Chapter 1

Introduction

Carrot (*Daucus carota* L.) is normally grown for its underground fleshy storage organ, which is harvested at the end of the first year of growth (Thompson, 1949; Salter and Goode, 1967). It is a popular vegetable and the root is well known as a source of carotene, which is a precursor of vitamin A. Carrot root is also rich in thiamine, riboflavin and sugar. The storage organ of carrot develops in the tap root and hypocotyl through secondary growth of cambium, which then enlarges and becomes fleshy (Esau, 1940). This fleshy storage organ has been variously named such as fleshy root (Havis, 1939), as true root (Salter and Goode, 1967), as swollen tap root (Benyamin and Wren, 1978), as root (Stanhill, 1977; Olymbios and Schwabe, 1977; Saini *et al.*, 1981; Salter *et al.*, 1981; Taksdal, 1984), as storage root (Barnes, 1977; Thomas *et al.*, 1983; Hole *et al.*, 1984). In this thesis, storage root is used to indicate the fleshy organ of carrot, distinguishing it from the fibrous roots.

The most desirable type of carrot storage root is uniform, smooth, slender and deep orange in colour. According to U.S.grading, fresh market carrot should have a minimum length of 15.2 cm (White and Strandberg, 1978), and in Australia carrot roots with a diameter of 1.5 - 3.0 cm are considered small, 3.0 - 4.5 cm as medium, and over 4.5 cm as large carrots (Salvestrin, 1984). Considerable variations in shape, size, and weight of carrot storage roots obviously influence the market value of this crop. The individual root weight, might vary from 50% - 60% (Salter *et al.*, 1981) to 100% (Austin and Longden, 1967).

Literature indicates that variation in carrot storage roots is due to genetic and environmental factors. Variation in seed size has been documented as a cause of the weight variation (Benyamin, 1982), while Gray and Steckel (1986) concluded that the variation resulted from differences in embryo length of carrot seeds. Variation in the size of the seedling, in the time of emergence, and even in shoot heights has been reported to be the cause of carrot yield variation (Mann and MacGillivray, 1949; Salter *et al.*, 1981; Benyamin, 1984; Hole *et al.*, 1984). Significant effects of environmental factors on the shape, size, and yield of carrot storage roots are reported by Barnes (1936), Thompson (1969), Olymbios and Schwabe (1977), Stanhill (1977), Strandberg and White (1979), and Benyamin (1984).

In intensive carrot production areas, the use of heavy farm machinary and excessive tillage have been reported to cause soil compaction (Millette *et al.*, 1981; Taksdal, 1984), which is associated with low yield and quality of this crop(Olymbios and Schwabe, 1977; Strandberg and White, 1979; Millette *et al.*, 1981; Taksdal, 1984; Bunyan, 1985).

In the tropics, soil compaction and surface crusting, which results from raindrop impact, are reported to be the cause of high bulk density of the soil (Lal, 1978). Reports indicate that some upland soils of tropical regions are often compacted and rigid, due to the existence of gravel horizons at different depths (Panabokhe and Quirk, 1957). This compact soil is associated with mechanical impedance to crop root development (Babaola and Lal, 1977a,b). Supra-optimal soil temperature ($>30^0$ C) at 5 cm depth during the growing season in the tropics, is believed to be the reason for significantly reduced crop yields (Lal, 1975; Prihar *et al.*, 1979; Tumuhairwe and Gumbs, 1983a; Vander Zaag *et al.*, 1986). In the dry season, water deficiency is another limitation, especially in areas without irrigation (Tumuhairwe and Gumbs, 1983b).

Mulching has been reported to increase crop yields in the lowland tropics through its effects in modifying soil temperature, improving water infiltration, conserving soil moisture, alleviating soil surface compaction and crusting, and supressing weed competition (Lal, 1978; Prihar *et al.*, 1979:Tumuhairwe and Gumbs, 1983a; Midmore, 1984; Midmore *et al.*, 1986; Vander Zaag *et al.*, 1986).

The interactions between bulk density and soil moisture regime, and between soil temperature and moisture are significant for root development (Maurya and Lal, 1981).

Crop diversification has been encouraged in South East Asia, and studies on adaptation of several crops to warm conditions, particularly after rice, have been undertaken (Vander Zaag *et al.,* 1986). In the tropics, carrot is commonly grown at high altitudes. Other cool-climate crops, such as potato and cabbage, are succesfully grown under mulch at lowland areas in the tropics (Tumuhairwe and Gumbs, 1983 a,b; Midmore *et al.*, 1986; Vander Zaag *et al.*, 1986). This suggests that similar practices could be utilized in carrot production to improve the yield and quality of this crop.

Chapter 2

Literature review

2.1 Soil physical conditions and their effects on the growth of roots, underground organs and yield of crops

2.1.1 The soil and plant root systems

Soils simplistically consist of solids, water, and gas with solid particles of irregular size and shape, occupying 40% to 60% of total volume of the soil (Russell, 1977). Between these soil particles are pore spaces, which vary in size and shape (Hanks and Ashcroft, 1980), and may be filled with air or water, depending on the moisture content of the soil. Trouse (1979) suggest that root penetration is maximal in soils of good physical condition. Such soils are moist with a loose structure and have a favourable pore size distribution and continuity.

For plant growth and development, the ratio of pore spaces occupied by air or water, and number of pores, which can be easily penetrated by the roots, are of major importance. Soil pores of >50 μm ECD (Equivalent Cylindrical Diameter) or transmission pores (Greenland, 1979: Hamblin, 1985) are essential and should occupy at least 10% of soil volume to obtain good drainage. Water is retained in pores in the range of 0.5 to 50 μm ECD, and Greenland (1979) indicated that 10% of the soil volume should be occupied by pores in this range if root growth is to be maximal. Since the majority of roots have diameters greater than 60 μm (Russell, 1977), the existance of continuous pores with diameters >250 μm is very important to ensure roots enter the pores and elongate with a minimum of mechanical impedance (Greenland, 1979).

Hegarty (1976) reported that unfavourable soil physical conditions resulted in inferior seedling establishment in calabrese, carrot, onion, and red beet. Since the root systems are important in controlling dry matter production in carrot (Benyamin and Wren. 1978). the physical conditions around the seeds were considered by Benyamin (1984) as the major source of root-weight variations. Modification in the synthesis of growth substances in roots is another possible effect of unfavourable soil conditions. Mizrahi and Richmon (1972) reported that under water stress or high osmotic pressure conditions, the concentration of cytokinins in root exudates is decreased. The production and translocation of these substances are also affected by unfavourable soil temperatures. Russell (1977) documented similar effects on auxin, gibberellins. cytokinins. ethylene. and abscisic acid under anaerobic soil conditions.

2.1.2 Soil compaction

In a compacted soil, root growth is often restricted. Raney *et al.* (1955) stated that due to lack of moisture or oxygen, and may be due to mechanical impedance, compact soil layers are unfavourable for root growth. McKibben *et al.* (1971) concluded that the compaction process of agricultural soils is basically a change in volume for a particular mass of soil. Trouse (1979) stated that during compaction, a two-step process occurs. Firstly is the destruction and the breaking of the structural units of the soil into small particles. The second step is pushing and clogging the particles into aggregates, in which the volume of large pores is reduced. Schuurman (1965) indicated that in a compacted soil, the pore volume and the number of large pores (96 to 300 μm) were reduced. On the other hand, the number of fine pores (<6 μm) increased with bulk density. Harris (1971) concluded that there are four possible factors involved in the soil compaction process, i.e. a compression of solid particles, of liquid and gases within pore spaces, a change in liquid and gas contents in pore spaces, and a rearrangement of the soil particles. Soil compaction is variously denoted as a change in bulk density, void ratio, and porosity (McKibben *et al.*, 1971; Harris, 1971). Harris (1971) assumed that the change, which is caused by an alteration in the void ratio (i.e. the ratio of the volume of voids to volume of solids), is greater than that due to a change in porosity. This author further stated that the pore-size distribution changes, as the bulk density changes. Increased bulk density resulted in a reduced proportion of larger pores. This conclusion was supported by the work of Schuurman (1965). Boone (1986) stated that the changes in the pore system, especially the decrease of the largest pores, is a very important aspect of soil compaction in relation to crop root growth. This author described the functional relationship between soil compaction and crop growth as a very complex system. (Figure 2.1).

Field traffic is considered to be the major cause of compaction in agricultural soils (Trouse, 1979; Hillel, 1980; Boone, 1986). Flocker *et al.* (1966) concluded that tillage, particularly at high soil moisture, frequently causes soil compaction. Dias and Nortcliff (1985) reported some changes in the thickness of topsoil after wheeled tractors had trafficed the surface. In these studies, the topsoil was compressed from 3 to 11.6 cm from the original surface, and the compression increased as the soil moisture content of the soil increased. Flocker *et al.* (1958) also found that bulk density of surface soil increased from 1.22 to 1.58 Mg m^{-3} after a tractor and a loaded jeep had been driven over the field. Animal trampling and rainfall drops have been reported by Cohron (1971) to contribute to an increase in soil bulk density.

Boone (1986) stated that compaction directly affects the soil physical, and indirectly the chemical and biological factors. Mechanical impedance, water, air, and heat are soil physical factors which are altered by soil compaction. This conclusion was similar to that of Raney *et al.* (1955), that slow water penetrability and limited storage capacity for available water, slower movement of oxygen or other gases, and impeded root growth, are often found in a compacted soil. Barley and Greacen

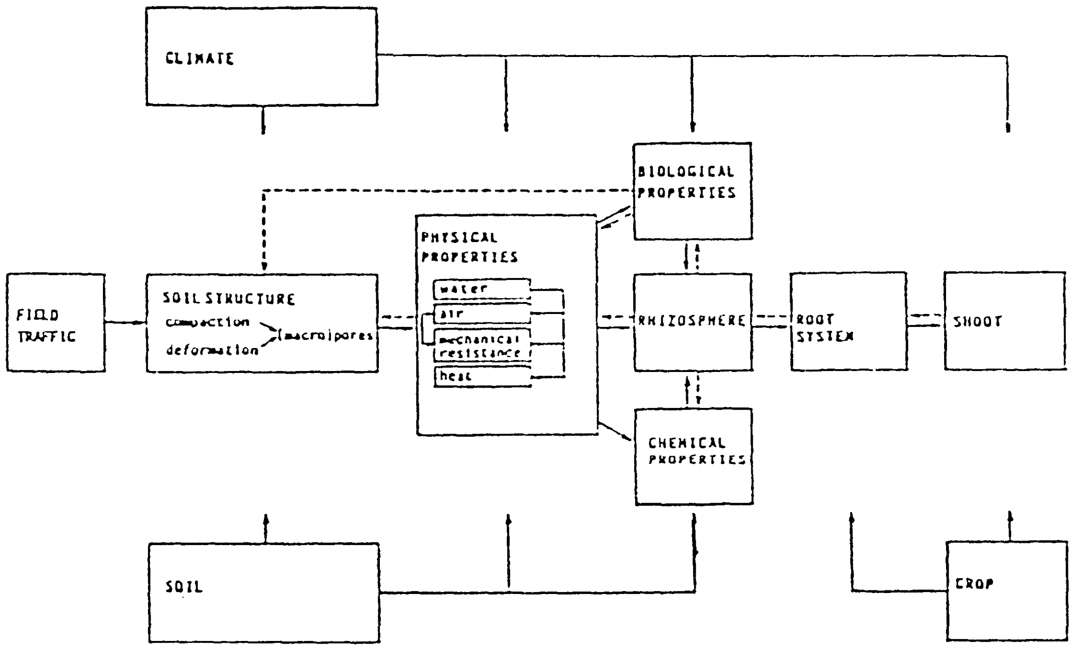

Figure 2.1: A functional reationship between soil compaction and crop growth (after Boone, 1986)

(1967) concluded that mechanical impedance, water supply, and aeration of the soil strongly affect the growth of roots and underground shoots at a given temperature. Due to its interdependence, these three factors may influence the roots and underground organs of the plants individually. Raney *et al.* (1955) concluded that in most cases, detrimental effects of soil compaction on crop root growth and yields, are through the interaction of these factors. Barley and Greacen (1967) also indicated that the effect of one factor may be altered by that of others. Boone (1986) suggested that the effects of these physical factors have to be discussed separately as well as in combination, due to their interdependence and interaction.

a. Mechanical impedance

Since most roots have diameters larger than 60 μm (Russell, 1977), root growth will be retarded because of mechanical impedance in a soil, in which most of the pores are small. In order to enter pores, roots can either decrease their diameters or exert pressures to enlarge or create pores (Russell, 1977). Taylor (1971) concluded that when a soil is compacted, there is an increase in soil strength, which resulted in a decrease in root extention rates. Trouse (1979) reported that compacting a soil by 0.15 Mg m^{-3} could reduce root growth to 50%, while elongation rates decreased to 10% when the soil was compressed 0.35 Mg m^{-3}.

Veighmeyer and Hendrickson (1948) reported that in a clay loam soil, roots could not penetrate the soil at a density of 1.46 Mg m^{-3}, while in a sandy soil, a density of 1.90 Mg m^{-3} was the upper limit for root penetration. Schuurman (1965) found the growth of oat roots and especially depth of rooting was markedly reduced in a compacted sand at a bulk density of 1.52 Mg m^{-3} compared to 1.24 Mg m^{-3}.

To penetrate a dense soil, plants exert forces to deform the soil (Schuurman, 1965). Taylor and Gardner (1963) concluded that the forces must be greater than the resistance of the soil, where the roots are growing.

