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THE EFFECT OF DIFFERENT RATES OF MULCH ON TOP AND ROOT GROWTH OF SOYBEANS.

IOWA STATE UNIVERSITY, PH.D., 1978

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The effect of different rates of mulch on top and root growth of soybeans

by

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A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of The Requirements for the Degree of DOCTOR OF PHILOSOPHY

Department: Agronomy
Major: Soil Management

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1978

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# INTRODUCTION

Agronomists today are faced with the problem of producing enough food for the rapidly expanding world population. Prerequisite to solving this problem is the identification of those factors which limit the growth and yield of food crops. Results of decades of research have shown that soil as well as aerial environmental factors have profound influence on the performance of crops. Soil temperature and soil moisture conditions influence greatly the growth and yield of crops grown under natural conditions.

Soil temperature and soil moisture are modified by certain environmental and cultural factors. Among the cultural factors which modify soil temperature and moisture is the application of mulch. Mulching is encouraged in areas of scanty and unreliable precipitation as well as in areas of excessively high soil temperature (Lal, 1974a).

The effects which the mulch may have on components of top and root growth is little investigated. Rather, interest has been focused on the yield as a measure of the mulch effect on crop growth. While yield may be the most important aspect, since it is the component we mostly want to increase, research that overlooks the other aspects of growth is far from complete. The growth of the different parts of the plant from germination to maturity must be studied and the influence of the environmental factors on it thoroughly ascertained. This is true for the shoot as well as the root.

The understanding of the root development of crop plants, their position, extent and activity as absorbers of water and nutrients is of paramount importance to a scientific understanding of plant production (Russell, 1977). Also the knowledge of modifications produced by variations in the subterranean environment, whether due to natural conditions, tillage or fertilizers, is important. The phenomena observed above the ground may be caused by soil factors which affect the development of the root system and consequently the absorptive capacity of the roots. The absorptive capacity of the root is determined by its morphological extension and its physiological condition. Though the final root pattern of a given plant under favorable environment is genetically determined, it is actually controlled by the physical or chemical environment in most field conditions (Pearson, 1974).

Generally speaking, the importance of a well-developed root system for all crops cannot be overemphasized. This guarantees a better crop and higher yield. Improvement in root development and function seems to offer considerable promise for raising the yield ceiling imposed by occasional water deficiencies. To meet plant needs, and effectively utilize subsoil stored water, roots must proliferate continuously into unexplored zones between rains and also deeper into the soil during periods of drought. Roots, therefore, should be disturbed as little as possible and farmers should be aware of the factors both cultural and environmental that impede root growth. Consequently, they also should be aware of the management practices that enhance root growth and prevent its impedance. It is necessary then to have a knowledge of root growth and factors that affect it. Such knowledge will be of vital importance in improving and developing better management practices to further root growth, make more efficient use of subsoil and irrigation water, and enhance nutrient absorption. This will assure a healthy shoot growth and high yield.

# LITERATURE REVIEW

## Mulches

### Effect of mulch on soil temperature

Due to the large amount of solar energy, the soil becomes a reservoir for the excess heat during the day and returns it to the atmosphere during the night. If heat is added to or removed from the soil, the temperature of the soil will change, the magnitude of the change depending on such factors as specific heat, thermal conductivity and density of the soil. The most important overall heat transfer mechanism in the soil is molecular conduction. Other mechanisms operate in the soil to effect heat transfer. These mechanisms include (a) soil moisture movement as a result of temperature gradient, (b) vapor distillation along a temperature gradient and (c) movement of air through the soil (R. H. Shaw, Department of Agronomy, Iowa State University, unpublished manuscript).

Soil temperature is an important factor in the growth of plants and is influenced by various physical and chemical properties of the soil as well as by cultural practices.

Among the cultural practices that influence soil temperature is the presence of mulches. Different types of mulches may have different effects on soil temperature. Mulches commonly used include plastics of different colors, chopped vegetative matter such as straw and corn stalks, gravels, and different types and colors of powder. In this discussion, emphasis will be placed on vegetative organic mulches although the other types will be mentioned where appropriate.

McCalla and Duley (1946) determined the soil temperature at the 2.5-cm depth in plots of corn to which 4480, 6720 or 17936 kg per hectare of straw mulch were applied. They reported that the temperature was lowered as much as 17.7$^{o}$C in the 17936 kg plot and 3 to 6$^{o}$C in the 4480 or 6720 kg plot. Jacks et al. (1955) reported that the mean monthly soil temperature at the 5 cm depth under 7.5 cm thick straw mulch was 16.6$^{o}$C compared to 21.2$^{o}$C on the bare soil. This was during summer in Germany. Working in Texas, Lemon (1956) showed that the application of 22400 kg per ha of chopped corn stalks lowered the soil temperature at the 7.5-cm depth but increased it slightly over that of the control at the 15-cm and 30-cm depths. Verma and Kohnke (1951) applied 3360 kg per ha each of wheat straw, broken corn stover and glasswool and reported that the soil temperature of the mulched plots were consistently lower than those of the bare plots. Van Wijk et al. (1959) concluded that oat straw mulch decreased the weekly average maximum soil temperature at the 10-cm depth. Other investigators (Anderson and Russell, 1964; Chaudhary and Prihar, 1974; Hanks et al., 1961; Burrows and Larson, 1962; Allmaras and Nelson, 1971; Lal, 1974a) have also reported that soil temperature was lowered by surface applied organic mulches.

The mechanism by which the soil temperature is lowered has been investigated and it is generally agreed that the reflectance property of the mulching material is an important factor in lowering the temperature. Apparently, light-colored straw may reflect considerably more energy than a bare darker colored soil. McCalla and Army (1961) stated that bright straw may reflect up to 80% more energy than bare dark soil. Net radiation may be lower in the spring and early summer but will be higher later in the summer for straw covered as compared to bare soil (Willis and Amemiya, 1973). Net radiation measures the net heat transfer between the sky and the ground. During the day, values are positive since incoming solar radiation exceeds back radiation from the ground. The daytime value is a measure of the energy being absorbed by the ground. During the night, radiation from the sky is almost nil so that net radiation is negative because energy is being radiated from the ground.

