaction on gravimetric moisture content.

Depth	Compaction treatment[Y]	Moisture 8-11-89	Moisture 6-26-89
cm		%	%
0-10	PDR	164.0 a[Z]	186.3 a
	2 Rolls	163.6 a	184.3 a
	5 Rolls	161.3 a	182.3 a
	Alley Way	164.3 a	192.6 a
	CV	5	5
10-20	PDR	181.0 a	190.6 a
	2 Rolls	173.3 a	188.0 a
	5 Rolls	176.3 a	194.3 a
	Alley Way	170.3 a	192.0 a
	CV	4	5
20-30	PDR	191.0 a	180.0 a
	2 Rolls	181.3 a	191.6 a
	5 Rolls	182.0 a	194.6 a
	Alley Way	179.6 a	195.3 a
	CV	6	12
30-40	PDR	201.0 a	213.6 a
	2 Rolls	219.3 a	211.6 a
	5 Rolls	224.3 a	206.6 a
	Alley Way	209.6 a	194.3 a
	CV	25	8

[Y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[Z] Values within a column followed by the same letter are significant (P = 0.05).

Yields

The 2R treatment had the largest number of carrots harvested with 66 carrots/3 meters (Table 31). The 5R treatment with 31 carrots, was significantly less than 2R. There were no significant differences between PDR, 2R and AW or PDR, 5R and AW in total number of carrots harvested.

The AW treatment had the least total weight in Mg/HA harvested with 14.1 (Table 32). The AW and 5R treatments significantly decreased Mg of carrots harvested compared to 2R. There was no significant difference in total carrot yield between PDR, 5R and AW; or between PDR and 2R.

The 5R and AW treatments significantly reduced the number and weight of #1 carrots harvested from 12 carrots/3 meters and 7.3 Mg/Ha for the PDR plots to 4 carrots and 2.8 and 2.2 Mg (Tables 31 and 32). There were no significant differences between PDR and 2R; or between all of the compaction treatments in weight and number of carrots harvested (Tables 31 and 32). Percent of marketable carrots was decreased by compaction treatment although the difference was not significant (Tables 33 and 34).

The PDR treatment produced the highest number and weight of jumbo carrots with 1.5 carrots/3 meters and 1.9 Mg/HA (Tables 31 and 32). The 2R and 5R treatments resulted in significantly fewer number of jumbo carrots, 0.5 and 0.2 per 3 meters. The AW treatment with 0.6 jumbo carrots/3 meters was not significantly different than the other treatments. The total weight of jumbo carrots harvested was significantly reduced by the compaction treatments to 0.7, 0.4 and 0.8 Mg/HA for 2R, 5R and AW.

Table 31. Effect of compaction on number of carrots harvested, September 13, 1989.

Tillage treatment[y]	Yield				
	Total	#1	Jumbo	Small	Cull
	Carrots/3 meters				
PDR	51 ab[z]	12 a	1.5 a	4 a	33 a
2R	66 a	8 ab	0.5 b	4 a	53 a
5R	31 b	4 b	0.2 b	1 a	25 a
AW	36 ab	4 b	0.6 ab	1 a	30 a
CV	35	51	71	62	45

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

Table 32. Effect of compaction on carrot yield 9-13-89.

Tillage treatment[y]	Yield				
	Total	#1	Jumbo	Small	Cull
	Mg/HA				
PDR	24.7 ab[z]	7.3 a	1.8 a	1.5 a	13.9 ab
2R	33.2 a	4.7 ab	0.7 b	1.9 a	25.9 a
5R	14.9 b	2.8 b	0.4 b	0.6 a	11.2 b
AW	14.1 b	2.2 b	0.8 b	0.7 a	10.3 b
CV	32	47	49	57	48

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

Percent jumbos by count had the same differences as by absolute number with 2R and 5R significantly smaller than PDR (Table 33). Percent jumbo carrots by weight was slightly different with PDR and AW significantly greater than 2R and 5R (Table 34).

There were no significant differences between treatments in number or weight of smalls harvested (Tables 31 and 32).

The 2R treatment had the most small carrots with 4/3 meters weighing 1.9 Mg/HA. The PDR treatment also had 4 carrots/3 meters weighing 1.5 Mg/HA. The 5R and AW treatments were much less with 1 carrot/3 meters weighing 0.6 and 0.7 Mg/HA. No differences in percent small carrots by count or weight were detected (Tables 33 and 34).

Treatments 5R and AW significantly reduced Mg/HA of cull carrots harvested over 2R from 25.9 to 11.2 and 10.3 (Table 32). However, no difference in percent culls was detected (Table 34). There were no significant differences in Mg of cull carrots harvested between PDR and 2R; or PDR, 5R, and AW (Table 32). No significant differences in number of cull carrots harvested were detected between treatments.

Table 33. Effect of compaction on carrot yield, percent by count, September 13, 1989.

Tillage treatment[y]	Yield			
	#1	Jumbo	Small	Cull
	- - - - - - - - Percent	- - - - - - - -		
PDR	24.6 a[z]	3.0 a	7.9 a	64.3 a
2R	12.6 a	0.6 a	7.2 a	79.4 a
5R	14.7 a	0.1 b	4.1 a	80.3 a
AW	12.9 a	1.7 ab	4.8 a	80.5 a
CV	49	59	58	12

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

Table 34. Effect of compaction on carrot yield percent by weight, September 13, 1989.

Tillage treatment[y]	Yield			
	#1	Jumbo	Small	Cull
	- - - - - - - percent	- - - - - - -		
PDR	30.2 a[z]	7.3 a	6.4 a	55.9 a
2R	15.1 a	2.2 b	5.8 a	76.6 a
5R	19.9 a	2.7 b	4.4 a	72.8 a
AW	18.1 a	5.8 a	5.1 a	70.8 a
CV	48	33	55	16

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

The PDR treatment had the longest carrot length with 19.1 cm (Table 35). The 5R treatment was second with an average of 18.7 cm. Treatments 2R and AW were significantly reduced to 16.1 and 15.9 cm. Average width of number one carrots and the length/width ratio was unaffected by treatment.

Table 35. Effect of compaction on carrot root size.

Tillage treatment[y]	Length	Width	Length/Width
	cm	cm	
PDR	19.1 a[z]	3.3 a	5.7 a
2R	16.1 b	3.4 a	4.7 a
5R	18.7 a	3.4 a	5.4 a
AW	15.9 b	3.3 a	4.7 a
CV	8	6	12

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

There were no significant differences in carrot root length density at any depth sampled (Table 36). Root length density tended to decrease with depth. The PDR and AW treatments had over twice as many roots in the top 10 cm than 2R and 5R. The 2R treatment had half as many roots at the 10 to 20 cm depth than the other treatments. At the 20 to 30 cm depth PDR and 2R had over twice as many roots as 5R and AW. At the 30 to 40 cm range root length densities were nearly the same.