Russell (1977) reported that in a compacted soil, the extention of cells in the zone of cell elongation behind the apical meristem of the roots is restricted.

b. Soil moisture

Water is the most important factor in the life of plants, and a limited supply of water consequently results in reduced plant growth. Soil water can only be absorbed by plant roots if the suction in the roots is higher than that in the soil (Gardner, 1960; Ritchie, 1974). As soil moisture content decreases soil moisture tension increases, thus plants have to develop higher suction to be able to absorb the soil water.

Gardner (1960) concluded that the rate of water absorption is determined by the rate of transpiration. Russell (1977) reported that the movement of soil water to the roots occurs radially and that this movement is also influenced by the rate of transpiration. Gardner (1964) determined that the pattern of water absorption by plant roots is determined by the relative distribution of roots with depth and the ability of the soil to retain and transmit the water to the roots. A similar finding was reported by Salter (1968) who also identified that the available water capacity, and the rooting systems of crops are important factors in respect to water availability. While the movement of water in a soil and the root absorption are due to a water potential gradient (Ritchie, 1974; Russell, 1977), the resistance of water to flow in the soil is determined by the soil water content (Ritchie, 1974).

Where water loss through transpiration is higher than that absorbed by the roots, the plants experience a water deficit (Gardner. 1960; Ritchie, 1974; Begg and Turner, 1976). These authors concluded that apart from the atmospheric factors, the status of water in soil also influences the severity of water deficit to plants. Plant-water deficit can reduce plant growth by affecting the anatomy, morphology, physiology. and biochemistry of plants. Russell (1977) reported that reduced root growth. which resulted in restricted absorption of water and nutrients, was due to decreases in metabolic activity of the roots and the metabolic requirement for nutrients by the whole plant.

Response of crop root growth and yield to soil moisture deficit

Results of experiments conducted by Peters (1957) indicated that water uptake by roots of corn was significantly related to the moisture content and moisture tension of the soil. As the moisture tension increased. water uptake and root elongation decreased. These two processes also decreased as the moisture content per unit tension decreased. Russell (1977) concluded that root extention of most plants starts to decrease when soil water potential is approximately -50 kPa. and that it continues to decline until the potential reaches -1000 kPa.

Salter and Goode (1967) reviewed the work of Nelson that a 13% reduction in carrot yield at a soil moisture tension of 608 kPa during the period of final root development (about 60 days after planting). This contrasts with a reduction of only 1.5% when the tension was applied at an early growth stage. This result was confirmed by Begg and Turner (1976), who concluded that irrigation was very important during the rapid development of plant organs, comprising economic yield because of the adverse effect of water deficit at this stage in reducing root growth and activity. Salter and Goode (1967) concluded from their review, that evidence that carrots are more sensitive to moisture stress at a certain growth stage was inconsistent. Barnes (1936) found that carrot storage roots were smaller under low soil moisture (18%) than under a medium (26%) or a high (34%) soil moisture content. A similar result was reported by Stanhill (1956, 1977). In addition, Stanhill (1956), and Orzolek and Carroll (1978) recorded less secondary root growth and a lower number of split and forked carrot roots at a high soil moisture content. White and Strandberg (1979) reported that saturated soil moisture conditions resulted in shorter and thinner storage roots of carrots. Millette (1983) found that the length and fresh weight of carrot roots, and the water use efficiency decreased when the water table was raised from 40 to 10 cm. Cavalchini (1972) in Italy, found that carrot yields were the highest when irrigation was applied at a soil moisture potential of -76 kPa. However, Silva *et al.* (1982) in Brazil, achieved the maximum yield by irrigating carrots at a soil water potential of -29 kPa. Henkel (1970) in Germany has reported that the highest yield was obtained with irrigation when the soil moisture reached 60% of field capacity.

In certain situations, roots continue to grow and plants produce higher yields with better quality under dry soil conditions. Hsiao and Acevedo (1974) reported that the growth of maize roots was the highest under water stress conditions, and they suggested that water stress reduced the shoot growth but did not significantly decrease CO_2 assimilation. This resulted in an increase in assimilate translocation for the root growth. Clements (1964) found that deeper rooting systems developed at the early stage, and that the yield of mature sugarcane was increased under water stress conditions. Clements (1964) concluded that these deeper root systems contributed to the continuation of root growth and made the plants more resistant to later water stress. Barnes (1936) and Stanhill (1956) measured higher quality in carrot roots under low soil moisture conditions. These authors found that carrot roots were significantly sweeter, stronger in flavour, deeper in colour, and the texture was smoother when grown under these low soil moisture conditions.

c. Soil aeration

Trouse (1971) emphasized that in relation to plant development, the supply of oxygen to the actively functioning underground parts of the plant, the removal of CO_2 from active root zone and the maintenance of a moisture layer in that zone, are of major importance. The failure of roots to supply adequate nutrient and moisture to the plants will result in restriction of growth, which in turn results in decreased functioning of roots.

Plants often experience lack of aeration when the rate of oxygen diffusion into the soil through air-filled pores, is slower than the rate of consumption of oxygen, which is consumed by roots and soil microorganisms. Cannell and Jackson (1981) stated that because of slow diffusion of oxygen in water, the main restriction to soil aeration is the presence of water-filled pores. An excess of water could impede the movement of CO_2 out of the soil, which would also restrict soil aeration. Russell (1977), and Cannell and Jackson (1981) indicated that the size, distribution, frequency, and continuity of soil pores have important effects on the rate of oxygen diffusion in both the gas and solution phases in the soil.

Under anaerobic soil conditions, considerable changes in biological, chemical, and physical processes may occur. Among these, the important changes which significantly affects plant growth, are toxic substances (organic acids, methane, ethylene), which are produced by anaerobic metabolism, and losses of soluble nitrogen compounds through denitrification (Russell, 1977; Cannell and Jackson, 1981).

Response of root growth to soil aeration

Morphological and physiological effects of anaerobic soil conditions on plant growth have been reviewed by Russell (1977), and Cannell and Jackson (1981). Russell (1952), and Taylor and Ashcroft (1972) indicated that plant roots were thicker, shorter, and darker in a soil with inadequate oxygen content than in a normal condition. These authors also found that root hairs were less developed in that poorly aerated soil. White and Strandberg (1979) reported that the length of tap roots of carrot seedlings was significantly decreased and more forked roots were produced after a short period of 12 hours water saturation.

Russell (1977) concluded that in poorly aerated media, plant roots become less permeable to water and this could result in reduced water and nutrient uptake.

Studies, which are reviewed by Cannell and Jackson (1981) indicated that restriction in cell elongation, cambial activity, and in differentiation of stele, were some of consequent effects of ethylene trapped by even a thin layer of excessive water in an anaerobic soil. Cannell and Jackson (1981) cited that ethanol as a product of anaerobic respiration could cause anoxia. which in turn resulted in injury and even death of membranes and cells of roots. A number of studies indicated that a high accumulation of CO_2 in root zone, which could result in restricted root growth, was considered to be responsible for reduced water uptake.

The mechanisms of endogenous plant hormones are also affected by anaerobiosis of rooting media, as reviewed by Rusell (1977). and Cannell and Jackson (1981). It was reported that production and transportation of gibberellins and cytokinins are decreased under anaerobic conditions, and that this results in inhibition in stem elongation and growth, and leaf senescence.

2.1.3 The interaction of mechanical impedance, moisture, and aeration, in compacted soils

Studies on the effect of interaction among these three physical factors on root growth. have been documented by many researchers (Barley and Greacen, 1967; Boone. 1986; Boone *et al.*. 1986). Boone *et al.* (1986) suggested that the relationship between soil structure and root growth can be evaluated from the relationship between mechanical impedance. aeration. and water potential.

a. Response of crop root growth and yield to soil compaction

Restriction in root growth, due to soil compaction, was found to result in a 25% to 35% yield reduction in cucumber (Smittle and Williamson, 1977). These researchers concluded that a soil strength of 850 kPa, measured by a soil penetrometer in the compact soil, decreased the ratio of length : diameter of the cucumber fruit. Chaudhary and Aggarwal (1984) reported that root growth of wheat was decreased at an applied pressure of 1000 kPa in the chamber of a pressure-plate apparatus.

Boone *et al.* (1986) observed limited elongation of potato roots in a dense soil. van Loon and Bouma (1978) found that roots failed to elongate vertically and this was possibly the reason for the shallower rooting depth observed in compacted soils. A similar finding was reported for barley by Goss and Russell (1980). In these studies, more branched roots grew and developed laterally in highly compacted soils.

Kubota and Williams (1967) reported that compaction decreased germination and establishment of barley and globe beet seedlings, which in turn resulted in yield reduction. These authors also recorded a reduction in sugarbeet yield at a bulk density of 1.50 Mg m^{-3}. Strandberg and White (1979) found impeded growth of carrot seedling in a dense soil. Decreases in the growth of soybean and sugarbeet seedlings as a result of increased soil compaction, were also documented by Draycott *et al.* (1970), Jaggard (1977), and Gebhardt *et al.* (1986). A close negative relationship between emergence of peas and penetrometer readings was documented by Hebblethwaite and McGowan (1980) (Figure 2.2). The decreased emergence was responsible for a 50% reduction in yield. Taylor and Burnett (1964) concluded that increased soil strength, due to increased soil bulk density, resulted in a yield reduction in cotton, sorghum, beans, and peas.

b. Mechanical impedance and soil moisture interaction

In compacted soils, an increase in bulk density results in a decrease in total porosity. This change causes an alteration in pore-size distribution of the soil (Harris, 1971). The change in pore-size distribution has the most important effect on agronomic practices (Warkentin, 1971), since the alteration in volume, size, and shape of the soil pores has considerable effects on water content and transmission in the soil. When a soil is compacted, the proportion of larger pores is reduced. This results in more water being retained at high suction in the small pores. Roots have to exert higher suction to withdraw water from these pores. Russell (1977) stated that the smaller the pore size, the greater the suction that has to be exerted. In a

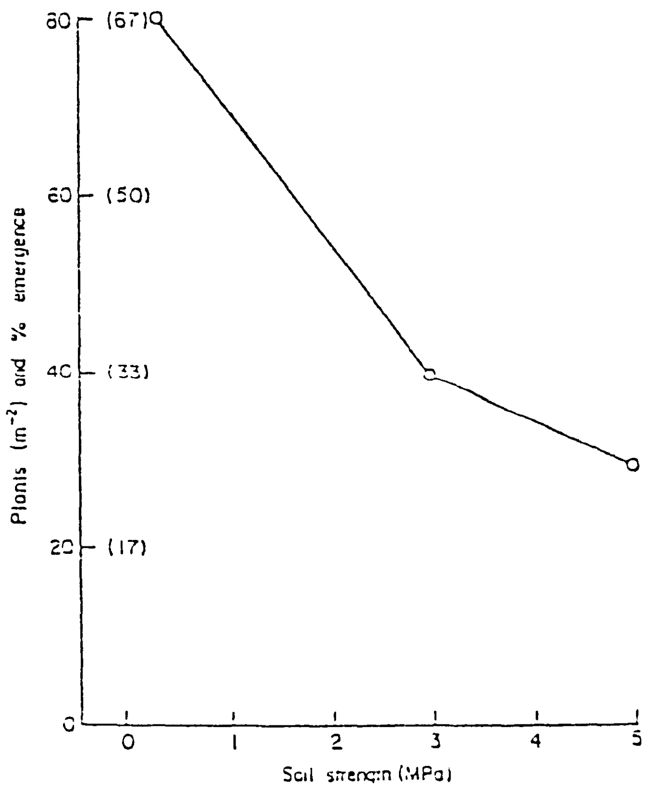

Figure 2.2: Emergence of peas in relation to penetration resistance (after Hebblethwaite and McGowan, 1980)

compacted soil, water stored in the soil and the amount of water available for plants is often increased, but plant growth may be reduced due to poor aeration and from the adverse effect of poor soil structure (Warkentin, 1971). This was confirmed by Trouse (1971), who showed that in compacted soils, permeability is reduced and runoff is increased, particularly on a sloping land. On the other hand, where water is ponded in a basin area, slow infiltration results in poor aeration which limits root activity and plant growth. Similar results were reported by Hadas *et al.* (1985).

Box and Taylor (1962) concluded that soil matric potential is a function of soil bulk density. In a condition where soil moisture and temperature are constant, an increase in bulk density resulted in an increase in soil matric potential. Hill and

Sumner (1967) concluded that in sandy loams, where large pores are dominant, the effect of compaction is more apparent in reducing total porosity than in increasing the number and relative volume of smaller pores. In this respect, high compaction decreases moisture content at a constant matric potential and reduces matric potential at a constant water content. Hill and Sumner (1967) further stated that in sands, the greatest effect of compaction is at a low suction, while in clays this effect is apparent at a high suction.

Maurya and Lal (1979) reported that increases in bulk density and moisture suction resulted in increased penetrometer resistance, and that this effect was more pronounced at a high suction. From their studies on different crops, Maurya and Lal (1979) concluded that the effect of moisture on root elongation was confounded with the effect of soil bulk density. In addition, the range at which moisture and bulk density was optimum for root elongation, was different with different crop species. Nevertheless, these authors generalized that the rate of root elongation was low at high bulk density and low soil moisture. Gingrich and Russell (1956), and Peters (1957) reported similar results.

In a study on potatoes conducted by Timm and Flocker (1966), tuber yield and quality was reduced at a moisture potential of -70.9 kPa. From these results, Flocker and Timm (1966) recommended that irrigation should be applied at a mean moisture potential of -50.6 kPa, regardless of the degree of compaction. Although Gill (1971) found that soil moisture was the most important factor affecting crop response to compaction. Eavis (1972) concluded that the effect of restricted water availability was only noticeable in drier compacted soils, where the moisture potential was less than -350 kPa.