Hanks et al. (1961) measured net radiation in plots covered with different types of mulch including straw. They reported that during the early part of the season, net radiation was lowest on the straw plot but at the end of the season, it was higher on the straw mulch than on the check. They attributed this fact to darkening of the straw with time. This darkness resulted in greater energy absorption. Lemon (1956) applied 35840 kg per ha of chopped sorghum stalks and measured the net radiation in the mulched and bare plots. He found that the amount of radiant energy absorbed by the ground was the same whether the soil was bare or mulched. Following sundown, however, radiation of heat from the bare soil exceeded that from the mulched soil. He concluded that the mulch acted as a pump as a result of the emissivity characteristics of the 2 surfaces and this was reflected in higher temperatures. Waggoner et al. (1960) conducted an in-depth experiment in Connecticut to study the energy budgets of soil under different types of mulches, including hay. They showed that the outgoing radiation was essentially the same above hay and bare soil although some conservation of energy was realized in the mulch due to a small reduction in evaporation. The major change they reported was in the vertical exchange of energy with the air by conduction and convection. During the day, hay on the surface became hot because the downward movement of heat was retarded by the insulating air and organic matter of the hay mulch, hence there was a measured loss of 0.2 ly/min in the exchange with the air. This midday loss exceeded the savings in evaporation resulting in a greater net loss from the hay than from the bare soil. Hence the storage of energy in the soil beneath the hay was half that in the bare soil in this experiment. At night, however, the hay reversed the process. The loss of energy from beneath the insulating hay was less than that from beneath the bare soil. This resulted in increased minimum temperature in the soil beneath the hay. Soil temperature is not the only soil property affected by surface applied mulches. Soil moisture is also profoundly affected.

Conservation of water by mulches

The use of mulches in soil moisture conservation and the influence of various types of mulches on soil moisture is well-discussed in literature. But, as in the case of soil temperature, review will be restricted to organic mulches. It is well-established that organic mulches help conserve soil moisture by aiding infiltration and reducing evaporation and runoff. In this section infiltration and evaporation aspects will be discussed while the aspect of mulches on runoff will be taken up in another section.

How organic mulches increase infiltration

Duley (1939) observed during an infiltration experiment on bare soil in Nebraska that the rapid reduction in the "rate of intake of water" as rainfall continued was accompanied by the formation of a thin compact layer at the soil surface. This layer, caused by the beating action of rainfall, is apparently the result of a severe structural disturbance. It restricts the infiltration of water by forming a relatively impervious seal on the surface. When a mulch of protective material is used on the soil surface, the forces of falling waterdrops acting on the surface of the soil are reduced. As a result, infiltration of water into the mulched soil is maintained at a higher rate and for a longer time than on bare soil. This gain in infiltration in the mulched soil is, however, realized only when the rains are of sufficient duration and intensity. If the intensity is too high, runoff may occur in the mulched plot (McCalla and Army, 1961).

Mannering and Meyer (1963) studied the effects of six rates of applied wheat straw mulch on infiltration and erosion using simulated rainfall. They reported that mulch rates of 2242, 4484 and 8968 kg/ha maintained very high infiltration rates resulting in essentially no runoff. They explained this benefit from mulching as being due to reduced soil surface sealing and to reduced energy of impact on soil particles by raindrops. Kidder et al. (1943) compared the effect on infiltration of surface mulches of soybean residues, corn stover and wheat straw and found that corn stover was more effective in preventing surface sealing, thus maintaining higher infiltration rates than soybean residue. Mannering and Meyer (1961) compared three different methods of corn stalk residue management on infiltration, runoff and erosion using simulated rainfall. These methods were (a) cornstalks as left by the corn picker (check), (b) cornstalks shredded after corn was picked, and (c) cornstalks shredded and disked once. They found that there was slight increase in infiltration as a result of shredding the cornstalk when compared to the check. When cornstalks were shredded and disked, infiltration was increased 75% compared to the check. Triplett et al. (1968) studied the effect of varying degrees of cover with corn stover mulch on water infiltration in a corn field. The treatments included no preplant tillage with 5, 45 and 70%

cover with corn stover. They reported that the no-till 70% cover plots had significantly higher infiltration rate and total infiltration than the other treatments at the end of 1 hour.

Evaporation and surface applied mulch

Mulching with plant residues not only aids infiltration, but it also reduces evaporation under certain conditions. The subject of evaporation from the soil is well-covered in literature (Hide, 1954; Lemon, 1956; McCalla and Army, 1961; Hillel, 1968; Bond and Willis, 1969, 1970, 1971; and Unger and Phillips, 1973).

In order to understand how mulches affect evaporation, the mechanism of evaporation must be known. Lemon (1956) has provided insight into this process.

Mechanism of evaporation

Evaporation from the soil is divided into three stages (Lemon, 1956).

1. The first stage which involves a rapid and steady rate of loss is dependent upon the net effects of water transmission through the soil as well as on the above the ground boundary conditions. These conditions include wind speed, temperature, relative humidity and radiant energy. The first stage ends when a dry diffusional soil barrier develops.

2. The second stage involves a rapid decline in the rate of water loss as the soil reservoir is depleted. At this stage, the above ground conditions are no longer as important. Intrinsic soil factors assume a dominant role in governing the rate of moisture flow to the surface.

3. In the third and final stage, water loss rates are relatively low and essentially constant, governed by adsorptive forces of molecular distances at the soil solid-liquid interface.

During the first stage, the pores between the aggregates are essentially filled with water and loss of water results in the thinning of the films between the aggregates.

Lemon (1956) has observed that the potentialities for reducing soil moisture evaporation lie in the first two stages and involve (a) decreasing the turbulent transfer of water vapor above the ground surface, (b) decreasing the capillary conductance of water to the surface by disrupting capillary continuity, and (c) decreasing the capillary conductance of water to the surface by the application of surfactants.

Plant residue mulches reduce evaporation primarily in the first stage by reducing the turbulent transfer of water vapor to the atmosphere and by shielding the surface against the effects of solar radiation (Bond and Willis, 1970; Unger and Phillips, 1973). Bond and Willis (1970) investigated the influence of surface residue and evaporation potential on first-stage drying. They measured evaporation with time from wetted columns of fine sandy loam treated with seven rates of surface residue. There were six trials with different evaporation potentials. They found that increasing rates of surface residue caused progressive decreases in the rate of first-stage drying. The lower rates of mulch were more efficient per increment of mulch. They also reported that for a given surface residue rate, the rate of evaporation increased as the evaporation potential increased.

Total water loss during the first stage decreased as the rate of the first-stage evaporation increased, leading them to suggest that more soil moisture could be conserved by increasing the rate of first-stage evaporation. Bond and Willis (1969), in addition, reported that cumulative evaporative losses were nearly the same for the varying rates of residue during stages 2 and 3 (Lemon, 1956) of water evaporation. Other investigators (Hide, 1954; Hillel, 1968) reported reduced evaporation with surface mulches.

The value of mulches in reducing evaporation is realized only when the surface of the soil is maintained moist. Many investigators (Russel, 1940; Jacks et al., 1955; Lemon, 1956; Army et al., 1961) attest to the validity of this statement. As early as 1940, Russel, working in Nebraska, stated that residues on the surface could reduce moisture losses due to evaporation during periods of frequently reoccurring rain, but appeared to be of little or no value where rains "are few and scattered."

Gardner (1959), discussing the solutions of the flow equation for the drying of soils and other porous media, observed that after a sufficient length of time, the cumulative evaporation under low evaporative conditions may approach very closely that under high conditions. As a result of this observation, he concluded that attempts to decrease evaporation by application of surface mulches will be of little value in the long run unless the lower initial evaporation rate permits greater downward percolation of water.