Table 36. Effect of compaction on carrot root length density.

Tillage treatment[y]	Depth			
	0-10	10-20	20-30	30-40
	cm/cm^3			
PDR	1.69 a[z]	0.29 a	0.15 a	0.04 a
2R	0.54 a	0.12 a	0.14 a	0.05 a
5R	0.70 a	0.30 a	0.07 a	0.07 a
AW	1.42 a	0.27 a	0.04 a	0.04 a
CV	94	72	95	129

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

There were no significant differences in carrot root or top fresh and dry weights sampled July 10, 1989 (Table 37).

Table 37. Effect of compaction on carrot plant growth.

Tillage treatment[y]	Fresh weight Tops	Fresh weight Roots	Dry weight Tops	Dry weight Roots
	grams			
PDR	35.3 a[z]	15.0 a	5.9 a	1.6 a
2R	35.2 a	14.0 a	6.0 a	1.7 a
5R	35.9 a	13.7 a	6.3 a	1.8 a
AW	25.4 a	9.3 a	4.9 a	1.2 a
CV	21	33	18	31

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

Onions

Soil Strength and Moisture

The onion soil strength results were similar to those of the carrots with the AW having a significantly higher soil strength than the PDR, 2R and 5R when averaged over all depths on May 24 (Table 38). The AW treatment had an average soil strength of 13.02 MPa while PDR, 2R and 5R treatments had average soil strengths of 11.39, 10.94, and 10.46 MPa respectively.

On May 24 there were no significant differences in soil strengths between treatments at the 5, 10, 15, 30 and 35 cm depths (Table 38). Soil strength in the 2R plots was significantly less than in 5R plots at depths of 20 and 25 cm. The PDR treatment was significantly less than 5R at 20 cm. Soil strength in the PDR treatment was significantly less than all compaction treatments at 40 cm.

Averaged over all depths there were no significant differences in soil strength between treatments on August 9 (Table 39). The PDR treatment had the lowest soil strength with 10.40 MPa and the AW treatment had the highest soil strength with 12.65 MPa.

The AW treatment had significantly greater soil strengths than 2R and 5R at depths of 5, 10, 15 and 20 cm on August 9, 1989 (Table 39). Soil strength in the 5R plots was significantly less than in the AW plots at a depth of 25 cm. Soil strength in the PDR treatment was significantly less than AW at 30 cm. The 5R plots had significantly lower soil strength than PDR at the 10 and 15cm depths.

Table 38. Effect of compaction on soil strength in onions, May 24, 1989.

Depth	Compaction treatment[y]				
	PDR	2R	5R	AW	CV
cm	MPa				
5	8.41 a[z]	8.62 a	11.19 a	9.44 a	19
10	10.32 a	9.28 a	11.84 a	11.20 a	13
15	9.62 ab	9.48 a	12.05 a	10.96 a	12
20	9.89 b	9.20 b	12.18 a	10.76 ab	11
25	11.15 ab	10.91 b	13.16 a	12.11 ab	9
30	13.84 a	12.93 a	15.34 a	14.92 a	12
35	15.27 a	15.39 a	18.02 a	17.26 a	11
40	15.93 b	18.27 a	19.66 a	18.71 a	6
Avg.	11.80 a	11.76 a	14.18 a	13.17 a	17

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.

[z] Values within a line followed by the same letter are not significant (P = 0.05).

Table 39. Effect of compaction on soil strength in onions August 9, 1989.

	Compaction treatment[y]				
Depth	PDR	2R	5R	AW	CV
cm	MPa				
5	8.08 ab[z]	6.92 b	5.95 b	10.14 a	21
10	10.76 ab	9.20 bc	8.26 c	11.81 a	12
15	10.80 ab	9.66 bc	8.43 c	12.13 a	12
20	10.25 ab	9.33 b	8.69 b	11.83 a	11
25	9.87 ab	9.51 ab	9.32 b	11.31 a	10
30	11.34 b	11.96 ab	12.32 ab	13.35 a	7
35	14.23 a	14.77 a	14.61 a	16.16 a	10
40	15.76 a	16.22 a	16.11 a	17.40 a	8
Avg.	11.39 a	10.94 a	10.46 a	1302 b	5

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.

[z] Values within a line followed by the same letter are not significant (P = 0.05).

There were no significant differences in gravimetric moisture contents between treatments on May 24 (Table 40). On August 9 gravimetric soil moisture content in AW was significantly lower than all other treatments at the 0-10 cm depth. Soil moisture in the PDR plots was significantly less than in the 5R plots and the AW plots were significantly lower in soil moisture than all other treatments at the 10-20 cm depth. There were no significant differences between treatments at the 20-30 cm depth. Soil moistures in PDR plots were significantly less than in 5R plots, and AW moisture was significantly less than in the 2R and 5R plots at the 30-40 cm depth.

Table 40. Effect of compaction on gravimetric soil moisture contents.

Depth	Compaction treatment[y]	Moisture 5-24-89	Moisture 8-9-89
cm		%	%
0-10	PDR	185.0 a[z]	179.6 a
	2R	184.5 a	182.3 a
	5R	180.0 a	177.3 a
	AW	175.0 a	163.0 b
	CV	5	2
10-20	PDR	183.5 a	188.3 b
	2R	183.0 a	191.3 ab
	5R	189.0 a	194.0 a
	AW	163.0 a	170.3 c
	CV	4	2
20-30	PDR	181.0 a	195.3 a
	2R	186.5 a	193.6 a
	5R	184.5 a	213.0 a
	AW	180.0 a	196.0 a
	CV	4	6
30-40	PDR	191.0 a	218.3 bc
	2R	216.0 a	235.0 ab
	5R	192.5 a	254.6 a
	AW	205.0 a	198.0 c
	CV	7	5

[y] PDR = plow-disk-roll; 2R = 2 rolls; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

Plant Measurements

Onion plant growth was affected by compaction treatment (Table 41). Plant fresh and dry weights were reduced with increasing compaction. The PDR plots averaged 63.3 gms fresh weight while 5R was 28.2 gms and AW averaged 12.0 gms. Leaf area was significantly reduced with compaction treatment. The 5R treatment significantly reduced leaf area from 666.6 cm^2

to 304.6 cm^2. The AW treatment had a significantly lower leaf area over all treatments with 133.3 cm^2. The AW treatment also significantly reduced root length from 979.0 cm to 561.3 cm. The 5R treatment at 760.3 cm was not significantly different from the other treatments.