Maurya and Lal (1979) found that increases in soil bulk density and moisture potential, resulted in increased total volumetric moisture content. However, Boone *et al.* (1978) indicated that volumetric soil water content, at any pressure potential, may be increased or decreased as the compaction increased, depending on the level of compaction. This could be associated with decreases in the volume of larger pores and increases in finer pores up to a certain volume. In their experiments, Boone *et al.* (1978) found that there was an interaction between compaction and irrigation effects on depth of root penetration in potatoes. At an effective penetration depth, where 80% of the roots were found, a moderate compaction with irrigation treatment resulted in shallower roots than without irrigation. This was associated with sufficient water available for root growth in the rooting zone. van Loon and Bouma (1978) recorded a reduction in potato yields and more secondary growth in topsoil compaction treatments compared to loose soils or irrigated treatments. In addition, low water availability and relatively slower root growth was observed in the early growth stage of potatoes in highly compacted topsoils. Shallow root systems and reduced yield of cotton were also reported by Camp and Lund (1964). Restriction in water uptake by roots of rye grass, due to short root systems, was observed by Cornish *et al.* (1984) at a soil bulk density of 1.30 Mg m^{-3} at a soil water potential of -0.3MPa.

c. Soil compaction and nutrient requirement

A shortage of water and nutrients, due to restricted root growth and activity, is often experienced by plants grown in compacted soils. Parish (1971) concluded that soil compaction affects the mass flow of nutrients. Transport of ions such as calcium and magnesium, which are transported by mass flow, were found to decrease as soil compaction increased. Parish (1971) also found that compaction, due to restriction on root extention, seriously decreased the uptake of immobile ions such as phosphate and potassium. However, Cornish *et al.* (1984) concluded that increasing the soil bulk density from 1.00 to 1.54 Mg m^{-3}, resulted in an increase in the uptake of phosphorus per unit length of rye grass roots. This increase was associated with increased mass of soil, and thus increased mass of available phosphorus within the root zone. This higher concentration of phosphorus in the rhizosphere soil was not offset by the reduced root elongation rate, so total phosphorus uptake was reduced.

Draycott *et al.* (1970) and Jaggard (1977) found an interaction between soil compaction and fertilizer requirement in sugarbeet. As soil compaction increased, nitrogen requirement increased but phosphate requirement decreased.

d. Soil aeration and moisture interaction

Taylor and Ashcroft (1972) stated that the effect of low oxygen in soil was more important than that of excessive CO_2, in reducing water absorption. Gingrich and Russell (1956) reported that a range of soil moisture tension between 101.3 and 303.3 kPa, was considered to be sensitive for root growth. These authors also indicated that at low moisture stress, root growth was limited by an oxygen content of 10.5%. This result supports the conclusion of Taylor and Ashcroft (1972) that plants require higher oxygen levels as the soil moisture potential increases.

Since oxygen is reqired for respiration and for root permeability, active and passive water uptake by roots are affected by soil aeration. Taylor and Ashcroft (1972) described the reduction in nutrients uptake as affected by the oxygen content, followed the order of K > N > P > Ca > Mg.

e. Soil aeration and mechanical impedance interaction

Tacket and Pearson (1964a) concluded that there was a highly significant interaction between subsoil density and oxygen content on depth of cotton root penetration. These authors observed that at a bulk density of 1.30 Mg m^{-3}, the minimum level of oxygen for root penetration was 5%, while the minimum level at a bulk density of 1.50 Mg m^{-3} was 10%. At bulk densities greater than 1.50 Mg m^{-3}, the effect of mechanical impedance on root growth was more pronounced than the effect of low oxygen.

In addition to level of oxygen, Tacket and Pearson (1964b) reported that the interaction between soil bulk density and CO_2 content on rate of root penetration was highly significant. These authors also concluded that rate of root elongation declined as the CO_2 level increased above 12%, when bulk densities were in the range of 1.30 to 1.60 Mg m^{-3} with a constant oxygen level of 21%. At a bulk density of 1.70 Mg m^{-3} the effect of mechanical impedance on the rate of root growth was more detrimental than the effect of high CO_2 level. It appeared that at this high bulk density, the effects of CO_2 and O_2 levels on root growth were overshadow by those of mechanical impedance. A similar result was reported by Eavis (1972). Olymbios and Schwabe (1977) associated the yield reduction of carrots with the effect of interaction between mechanical impedance and low aeration. Gill and Miller (1956), Eavis (1972), and Olymbios and Schwabe (1977) concluded that abnormal shape of roots observed in a compacted soil resulted from poor soil aeration. Taylor and Ashcroft (1972) concluded that iron chlorosis observed in orange seedlings grown in a compacted soil, resulted from the combined effects of poor aeration and mechanical impedance.

2.1.4 Manure and soil physical properties

In addition to providing nutrients, the decomposition of animal and plant residues produces polysaccharide gums, which act as cementing agents in the formation of stable aggregates (Donahue *et al.*, 1971). Incorporating organic manures into a soil, to improve the physical properties of the soil, has commonly been practiced and the results of the studies have been documented. Jenkins (1935) reviewed a number of reports on the effects of farm-yard manure on soil moisture content. Keen (1927) concluded that drainage and aeration of a heavy soil could be improved by incorporating manure into the soil. Alderfer and Merkle (1943) reported that the addition of manure increased the number of granules at 7.5 - 15 cm level, and that water infiltration rate increased as a consequence of this. Sprague and Marrero (1931) and Jenkins (1935) reported that farm-yard manure is often incorporated into compacted and cracked sandy and loam soils to eliminate the adverse effect of compaction and to provide a favourable condition for plant growth. A similar practice was suggested by Olu *et al.* (1985).

Salter and Haworth (1961) found that incorporating farm-yard manure at 45 t ha^{-1} $year^{-1}$ into a sandy loam soil over a six-year period, increased the available water holding capacity of the soil by 33%. In this experiment, the greatest increase (75%) was recorded in 0 - 15 cm soil layer. A similar result was reported by Salter and Williams (1963), who found that manure improved the pore-size distribution and structure of the soil, to provide available moisture retention. Salter *et al.* (1967)

concluded that the relationship between moisture content and log matric potential of a sandy loam soil was linear, and the manured soil always had higher matric potential than unmanured soil at equivalent water contents.

2.2 Soil temperature and moisture relationship and its effect on root growth and crop yields

2.2.1 Soil temperature

Besides soil heat flux and soil water flux, radiation and thermal energy balances have dominant influences on soil temperature (Voorhees *et al.*, 1981). These researchers (1981) stated that mean solar radiation is about 1.39 kW m^{-2}, and that only 33% of this radiation directly reaches the surface of the earth (Figure 2.3). Net radiation recieved at a soil surface, is expressed as :

$$Rn = Rs(1 - \rho) + Rl \tag{2.1}$$

where Rl is the net long wave radiation, Rs is global short wave radiation and ρ is albedo (Hanks and Ashcroft, 1980). As albedo or the reflection coefficient determines the amount of global radiation reflected by the surface (Voorhees *et al.*, (1981), there is a direct relationship between the effect of colour and roughness of the surface, and the radiation balance at the surface (Qashu and Evans, 1967). Voorhees *et al.* (1981) concluded that the albedo may vary from 0.02 to 0.85. Hanks and Ashcroft (1980), and Voorhees *et al.* (1981) reported that wet or black surfaces have a lower albedo than dry or white surfaces. In addition, Voorhees *et al.* (1981) concluded that plant residues reflect greater radiant energy than soil surfaces.

Hanks and Ashcroft (1980) stated that soil mulch or a mulch placed on the surface of a soil becomes an insolator for heat flows into or out of the soil. Willis and Raney (1971) concluded that thermal conductivity, thermal diffusivity, and heat capacity increased as the soil water increased. These authors also reported that both the thermal conductivity and diffusivity increased as the soil bulk density increased.

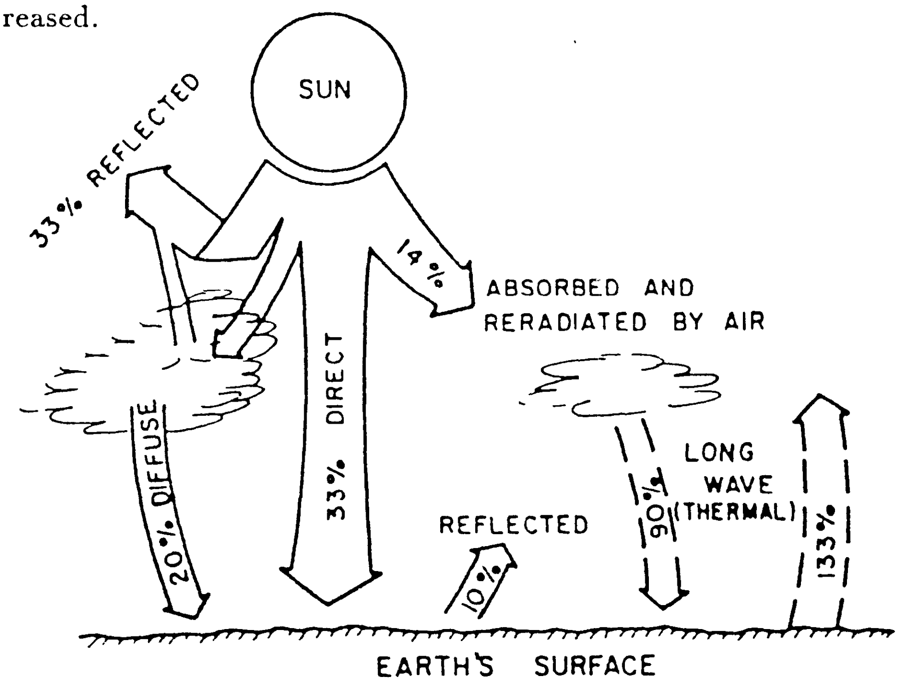

Figure 2.3: Schematic of radiation balance at Earth's surface (annual global average) (after Voorhees *et al.*, 1981)

As radiation reaches a soil surface, the temperature at the surface increases. Fluctuation in soil temperature is much greater at the surface than at lower depth of the soil. The time, at which the soil temperature at the surface reaches the maximum, is usually earlier than that reached at the lower depths (Figure 2.4). A similar time lag occurs at night time, when the heat energy is released from the soil (Hanks and Ashcroft, 1980; Voorhees *et al.*, 1981).

a. The effect of soil temperature on root growth

Voorhees *et al.* (1981) stated that the growth and function of roots, and the final yield of crops are affected by soil temperature, which can directly be modified by cultural practices (Figure 2.5).

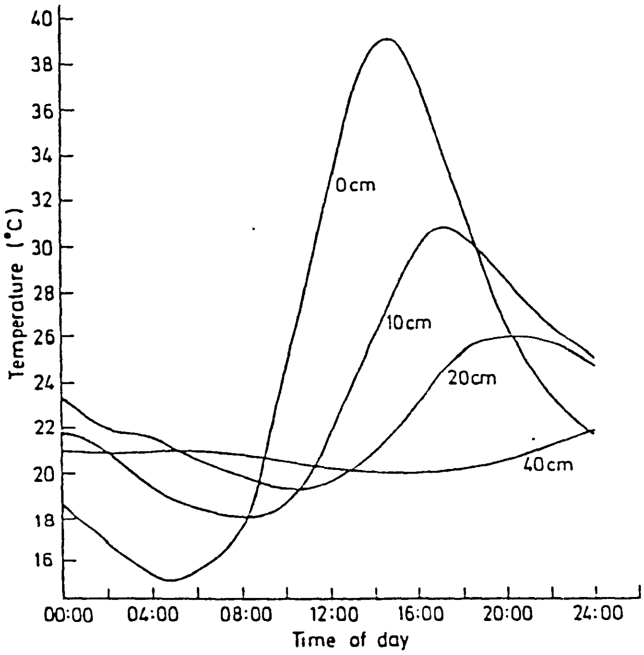

Figure 2.4: Soil temperature at four soil depths: 0.10.20.40 cm (after Hanks and Ashcroft, 1980).

Soil temperature affects crop growth through its effect on physiological aspects of root growth, such as the rate of water and nutrient absorption, translocation, and respiration. Voorhees *et al.* (1981) stated that the effect of temperature on these processes was at the cellular level. Each of these processes has a different response to temperature (Q_{10}). In relation to the physiological processes and growth, temperature is commonly described as cardinal temperatures, which includes minimum, optimum, and maximum temperature. Based on the level of effects produced, Montheith (1979) distinguished three kinds of temperature effects on plant growth as reversible, irreversible, and catastrophic effect.