Army et al. (1961), in a field experiment in Texas, reported that residues on the soil surface could materially improve soil moisture storage by increasing depth of water percolation only if there were frequent rains. If the rains were not frequent, the cumulative moisture loss on the mulched soil lags behind the bare soil but eventually reaches approximately the same moisture content in the total profile.

Control of runoff by surface applied plant residue mulch

Surface runoff is the portion of the rain which is not absorbed by the soil and does not accumulate on the surface, but runs downslope and collects in gullies and streams (Hillel, 1971). Runoff occurs where rain intensity exceeds the infiltration rate. Runoff does not begin immediately. The rain first collects in surface depressions and forms puddles, the total volume of which is termed "the surface storage capacity" (Hillel, 1971). It is only when the storage capacity is filled and the puddles begin to overflow that runoff begins. According to Meyer (1971), the countless raindrops that fall on a square kilometer of midwestern soil annually is equivalent to 3,300 metric tons of TNT. Mulches reduce runoff by breaking raindrop impact which breaks down the soil causing surface sealing and crusting and hence reducing infiltration and increasing runoff (Van Doren and Stauffer, 1943; Hillel, 1971; Wischmeier, 1973).

Duley and Russel (1941) observed that residue from oats protected the land effectively against both runoff and erosion. Zingg and Whitfield (1957) showed that a field with stubble mulch on it retained 1.3 to 2.5 cm more water than a moldboard plowed field.

Van Doren and Stauffer (1943) studied the effect of crop and surface mulches on runoff, soil losses and soil aggregation and found that corn stover was more effective in reducing runoff than soybean residues. They attributed the finding to the fact that the corn stalks and leaves provided greater volume of mulching material than soybean residues.

Meyer (1960) reported decreased runoff with increased quantities of residue cover and Wischmeier (1973) stated that partial covers of residue mulch substantially reduce runoff velocity, thereby increasing the depth of the cushioning film of water held on the surface during rainfall.

After 3 hours of sprinkling, the subsoil of mulched and unmulched soil had infiltration rates of 1.1 and 1.9 cm per hour, respectively. Over the same period, the topsoil of unmulched and mulched soils had infiltration rates of 1.4 and 4 cm per hour, respectively (Fenster, 1977).

Moody et al. (1963) measured runoff from corn plots treated with 6720 kg/ha of wheat straw mulch. They reported that a total of 6.17 cm of runoff was recorded from the bare soil compared to only 0.91 cm from the mulched plot. Jones et al. (1969) recorded a loss of approximately 27% of precipitation on the unmulched plots of corn compared to only 4.5% on the mulched plots.

Effect of mulch on water storage in the soil

It has been shown in previous sections that surface applied residue mulch increases infiltration rate and reduces evaporation and runoff. It follows then that moisture in the soil under the mulch should be higher than in the bare soil. Numerous investigations have established this fact. In 1943, Alderfer and Merkle (1943) applied different types of mulching materials, including wheat straw and corn stover, on the soil surface and also incorporated these mulches into the soil. They reported that the surface mulching resulted in a pronounced increase in soil moisture during the driest periods of their work. Verma and Kohnke (1951) investigated the effect on soybean yields of organic mulches applied on the soil surface. They reported that wheat straw and corn stover increased the soil moisture content of both the surface and the subsoil.

The increase over that of bare soil was 2 to 4% by weight on the average. Greb et al. (1967) applied varying quantities of wheat straw mulch on soil surfaces at three locations in the Great Plains area and reported a progressive increase in soil water storage with increasing rates of surface applied mulch regardless of the quantity of precipitation that occurred during the fallow period. This was true in all the locations except one. Net gains at the end of the fallow ranged from 1 to 4 cm for all the locations and was significant at 95% level of probability in 6 out of 9 years of experiments. Moody et al. (1963) applied 6720 kg/ha of straw mulch on the surface and showed that an average of 1.22 to 2.21 cm more of soil moisture was conserved compared to the bare soil. Jones et al. (1969) obtained greater soil water in the top 30 cm of straw-mulched soil than from unmulched soil throughout the growing season in their 3 years of study.

Other investigators (McCalla and Army, 1961; Bond and Willis, 1969) have obtained results showing that mulching helps conserve soil moisture. In the tropics, the same finding has been reported. Chaudhary and Prihar (1974), working in India, reported higher moisture content at the 0-7.5 cm layer under straw mulch and, in Nigeria, Lal (1974a) showed that plots of maize mulched with rice and forest litter had higher soil moisture content in the 0-10 and 10-20 cm depths than the unmulched plots. This difference lasted throughout the growing season.

Roots

It was in the 1920's that Weaver did his classical work on roots which culminated in the publication of his book "Root development of field crops" (Weaver, 1926). One would have expected roots to receive the same amount of attention as other parts of the plant, but surprisingly, studies of roots have been neglected until recently. In some plants, especially crops, practically nothing has been done to analyze and understand how the root system functions in its complex environment. However, not all aspects of root studies have been neglected. There is, for example, considerable understanding in the purely physiological aspect dealing with such phenomenon as movement of ions across root membranes (Epstein, 1966, 1972; Laties, 1969).

The apparent lack of interest in the past has been attributed to a combination of reasons. The variability and complexity of the root system make root investigation in a complex environment, such as the soil, a formidable task. This is made worse by lack of adequate methods of characterizing roots. Russell (1977), however, believes that the more cogent reason is that the performance of the root system seems to be of a minor interest compared to other subjects.

Whatever the reasons that had caused the lag in knowledge on roots, scientists have come to realize that to understand the shoot system and its functions, the roots must be understood. The fact that three books (Carson, 1974; Torrey and

Clarkson, 1975; and Russell, 1977) and many reviews (e.g., Allmaras et al., 1973; Tinker, 1976; Newman, 1976; Taylor and Klepper, 1978) have been published recently on roots and their functions attest to the renewed or more appropriately discovered interest in roots. One offshoot of this is the finding (Audus, 1972) that in addition to the traditional functions of roots in water and nutrient absorption and also anchorage, roots are also sources of growth regulating substances in plants. A complete review of roots would be impossibly long so only field aspects of roots will be emphasized. These include the root systems, the methods of studying them, their morphology and distribution, as well as the effect of soil factors on them. The effect of soil moisture and temperature will be reviewed later. In this section, the effect of soil structure and strength as well as soil aeration will be discussed. Where necessary, emphasis will be placed on soybean roots because soybeans were used in the experiments reported in this dissertation.

Roots: morphological and anatomical aspects

Root systems of plants are very variable as a result of environmental and genetic factors (Pearson, 1974; Russell, 1977). When environmental conditions are favorable, the final root form is determined mostly by genetic factors. Hence, monocotyledonous plants have a different root form from dicotyledonous plants. Despite these varying forms which roots display, they all have one characteristic in common, i.e., the continued elongation of the root, be it monocotyledonous or dicotyledonous, primary or secondary, depends on the division and subsequent extension of cells in the apical meristem (Esau, 1960; Russell, 1977). The differentiation of cells in the root apex is the process primarily responsible for the establishment of the root systems and their continuing absorption of water and nutrients. This process, therefore, determines the rate of root extension and hence the potential volume of soil available to the roots.