Table 41. Effects of compaction on onion plant growth July 18, 1989.

Tillage treatment[y]	Fresh weight	Dry weight	Leaf area	Root length
	------ 10 plants	---------	---------	---------
	gms	gms	cm^2	cm
PDR	63.7 a[z]	5.3 a	666.6 a	979.0 a
5R	28.2 b	2.8 b	304.6 b	760.3 ab
AW	12.0 c	1.2 c	133.3 c	561.3 b
CV	20.3	21	11	24

[y] PDR = plow-disk-roll; 5R = 5 rolls; AW = alley way.
[z] Values within a column followed by the same letter are significant (P = 0.05).

Discussion

Carrot yield tended to decrease and carrot length significantly decreased with increasing soil strength. These results agree with the results of Taksdal (1984) who found a reduction in yield of marketable carrots with increasing compaction of a mineral soil. As in the tillage study, the reduction in yield and length can be attributed to an increase in soil strength and reduction in oxygen in the root zone. This would agree with the results of Olymbios and Schwabe (1977) who found that a reduction in taproot weight in compacted soils was due to the combined affects of lowered aeration and increased mechanical pressure.

Onions had reduced plant size with increasing compaction. Onion top growth was affected by adversly changing the root environment. Schuurman (1965) found reduced root growth in oats due to compaction reduced top growth by limiting uptake of water and nutrients. The reduction of plant growth with increasing compaction agrees with the results of Flocker (1960) with potatoes, Taylor (1964) with cotton and grain sorghum and Doty et al. (1975) with millet and sweet corn.

Summary

Soil strength tended to increase in the top 25 cm with the number of heavy roller passes. The previous alley way had the highest soil strength of all the treatments.

Quality of carrots was affected by compaction treatment. The total number and weight of carrots was reduced by compaction. Number one carrots were reduced significantly both in number and weight harvested. Number and weight of culls were not affected.

Onion growth was noticeably affected by compaction. Since the stand was too thin to harvest, no yield data was taken. Plant measurements taken earlier in the season showed a dramatic reduction in plant size, leaf area and root length with increases in compaction.

Conclusions

Carrot length is decreased with increased compaction. Increased soil strength and decreased drainage and aeration cause a reduction in carrot tap root growth. Due to the reduction in carrot size, total and marketable yield of carrots is reduced.

Onion growth is reduced with increasing compaction. Compaction increases soil strength and decreases aeration which causes a reduction in top weight, leaf area and root length.

LITERATURE CITED

Doty, Coy W., Robert B. Campbell and Donald C. Reicosky. 1975. Crop response to chiseling and irrigation in soils with a compact A 2 horizon. Trans. Am. Soc. Agric. Eng. 18:668-672.

Flocker, W.J., H. Timm and J. A. Vomocil. 1960. Effect of soil compaction on tomato and potato yields. Agron. J. 52:345-348.

Newman, E. I. 1966. A method of estimating the total length of a root sample. J. appl. Ecol. 3:139-145.

Olymbios, C. M. and W. W. Schwabe. 1977. Effects of aeration and soil compaction on growth of the carrot, Daucus carota l. J. of Hort. Sci. 52:485-500.

Schuurman, J. J. 1965. Influence of soil density on root development and growth of oats. Plant and Soil 22:352-374.

Strandberg, J. O. and J. M. White. 1979. Effect of soil compaction on carrot roots. J. Amer. Soc. Hort. Sci. 104(3):344-349.

Taksdal, G. 1984. Effects of tractor wheelings on carrot quality. Acta Hort. 163:255-260.

Taylor, H. M., L.F. Locke, and J. E. Box. 1964. Pans in southern Great Plains soils: III. Their effects on yield of cotton and grain sorghum. Agron. J. 56:542-545.

Taylor, Howard M., Gene M. Roberson, Jesse J. Parker Jr. 1966. Soil strength-root penetration relations for medium to coarse textured soils. Soil Sci. 102:18-22.

Tennant, D. 1975. A test of a modified line intersect method of estimating root length. J. of Ecol. 63:995-1001

Veihmeyer, F. J. and A. H. Hendrickson. 1948. Soil density and root penetration. Soil Sci. 65:487-493.

CARROT AND ONION GREENHOUSE EXPERIMENTS

Introduction

Seedling growth is affected by soil compaction. A study by Unger and Danielson (1965) indicated that a reduced supply of oxygen may be responsible for reduced growth of young corn plants under poorly aerated conditions. Asady et al. (1985) found root lengths of edible bean seedlings declined with decreasing air filled porosity. White and Strandberg (1979) in a study on carrot seedlings found that many physical and biological factors that cause defects in mature carrots act within 24 days of germination.

In this study polyvinyl chloride cylinders were filled with muck and marl soils with varying degrees of compaction and moisture contents. Carrot and onion seedlings were grown in the cylinders. The objectives of this study were to 1) determine carrot and onion seedling response to compacted layers and 2) determine carrot and onion seedling response to different soil moisture contents.

Materials and Methods

Polyvinyl chloride cylinders with an inside diameter of 7.6 cm and a wall thickness of 0.64 cm were used to make soil containers of three stacked cores as in the proceedure described by Asady et al. (1985). Each three layered container consisted of top and middle cores that were 2.5 cm in height and a bottom core that was 7.6 cm in height. The cores were filled with a Houghton muck (Euic, Mesic, Typic Medisaprist). The soil was passed through a no. 10 sieve prior to filling the cores. The soil was compressed into the cores with a piston (7.6 cm diameter) attached to a hydraulic press (Carver type, model 20505-11). Bulk densities of 0.25, 0.35, and 0.45 g/cm^3 (LBD, MBD and HBD) were established by pressing the specified quantity of soil into the middle core. Compacted cores with the specified bulk densities were placed between the top and bottom cores that had bulk densities of 0.35 g/cm^3. The cores were sealed together into one air and water tight container by wrapping them with duct tape. The cores were saturated over night, drained and planted with 9 carrots <u>Daucus carota</u>, Six Pak II February 3, 1989 and <u>Allium cepa</u> var. Spartan Banner March 29 1989. The cores were weighed daily and the moisture contents were kept constant. The plants were grown in a greenhouse in a randomized complete block design with 4 replications. Duncan's multiple range test was used to seperate and rank treatment means.

Carrots were thinned to 3 plants per core 21 days after seeding. They were harvested 41 days after seeding and plant measurements of root length density in the treatment core and taproot length were taken. Root lengths were estimated using the Newman method (1966) as revised by Tennant (1975). The roots were extracted by sieving the soil through a No. 10 sieve and removing the roots with tweezers. Roots growing along the container wall were discarded prior to sieving.