Walker (1969) reported that a 20% increases in total maize seedling dry weight was recorded as a result of one degree increment in soil temperature from 12^0 to 26^0C, but a 12% reduction was found when the temperature increased above 26^0C. Voorhees *et al.* (1981) concluded that the optimum temperature for most plant species is in a range of 20^0 to 30^0C. Gardwood (1968) and Pearson *et al.* (1970) reported that diameter and elongation rate of roots decreased as soil temperature increased over 32^{0}C. Cooper (1973) concluded that colour of most roots becomes darker in a temperature range of 10^0 to 30^{0}C. This was associated with advanced maturity or suberization of the root tissue as the temperature increased. Bradley *et al.* (1967) reported that the best colour of carrot roots was obtained when the average soil temperature remained below 18.5^{0}C for at least several weeks before harvest.

b. The effect of soil temperature on water and nutrient uptake

The viscosity of water decreases as the temperature increases. Voorhees *et al.* (1981) reported that the viscosity of water at 25^{0}C is about half of that at 0^{0}C. However, the permeability of cell membrane and the metabolic activity increases as temperature increases. This results in increases in both passive and active water absorption. Mack (1965) reported that as soil temperature increased from 9^0 to 18^{0}C, the absorption of N, P, and K by barley roots greatly increased. Lal (1974b) found that at soil temperature of higher than 35^{0}C, total N, P, K, and Zn absorbed by roots of maize seedlings decreased. Gammore-Neumann and Kafkafi (1985) observed that maximum absorption rate of total nitrogen, in both ammonium and nitrate form, was at a temperature of 25^{0}C.

c. Response of crop yields to soil temperature

Kanemasu *et al.* (1975) indicated that the optimum temperature for sorghum growth was 23^{0}C, while that for carrot was recorded by Richards *et al.* (1952) and Hegarty (1973) in the range of 18^0 to 25^{0}C. Hurd and Graves (1985) reported that increasing root temperature up to 27^{0}C resulted in a 10% increase in tomato yield, while Gosselin and Tradel (1986) concluded that maximum yield of pepper was obtained at a temperature of 30^{0}C.

Bourke *et al.* (1984) reported that a minimum soil temperature of 18^{0}C was required for good establishment of cassava. A similar minimum temperature was required for that of American ginseng (Lee *et al.*, 1986). Although tuber initiation of potatoes occured rapidly at relatively low temperatures of 10^0 to 15^0C (Epstein, 1966), more uniform shapes of tubers and the highest yield was obtained at soil temperatures in the range 15^0 to 24^0C (Yamaguchi *et al.*, 1964).

Lal (1974b) recorded a significant reduction in shoot and root growth, and in the transpiration rate of maize seedlings, under both a constant temperature of 35^0C and a fluctuating temperature regime of between 30^0 to 40^0C. Evenson *et al.* (1978) observed better growth of ginger under the fluctuating temperature with the optimum of 29^0C than under a constant temperature of 27.5^0C. However, Keating and Evenson (1979) reported that sprouting and sprout elongation of cassava stem cuttings under constant soil temperatures was not significantly different from that under alternating temperatures below 28.5^0C.

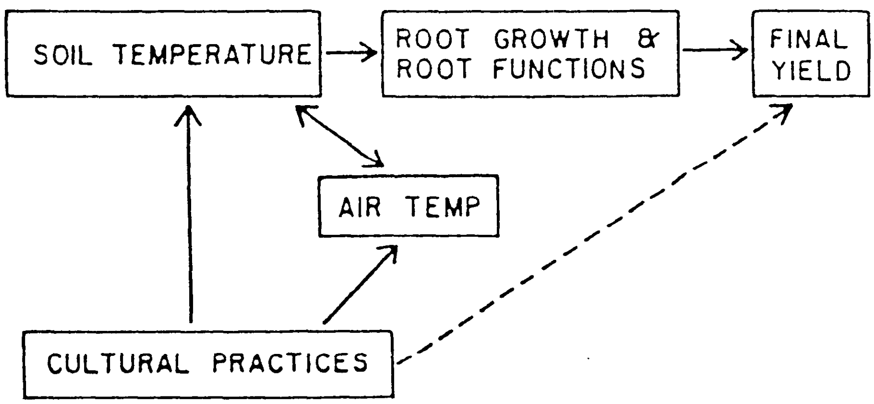

Figure 2.5: Schematic of relationship between soil temperature modification and final yield (after Voorhees *et al.*, 1981)

2.2.2 The effects of soil temperature and moisture on root growth

Willis and Raney (1971), and Hanks and Ashcroft (1980) stated that soil water content influences the distribution of heat in the soil. The thermal conductivity, heat capacity, and thermal diffusivity, are reported to increase with soil water content. Voorhees *et al.* (1981) reported that a dry surface, either soil or vegetation, reflects more incoming radiant energy compared to a wet surface. In a dry soil, water is less available for evaporation and the energy goes into heating the soil or the air (Hanks and Ashcroft, 1980).

The effect of temperature on the viscosity of water is thought to be the cause of decreased water and nutrient uptake at low soil temperatures. Mack (1965) recorded greater absorption of N, P, and K during the early growth stage of barley, either as the soil moisture or soil temperature increased. This researcher found that the availability of P from the soil rather than from fertilizer, is more affected by soil temperature than by soil moisture. Knavel and Mohr (1967) reported that soil temperature affects CO_2 and O_2 contents, and nitrification in soil, through its effect on soil moisture. Standford *et al.* (1973) confirmed that nitrification increases in a better soil moisture and at a more favourable soil temperature. Higher mean soil temperature was recorded by Tumuhairwe and Gumbs (1983b) on un-irrigated plots than on irrigated plots. Increasing the frequency of irrigation was reported to result in decreasing the mean soil temperature. .

Mulching and irrigation are reported to offer great adventages in improving soil condition and increasing crop yields, through modification of soil temperature and soil moisture (Prihar *et al.*, 1979; Voorhees *et al.*, 1981; Tumuhairwe and Gumbs, 1983b; Midmore *et al.*, 1986).

2.2.3 Mulching

Jacks *et al.* (1955) defined mulching as: "the use of crop residues, manure, leaves, peat and other litter as well as paper, glasswool, metal foil, cellophane and convenient manufactured materials as mulches, with or without shallow tillage, for the purpose of increasing soil productivity". The beneficial effects of mulching on root growth and crop yields are associated with its effects on soil moisture, temperature, and structure (McCalla and Duley, 1946; Jacks *et al.*, 1955; Hanks *et al.*, 1961; Prihar *et al.*, 1979; Poincelot, 1980; Maurya and Lal, 1981; Tumuhairwe and Gumbs, 1983a,b; Midmore *et al.*, 1986; Simpson and Gumbs, 1986a,b; Vander Zaag *et al.*, 1986). Protecting a soil surface by mulching prevents water loss by evaporation, modifies soil temperature, and supresses weed growth (Hanks *et al.*, 1961).

a. Effect on soil moisture

The advantage of mulches in conserving soil moisture is widely reported in the literature. Hanks *et al.* (1961) recorded significantly less evaporation under mulches (straw, gravel, and plastic) than on bare soil, but they found no differences among the different mulch materials they used. Tukey and Schoff (1963) recorded approximately 25% to 30% less evaporation and 300% greater infiltration rate under mulches (decomposing and non-decomposing materials) than on bare soils. A similar finding was reported by Black and Greb (1962). These authors associated NO_3 accumulation with higher soil moisture under plastic mulch. Midmore *et al.* (1986) concluded that mulches were more effective in conserving moisture at shallower soil depths. Nevertheless, Simpson and Gumbs (1986a) recorded a higher moisture content at 0-15 cm and 15-30 cm soil depths under mulches than on bare plots. Tumuhairwe and Gumbs (1983b) also recorded an increase of 40% and 20% available water content under organic mulches, with or without irrigation respectively. In this experiment, the 70% available water content required for high cabbage yields, was achieved in mulched plots by applying 50% less water than to unmulched plots.

The effectiveness of mulches in conserving soil moisture varies with materials and the colour of mulches (Stephenson and Schuster, 1946; Turk and Patridge, 1947; Tukey and Schoff, 1963; Courter and Oebecker, 1964; Lippert *et al.*, 1964; Hopen, 1965; Aase *et al.*, 1968; Maurya and Lal, 1981; Chaudhary and Chopra, 1983). Straw and gravel mulches, due to their higher permeability, are reported to be less effective in conserving soil moisture (Hanks and Woodruff, 1958). However, Benoit and Kirkham (1963) suggested that gravel mulch was more effective than dust or ground corn cob mulch, while Stephenson and Schuster (1946) concluded that straw is superior in saving moisture compared to trashy mulch. In the experiment with orchard soils, Turk and Patridge (1947) found that straw was more effective than peat, in decreasing moisture loss. However, higher soil moisture was recorded in the upper 15 cm soil layer under straw and peat moss than under plastic mulch. Unger and Parker (1968) recorded less evaporation (19% and 57% respectively) in plots, where straw was placed in a layer just below or on the soil surface, compared with straw mixed uniformly in the soil.

Polyethylene sheets,which are extensively used in intensive crop production (Wells and Loy, 1985), are also reported to have beneficial effects in conserving soil moisture (Harris, 1965; Lippert *et al.*, 1964;Knavel and Mohr, 1967). Hopen (1965) recorded higher soil moisture at 0-30 cm depths under polyethylene mulches than in unmulched plots. Ekern *et al.* (1967) concluded that placing a polyethylene film on a soil surface, prevents heat flows into and water vapour evaporation from the soil. In dry tropical regions in Africa, plastic mulches were reported to result in significant increases in the yield of vegetable crops (Anon., 1986). A similar finding was reported by Lal (1974a).

Russell (1939) reported that the thickness of mulches applied on the surface of a soil have little effects on the effectiveness of mulches for moisture conservation. In this experiment, reduction of only 7% in evaporation was recorded under straw mulch at a rate of 31 t ha^{-1} than at 4.5 t ha^{-1}. Mc Calla and Army (1961) concluded that 2 t ha^{-1} straw generally provides sufficient protection, and that the minimum quantity would depend on climatic conditions, soil type, and other factors.

b. Effect on soil temperature

The most effective means of modifying soil temperatures is probably a surface mulch, particularly plant residues (Voorhees *et al.*, 1981). Gradwell (1955) reported that soil temperature during winter was increased by surface mulch mainly through insulation effects. McCalla and Duley (1946) reported that organic mulches keep the soil temperature cool during summer and warm during winter. Voorhees *et al.* (1981) stated that modification in soil temperature brought about by mulches, is mainly due to alteration of albedo, thus through changes in the net radiation balance at the soil surface. Maurya and Lal (1981) working at Ibadan, Nigeria, found that straw mulch reduced the maximum soil temperature at 5 cm depth by 3^0C, while black and white polyethylene (transparent) mulches increased the minimum by 2^0 and 5^0C respectively, compared to bare soils.

Allmaras *et al.* (1973) reported that applying 1 t ha^{-1} small grain residues as mulch, resulted in about 0.15 to 0.30^0C decrease in soil temperature at a depth of 10 cm. A decrease of 8^0C at 5 cm depth was recorded by Lal (1974a) with residue application of 4 t ha^{-1}, under warmer and drier climates at Ibadan. Allmaras and Nelson (1971) found that 4.5 t ha^{-1} of straw mulch reduced mean daily temperatures up to 2^0C at 5 cm depth.

The physical condition of mulch is an important factor in determining its effect on soil temperature (Jacks *et al.*, 1955). Due to lower albedo of black mulch, soil temperature under this mulch is usually higher than under bright coloured materials (Jacks *et al.*, 1955; Clarkson, 1960; Hanks *et al.*, 1961). Kanemasu *et al.* (1975) reported that white clay is highly reflective (albedo = 65%), which results in lowering of soil temperature.

Plastic mulch modifies soil temperature by altering the reflection coefficient (albedo) and the amount of heat used for evaporation (Voorhees *et al.*, 1981). Clarkson (1960) recorded about 2.8^0C higher soil temperature under black plastic than on bare soils. An increased soil temperature of 8^0 to 12^0C was measured in the upper 5 cm, by Jacobsohn *et al.* (1980) during a hot season under a black plastic sheet. Takatory *et al.* (1964) reported that the increase in soil temperature under black plastic was less than under clear plastic mulches. However, during the night the soil was warmer under the black plastic mulch. Similar results were reported by Harris (1965), Hopen (1965), Dinkel (1966), and Knavel and Mohr (1967). Hanks *et al.* (1961) and Kanemasu *et al.* (1975) associated the higher soil temperature under clear plastic compared with bare soils, with the "greenhouse effect" produced under the plastic, the lower ventilation of the soil surface, and increased incoming net radiation under the plastic.

Russell (1939) stated that the thickness of mulch has little effect on soil moisture conservation, but Maurya and Lal (1981) reported that soil temperature, particularly at the hottest time of the day (1400 - 1500 hours), could effectively be reduced by applying a 10 cm thickness of straw mulch. These authors recorded a 69.4% and 91.7% higher seed yield of maize in mulch treatments of 5 cm and 10 cm thickness respectively.

Voorhees *et al.* (1981) concluded that the effectiveness of organic mulch decreases with time. As the colour of mulches becomes darker, the albedo decreases. Hanks *et al.* (1961) found no differences in net radiation recorded on surfaces covered with fresh straw compared to bare soils, after 3 months. Moody *et al.* (1963), Voorhees *et al.* (1981), Maurya and Lal (1981), and Midmore *et al.* (1986), reported that the effect of mulch on soil temperature is more pronounced at the early growth stage of crops. As the canopy develops, the difference in soil temperature between mulched and bare soils becomes smaller. Voorhees *et al.* (1981) also concluded that differences in albedo between mulched and bare soils, decreased as the soil moisture decreased.

c. Effect on soil structure and soil aeration

Apart from soil temperature and soil moisture, the structure and aeration of the soil are also influenced by mulch application (Jacks *et al.*, 1955; Schales and Sheldrake, 1966). Qashu and Evans (1967) observed that the surface of bare soils dried 12 - 19 days earlier than that of black granular mulch. These authors also found that the surface of bare soils cracked. Van Doren and Stauffer (1943) concluded that decreased infiltration rates in bare soils was due to a compact layer 3 mm thick on the surface, which was produced as a result of rain drops and runoff action. Stephenson and Schuster (1946) found an increased proportion of aggregates larger than 1.0 mm in the layer of 2.5 - 5 cm, under organic mulches.