Monocotyledonous roots are different from dicotyledonous roots as far as the development of the root system is concerned. In monocotyledonous plants, virtually all the root system develops from the apical meristem and final root diameter is determined by the extent to which the apical cells finally expand. As a result, the monocotyledonous root maintains more or less a uniform diameter. In contrast, in the dicotyledonous plants, the diameter of the older parts of the root continues to increase as a result of tangential division of the cambial cells. This results in greater diameter for the older parts of the roots (usually near the soil surface) compared to newer parts (usually deep down in the profile). This nonuniformity in root diameter is a problem in utilizing root dry weight as an index in the study of absorption of nutrients and water by roots. This will be discussed more fully later in this review.

One other anatomical aspect of interest is in root branching. Laterals are initiated by cell division in the pericycle of the parent root member and penetrate through the cortex into the soil. This characteristic habit of root branching has some implications with regard to the survival of the roots in an unfavorable condition. Because the meristematic cells are in the pericycle, unfavorable conditions such as drying of the soil and the cortex will not hamper the revival of meristematic activity when favorable conditions return. Also, if one part of the root system is experiencing a favorable environment while another part is not, there may be more proliferation in the part that experiences a favorable environment to compensate for a lack of growth in the other part (Russell, 1977).

Methods of studying roots and problems of root research

It was noted earlier that interest in studying roots was renewed only recently. It is not surprising that previous lack of interest could have been partly due to the problems involved with root research. In this section, the methods commonly used to study roots and difficulties associated with them will be discussed.

Several methods have been used to study roots under varying conditions. These methods can conveniently be divided into three broad categories: (1) root extraction methods which include (a) the coring method and (b) the slab or monolith method; (2) direct observation methods under which come (a) the trench profile method and (b) Rhizotron; and (3) root "estimation" methods which include (a) radiotracer methods and (b) water and nutrient extraction methods.

Root extraction methods These methods are suited for quantitative studies of roots in the field. These include the coring and the monolith methods. Of the two listed, the coring method is more often used, most likely because it is less tedious (Böhm et al., 1977).

Coring method In the coring method, soil cores are obtained by driving hollow tubes into the soil to a desired depth. The core is sectioned into desired segments, usually corresponding to certain depth intervals. Each soil segment is soaked in water or in another solution and then transferred to a fine mesh sieve. The soil is washed through leaving the roots (both new and old) on the sieve. The new roots are separated and stored in a volumetric mixture of alcohol and water for the determination, later, of dry weight, length, and surface area. Various mechanical devices (Kelley et al., 1947; Welbank and Williams, 1968; Ellis and Barnes, 1971) have facilitated obtaining the samples. This method affords a fairly simple way of obtaining some information on the vertical distribution of roots in the profile and the maximum rooting depth. Also, samples taken at various distances from the plant can provide information on the lateral spread of the roots while periodical sampling may give some insight into the growth rate of the roots. Its chief disadvantage is that it cannot give a complete overall picture of the entire root system. One source of error is the incomplete separation of roots from the soil and the loss of root fragments.

The monolith method  This method involves excavating some block of soil with the root system intact, inserting pins to hold the roots in place, washing away the soil, thus leaving the root system approximately the way it was in natural soil. This method was classified as the pinboard method (Schuurman and Goedewaagen, 1965). Nelson and Allmaras (1969) described a modified pinboard method and called it an improved monolith method. A version of the Nelson and Allmaras (1969) method, modified by eliminating the use of photography has been described by Sivakumar (1977) and Böhm et al. (1977). The chief advantage of the monolith method is that it gives a fairly complete picture of the structure and shape of the root system and of the total amount of roots. It is also suitable for both the quantitative and qualitative analysis of the root system. Its main disadvantage is that it is very laborious and needs expensive equipment (Böhm et al., 1977). Replication is difficult in the field and the method is very destructive. Böhm et al. (1977) estimated that 24 $m^2$ of the plot area was required for the movement of machinery and the extraction of one soil block.

Direct observation methods    In these methods, roots are observed directly either in field profiles, glassboxes or underground root compartments.

Trenching method    Weaver (1926) washed intact root systems free of soil by a laborious method and described root positions in the profile. This was a classical work but the labor involved has largely hindered its use in the field. Naturally, modifications were sought to make it easier. The pinboard method (Schuurman and Goedewaagen, 1965; de Roo, 1969) and the trench profile method (Böhm, 1976, 1977; Böhm et al., 1977) recently have been used. In the pinboard method, a smooth vertical face of soil is exposed. A board perforated with holes about 10 cm apart vertically and horizontally is placed against the face of the soil. Steel pins are driven through the holes into the soil, deep enough to pass through the root system. The soil is subsequently washed off and the root system is held in place by the steel pins.

In the trench profile method, a trench is dug deep enough for someone to work inside it. The face of the soil profile at right angles to the crop row is smoothed. About 0.5 cm of soil is washed off with a water sprayer exposing the roots which are mapped with the help of a grid frame. The trenching method gives a very good qualitative picture of the root system, but is not suitable for quantitative work. It is especially useful for the study of the response of root systems to the environment, e.g., soil compaction and unfavorable subsoil conditions. It is particularly suited for examination of shallow root systems.

The Rhizotron Root observation boxes have been used in various forms for the study of roots in the laboratory, but Rogers (1934) and Pearson and Lund (1968) extended their use to the field. Pearson and Lund (1968) dug a pit 2 m deep, 3.5 m long and 2 m wide at the end of an area to be planted with cotton. They installed a glass panel along one side of the pit at a distance 1 m from the wall. The space between the wall and the glass was filled with soil which was then wetted and allowed to settle for 1 week before planting. Root growth of cotton was observed through the glass wall. The root observation laboratory (Rogers, 1934) or Rhizotron (Taylor, 1969; Taylor et al., 1970) is a more sophisticated offspring of the glass-walled trench. The Rhizotron is essentially an underground chamber large enough for people to work inside it. It is made up of compartments one side of which is covered with some type of transparent glass or plexiglass panels. Root growth inside the compartment is observed through the glass panel. Detailed description of the root observation laboratories (Rhizotron) can be found elsewhere (Rogers, 1934; Taylor, 1969). The main advantage of the Rhizotron is that root growth can be observed in a setting very closely approximating that in the field. The above ground parts of the plant are exposed to the same environment as the other plants in the field. It also enables one to characterize precisely the environments of the root and shoot. However, certain problems, apart from cost of installation, are associated with this technique. As has been pointed out by Russell (1977), the validity of conclusions regarding quantitative analyses obtained from the Rhizotron depends on the uniformity of root growth throughout the root zone, including the glass panels. Plexiglass panels sometimes allow soybean roots to concentrate at the soil-panel interface (Taylor and Böhm, 1976).