Onions were thinned to 4 plants per core 16 days after seeding. Five hundred mls of a 1% nitrogen solution were added 27 and 28 days after seeding. Plants were harvested 38 days after seeding and plant measurements of top fresh weight, root penetration ratios (number of roots leaving the treatment core divided by the number of roots entering) and root length densities in each core were taken. The root penetration ratio was determined for the center 20.3 cm^2 of the middle core to eliminate roots growing along the container sidewalls. Root lengths were determined as previously described.

Carrot and onion experiments were done in 1990 using a marl soil (martisco, fine-silty carbonic, mesic histic Humaquept) with a 14 % organic matter content. The proceedure was the same as in 1989 with the exception of the middle treatment cores packed to bulk densities of 0.9, 1.1 and 1.3 g/cm^3 (LD, MD, and HD). Field capacity of the middle treatment core was determined to be 59.8% gravimetric at a bulk density of 1.1 g/cm^3. The cores were allowed to reach gravimetric moisture contents of 25, 30, and 35 percent (LM, MM, and HM) for each of the three bulk densities. Onion variety Spartan Banner was seeded December 14, 1989 and carrot variety Six Pak II was seeded April 3, 1990.

The onions were thinned down to 4 plants per core 20 days after seeding. Ten ml of a 200 ppm N solution as $CaNO_3$ was added 31, 33, 46, and 47 days after seeding. Zinc and Mg was applied foliarly using a mister spray bottle 42, 45, and 49 days after seeding with 100 ppm Mn as $MnSO_4$ and 50ppm Zn as $ZnSO_4$.

Carrots were thinned to 4 plants per container 12 days after seeding. Ten ml of a 200 ppm N solution from a 20-20-20 fertilizer was added to each core 27 days after seeding.

The onions were harvested 65 days after germination. Plant measurements of leaf area, root length, and shoot fresh and dry weights were taken. Soil strength was measured for each core using a spring loaded penetrometer. Root lengths were estimated as previously described.

Carrots were harvested 38 days after seeding. Plant measurements of leaf area, shoot fresh and dry weight, root length and diameter of the tap root in the middle core were taken. Soil strength and root lengths were measured as in the onion study.

Results

Houghton Muck

Carrots

Root length in the treatment core decreased with increasing bulk densities (Table 42). The low bulk density treatment had the largest root length density with 4.0 cm/cm^3. This was significantly larger than the high bulk density treatment with 2.5 cm/cm^3. The middle bulk density treatment had a density of 3.8 cm/cm^3 and was not significantly different than either of the two other treatments.

Average tap root length significantly decreased with 0.45 g/cm^3 bulk density (Table 42). The average length with the low bulk density tap root was 7.7 cm and the middle bulk density was 8.1 cm. Both of these were significantly larger than the 0.45 g/cm^3 treatment which had a 4.8 cm average tap root length.

Carrot top growth decreased with 0.45 grams\cm^3 bulk density although the decrease was not statistically significant (Table 42).

Table 42. Compaction affect on carrot plant measurements March 16, 1989.

Tmt[y]	Root length density	Tap root length	Dry wt. tops
	cm/cm^3	cm	grams
LBD	4.0 a[z]	7.7 a	0.56 a
MBD	3.8 ab	8.1 a	0.55 a
HBD	2.5 b	4.8 b	0.45 a
CV	23	12	31

[y] LBD = 0.25 gms/cm^3 bulk density; MBD = 0.35 gms/cm^3 bulk density; HBD = 0.45 gms/cm^3 bulk density.
[z] Values within a column followed by different letters are significant (P = 0.05).

Onions

No differences in plant weight were detected between the bulk density treatments at the .05 level (Table 43). The low bulk density treatment produced the least plant growth with tops weighing 5.6 gms and the middle (0.35 g/cm^3) bulk density treatment produced the most, 6.6 grams.

The root penetration ratio (RPR) decreased with increasing bulk density in the middle core (Table 43). The low bulk density resulted in a ratio of 0.60 which was significantly greater than the 0.34 with the high bulk density. The RPR of 0.49 with the middle bulk density was not significantly different than either of the other two ratios.

Root length densities in the top core increased with increasing bulk density of the treatment core (Table 43). The low bulk density treatment with 1.0 cm/cm^3 was significantly lower than HBD (0.45 g/cm^3) with 1.8. The middle bulk density treatment with a root length density of 1.5 cm/cm^3 was not significantly different than the other treatments. No differences were detected between treatments in the middle and bottom cores or total root length densities although the lowest bulk density produced the lowest root density.

Table 43. Compaction affects on onion growth, 5-16-89.

Tmt[x]	FR. wT.	RPR[y]	Root length density Top	Middle	Bottom	Total
	grams		- - - - - -	cm/cm^3	- - - - -	
LBD	5.6 a[z]	0.60 a	1.0 b	1.2 a	1.2 a	1.2 a
MBD	6.6 a	0.49 ab	1.5 a	1.9 a	1.6 a	1.6 a
HBD	6.2 a	0.34 b	1.8 a	1.7 a	1.1 a	1.3 a
CV	33	34	29	73	26	25

[x] LBD = 0.25 gms/cm^3 bulk density; MBD = 0.35 gms/cm^3 bulk density; HBD = 0.45 gms/cm^3 bulk density.
[y] Root Penetration Ratio.
[z] Values within a column followed by different letters are significant (P = 0.05).

Marl Soil

Onions

Soil Strength

There were no significant differences in soil strengths in the top core between treatments (Table 44).

In the treatment core, the 0.9 g/cm^3 bulk densities had lower soil strengths than the 1.1 g/cm^3 bulk density cores (Table 44). The 1.3 g/cm^3 bulk density cores had the highest soil strengths. All the 0.9 g/cm^3 bulk density treatments were significantly greater in soil strength than the 1.3 g/cm^3 bulk density treatments. The 1.1 g/cm^3 bulk density values were in between the low and high bulk density values. Soil strength in the MMMD treatment was significantly greater than the 0.9 g/cm^3 treatments. All 1.1 g/cm^3 treatments were significantly less than LMHD; and HMMD was significantly lower than all high bulk density treatments. There were no significant differences within the density treatments.

The soil strengths in the bottom cores decreased with increasing moisture levels (Table 44). All 25 percent moisture levels were significantly greater than the 35 percent moisture treatments. The 30 percent moisture treatments were not significantly different than either the high or low moisture levels except for HMMD which was significantly lower than all 30 percent moisture treatments.