Tukey and Schoff (1963) found that soil aeration also increased under organic mulches, particularly where fibrous materials, such as legume hay and straw were used. However, better aeration (O_2 : CO_2 = 5 : 1) was found under non-organic but fibrous mulch, e.g. glass-fibre.

Increased potato yield under straw mulch treatment, due to reduced maximum soil temperature, was reported by Vander Zaag *et al.* (1986). A similar result was reported by Tumuhairwe and Gumbs (1983a,b) on cabbages, by Maduakor *et al.* (1984) on yams, by Tripathi *et al.* (1985) on wheat, and by Chaudhary *et al.* (1985) on summer mung beans.

Acceleration on the emergence of carrot seedlings under clear plastic mulch was reported by Finch-Savage (1986) to result in higher percentage of emerged seedlings. Dinkel (1966) concluded that the use of clear plastic mulch encouraged germination accelerated the growth of early sweet corn, in a cold region like Alaska.

2.2.4 Irrigation

Irrigation is aimed to alleviating plant water stress, by increasing the available water to plants (Unger, 1981). Voorhees *et al.* (1981) stated that irrigation is also a manner for stabilizing fluctuations in soil temperature. Much of the incoming radiant energy on a wet soil is used for evaporation, thus the temperature of a wet soil is lower than a dry soil. Voorhees *et al.* (1981) reported that at 300 mm depth irrigated soil had a temperature 1.1^{0}C lower than unirrigated soil. A temperature difference between treatments persisted for 5 days after irrigation. Prihar *et al* (1979) concluded that irrigating at a soil moisture potential of -25 kPa at 10 cm depth, resulted in a 27% higher yield of potatoes than when irrigation was carried out at -50 kPa. This higher yield was associated with reduced maximum soil temperature under frequent irrigation. A similar result was reported by Box *et* *al.* (1963), and Tumuhairwe and Gumbs (1983b).

Chapter 3

Effects of soil bulk density and water regime on carrot yield harvested at different growth stages

3.1 Introduction

The most important problem encountered by carrot growers is poor establishment of seedlings, abnormal root growth and low yields, which finally affect the value of marketable fresh roots (Orzolek and Carroll, 1978; Strandberg and White, 1979).

Results of studies have indicated that a number of environmental conditions have significant influences on the the shape, size, and yield of carrot roots (Barnes, 1936; Thompson, 1969; Stanhill, 1977; Benyamin, 1984). Cultural practices such as nutrition (Barnes, 1936; Woodman, 1943; Southards and Miller, 1962; Salvestrin, 1984), length of growing season (Chipman, 1959; Austin and Longden, 1967; Phan and Hsu, 1973), plant density (Mann and MacGillivray, 1949; Banga, 1955; Bienz, 1965; Curah, 1976; Stanhill, 1977; Salter *et al.*, 1979, 1980; McCollum *et al.*, 1986), and soil structural conditions (White, 1978; Orzolek and Carroll, 1978; Millette *et al.*, 1981; Strandberg and White, 1979; Taksdal, 1984), are reported to have effects on yield and quality of carrot roots.

Most studies have indicated that soil compaction has direct effects on root growth as a result of increased impedance to root elongation, restriction in soil water availability, reduced soil aeration, or a combination of these factors. The critical effect of these factors varies with the soil type, the climatic condition, plant species, and possibly with the stage of development of the plant (Rosenberg, 1964).

Excessive tillage in bed preparation results in adverse soil structure, particularly in fine textured soils and or where the soils are compacted. This is considered to be a major cause of reduction in carrot yield and quality (Millette *et al.*, 1981). White (1978) concluded that rolling, as one of the tillage practices used in carrot production, contributes markedly to soil compaction. This researcher reported that higher carrot yields and fewer forking roots were found in the non-rolled treatment. Taksdal (1984) concluded that tractor wheel compaction resulted in a reduction in carrot length, and yield of grade I carrot, and an increase in conical roots.

Studies on carrot response to soil compaction (e.g. Olymbios and Schwabe, 1977; Strandberg and White, 1979; White, 1978; Orzolek and Carroll, 1978; Millette *et al.*, 1981; Taksdal, 1984), have been conducted at constant soil moisture. On the other hand, experiments on carrot irrigation have been mostly carried out in loosely compacted soils (e.g. Salter and Goode, 1967; Henkel, 1970; Cavalchini, 1972; Silva *et al.*, 1982; Millette, 1983).

The effect of soil bulk density on root elongation rate of soybean, maize, cowpea, and pigeon pea, is often confounded by the effect of soil moisture regime (Maurya and Lal, 1979). Although the optimum range of moisture and densities varies with crop species, these researchers have found that root elongation rates (cm day^{-1}) of cowpea are low at high bulk densities (e.g. from 1.50 to 1.80 Mg m^{-3}) and low soil moisture content (e.g. from 11% to 1%).

There is very little information on the interaction of soil bulk density and moisture regime on carrot root growth, and no information is available on the stages at which carrot growth are sensitive to this interaction.

In the study reported here, carrots were grown in PVC pots at four bulk densities and with two watering regimes, with harvest being taken at three different stages of growth. The objectives of the experiment were :

1. to study the response of carrot growth and yield to different levels of soil bulk density and moisture regime.

2. to obtain information on the effects of these variables at different stages of carrot growth.

3.2 Materials and methods

3.2.1 Treatments and experimental design

A factorial combination of four soil bulk densities, two water regimes, and three harvesting times, were arranged in a randomized complete block design with three replicates. The treatments employed were as follows :

4 bulk densities (1.25, 1.40, 1.55, and 1.70 Mg m^{-3})

× 2 water regimes (high and low water regime)

× 3 harvesting times (68, 103, and 153 days after planting).

The experiment was conducted in the glasshouse of the Department of Agronomy and Soil Science, University of New England, Armidale, from July 5 to December 3, 1985.

3.2.2 Soil and carrot variety

Top soil of a loamy sand collected from Teatree Creek, Bundarra road, Armidale, was used in this experiment. Details of the particle size distribution of the soil used in this experiment are presented in Appendix A.1. The soil, which had pH of 6.0, had been steam sterilized at 75^{0}C for 30 minutes, before being passed through a 0.25 cm sieve and air dried.

Hybrid-4 seed, which is the first hybrid carrot variety bred and produced in Australia (Anon., 1985), was used in this experiment. This variety has a smooth, stump-end and medium length storage roots. The normal size of the storage root is 20 - 23 × 3 cm, and it is rich orange in colour. The tops of this variety grow strongly (Anon., 1985).

3.2.3 Pots

White polyvinyl chloride (PVC) pipes of 15 cm internal diameter and 31 cm long were used as pots. The pipes were split lengthwise, then rejoined with plastic insulation tapes and wires of 1.60 mm. This was done to facilitate washing and to prevent breaking roots by re-opening the split. To allow good drainage, a PVC disk having several holes of 0.2cm in diameter was fixed to the bottom of the pipe.

3.2.4 The treatments

a. Soil bulk density

Different bulk densities were obtained by compacting different mass of soil to achieve the same volume of soil in the pots. The lowest bulk density (1.25 Mg m^{-3}) was produced by placing the soil into the pot and tapping it lightly on the floor. To produce bulk densities of 1.55 and 1.70 Mg m^{-3}, a small amount of water was mixed with the air dried soil, and was divided into five equal portions on a weight basis. A bulk density of 1.40 Mg m^{-3} was produced in a similar manner with these two bulk densities, but no water was added. Details of mass of soil used and amount of water added to produce different bulk densities, are presented in Appendix A.2. Every portion of soil was placed in the pot and compacted using a flat steel rammer, whose diameter was slightly smaller than the inside diameter of the pot. To obtain a uniform compaction, this portion of soil was compacted several times to achieve a depth of 5 cm. This resulted in a total soil depth of 25 cm.

b. Watering regime

Two watering regimes were designated as the high and low water regime. In the high water regime, soil moisture content in the pot was allowed to deplete to 70% of field capacity (i.e. the moisture potential was approximately -70 kPa). In the low water regime, the soil was allowed to dry to 30% of field capacity (i.e. the moisture potential was about -800 kPa) before rewatering. The water stress was imposed 55 days after planting. Five tensiometers of mercury manometer type (Richards, 1965) were placed at random in the pots for each bulk density treatment, to monitor the soil water potential in the high water regime. Soil moisture content and water loss was computed daily, based on the weight of the pots. Soil samples were taken using a small core, and the moisture content was determined gravimetrically to monitor the soil moisture content. Soil moisture potential in the low water regime was determined using a thermocouple psychrometer. Soil samples were taken periodically at random from each bulk density treatment in this water regime, using a small core, before being measured in the psychrometer. An amount of 5 g polystyrene beads per pot was placed on the surface of the soil in all pots, to reduce evaporation.

However, during the first growth stage, the plants in all treatments exhibited symptoms of nitrogen and phosphorus deficiency, which were indicated by the purple and yellow leaves at the base of the plants (Wallace, 1961). Due to this disorder, and to unreliable readings of the tensiometers, it was decided to cease the water stress treatment at this time and to re-start it after the first harvest (68 days after planting). Eight vacuum-gauge tensiometers (Richards, 1965) were installed at random in pots at each bulk density treatment 90 days after planting, to replace the previous tensiometers. Since the readings of these tensiometers were sometimes unreliable, watering was based on the weight of the pots. Gently watering brought the moisture content in the pots back to the weight corresponding to field capacity.

c. Harvesting time

Plants were harvested at three different times, namely on September 16, October 22, and December 3, 1985, i.e. 68, 103, and 153 days after planting the pre-germinated seeds respectively. An additional four pots at each bulk density level were maintained to monitor the development of storage roots, and these observations were used to determine harvest times.

3.2.5 Management

Prior to compaction, the soil for each pot was mixed thoroughly with the nutrient solutions using a small cement mixer. The same amount of inorganic fertilizer was given as a basal nutrient to all pots. The amount of fertilizer applied , was based on the results of a preliminary experiment. The rates of elements and chemicals used, are presented in Appendix A.3. An amount of 150 kg N ha^{-1}, 60 kg P ha^{-1}, and 90 kg K ha^{-1}, was applied as a basal application. The soil was then compacted to the desired bulk density. Before planting, moisture content in all pots was brought to field capacity.

Sixteen pre-germinated carrot seeds with radicles only as long as the seed coats, were planted in each pot on July 10, 1985. A small amount of soil was sprinkled over the seeds and approximately 50 mls of water was used to moisten the soil surface. All pots were then covered with plastic sheets and newspapers to provide high humidity and to protect seedlings from direct sunlight. The plastic sheets and newspapers were removed seven days later, by which time the plumules had already appeared. In the next seven days, the seedlings were thinned to three plants per pot. Another 395 kg N ha^{-1}, 200 kg P ha^{-1}, and 41 kg K ha^{-1}, was given periodically from 38 days after planting until the last harvesting time, with a week alternative application in the forms of NH_4NO_3, $(NH_4)H_2PO_4$, $(NH_4)_2HPO_4$ or aquasol. All pots were placed on a bench in the glasshouse and rerandomized every seven days.

3.2.6 Data collection

Soil moisture data in the high water treatment was obtained by both recording the tensiometer readings and weighing the pots daily. For the low water treatment, psychrometer readings were recorded periodically.

At each harvest, the roots were carefully washed and the lateral roots were separated from the storage roots. The compound leaves, including the petiole, is referred to as tops in this thesis. Data for the storage roots and for the tops are presented as the fresh weight of each plant. The storage root length was measured from the cotyledonary node to the root tip (White and Strandberg, 1978). The diameter of the storage root was determined 1-2 cm below the hypocotyl area (crown) using calypers (Strandberg and White, 1979). Data on the length, diameter, and the fresh weight of storage roots, was used to calculate the cylindricality or the shape index of carrot using the equation :

$$C = \frac{W}{\pi r^2 h} \tag{3.1}$$

where W is the storage fresh weight, and r and h are the radius and the length of the storage root respectively (Thompson, 1969). The storage root : tops fresh weight ratio was computed from the fresh weight of storage roots and of tops. The total root length was measured using a Bizzometer, a root length measuring instrument, which utilizes television based scaling. This method, which was developed by Newman (1966) and refined by Evans (1970), relies on a linear relationship between total length (L) and the number of intersections (N), with a set of parallel scan lines of pitch (D) (Anon., 1982):

$$L = \frac{1}{2}\pi D N \tag{3.2}$$

On the day before the third harvest, penetration resistance of the soil in each bulk density treatment was measured using a soil cone penetrometer with a cross-sectional area of cone of 1.29×10^{-4} m^2. The force on the tip of the cone moving at a constant velocity, the "cone index", was used as an index of soil strength (Anon., 1983). The resistance of the soil to the penetrometer is expressed in kPa, by dividing the penetrometer reading (kN) by the cross-sectional area of the cone (m^2). The day before this measurement was conducted, all pots were watered to field capacity. The soil moisture content for each bulk density was determined after the readings of penetration resistance were taken. The relationship between the resistance of the soil to penetrometer and bulk density, and the soil moisture content at which the penetrometer readings were taken for each bulk density, are presented in Figures

3.4, and 3.5 respectively.

3.2.7 Data handling

A standard computer programme NEVA (Burr, 1982) was used to analyse the variance and means of the effects of soil bulk density and water regime either within each harvest or over all harvest times. Residuals were examined and where necessary logarithmic transformation was applied in order to stabilize the variance. Differences among means were tested using Duncan's multiple range test. Minitab and Lines programmes were used to compute the relationship between the soil moisture potential and moisture content.