Other problems associated with the Rhizotron include the fact that only a small part of the root system is visible and may not be representative of the entire root system. Also, light in the Rhizotron can sometimes affect the performance of the roots in the compartments. For example, Pearson (1974) reported that the root extension of peanut (*Arachis hypogea* L.) was markedly affected by light. Despite these shortcomings, the Rhizotron is a remarkable achievement offering unlimited opportunities for the study of roots in the field.

*"Estimation" methods* Certain methods of root investigation are more or less indirect. Root systems are inferred from the behavior of substances which make contact with the roots. These so-called "estimation" methods include (a) the use of tracers to determine the extent of the root system and (b) determining the distribution of the roots from the zone of water depletion by the roots. These methods are adequate for certain studies and are usually used as alterna-

tives to the tedious methods described earlier.

Tracer methods The fact that certain radioactive substances emit measureable rays when injected into the soil or plant is the basis for the tracer method of studying roots. Relative activity of roots in absorbing ions from different parts of the profile has been measured with tracers. The most popular tracer for this kind of study is $^{32}P$ which was first proposed by Hall et al. (1953). Here the $^{32}P$ is injected at various depths and distances from the plant and, because of low mobility of phosphorus in the soil, this technique is satisfactory for determining when roots arrive at a given location in the profile or for estimating rooting depth (Pearson, 1974).

Radioactive tracers can also be injected into plant tissues and become sufficiently uniformly distributed in the root system. By measuring the activity of the emitted rays, the volume or weight of living roots present can be determined. The procedure is to inject a tracer into the shoot, wait sufficiently long to allow for uniform distribution of the tracer in the root system. Then either of two methods can be used to measure the activity depending on the purpose of the investigation. In one method (the destructive method), core samples are taken and the activity of the tracer in the cores is measured. This method has been employed by some investigators using $^{32}P$ (Racz et al., 1964; Lipps and Fox, 1964; Maurya et al., 1974; Atkinson, 1974) and $^{86}Rb$ (Russell and Ellis, 1968; Ellis and Barnes, 1973). In another method (the nondestructive method), the activity is measured _in situ_. In one experiment (Mercer et al., 1975), the gamma activity of $^{42}K$ was measured by lowering a scintillation counter down an aluminum tube similar to that used in measurement of soil moisture with the neutron probe. With this set-up, root activity at different depths can be measured.

The accuracy of the tracer methods depends on how well the assumptions inherent in these methods are fulfilled. Where the isotope is injected into the soil for the determination of rooting depth, it is assumed (Pearson, 1974) that (a) roots have equal chances of encountering the tracer in each soil layer, (b) that the applied material is essentially immobile in soil but remains equally available for absorption at each locus, and (c) that the specific activity of the applied tracer remains uniform at all locations of injection. These assumptions are difficult to be met under certain environmental conditions, e.g., in the presence of high amount of Fe and Al which can immobilize the $^{32}P$.

For a reasonably accurate estimation of the root system by injection of tracers into plant shoots, it is necessary that the tracer material be distributed uniformly in the tissues of the root systems. It is also desirable that the time required for distribution be short.

The main advantage of the tracer method lies in the fact that it is largely nondestructive compared to the other methods and in certain cases relatively simple. However, it has certain drawbacks. Russell (1977) has pointed out the disadvantages of using $^{86}Rb$. These include the fact that the method estimates fractions, not the actual weights or volumes of roots in the different layers. There is also limitation in its use. For example, root weights or volumes cannot be estimated near the soil surface where most of the radioactivity is contributed by the bases of the shoots.

Lay (1973) has also pointed out that elaborate equipment is needed if a large number of samples are to be analyzed.

Despite these shortcomings, the tracer methods have been of much help in root research in the field.

Water extraction method Roots are the organs of water extraction in the soil. If the pattern of water extraction in the profile is known, it is often possible to infer the pattern of root distribution. This is the basis for the water extraction method of estimating the root distribution. It is particularly useful in studying the fluctuation in the effective rooting depth (Letey and Peters, 1949). The neutron meter is often used to study the changes in the water content of the soil and hence the water extraction patterns of the roots. Inherent in the water extraction method are the assumptions (1) that during the period of measurement, there is no appreciable transfer of water from one part of the profile to the other, and (2) that the vertical distribution of water in the profile is uniform at the beginning of measurement. Both of these assumptions as pointed out by Pearson (1974) are not always true in the field. Despite these shortcomings, the chief advantage of the water extraction method is that the ability of roots to extract water, which is usually of major interest, is measured. This eliminates the assumptions about root mass, activity and rate of extension.

## Some problems of root research

The problems of root research do not lie only in techniques of investigating roots. There are also inadequacies in the quantitative indices used to study roots and their functions. Such indices used at present in most investigations include (1) root weight, (2) root length, (3) root surface area, and (4) root activity. Depending on the type of information being sought, one index may be more suitable than another. For example, in most modelling of water uptake by plant roots (Gardner, 1960, 1965; Cowan, 1965; Newman, 1969a, 1969b, 1974; Allmaras et al., 1973; Taylor and Klepper, 1975, 1978; Hillel et al., 1976; Tinker, 1976) and calculation of water uptake by roots (Taylor and Klepper, 1975; Willatt and Taylor, 1978) root length or root length density is employed. When nutrient uptake is the primary concern (Passioura, 1963; Barley, 1970; Raper and Barber, 1970; Barber, 1971, 1974, 1978), root surface area or root weight is more appropriate.

Root weight The interpretation of results using root weight assumes that root mass is directly related to root activity. Pearson (1974) has enumerated two reasons why this assumption may not be valid. These reasons are: First, roots are never quantitatively fully recovered from the soil. This is attested to by the difficulty in the methods discussed earlier. Second, root morphology may change with changes in the environment. Experimental evidence shows that under certain environmental conditions, e.g., in the presence of a water table (Reicosky et al., 1972), only a small amount of the roots is responsible for most of the water absorption. In this case, root weight will be a poor indicator of the water extraction activity of the roots. Other environmental factors (e.g., soil compaction and anaerobiosis) can also modify the root system and weight and this aspect is taken up in later sections.

Root surface area It was mentioned earlier that root surface area may be a better parameter in studies concerning the flux of nutrients into plant roots. The methods presently available are either tedious (Melhuish and Lang, 1968; Raper and Barber, 1970) or unreliable (Williams, 1962; Corley and Watson, 1966). The most used method is that of obtaining, with a microscope, the diameters of representative root members as well as the total root length of the sample. From these parameters the surface area is calculated.

Root length Three main methods have been used to obtain total length of root samples. These are (a) the direct method, (b) the line counter method (Reicosky et al., 1970), and (c) the line intercept method (Newman, 1966; Rowse and Phillips, 1974).