Table 44. Affect of bulk density and moisture content on soil strength of a martisco marl soil, 2-17-90

Tmt[y]	Soil Strength					
	Top core		Middle core		Bottom core	
	- - - - - - - -MPa - - - - - - - - - - - -					
LMLD	5.820	a[z]	3.686	de	11.270	a
MMLD	5.188	a	3.890	de	9.656	abc
HMLD	5.404	a	3.315	e	8.503	bcd
LMMD	4.667	a	6.377	bcd	11.462	a
MMMD	6.485	a	7.757	bc	9.368	abc
HMMD	3.603	a	5.189	cde	7.062	d
LMHD	3.819	a	10.808	a	10.670	ab
MMHD	6.399	a	9.079	ab	9.367	abcd
HMHD	5.404	a	8.791	ab	7.907	cd
CV	33		26		16	

[y] LMLD = 25% moisture, 0.25 g/cm^3 bulk density; LMMD = 25% moisture, 0.35 g/cm^3 bulk density; LMHD = 25% moisture, 0.45 g/cm^3 bulk density; MMLD = 30% moisture, 0.25g/cm^3 bulk density; MMMD = 30% moisture, 0.35 g/cm^3 bulk density; MMHD = 30% moisture, 0.45 g/cm^3 bulk density; HMLD = 35% moisture, 0.25 g/cm^3 bulk density; HMMD = 35% moisture, 0.35 g/cm^3 bulk density; HMHD = 35% moisture, 0.45 g/cm^3 bulk density.

[z] Values within a column followed by different letters are significant (P = 0.05).

Root Length Density

The LMMD treatment had the highest root length density in the top core with 1.30 cm/cm^3 (Table 45). Root length density was significantly greater with LMMD than with any of the other treatments except LMHD, MMLD, MMMD and HMMD. The low moisture treatments tended to have larger root length densities than the middle moisture treatments which were larger than the high moisture treatments. There were no significant differences between the 30 and 35 percent moisture treatments and LMLS.

Root length densities in the middle core decreased with increasing moisture (Table 45). The LMMD treatment produced the largest RLD in the middle core with 1.0 cm/cm^3 and was significantly larger than all of the middle moisture treatments. There were no significant differences within the low and middle moisture treatments across soil density. The high moisture treatments had the smallest root length densities. Within the high moisture treatments, the 1.1 g/cm^3 bulk density RLD was significantly higher than in both the 0.9g/cm^3 and 1.3g/cm^3 bulk density cores. The 1.1 g/cm^3 bulk density cores always had the largest RLD in the middle core but only in the high moisture treatment was the difference significant.

The RLD of the bottom core was greatest for the low strength treatments (Table 45). The high bulk density treatments had the lowest RLD. The LMLD core had the highest

RLD with 0.4 cm/cm^3 which was significantly greater than all other treatments except HMLS.

High soil strengths in the low moisture treatment reduced total RLD (Table 45). Overall root length density tended to decrease with increasing moisture contents. The low moisture medium bulk density had the highest total RLD and was significantly greater than all other treatments except LMLD. The high density, high moisture treatment had the smallest total RLD and was significantly smaller than all the low moisture treatments and MMLS and HMMS. In both the low and high moisture treatments the 1.1 g/cm^3 bulk density produced the largest RLD.

Table 45. Compaction and moisture affects on onion root length densities, 2-17-90.

Tmt[y]	Top core	Middle core	Bottom core	Total
	- - - - - - - -	- - - - - cm/cm^3	- - - - - - - -	- - - - - - - -
LMLD	0.6 b[z]	0.9 ab	0.4 a	0.5 ab
LMMD	1.3 a	1.0 a	0.2 bc	0.6 a
LMHD	1.0 ab	0.7 abc	0.1 d	0.4 c
MMLD	0.8 ab	0.7 bc	0.2 bc	0.4 bc
MMMD	0.8 ab	0.7 bc	0.1 bcd	0.3 cd
MMHD	0.7 b	0.6 cd	0.1 cd	0.3 cd
HMLD	0.5 b	0.3 d	0.2 ab	0.3 cd
HMMD	0.8 ab	1.0 a	0.1 cd	0.4 bc
HMHD	0.4 b	0.3 d	0.1 cd	0.2 d
CV	40	28	53	25

[y] LMLD = 25% moisture, 0.25 g/cm^3 bulk density; LMMD = 25% moisture, 0.35 g/cm^3 bulk density; LMHD = 25% moisture, 0.45 g/cm^3 bulk density; MMLD = 30% moisture, 0.25g/cm^3 bulk density; MMMD = 30% moisture, 0.35 g/cm^3 bulk density; MMHD = 30% moisture, 0.45 g/cm^3 bulk density; HMLD = 35% moisture, 0.25 g/cm^3 bulk density; HMMD = 35% moisture, 0.35 g/cm^3 bulk density; HMHD = 35% moisture, 0.45 g/cm^3 bulk density.
[z] Values within a column followed by different letters are significant (P = 0.05).

Plant Measurements

Leaf area and fresh weight decreased with increasing soil moisture (Table 46). The largest leaf areas were 17.3 and 17.5 cm^2 for LMLD and LMMD. The low moisture treatments had the largest fresh weights and leaf areas. Leaf areas and weights on the 35 percent moisture treatments were the smallest. High moisture and high bulk density treatments resulted in smaller plants.

Table 46. Affect of compaction and moisture on onion top growth, 2-17-90.

Tmt[y]	Fr. wt	LA
	grams	cm^2
LMLD	0.8 a[z]	17.3 a
LMMD	0.8 ab	17.5 a
LMHD	0.5 ab	12.6 abcd
MMLD	0.6 ab	15.1 ab
MMMD	0.4 bc	10.3 bcd
MMHD	0.4 bc	13.4 abc
HMLD	0.3 bc	8.9 cd
HMMD	0.4 bc	10.7 bcd
HMHD	0.3 c	7.4 d
CV	30	28

[y] LMLD = 25% moisture, 0.25 g/cm^3 bulk density; LMMD = 25% moisture, 0.35 g/cm^3 bulk density; LMHD = 25% moisture, 0.45 g/cm^3 bulk density; MMLD = 30% moisture, 0.25g/cm^3 bulk density; MMMD = 30% moisture, 0.35 g/cm^3 bulk density; MMHD = 30% moisture, 0.45 g/cm^3 bulk density; HMLD = 35% moisture, 0.25 g/cm^3 bulk density; HMMD = 35% moisture, 0.35 g/cm^3 bulk density; HMHD = 35% moisture, 0.45 g/cm^3 bulk density.
[z] Values within a column followed by different letters are significant (P = 0.05).

Carrots

Soil Strength

There were no significant differences in soil strength in the top core between the 1.3g/cm^3 and 1.1g/cm^3 bulk density treatments and LMLD and MMLD (Table 47). Soil strength in the HMLD was significantly lower than in the LMLD, LMMD, LMHD and HMHD treatments.