3.3 Results

3.3.1 Yield and quality

In this experiment five yield parameters were recorded and statistically analysed. These parameters were the fresh weights of storage roots and of tops, and also the length of storage and of lateral roots. One quality parameter, that is carrot shape, was also measured and statistically analysed.

a. Storage root fresh weight

The effects of soil bulk density and water regime on the fresh weight of carrot storage roots at each harvest were analyzed and are presented in Figure 3.1[a,b,c]. The attempt to impose water stress before the first harvest (section 3.2.4b) resulted in a reduction in storage root fresh weight in the low water treatment, at the bulk density of 1.25 Mg m^{-3} (Figure 3.1[a]). At this harvest, the storage root fresh weight decreased as the bulk density increased.

At the second harvest (Figure 3.1[b]), the storage root fresh weight at the bulk densities of 1.25 and 1.40 Mg m^{-3} was significantly higher in the high than the low water regime, but there were no significant differences at the other two bulk densities. In both the high and the low water regime, at this second harvest, the yield was significantly decreased only at the bulk density of 1.70 Mg m^{-3}.

At the third harvest (Figure 3.1[c]), the storage root fresh weight was significantly higher under the high than the low water regime at each bulk density. In both these water regimes, as at the second harvest, the yield was significantly reduced only at the highest bulk density.

b. Tops fresh weight

Tables 3.1, 3.2, and 3.3 respectively presents the effects of bulk density × harvest interaction, of water regime × harvest interaction, and of the bulk density × water regime interaction ($P< 0.001$, $P< 0.001$, and $P< 0.01$). At the first harvest, the effect of bulk density on the tops fresh weight was not significant (Table 3.1). However, the tops fresh weights were significantly higher at the lower three bulk densities of 1.25, 1.40, and 1.55 Mg m^{-3} than at 1.70 Mg m^{-3}, at both the second and the third harvest. There were no significant differences among those lower three bulk densities.

Unlike the storage root fresh weight, no significant watering effect was measured on the tops fresh weight at the first harvest (Table 3.2). At the second and the third harvest, tops fresh weight was 42% and 19% higher in the high water regime respectively.

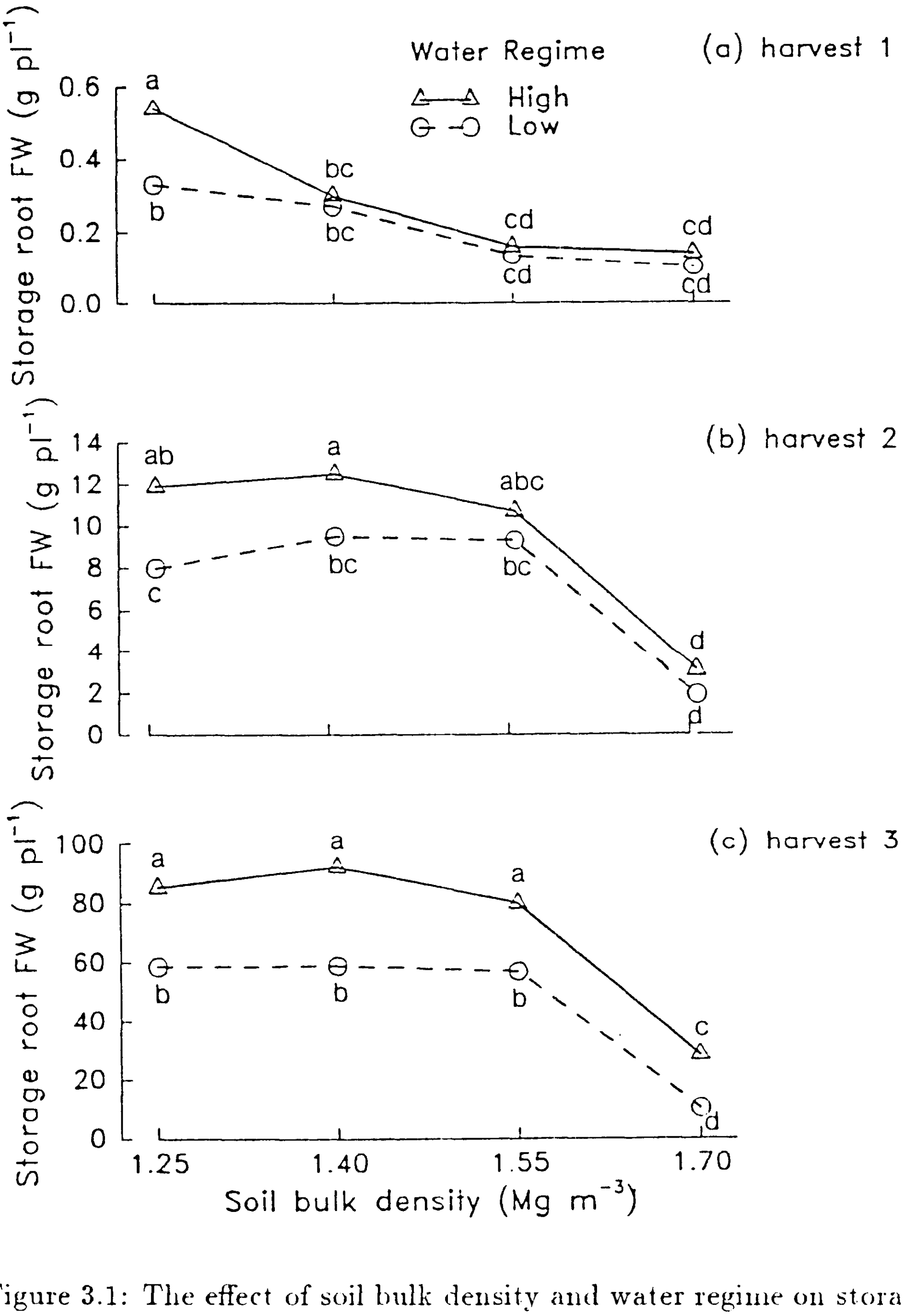

Figure 3.1: The effect of soil bulk density and water regime on storage root fresh weight analysed separately at harvest 1,harvest 2,harvest 3 [a,b,c]. Points marked with the same letter within harvests are not significantly different ($P > 0.05$)(Duncan's multiple range test).

Table 3.1: The effect of soil bulk density and harvest time on tops fresh weight (g $plant^{-1}$)

Soil bulk density ($Mg\ m^{-3}$)	Harvest 1 (68 dap)	Harvest 2 (103 dap)	Harvest 3 (153 dap)
1.25	0.43 *d*†	6.95 *b*	13.33 *a*
1.40	0.52 *d*	6.86 *b*	14.39 *a*
1.55	0.53 *d*	6.63 *b*	14.05 *a*
1.70	0.38 *d*	2.95 *c*	6.44 *b*

†Data followed by the same letter are not significantly different ($P > 0.05$) (Duncan's multiple range test).

Table 3.2: The effect of water regime and harvest time on tops fresh weight (g $plant^{-1}$)

Water regime	Harvest 1 (68 dap)	Harvest 2 (103 dap)	Harvest 3 (153 dap)
Low	0.46 *e*†	4.83 *d*	11.00 *b*
High	0.48 *e*	6.86 *c*	13.10 *a*

†Data followed by the same letter are not significantly different ($P > 0.05$) (Duncan's multiple range test).

In both water regimes, the tops fresh weight was significantly higher ($P < 0.01$) at bulk densities of 1.25, 1.40, and 1.55 $Mg\ m^{-3}$ than at 1.70 $Mg\ m^{-3}$ (Table 3.3). However, the tops weight among the lowest three bulk densities were not significantly different. At all bulk densities, the high water treatment resulted in higher tops fresh weight than the low water treatment.

c. Storage root : tops fresh weight ratio

The effects of the water regime × harvest interaction, bulk density × harvest interaction, and bulk density × water regime interaction on the storage root : tops fresh weight ratio were significant ($P < 0.05$, $P < 0.001$, $P < 0.05$; Table 3.4, 3.5, and

Table 3.3: The effect of soil bulk density and water regime on tops fresh weight (g plant^{-1})

Soil bulk density ($Mg\ m^{-3}$)	Water regime Low	High
1.25	6.0 *b*†	7.8 *a*
1.40	7.3 *ab*	7.2 *ab*
1.55	6.3 *b*	7.8 *a*
1.70	2.1 *d*	4.4 *c*

†Data followed by the same letter are not significantly different ($P > 0.05$) (Duncan's multiple range test).

3.6). The storage root : tops fresh weight ratio at all soil bulk densities increased significantly over time (Table 3.4). In both the high and the low water regimes, the storage root : tops ratio increased significantly over time, with the greatest increase being in the high water treatment.

At the first harvest, the storage root : tops ratio decreased significantly as the bulk density increased (Table 3.5). At 1.55 Mg. m^{-3}, the ratio was lower than at 1.40 Mg m^{-3}, but was not significantly different from the ratio at 1.70 Mg m^{-3}. At both the second and the third harvests, the ratio was significantly higher at the lower three bulk densities of 1.25, 1.40, and 1.55 Mg. m^{-3} than at 1.70 Mg m^{-3}. There was no difference found among these lower three bulk densities.

In the high water regime, the storage root : tops fresh weight ratio at the lower two bulk densities of 1.25 and 1.40 Mg m^{-3}, was significantly higher than that at the higher two bulk densities of 1.55 and 1.70 Mg m^{-3} (Table 3.6). In the low water regime, a bulk density of 1.70 Mg m^{-3} resulted in a significantly lower ratio of storage root : tops fresh weight than the lower three bulk densities (1.25, 1.40, and 1.55 Mg m^{-3}). The ratio at 1.40 Mg m^{-3} was significantly lower than that at 1.25 Mg. m^{-3}, but was not different from the ratio at 1.55 Mg m^{-3}. The high water treatment resulted in a significantly higher ratio of storage root : tops fresh weight only at a bulk density of 1.40 Mg. m^{-3} (Table 3.6).

Table 3.4: The effect of water regime and harvest time on storage root : tops fresh weight ratio

Water regime	Harvest 1 (68 dap)	Harvest 2 (103 dap)	Harvest 3 (153 dap)
Low	0.53 *d*†	1.44 *c*	4.56 *b*
High	0.63 *d*	1.32 *c*	5.49 *a*

†Data followed by the same letter are not significantly different (P> 0.05) (Duncan's multiple range test).

Table 3.5: The effect of soil bulk density and harvest time on storage root : tops fresh weight ratio

Soil bulk density ($Mg\ m^{-3}$)	Harvest 1 (68 dap)	Harvest 2 (103 dap)	Harvest 3 (153 dap)
1.25	1.09 *de*†	1.38 *cd*	5.59 *a*
1.40	0.60 *f*	1.67 *c*	5.71 *a*
1.55	0.29 *g*	1.51 *c*	5.99 *a*
1.70	0.32 *fg*	0.96 *e*	2.82 *b*

†Data followed by the same letter are not significantly different (P> 0.05) (Duncan's multiple range test).

d. Storage root length

There was a significant effect of the soil bulk density × harvest time interaction ($P < 0.001$) on the storage root length (Table 3.7). From the overall statistical analysis of the storage root length data for all harvests, it was found that the effect of the bulk density × water regime interaction was significant ($P < 0.05$). However, the effect of the bulk density × water regime is presented separately for each harvest in Figure 3.2 [a,b,c].

At all harvests, the storage root length decreased significantly as the soil bulk density increased above 1.40 $Mg\ m^{-3}$. However, at the first harvest, the length at 1.55 $Mg\ m^{-3}$ was not different from that at 1.70 $Mg\ m^{-3}$. A 27%, 58%, and 55% reduction in the length of the storage root was recorded at 1.70 $Mg\ m^{-3}$ compared

Table 3.6: The effect of soil bulk density and water regime on storage root : tops fresh weight ratio

Soil bulk density ($Mg\ m^{-3}$)	Water regime Low		High	
1.25	2.51	*abc*†	2.87	*ab*
1.40	2.14	*d*	3.18	*a*
1.55	2.79	*bcd*	2.41	*cd*
1.70	1.27	*e*	1.46	*e*

†Data followed by the same letter are not significantly different (P> 0.05) (Duncan's multiple range test).

to 1.25 Mg m^{-3}, at the first, the second, and the third harvest respectively.

Table 3.7: The effect of soil bulk density and harvest time on storage root length (cm)

Soil bulk density ($Mg\ m^{-3}$)	Harvest 1 (68 dap)		Harvest 2 (103 dap)		Harvest 3 (153 dap)	
1.25	2.82	*g*†	10.67	*c*	15.31	*a*
1.40	2.72	*g*	10.86	*c*	14.86	*a*
1.55	2.25	*h*	9.00	*d*	12.22	*b*
1.70	2.06	*h*	4.53	*f*	6.86	*e*

†Data followed by the same letter are not significantly different (P> 0.05) (Duncan's multiple range test).

At the first harvest, there was a difference in the storage root length recorded between the high and the low water treatment at 1.25 Mg m^{-3}, although the water stress was not applied until after this harvest (Figure 3.2[a]). At the second and the third harvests, at 1.70 Mg m^{-3}, a section of the storage roots was harvested from above the soil surface (Figures 3.2[b,c]). At the second harvest (Figure 3.2[b]), a significant difference of a 19% and 23% in the length was recorded above the soil surface, in the high and the low water treatment respectively. The corresponding figures at the third harvest were 13% and 24% (Figure 3.2[c]).