In the direct method, the length of the individual root member in the sample is separately measured. The total length of the sample is obtained by measuring the lengths of the individual root members.

The line counter method used by Shearer (Reicosky et al., 1970) and Reicosky et al. (1970) is reported as a reliable method of obtaining root length. It involves running the line counter over the projected image of the root. By knowing the scaling factor, the line counter reading is converted to the actual root length.

The line intercept method of Newman has found a wide acceptance among root investigators. Newman (1966a) developed a theory from which root length can be estimated by the equation:

$$R = [\pi NA/(2H)]$$

where R is the total length of root in a field of area A, N is the number of intersections between the roots and random straight lines of total length H. Thus, by knowing A and H and counting N, R can be estimated.

Probably because of the simplicity of this method and ease of calculations involved, it has become popular among investigators. Different methods are employed in obtaining the number of intercepts. In one version that has been used (Rowse and Phillips, 1974), the intersections are counted by moving the root sample between a light source and a modified binocular microscope fitted with a photoelectric counting device such that whenever a root passes between these two, the beam of light is interrupted and a count is accumulated on a scaler. In a most recent modification of this instrument (J. F. Andrews, Department of Agricultural Engineering, Iowa State University, Ames, Iowa, personal communication), a laser light source and a light sensitive diode is used instead of a microscope. In this instrument, the tray containing the roots is moved along a prearranged path by means of a motor. The root samples then intersect the laser beam mounted below the tray. The number of intersects is recorded. Root length is estimated from a standard curve of known string length and number of intersections. To obtain a fairly accurate estimate, the roots in the tray must not overlap. It has also been found helpful to pour some water into the tray to prevent drying of the roots during measurement. Reicosky et al. (1970) compared the direct, line counter and the line intercept methods and found little difference in accuracy among them. However, the time it took to get the measurements differed

-1.0, 1.5 and 5.0 hours for the Newman, line counter and direct methods, respectively. Brewster and Tinker (1970) using leek roots found Newman's method and the line counter method only fairly satisfactory and preferred the direct method.

### The root system

The different methods of obtaining root samples and estimating root length of the samples were reviewed in the previous sections. Despite the tediousness and shortcomings of these methods, they have been invaluable in advancing the knowledge of the root systems of both trees and crops. In this section, the root systems of crops with particular emphasis on soybeans will be reviewed.

Prior to the advent of the quantitative analysis of the root system and estimation of the root lengths, most studies on roots had been mainly qualitative. Hence, Weaver (1926) made some excavations and mapped roots *in situ*. Then it was considered more convenient to show visual evidence and hence photographs of roots accompanied by qualitative descriptions were introduced (Borst and Thatcher, 1931; Foth, 1962; Nelson and Allmaras, 1969). As quantitative displaced qualitative evaluations, a better understanding of the root system began to evolve.

In discussing the root system, the concept of root configuration, defined by Allmaras et al. (1973) as the distribution of root elements among and within the various compartments of the root zone, is perhaps more appropriate. Whether from qualitative or quantitative analysis, one obvious fact is that species differ in their root configuration. For example, the root configuration of corn was found to differ from that of soybeans growing in the same experimental site (Allmaras et al., 1975). It is known that the nature of root configurations is genetically controlled (Troughton and Whittington, 1969; Zobel, 1975; Russell, 1977) and can be modified by the environment. Even within the same species, varietal differences in root morphology have been reported in soybeans (Raper and Barber, 1970), wheat (Hurd, 1968; Yu et al., 1969), and rice (Chang et al., 1972). Under field conditions, however, these varietal differences tend to be masked by the environmental influences and may not readily be detectable. One characteristic common to most root systems is the tendency for most of the root weight to be concentrated at the upper 0-30 cm layer of the profile, especially when environmental factors are not limiting. This characteristic is true for a number of species including corn (Foth, 1962; Nelson and Allmaras, 1969; Allmaras and Nelson, 1971; Follett et al., 1974; Mengel and Barber, 1974; Allmaras et al., 1975; Barber, 1971, 1978) and soybeans (Raper and Barber, 1970; Mitchell and Russell, 1971; Stone et al., 1976; Sivakumar et al., 1977; Böhm et al., 1977). In soybeans, for example, Mitchell and Russell (1971) reported that at 31 days after planting, 93% of the total root weight was in the 0-15.2 cm zone. Böhm et al. (1977) also showed that 87% of the roots were concentrated in the 0-15 cm depth at 44 days after planting.

The soybean plant has a taproot from which laterals grow out. The manner of this growth seems to be unresolved yet. Mitchell and Russell (1971) reported that the laterals grew out into the interrow position and on coming in contact with laterals from the adjacent row, turned down sharply and grew vertically downwards. Intraspecific competition is the reason used to explain this phenomenon. However, Böhm (1977) showed (supported by a photograph) that roots from adjacent rows interpenetrated each other.

Factors affecting the root configuration As was pointed out earlier, root configuration is affected by genetic factors, but environmental effects on the root morphology and functions often are of most interest in the study of roots. Root configuration is also affected by soil factors which include soil strength, soil temperature, soil water and nutrients, soil reaction and soil aeration.

Soil strength and structure Taylor (1974) defined soil strength as the ability of the soil to resist deforming forces applied to it, including the microscale forces involved with plant root extension and radial growth.

In order to understand how soil strength and structure affect the growth of roots, the mechanism by which roots elongate and extend into the soil must be known. Roots increase in length by the division of meristematic cells at the tip and subsequent elongation of those cells. The force behind the elongation is the turgor pressure. It follows then that roots can elongate only if the turgor pressure is greater than the combined pressure of the cell wall and any external constraints from the soil (Taylor, 1974; Russell, 1977).

Roots extend into the soil by penetrating through voids in the soil. One consequence of this manner of growth is that a root tip can only penetrate through a pore space if its diameter is less or equal to that of the pore space. If the diameter of the root is greater than that of the pore space, two possibilities are open to the root if it is to penetrate through the space. It can either decrease its diameter or apply pressure thus expanding the diameter of the pore space. Where the soil structure is such that the root cannot push the particles apart to expand the pore, the root tip does not penetrate. This was demonstrated by Wiersum (1957) who, in an experiment dealing with root penetration through a porous solid phase, found that roots could not penetrate the original pore, the diameter of which was less than that of the extending zone of the root. He also found that when roots were restricted in their elongation by an external force, their diameter usually increased.

The implication of this phenomenon of root growth is that any process or structure that decreases the size of the pores in the soil is likely to put more constraints on the elongation of the roots. The questions then are, what maximum pressure can the root exert and what minimum pressure will appreciably reduce root elongation? To answer these questions, some investigators sought the quantitative relationships between external pressure and root growth under favorable conditions. The concept of root growth pressure (RGP) defined as the pressure available for roots to accomplish work against external constraint (Taylor, 1974; Russell, 1977) was adopted. To find the maximum pressure that roots can exert, RGP was mathematically related to the longitudinal forces in the root and the cross-sectional area of the root by the equation (Taylor, 1974):

$$RGP = (\Sigma ft - \Sigma fcw)/A$$

where RGP is root growth pressure

$\Sigma ft$ is the summation of the longitudinal forces in the root that arise as a result of cellular turgor pressure

$\Sigma fcw$ is the summation of the longitudinal forces that arise in the cell walls and tend to resist cellular elongation

A is the cross-sectional area of the root at the plane where force is determined.