The soil strength increased in the middle treatment core with increasing bulk densities (Table 47). The 0.9 g/cm^3 bulk density treatments and LMMD were significantly lower than all other treatments. The 1.3 g/cm^3 bulk density treatments were all significantly stronger than the lower bulk density treatments. Within the 1.3 bulk density treatments, LMHD was significantly greater than MMHD. There were no significant differences between LMHD and HMHD; or MMHD and HMHD.

The low moisture, 1.1 g/cm^3 bulk density treatment had a significantly lower soil strength in the bottom core than all other treatments (Table 47). There were no other significant differences between treatments.

Table 47. Compaction and moisture affects on soil strength of a martisco marl soil May 7,1990.

Tmt[Y]	Soil Strength Top core	Middle core	Bottom core
	- - - - - - -	MPa - - - - - - - -	
LMLD	6.92 a[z]	4.85 e	7.06 a
MMLD	5.81 ab	4.96 e	7.42 a
HMLD	5.45 b	4.69 e	6.91 a
LMMD	6.77 a	5.52 e	5.52 b
MMMD	6.42 ab	6.45 c	7.85 a
HMMD	6.12 ab	6.23 cd	7.83 a
LMHD	6.90 a	8.53 a	7.29 a
MMHD	6.26 ab	7.41 b	7.57 a
HMHD	6.90 a	8.08 ab	7.49 a
CV	12	9	8

[Y]LMLD = 25% moisture, 0.25 g/cm^3 bulk density; LMMD = 25% moisture, 0.35 g/cm^3 bulk density; LMHD = 25% moisture, 0.45 g/cm^3 bulk density; MMLD = 30% moisture, 0.25g/cm^3 bulk density; MMMD = 30% moisture, 0.35 g/cm^3 bulk density; MMHD = 30% moisture, 0.45 g/cm^3 bulk density; HMLD = 35% moisture, 0.25 g/cm^3 bulk density; HMMD = 35% moisture, 0.35 g/cm^3 bulk density; HMHD = 35% moisture, 0.45 g/cm^3 bulk density.
[z] Values within a column followed by different letters are significant (P = 0.05).

Root Length Densities

The low moisture medium bulk density treatment had the highest root length density of all treatments in the top core with 4.2 cm/cm^3 (Table 48). All significant differences in root length density were between moisture treatments with none occuring between bulk density treatments. The low moisture treatments had the largest root length density and the 35 percent moisture treatments had the smallest. The low moisture treatments had the largest root length density and the 35 percent moisture treatments had the smallest. The 25 percent moisture treatments all had significantly greater root length densities than the 35 percent moisture treatments with the exception of no difference between LMLD, LMHD and HMMD. With the exception of LMMD being significantly greater than MMLD and MMHD there were no significant differences between the 25 and 30 percent moisture treatments. No differences in root length densities (RLD) between the 30 and 35 percent moisture treatments were detected with the exception MMMD being significantly greater than HMLD. The treatments with a 1.1 g/cm^3 bulk density middle core had a larger RLD than the other treatments although this increase was not significant.

Table 48. Compaction and moisture affects on carrot root length densities 5-11-90.

Tmt[y]	Top core	Middle core	Bottom core	Total
	cm/cm^3			
LMLD	3.8 ab[z]	4.8 ab	2.0 b	2.9 b
LMMD	4.2 a	5.5 a	1.5 b	2.8 b
LMHD	3.6 ab	4.6 abc	1.1 b	2.3 b
MMLD	3.1 bcd	3.9 bcd	4.9 a	4.4 a
MMMD	3.4 abc	5.3 ab	5.0 a	4.8 a
MMHD	3.1 bcd	3.4 cde	4.6 a	4.1 a
HMLD	2.3 d	3.2 cde	5.9 a	4.6 a
HMMD	2.9 bcd	2.7 de	5.1 a	4.2 a
HMHD	2.6 cd	2.5 e	5.7 a	4.4 a
CV	19	22	21	15

[y] LMLD = 25% moisture, 0.25 g/cm^3 bulk density; LMMD = 25% moisture, 0.35 g/cm^3 bulk density; LMHD = 25% moisture, 0.45 g/cm^3 bulk density; MMLD = 30% moisture, 0.25g/cm^3 bulk density; MMMD = 30% moisture, 0.35 g/cm^3 bulk density; MMHD = 30% moisture, 0.45 g/cm^3 bulk density; HMLD = 35% moisture, 0.25 g/cm^3 bulk density; HMMD = 35% moisture, 0.35 g/cm^3 bulk density; HMHD = 35% moisture, 0.45 g/cm^3 bulk density.

[z] Values within a column followed by different letters are significant (P = 0.05).

The RLDs of the middle core followed the same trend as the top core with the low moisture treatments having larger RLDs than the higher moisture treatments (Table 48). The 25 percent moisture treatments were all significantly greater than the 35 percent treatments. The low moisture medium bulk density had a significantly larger root length density than MMLD and MMHD; and LMLD was significantly larger than MMHD. There were no other significant differences between the two moisture treatments nor within the 25 percent moisture treatments. The medium moisture medium bulk density treatment was significantly larger than all 35 percent moisture treatments and MMHD. There were no other significant differences between the 30 percent moisture treatments. The medium moisture medium bulk density treatment was significantly larger than HMHD. There were no other significant differences between the 30 and 35 percent moisture treatments. No significant differences within the 35 percent moisture treatments was detected.

In the bottom core all 25 percent moisture treatments had significantly smaller RLDs than all the other treatments (Table 48). There were no significant differences in root length densities between the 30 and 35 percent moisture treatments.

The 25 percent moisture treatments all had significantly smaller total RLDs than all other treatments (Table 48). There were no significant differences within any of the moisture treatments.

Plant Measurements

Fresh and dry weight of carrot tops and leaf area increased with increasing moisture content (Table 49). It would appear that the plants were under moisture stress with the drier treatments producing smaller plants. The 25 percent moisture treatment had the smallest weight and leaf area and the 35 percent moisture treatment had the largest. All differences between moisture treatments were significant at the 0.05 level. Bulk density of the treatment core did not affect plant growth with no significant differences within any of the moisture treatments detected.

Table 49. Compaction and moisture affects on carrot growth, 5-11-90.