The effect of water regime on the storage roots in the soil, was not significant at the second harvest (Figure 3.2[b]). However, at the third harvest (Figure 3.2[c]), the storage root in the soil was significantly longer in the high than in the low water treatment, at the lowest and the highest bulk densities.

e. Total root length

Measurement on the total root length was carried out at only the second and the third harvests. There was a significant interaction of soil bulk density $\times$ water regime ($P < 0.001$). Figures 3.3[a,b] present the effects of bulk density and water regime on total root length of carrot (m $plant^{-1}$) for each harvest.

At the second harvest (Figure 3.3[a]), in both water regimes, the total root length at the lower three bulk densities (1.25, 1.40, and 1.55 Mg m^{-3}) was greater than at 1.70 Mg m^{-3}. However, there were no differences among these lower three bulk densities. The total root length was significantly higher in the high than in the low water regime, only at the lowest (1.25 Mg m^{-3}) and in the highest (1.70 Mg m^{-3}) bulk density.

At the third harvest (Figure 3.3[b]), the effect of bulk density on the total root length in the high water regime, was similar to that at the second harvest. In the low water regime, the bulk density of 1.40 Mg m^{-3} resulted in the highest total root length. At this harvest, the total root length at each bulk density was greater in the high than in the low water regime.

f. Carrot shape (cylindricality C)

There were significant interactions of soil bulk density $\times$ harvest time ($P < 0.001$), and bulk density $\times$ water regime ($P < 0.01$) on cylindricality (shape index) of carrots (Tables 3.8, 3.9).

At each harvest (Table 3.8), the cylindricalty was between 0.33 to 0.73, suggesting that carrot shape was between conical and cylindrical (Thompson, 1969).

At the first harvest (Table 3.8), the highest bulk density of 1.70 Mg m^{-3} resulted in significantly lower cylindricality than the lower three bulk densities, while there

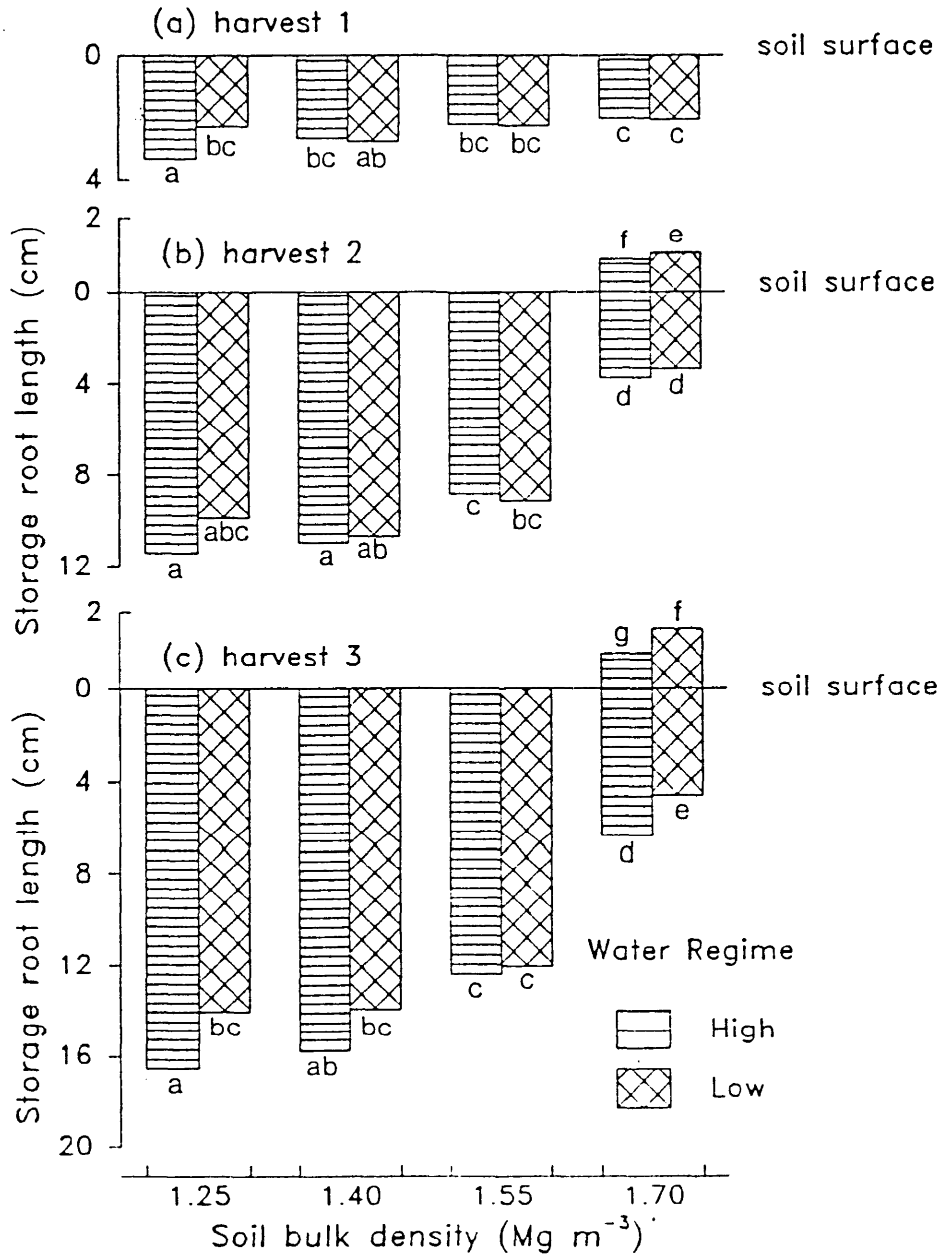

Figure 3.2: The effects of soil bulk density and water regime on storage root length (cm), analysed separately at harvest 1,harvest 2, and harvest 3 [a,b,c]. Points marked with the same letter within harvests are not significantly different ($P > 0.05$) (Duncan's multiple range test).

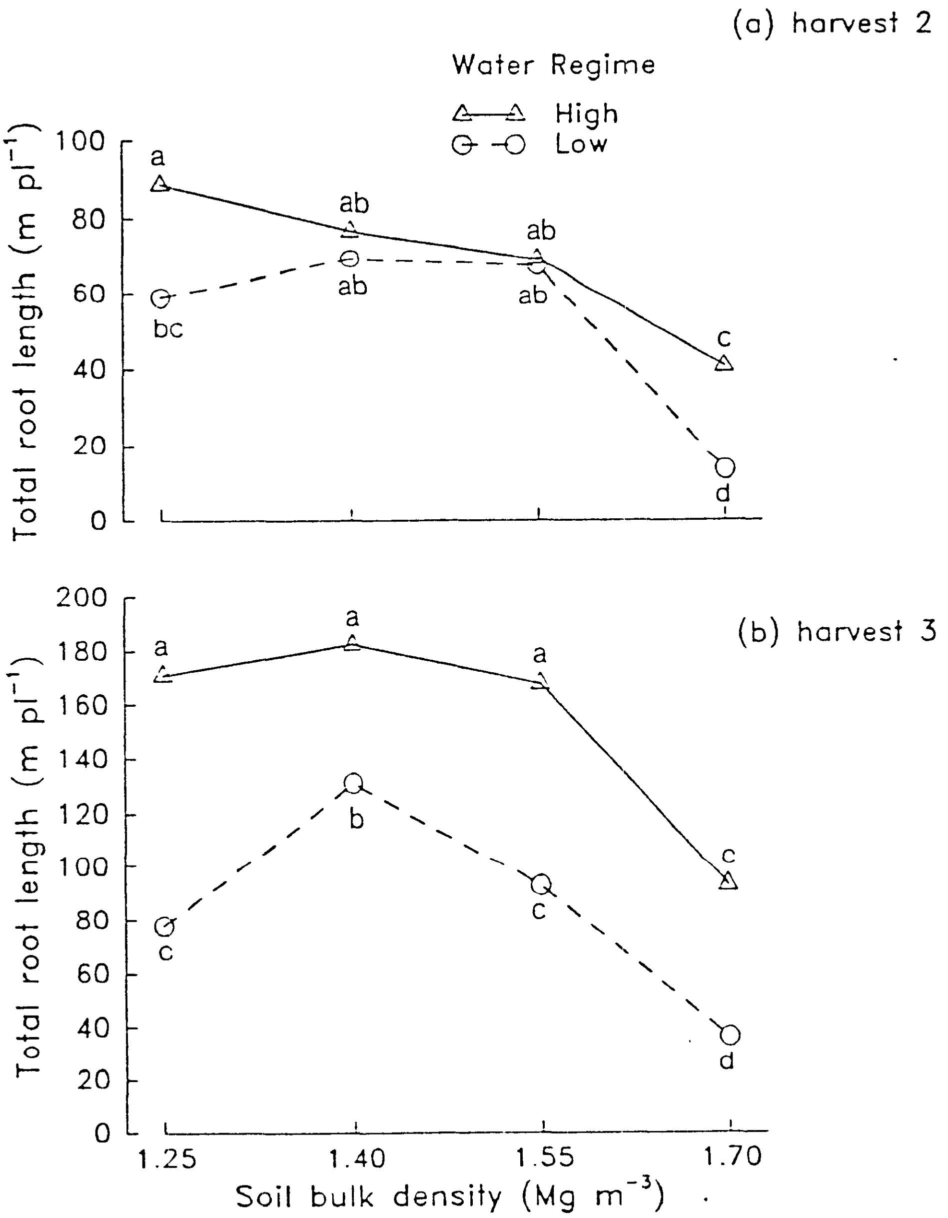

Figure 3.3: The effect of soil bulk density and water regime on total root length, analysed separately at harvest 2 and harvest 3 [a,b]. Points marked with the same letter within harvests are not significantly different (P> 0.05)(Duncan's multiple range test).

were no differences among these three bulk densities. At the second harvest, increased bulk density resulted in significantly decreased cylindricality. As at the first two harvests, the highest cylindricality at the third harvest was recorded at the lowest bulk density of 1.25 Mg m^{-3}, and the lowest at 1.70 Mg m^{-3}.

The effect of water regime on cylindricality was significant at each bulk density (Table 3.9). The cylindricality was always greater in the high than in the low water regime. In both water regimes, the highest cylindricality was found at the bulk density of 1.25 Mg m^{-3}. There was no difference recorded between the cylindricality at 1.40 and 1.55 Mg m^{-3}.

Table 3.8: The effect of soil bulk density and harvest time on cylindricality (C) of carrots

Soil bulk density ($Mg\ m^{-3}$)	Harvest 1 (68 dap)		Harvest 2 (103 dap)		Harvest 3 (153 dap)	
1.25	0.68	*abc*†	0.70	*ab*	0.73	*a*
1.40	0.65	*bc*	0.55	*e*	0.58	*de*
1.55	0.63	*cd*	0.48	*f*	0.55	*e*
1.70	0.45	*f*	0.34	*g*	0.42	*f*

†Data followed by the same letter are not significantly different (P> 0.005) (Duncan's multiple range test).

Table 3.9: The effect of soil bulk density and water regime on cylindricality (C) of carrots

Soil bulk density $Mg\ m^{-3}$	Water regime			
	Low		High	
1.25	0.62	*b*†	0.79	*a*
1.40	0.56	*cd*	0.62	*b*
1.55	0.53	*d*	0.58	*bc*
1.70	0.36	*f*	0.45	*e*

†Data followed by the same letter are not significantly different (P> 0.05) (Duncan's multiple range test).

3.3.2 Soil physical environment

a. Soil strength and moisture content

As mentioned in subsection 3.2.6 (Data collection), measurements on the soil strength and moisture content were carried out at the end of the experiment, after all pots had been watered to field capacity one day before the measurements. Figure 3.4 illustrates a highly significant ($P < 0.001$) relationship between soil bulk density and soil strength. The soil strength, as indicated by the cone index of penetrometer, increased as the bulk density increased.

Soil moisture content remaining in pots at the end of the experiment (Figure 3.5), was measured after the penetrometer readings were taken. As the bulk density increased from 1.40 to 1.70 Mg m^{-3}, the soil moisture content was significantly increased. However, there were no differences in moisture content recorded between the lower two bulk densities of 1.25 and 1.40 Mg m^{-3}, or between the higher two bulk densities of 1.55 and 1.70 Mg m^{-3}.

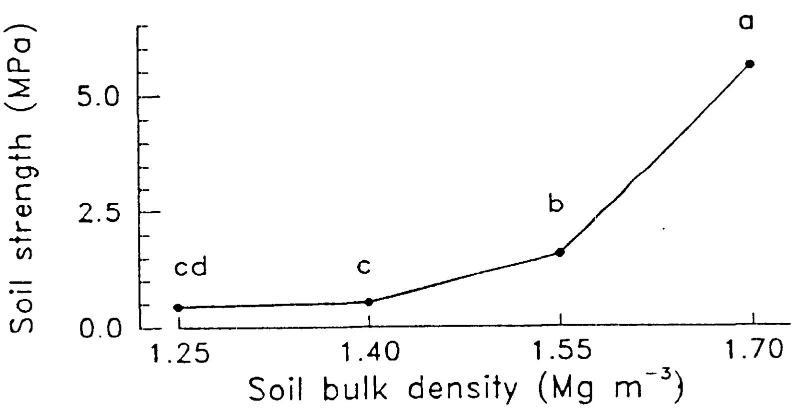

Figure 3.4: Soil strength (MPa) at each bulk density as measured by the cone penetrometer. Points marked with the same letter are not significantly different ($P > 0.05$)(Duncan's multiple range test).