Taylor (1974) has drawn attention to the difficulties of measuring directly either the turgor pressure or the cell wall constraint. But despite these, maximum root pressures of

9-13 bars have been obtained by a number of investigators (Gill and Bolt, 1955; Stolzy and Barley, 1968; Taylor and Ratliff, 1969a).

Though it is informative to know the RGP, for practical purposes under field conditions, the minimum pressure that appreciably reduces root elongation commands more attention. This is because these pressures can slow the growth of roots and hence hamper their functions as absorbers of water and nutrients. A number of investigations have been undertaken to solve the problem (Gill and Miller, 1956; Abdalla et al., 1969; Goss and Drew, 1972; Russell and Goss, 1974; Barley, 1963; Goss, 1977). In one such investigation, Russell and Goss (1974) found that when 0.2 bar pressure was applied, the elongation of barley (*Hordeum vulgare* L.) seminal roots was reduced to about 1/2 that of the control. When 0.5 bar pressure was applied, it was reduced to 1/5. Further increases up to 1 bar caused slight reductions. The results of several experiments they conducted were combined to give the mathematical relationship

$$Y = 0.079 + 0.92 - 3.87x$$

where Y is the rate of root elongation when x bars external pressure is applied. Y is expressed as a ratio to that at 0 applied pressure.

Another facet of importance in the study of root elongation and mechanical impedance is trying to understand the mechanism by which the roots are restricted. This is not clear at present and only speculative statements can be made. Because of the observations (a) that roots can exert pressures of up to 9-13 bars and yet are restricted in elongation by pressures as low as 0.2 bar and (b) that cells experiencing external pressure are shorter but increased in their cross-sectional area (Barley, 1965; Russell and Goss, 1974), it is likely that any explanation based entirely on the turgor pressure is inadequate. Metabolic processes which control the extension of the walls of expanding cells have been linked to hormones (Ridge and Osborne, 1970; Davies, 1973). So, in searching for a satisfactory answer to the problem, the hormone connection has not been left out. Recently, Osborne (1976) demonstrated that treatment of roots with ethylene or abscisic acid could lead to a reduction in cell length and an increase in cross-sectional area. It is speculated that hormones will reduce cell wall constraints upon turgor development.

In the field, the soil strength which roots must overcome has often been measured by penetrometer (metal probe which measures the amount of force needed to drive it into the soil) (Taylor and Ratliff, 1969b; Lowry et al., 1970) or inferred from bulk density measurements (Taylor and Gardner, 1963; Russell, 1977). Taylor (1974) has pointed out the difficulty in measuring the soil strength to be overcome by roots in order to penetrate. These include the fact that penetrometers have larger diameters than roots and different penetrometers give different values of soil strength. Also roots are easily deformed and have mucigel at the tip (Leiser, 1968) which reduces the coefficient of friction between the root and soil surface. Penetrometers lack these properties. However, penetrometers which approximate the shape and size of the roots (needle penetrometers) have been constructed and used (Greacen et al., 1968) but penetrometer readings are largely empirical (Baver et al., 1972; Taylor, 1974; Russell, 1977).

The use of bulk density values to infer soil strength is also beset with problems. As observed by Russell (1977), the bulk density may be closely related to root penetration in a particular soil but considerable discrepancies may occur in a wide range of soils. Also, with variation in moisture content of the soil, the relationship between bulk density and root penetration may be affected. This shortcoming cannot be solved by relating root penetration to "wet" bulk density.

Despite the difficulties discussed above, some experimental observations have been made on the relationships between root penetration and mechanical constraints in the soil. The effect of bulk density of soil on the root growth of sudangrass and soybeans was studied by Zimmerman and Kardos (1961). A significant negative correlation was found between bulk density and penetrating root weight for both plants. Roots could not penetrate below the soil surface of the different soils they used when the bulk densities were 1.8, 1.9 and 2.0 $g/cm^3$.

In two field experiments conducted with Amarillo fine sandy soil, Taylor and Burnett (1964) reported that soil strength was the only physical factor of the soil controlling growth of roots through this soil when moistened. Soil strength of 25 to 30 bars (measured with one specific penetrometer) at field capacity prevented root penetration while roots grew through the soil layer at strength of 19 bars. Fryrear and McCully (1972) reported that roots of premier sideoats grass failed to penetrate a compacted layer of the soil on which the grass was grown. Soil density was reported to be one of the principal factors affecting the development of the root systems of apples (Bul'Botko, 1973). Taylor and Ratliff (1969b) showed, in a short-term experiment, that root elongation rates of cotton and peanuts were decreased as soil strength increased. An increase in penetrometer resistance of 30 bars decreased elongation rate to 50% of maximum for cotton and for peanuts the resistance was 19.1 bars. Using radioactive rubidium, Trouse and Humbert (1961) found rooting efficiency of sugarcane decreased with increased soil density. Barley (1963) reported that the radicles of corn were prevented from elongating by an ambient effective pressure of 0.6 $kg/cm^2$. He suggested that root growth could be reduced by small negative pressures in the pore water. Discrete ped density has been reported by Edwards et al. (1964) to affect corn root penetration in an Illinois planisol over silt loam. Large corn roots were confined to the larger spaces between peds but many medium and small roots penetrated about 1/2 of the total discrete peds in the claypan B horizon directly under a corn hill. Discrete ped bulk density of about 1.80 $g/cm^3$ was suggested as probably the threshold ped density above which roots cannot penetrate peds in this soil.

Several factors modify the effects of the compaction of soil on root growth. These include soil moisture (Taylor and Gardner, 1963; Baver et al., 1972; Russell, 1977) soil aeration (Eavis and Payne, 1969; Hopkins and Patrick, 1969; Baver et al., 1972) and the interaction between soil moisture and soil aeration (Scott and Erickson, 1964; Hopkins and Patrick, 1969; Baver et al., 1972). Decreased soil moisture results in increased strength of the soil and, consequently, extending roots are subjected to greater impedance (Taylor and Gardner, 1963; Baver et al., 1972; Mirreh and Ketcheson, 1973; Russell, 1977).