Tmt[w]	Fr. wt	Dry wt.	LA[x]	Diameter[y]
	grams	grams	cm^2	cm
LMLD	1.5 c[z]	0.2 c	49.5 c	0.08 cd
LMMD	1.5 c	0.2 c	52.9 c	0.06 d
LMHD	1.8 c	0.2 c	59.1 c	0.05 d
MMLD	3.6 b	0.5 b	116.4 b	0.16 a
MMMD	3.2 b	0.4 b	109.3 b	0.13 abc
MMHD	3.6 b	0.5 b	110.1 b	0.10 bcd
HMLD	4.9 a	0.7 a	147.5 a	0.14 ab
HMMD	5.2 a	0.7 a	148.9 a	0.12 abc
HMHD	5.0 a	0.7 a	153.8 a	0.17 a
CV	13	14	15	25

[w]LMLD = 25% moisture, 0.25 g/cm^3 bulk density; LMMD = 25% moisture, 0.35 g/cm^3 bulk density; LMHD = 25% moisture, 0.45 g/cm^3 bulk density; MMLD = 30% moisture, 0.25g/cm^3 bulk density; MMMD = 30% moisture, 0.35 g/cm^3 bulk density; MMHD = 30% moisture, 0.45 g/cm^3 bulk density; HMLD = 35% moisture, 0.25 g/cm^3 bulk density; HMMD = 35% moisture, 0.35 g/cm^3 bulk density; HMHD = 35% moisture, 0.45 g/cm^3 bulk density
[x]Leaf Area
[y]Diameter of carrot tap root in the middle core.
[z] Values within a column followed by different letters are significant (P = 0.05).

The diameter of the tap root in the middle core increased with increasing moisture content (Table 49). The diameter was largest in HMHD with 0.17 cm. The high moisture treatments all produced significantly larger root diameters than the low moisture treatments with the exceptions of HMMD and LMLD. Root diameters tended to decrease with an increase in bulk density. However, only the 30 percent moisture treatment had any significant differences in tap root diameter with MMLD being greater than MMHD. There was little difference between the 30 and 35 percent moisture treatments in root diameter with only MMHD being significantly smaller than HMHD. The 30 percent moisture treatments had larger tap root diameters than the 25 percent moisture treatments with MMLD being significantly greater than all of the low moisture treatments and MMMD significantly greater than LMMD and LMHD. No significant differences between MMHD and the low moisture treatments were detected.

Discussion

Houghton Muck

Carrots

Increasing bulk density of the treatment core without altering water content increased the strength of the soil which caused a reduction in carrot root length. Roots can only pass through pores exceeding the diameter of the root tip (Wiersum 1957). Once the root has entered a pore it expands by exerting a force greater than the mechanical strength of the soil (Cannell, 1977). Root growth is therefore restricted when the strength of the soil is greater than the force exerted by the root. The reduction in carrot root length was caused by the high soil strength of the treatment core. Previous research has shown that root growth decreases with increasing soil strength (Eavis, 1972, Taylor, 1964). Asady et al (1985) found that roots of dry edible beans were not able to enter a compacted core due to the large diameter of the roots in relation to the small pore diameters and low metabolic energy of the root. The carrot greenhouse results on a Houghton muck are similar to those of

Strandberg and White (1979) who found a decrease in carrot taproot growth with an increase in soil strength. Willat (1986) found a decrease in root length density of barley with increasing soil strength. The carrots showed the same trend with a lower root length density in the high bulk density core.

Onions

The root penetration ratio (RPR) was decreased by increasing compaction of the middle core. As in the carrots, increasing compaction and soil strength reduced root growth. These results agree with those of Asady et. al. (1985) who found a decreasing RPR in dry edible beans with increasing compaction. He attributed the reduced RPR to a decrease in air filled porosity. He found that a reduction in root growth was directly related to increased aeration stress and mechanical resistance.

There were no differences in onion root length densities in the middle and bottom cores. Root length densities did increase in the top core with increasing compaction in the middle core. The increase in root length densities is due to the compacted middle core. The onions had reduced penetration of the compacted layer which caused the plant to increase the rooting density in the top core. These are similar to the results of Taylor and Burnett (1965) who found an increasing percentage of cotton roots above a compacted layer. Asady et al. (1985) also found an accumulation of dry bean roots above a compacted layer in a similar greenhouse experiment.

Marl Soil

Onions

Shoot and root growth was decreased by increasing moisture contents. Reduced plant growth can be brought on by reduced aeration in the root zone. The low moisture treatments had larger overall root length densities than the middle and high moisture treatments. The high moisture treatments had the smallest total RLD. It would appear that high gravimetric moisture contents are detrimental to onion root growth. The oxygen diffusion rate is lower at high moisture contents because oxygen is less soluble in water than air. These anoxic conditions cause a decrease in onion root growth. These results are similar to those of Unger and Danielson (1965) who found reduced growth of young corn plants under poorly aerated conditions. They determined that the reduced growth was due to a reduced supply of oxygen. Since roots supply water and nutrients to the shoot, reduced root growth will restrict the flow of these materials and cause reduction in shoot growth.

Overall root length density tended to decrease with the high bulk density treatment. The difference was significant in the low moisture treatments. The largest reduction came in the middle core. This would agree with the results of the Houghton muck experiment where increasing soil strength in the treatment core prevented penetration by onion roots.

Carrots

Soil strength is affected by both water content and bulk density (Taylor and Ratliff, 1969). Water content was not uniform throughout the profile due to plant uptake. In these treatments the soil strength was more affected by bulk density than moisture treatment. Because of differences in plant size and water uptake, soil strength did not correlate with treatment as would be expected.

Plant response in the 1990 carrot greenhouse experiment was due to moisture rather than increasing bulk density of the treatment core. The experiment was run from April through mid May. During this time day length and strength of the sun were increasing. This created a greater demand for water and the plants were water stressed. The root length density was highest in the top two cores in the low moisture treatments. The moisture content in the cores was highest near the surface because the plants were watered from the top. Graecan and Oh (1972) found that in an otherwise uniform soil, roots proliferate in wetter zones not because of availability of water but rather because mechanical resistance is low. Trouse (1972) states that in a field situation where moisture content is not uniform, roots appear to develop in most portions of the soil they can reach where the moisture content is adequate or above the permanent wilting point. In this case it appears that the roots developed near the surface to maximize water uptake. The higher moisture treatments had greater total root length densities and higher root length densities in the bottom core. These treatments had more available water and the roots grew throughout the core.

Carrot top growth was reduced by decreasing moisture contents. Water stressed plants have a decreased transpiration rate. Total plant biomass will be reduced when transpiration is reduced by water stress (Taylor, 1981).

Summary

Carrot tap root length and total root length density on a Houghton muck decreased with a 0.45 g/cm^3 bulk density when soil moisture was kept constant. The high bulk density increased the soil strength which impeded root growth.

On a Houghton muck with constant soil moisture contents, root length above the treatment core was increased with increasing bulk densities. Root penetration ratio was decreased with an increase in bulk density to 0.45 g/cm^3. No differences in top growth were detected. Soil strengths were increased by increases in bulk density and decreases in soil moisture content.