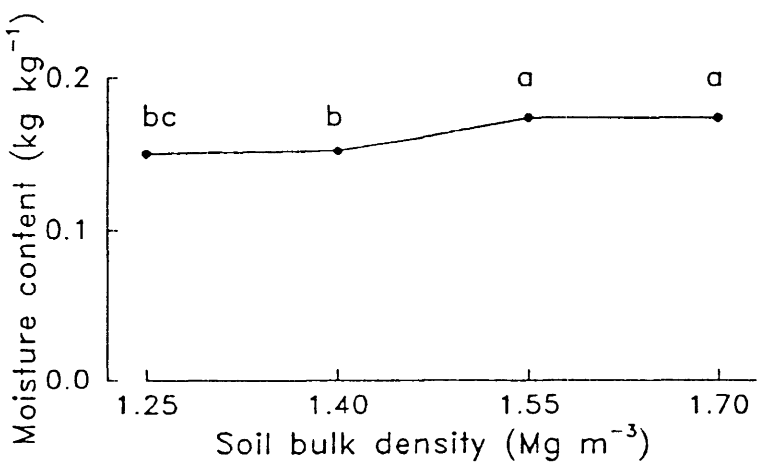

Figure 3.5: Soil moisture content remaining in pots at the end of experiment (kg kg^{-1}) (measured after the penetrometer readings were taken). Points marked with the same letter are not significantly different ($P > 0.05$)(Duncan's multiple range test).

3.4 Discussion

All yield parameters measured in both water regimes and at all soil bulk densities, increased with time (Figures 3.1, 3.2, 3.3; Tables 3.1, 3.2, 3.5, 3.7).

At the first harvest, there was a difference in the storage root weight (Figure 3.1[a]) and in the storage root length (Figure 3.2[a]) between the high and the low water regime, at the bulk density of 1.25 Mg m^{-3}. Although the water stress was not properly imposed until after the first harvest, an attempt was made at 55 days after planting, and this is believed to have resulted in the measured effects. At the lowest bulk density of 1.25 Mg m^{-3}, most pore space would be expected to be occupied by large pores (> 100 μm) (Russell, 1977). Water held in these pores would be readily available to plants and hence the soil moisture effect was most noticeable at this low bulk density.

In the present experiment, the tops fresh weight was not significantly different among the soil bulk densities at the first harvest (Table 3.1). Olymbios and Schwabe (1977) also reported a non significant effect of soil bulk density on total number of carrot leaves harvested at 107 days. Differences in tops weight was associated with differences in leaf areas of individual leaf and leaf dry weight. These researchers also reported that the effect of bulk density was greater on storage root weight than on tops weight, as indicated by 32% and 19.3% reduction in storage root and tops weight respectively compared to control treatment. In the present experiment, nitrogen and phosphorus deficiencies during the first growth period, would have contributed to the non significant effect on tops weight.

At the second harvest, total root length in both water regimes was significantly lower at a bulk density of 1.70 Mg m^{-3} than at the other three bulk densities (Figure 3.3[a]). This was due to decreased root elongation at the highest bulk density. The roots had to exert a high pressure in order to penetrate and to extend at the bulk density of 1.70 Mg m^{-3}, as indicated by the high cone penetrometer readings (Figure 3.4). Trouse (1971) concluded that crops might experience water stress in a compacted soil, because of the inability of roots to absorb enough moisture and of slow water movement in the root zone. At a bulk density of 1.70 Mg m^{-3} in the experiment reported here, carrot root growth was restricted, presumably because of the high mechanical impedance and lack of aeration as the air-filled porosity at field capacity is very low (0.05 mm^{-1}). Boone *et al.* (1978). and van Loon and Bouma (1978) also reported a decrease in root elongation of potatoes in a compacted soil. Parish (1971) found that in a compacted soil. a restriction on root extention resulted in a decrease in water and nutrient uptake by plants. Benyamin and Wren (1978) concluded that decreased carrot tops growth, which was associated with reduced lateral roots. was caused by a reduction in the supply of hormones produced by the lateral roots. In the present experiment, carrot tops fresh weight

was significantly lower at 1.70 Mg m^{-3} than at the lower three bulk densities (Tables 3.1, 3.3). This was associated with reduced root length at the highest bulk density of 1.70 Mg m^{-3}, which was in agreement with the findings of Parish (1971). and Benyamin and Wren (1978).

The storage root length was significantly reduced at the bulk density of 1.70 Mg m^{-3} (Figure 3.2[b]). van Loon and Bouma (1978) reported that shallower rooting systems in potatoes was associated with inhibition in vertical elongation of the roots. A similar finding in carrot seedlings was also documented by Strandberg and White

(1979). Russell (1977) stated that in roots undergoing mechanical impedance, the zone of cell elongation behind the apical meristem is short, because of the inhibition in cell extention in this zone. This is most likely the reason for the shorter length of carrot storage root found in the present experiment, and for those of Strandberg and White (1979), and van Loon and Bouma (1978).

As the total root length, tops fresh weight and storage root length decreased at bulk density of 1.70 Mg m^{-3}, the storage root fresh weight also reduced at this highest bulk density (Figure 3.1[b]). Benyamin and Wren (1978) concluded that individual leaves of carrots are effective both as photosynthetic organs and as exporters of assimilates. These researchers also found that reduced length of storage roots to 3 - 6 cm, resulted in reduction of the absolute growth rate (AGR) and the final weight of carrot storage roots. The reduction of storage root weight recorded in the present experiment, was most likely due to decreased tops fresh weight and reduced storage root length. This is supported by the conclusions of Benyamin and Wren (1978). The result of the present experiment was also similar to that of Brereton *et al.* (1986) who reported that the reduction in yield of sugarbeet and beans was due to decreased total root length.

In the experiment reported here, there were no differences in the five parameters (i.e. the length of lateral and storage roots, the fresh weights of tops and storage roots, and the storage root : tops ratio) recorded, among the lower three bulk densities of 1.25, 1.40, and 1.55 Mg m^{-3}, at the second harvest. Although the soil strength measured in the present experiment increased significantly as the bulk density increased from 1.40 Mg m^{-3} (Figure 3.4), it was evident that roots were able to penetrate and extend at the bulk density of 1.55 Mg m^{-3}. Soil moisture content was higher at the higher bulk density (Figure 3.5).Schuurman (1965) and Russell (1977) indicated that the pore space occupied by fine pores (< 6 μm) was greater at a bulk density of 1.52 than at 1.25 Mg m^{-3}, and that this resulted in a higher moisture retention at the higher bulk density. Taylor and Gardner (1963) reported that roots can still extend at a high bulk density provided that the moisture content is high. Goss and Russell (1980) found that more branched roots developed in a highly compacted soil. The results of the present experiment are in agreement with the findings of Schuurman (1965), Russell (1977), Taylor and Gardner (1963), and Goss and Russell (1980). Flocker *et al.* (1960) reported that a bulk density of 1.63 Mg m^{-3} was severe for potatoes, while Olymbios and Schwabe (1977) found that carrot yield was seriously decreased at a bulk density of 1.45 Mg m^{-3}. Veighmeyer and Hendrickson (1948) indicated that in a coarser soil, roots of sunflower could still penetrate a compact layer at a bulk density of higher than 1.46 Mg m^{-3}. Flocker *et al.* (1960) conducted their experiments on a sandy loam, Olymbios and Schwabe (1977) grew carrots on a silt loam, whereas in the present experiment carrots were grown in a loamy sand. Differences in soil texture, and or crop species possibly contributed to differences between the results of Flocker *et al.* (1960), Olymbios and Schwabe (1977), and of the present experiment, in which the effect of bulk density of 1.55 Mg m^{-3} on carrot yield was not significantly different from that of 1.40 and 1.25 Mg m^{-3}.

At this second harvest, the effect of water regime on total root length was significant at the bulk densities of 1.25 and 1.70 Mg m^{-3}, with the higher total root length in the high water regime. As explained above, which was also supported by Russell (1977), the soil moisture effect was most significant at the lowest bulk density of 1.25 Mg m^{-3}. Taylor and Gardner (1963) and Russell (1977) reported that a decrease in water potential results in an increase in soil strength, and this consequently causes extending roots to undergo greater mechanical impedance. Maurya and Lal (1979) concluded that root elongation rates of soybean, maize,cowpea, and pigeon pea are low at high bulk density ranges from 1.50 to 1.80 Mg m^{-3}, with a low soil moisture content from 11% to 1%. This is most likely the reason for the lower total root length at 1.70 Mg m^{-3} in the low than in the high water regime. The result of the present experiment is supported by that of Taylor and Gardner (1963), Russell (1977), and Maurya and Lal (1979).

The effect of water stress on the total length of storage root was not significant, when averaged over all bulk densities (Figure 3.2[b]). However, at the highest bulk density of 1.70 Mg m^{-3}, 0.90 cm of length of storage root in the high water regime, was above the soil surface, and this rose to 1.02 cm in the low water regime. This result is similar to that of Olymbios and Schwabe (1977) who recorded 0.60 cm of length of carrot storage root above the soil surface at a bulk density of 1.45 Mg m^{-3}, harvested at 107 days. Schuurman (1965) concluded that plants exert forces to deform a dense soil, in order to penetrate and extend. The force must be greater than the resistance of the soil in which the roots are growing (Taylor and Gardner, 1963). In the present experiment, the force required to deform the highest compacted soil was in excess of 5.50 MPa (Figure 3.4).

At the third harvest, the total root length at all bulk densities was significantly greater in the high than in the low water regime (Figure 3.3 [b]). In the high water regime, the total root length decreased by approximately 44%, as the bulk density increased from 1.55 to 1.70 Mg m^{-3} (Figure 3.3[b]). This was in agreement with that reported by Trouse (1979) that increasing bulk density by 0.15 Mg m^{-3} resulted in a reduction in root growth of up to 50%. In the present experiment, a 44% reduction was recorded as the bulk density increased from 1.55 to 1.70 Mg m^{-3} (Table 3.3). Benyamin and Wren (1978) concluded that a 50% reduction in lateral roots resulted in an immediate and persistent reduction in relative growth rate (RGR) of carrot tops. Brereton *et al.* (1986) reported that increasing the bulk density from 1.01 to 1.48 Mg m^{-3} resulted in a 49% reduction in total root length and a 59% reduction in the yield of field grown sugarbeet. In the present study, a 44% decrease in total root length was associated with a 64% reduction in the storage root fresh weight (Figure 3.1[c]). The magnitude of the difference between the result of the present experiment and that reported by Brereton *et el.* (1986) is most likely due to the difference in crop species, site of the experiment, and in the range of soil bulk density.

Similar results were found in the third harvest, where total root length decreased at a bulk density of 1.70 Mg m^{-3}, the tops fresh weight (Table 3.1), the storage root length (Figure 3.2[c]), the storage root fresh weight (Figure 3.1[c]), and the storage root : tops ratio (Table 3.5) were also significantly reduced at this bulk density.

In the low water regime, the total root length at a bulk density of 1.25 Mg m^{-3} was significantly less than at 1.40 Mg m^{-3} (Figure 3.3[b]), but was not different from that at 1.55 Mg m^{-3}. In compacted soil, Eavis (1972) found that the effect of mechanical impedance and aeration deficiency on root growth was more apparent at a high soil moisture level. Under low moisture conditions, the effect of restricted water availability was pronounced. Hill and Sumner (1967) concluded that in sands, where most pore volume was occupied by large soil pores, the effect of compaction was more pronounced in a low moisture sucton range. The results found in the present experiment were in agreement with that documented by Eavis (1972), and Hill and Sumner (1967).

The reduction in total root length at a bulk density of 1.55 Mg m^{-3} in the low water regime (Figure 3.3[b]) might be more closely associated with the restriction in available moisture for root growth than with the effect of mechanical impedance. At a bulk density of 1.25 Mg m^{-3}, the lower total root length was most likely due to lack of water.

Although there was a significantly different effect of bulk density on the total root length in the low water regime, there was no difference in the fresh weight of storage root (Figure 3.1[c] and of tops (Table 3.3) recorded among the lower three bulk densities of 1.25, 1.40, and 1.55 Mg m^{-3}. Stanhill (1977) reported that the maximum yield of carrot leaf was achieved at 105 days after emergence whilst the storage root reached a maximum yield 15 days later. In the present experiment, the maximum yield of tops and storage root had probably been achieved after the second harvest (103 days).

The weight and the length of carrot storage root, and other yield parameters measured in the present experiment. increased until 153 days when the experiment terminated. The cylindricality increased with time only at the lowest bulk density of 1.25 Mg m^{-3}. Thompson (1969) reported that weight, diameter, and length of carrot storage roots increased with age. This author also found that the cylindricality (C) of carrot variety Autumn King increased up to 130 days and then remained constant. The results of the present experiment using the variety Hybrid-4, were similar to that of Thompson (1969) for the variety Autumn King. However, in the experiment reported here, the cylindricality decreased as the bulk density increased, at all harvests (Table 3.8), which suggested that increased bulk density resulted in increased conical storage roots. This result is in agreement with that of Taksdal (1984), who reported that increased tractor wheel compaction resulted in more conical roots of carrots. These results were also supported by Strandberg and White (1979), who found more abnormal carrot storage roots with increased soil compaction. In the present experiment, the cylindricality was always higher in the high than in the low water regime (Table 3.9), which indicated that carrot shape was more cylindrical in the high water regime. Strandberg and White (1979) reported that long, slender carrots were produced in dense soils in a high moisture condition. This was associated with the effect of moisture on soil strength (Taylor and Gardner, 1963 ; Russell, 1977). The result of the present experiment is in agreement with that of Taylor and Gardner (1963), and of Strandberg and White (1979).