Onion growth on a marl soil decreased with increases in soil moisture content. Top growth and total root length density were decreased with increases in soil moisture. The high moisture contents restricted aeration which caused a decrease in plant growth.

Carrot growth increased with increasing soil moisture content in the marl soil. Top growth was increased by increases in soil moisture from 25 to 30 and 35 gravimetric percent moisture. Root length densities were not affected as much as top growth. Root length densities increased with increasing moisture contents but there were no significant increases between 30 and 35 percent gravimetric moisture contents.

Conclusions

A high bulk density layer in a Houghton muck can reduce carrot taproot length. The root length density in the compacted layer is also decreased. Root growth is decreased by a high soil strength produced by the increased bulk density.

A high bulk density layer in a Houghton muck increases onion root length density in the area above it. Reducing the root penetration ratio of the compacted layer causes the plant to compensate and increase the amount of roots in the area above the compacted layer.

Increasing gravimetric soil moisture content from 25 to 35 percent in a marl soil increases carrot growth when the plants are under water stressed conditions. Top growth is significantly increased with an increase in soil moisture. Total carrot root lengths are increased with an increase in soil moisture above 25 percent gravimetric moisture.

Total onion root and top growth in a marl soil is decreased with increases in gravimetric soil moisture contents above 25 percent. Increasing the moisture content decreased aeration. Decreased aeration in the root zone inhibits root growth which caused a decrease in plant size.

Onions grown with 25 percent moisture content had decreased root and top growth with increased compaction. The high bulk density layer increased soil strength which reduced root growth. The reduced root growth caused a decrease in top size.

Increasing bulk density increased the soil strength of a marl soil by rearrangement of soil particles. Soil strength was less affected by moisture content.

Literature Cited

Asady, G. H., A. J. M. Smucker, and M. W. Adams. 1985. Seedling test for the quantitative measurement of root tolerances to compacted soil. Crop Sci. 25:802-806.

Cannell, R. Q. 1977. Soil Aeration and compaction in relation to growth and soil management. Adv. Appl. Biol. 2:1-86.

Eavis, B. W. 1972. Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam. Plant and Soil 36:613-622.

Greacen, E. L. and J. S. Oh. 1972. Physics of root growth. Nature, New Biol. 235:24-25.

Newman, E. I. 1966. A method of estimating the total length of a root sample. J. Appl. Ecol. 3:139-145.

Strandberg, J. O. and J. M. White. 1979. Effect of soil compaction on carrot roots. J. Amer. Soc. Hort. Sci. 104(3):344-349.

Taylor, Howard M. 1981. Root Zone Modification: Fundamentals and Alternatives. p 13 In G. F. Arkin and H. M. Taylor (ed.) Modifying the root environment to reduce crop stress. Am. Soc. Agric. Eng., St. Joseph, MI.

Taylor, Howard M. and Earl Burnett. 1965. Influence of soil strength on the root growth habits of plants. Soil Sci. 98:174-180.

Taylor, H. M., L.F. Locke, and J. E. Box. 1964. Pans in southern Great Plains soils: III. Their effects on yield of cotton and grain sorghum. Agron. J. 56:542-545.

Taylor, Howard M. and Larry F. Ratliff. 1969. Root elongation rates of cotton and peanuts as a result of soil strength and water content. Soil Sci. 108:113-119.

Tennant, D. 1975. A test of a modified line intersect method of estimating root length. J. of Ecol. 63:995-1001

Trouse, A. C. 1972. In K.K. Barnes et. al. Compaction of Agricultural Soils. Am. Soc. Agric. Eng., St. Joseph, MI. pp. 244-249

Unger, Paul W. and Robert E. Danielson. 1965. Influence of Oxygen and Carbon Dioxide on germination and seedling development of corn (Zea mays L.). Agron. J. 57:56-58.

White, J. M. and J. O. Strandberg. 1978. Early root growth of carrots in organic soil. J. Amer. Soc. Hort. Sci. 103(3):344-347.

Wiersum, L. K. 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant and Soil 9:75-85.

Willat, S. T. 1986. Root growth of winter barley in a soil compacted by the passage of tractors. Soils and Tillage Research 7:41-50.

Summary and Conclusions

Zone tillage caused a decrease in soil strength of organic soils. The paratill was slightly better in reducing the soil strength than the rotill. No difference in soil moisture content between tillage treatments was detected.

Reduced soil strength in the zone tillage treatments resulted in an increase in total root length, total yield and marketable yield of carrots. Only under flooded conditions did zone tillage reduce the amount of culls harvested.

Carrot seedling emergence is decreased by zone tillage. Loose soil caused by zone tillage reduces seed soil contact which reduces germination. Firming the bed with a roller did slightly increase emergence.

Compaction decreases carrot tap root length, total yield and yield of marketable carrots. An increase in soil strength accompanied with decreased drainage and aeration decrease root growth. Onion growth was also reduced by increased compaction.

Compacted layers affect carrot and onion seedling growth. Carrot root lengths and onion root penetration ratios are decreased by high bulk density layers. Carrot top and root length was increased with increasing gravimetric moisture percents. Onion top and root growth was decreased with increasing gravimetric soil moisture contents. Reduced aeration reduced root growth which affected top growth. Onion root and top growth is decreased by increasing compaction at low soil moisture contents. The increase in bulk density causes an increased soil strength which inhibits root and top growth.

Recommendations

Compaction adversely affects carrot and onion growth. Field operations that cause compaction to occur should be minimalized. Where compaction does occur it should be alleviated.

Zone tillage can increase the size and marketable yield of carrots. More work needs to be done to determine the effects of zone tillage on onions.

Zone tillage does reduce the stand of carrots. Further study is needed to determine why and how emergence is reduced. If seedling emergence can be increased without greatly increasing the soil strength, zone tillage can dramatically increase carrot yields.

APPENDIX

APPENDIX I.

Volumetric Moisture Contents
Houghton muck (Euic, Mesic, Typic Medisaprist)
0-40cm

Depth (cm)	Sat.	10 cm	20 cm	30 cm	40 cm	60 cm
0-10	75.90	70.23	67.79	66.18	64.73	63.48
10-20	74.88	68.28	65.91	64.12	63.08	61.25
20-30	76.15	69.37	66.99	65.29	64.27	62.51
30-40	77.62	71.62	69.19	67.58	66.19	65.03

Depth	1/10 Atm	1/3 Atm	1 Atm	B.D.
0-10	61.78	58.47	55.72	0.39
10-20	59.52	55.71	53.28	0.40
20-30	61.14	58.20	56.12	0.38
30-40	63.81	60.90	58.66	0.36