Soil aeration affects root penetrability as a result of the oxygen content in the soil. In well-aerated soil, plant roots can obtain the necessary oxygen required for respiration and hence are able to penetrate deeper into the soil if other environmental conditions are not limiting. Where the supply of oxygen is limiting, the effect of external pressure on root growth is enhanced (Eavis and Payne, 1969). That soil compaction and oxygen content interact to influence root penetration has been suggested. Hopkins and Patrick (1969) found that at the highest compaction levels or at the lowest oxygen content, little or no penetration occurred, but at intermediate levels of compaction and oxygen, both factors were operative in determining root penetration. Similar results were obtained by Scott and Erickson (1964) who found that alfalfa roots penetrated dense uncemented layers of bulk density as high as 1.90 g/$cm^3$ but did not proliferate unless extra oxygen was present. Sugar beets were severely restricted by dense horizons but penetrated when extra oxygen was present. In a survey of mature orchards in which air space at field capacity and density of five roots were determined, Patt et al., (1966) reported that soil aeration influenced root density and tree productivity.

## Effect of Soil Temperature on Crop Growth

It was shown in previous sections that organic mulches affect soil temperature. Soil temperature, in turn, has a profound effect on plant growth. In addition to some direct effects, soil temperature also interacts with soil moisture and soil aeration to influence crop growth. For the purpose of this discussion, crop growth is divided into top growth and root growth. Both are interrelated and what affects one will affect the other. The influence of soil temperature, therefore, which directly affects the roots, will also affect top growth. For the sake of clarity, the effects of soil temperature on these two systems of the plant will be reviewed separately.

Soil temperature and top growth

It is useful to review briefly some components of top growth and then determine how these components are affected by soil temperature.

The growth of plants is quantitatively analyzed by certain growth variables among which are leaf area index (LAI), plant height, and dry matter of the top. The early attempt to analyze yield in relation to plant growth was made on cotton (Watson, 1952). Measurements were made on daily plant height and on the rate of flowering. Yield was interpreted based on these measurements.

The yield of a field crop according to Watson (1952) is the weight per unit area of the harvested product. So it is more logical to base the analysis of yield on the changes that occurred during the growth of the plant. The concept of efficiency index or relative growth rate was introduced and defined as

$$\text{relative growth rate } R = 1/w \cdot dw/dt$$

where w = dry weight of plant at any time (t).

As dry matter increases, however, leaf size becomes a better measure of the growing material of the plant (Watson, 1952). The rate of increase of dry matter per unit of leaf area is a measure of the balance between the rate of photosynthesis and the rate of dry matter loss through respiration. This is called net assimilation rate (NAR) and is defined as

$$NAR = (1/L) \cdot (dw/dt)$$

where L is the total leaf area of the plant.

The progress of dry matter accumulation and yield can, therefore, be completely described by two attributes, net assimilation rate and leaf area (Watson, 1952).

The technique of quantitatively analyzing growth as described above is called growth analysis technique. Radford (1967) has pointed out the pitfalls and difficulties associated with the traditional growth analyses and introduced an alternative approach which enables a continuous trace of changes with time to be made. Koller et al. (1970) used the technique to analyze the growth of soybean community.

Soil temperature affects all the attributes of top growth, plant height, leaf area, and dry matter accumulation. Weaver (1926) observed that temperatures below $5^{o}C$ will practically halt the growth of all crops. Too high a temperature, on the other hand, will severely damage the growth mechanism of the plant and hence halt growth. Therefore, there must be an optimum temperature at which crops grow best and this temperature varies for the different crops (Willis et al., 1957; Nielsen and Cunningham, 1964; Heinrichs and Nielsen, 1966; Walker, 1967, 1969; Willis and Amemiya, 1973). Langridge and McWilliam (1967) noted that the favorable effect of increasing temperature on growth is largely kinetic while that of decreasing temperature has to do primarily with gas solubility. Menderski and Jones (1963) installed heating cables beneath the rows of corn in Ohio where the normal soil temperature is below the optimum for corn growth. By use of the cable, they increased soil temperature 6 to 9$^{o}$C and reported an acceleration of plant development and significant increases in dry matter production. Corn height increased in the period 22 to 65 days after planting. Dry weight was doubled if heating commenced at emergence or tripled if heating commenced at planting and continued for 30 days after planting. At 60 days, no difference existed between the heated and unheated plants. Walker (1969) determined that each degree increase in soil temperature from 12 to 26$^{o}$C increased total seedling dry weights of corn an average of 20% greater than weights at previous soil temperatures. Between 26 and 35$^{o}$C, however, each degree increase in temperature decreased dry weights an average of 12%. In a controlled greenhouse experiment, Nielsen et al. (1961) showed that the yields of corn and bromegrass tops increased steadily with increases in soil temperature. Power et al. (1970) grew barley to maturity at soil temperatures of 9, 15.5 and 22.2$^{o}$C in a growth chamber and reported that the least dry weight of tops was recorded at 9$^{o}$C and the highest at 22$^{o}$C. Van Wijk et al. (1959) investigated the effect of soil temperature at the 10 cm depth on the early growth of corn in Iowa, South Carolina, Ohio and Minnesota. They found that early season growth of corn was decreased by low temperature in Iowa, Minnesota and Ohio. In South Carolina, where the soil temperatures were considerably higher than in the other states, the growth rate was not influenced much by soil temperature.

Root temperature can influence the performance of the shoot in a number of ways--through affecting the absorption of water and nutrients, through modifying the balance of growth substances or by influencing the apical mechanism of the shoot (Watts, 1972, 1973; Russell, 1977). In greenhouse experiments, Knoll et al. (1964a,b) demonstrated that low root zone temperatures adversely affected dry weight of corn at all stages of development, while high root zone as well as high soil temperature stimulated dry weight production. Barlow and Boersma (1972) used a linear variable differential transducer (LVDT) to measure short-term leaf elongation rate and demonstrated that leaf elongation rate increased rapidly where plant roots were released from low temperature. Investigations by a number of workers (Brouwer and Hoagland, 1964; Nielsen and Cunningham, 1964; Kleinendorst and Brouwer, 1965; and Davidson, 1969a) show that, in general, a combination of root and shoot temperature which favors the maximal growth of shoot leads to the lowest root weight relative to the shoot.

The influence of soil or root temperature on the soybean plant has not been investigated much. Corn is preferred, probably as a result of its sensitivity to variations in soil and root temperatures. One of the early attempts at investigating the effect of root zone temperature on soybean growth was made by Earley and Cartter (1945). They grew Dumfield and

Hudson Manchu soybean plants in box-like units maintained at different temperatures. They measured, among other attributes, dry matter production of the tops of these plants. Their results showed that the dry matter production of the soybean plants was markedly affected by the root zone temperature. They found that the dry matter production of the tops depended on the relationship between photoperiod, light intensity and root zone temperature. But irrespective of light intensity and photoperiod, root temperature as low as 12$^{o}$C and as high as 37$^{o}$C decreased dry matter production. Plant growth responded to increasing root zone temperature from 2 to 22$^{o}$C. There was no further response when the temperature was increased further up to 27$^{o}$C.

Soil temperature and root growth

Soil and root temperatures affect the morphology as well as the physiological functions of the root. But in this review, emphasis will be on the morphological aspect. Soil temperature greatly affects the morphology of the roots. According to Nielsen (1974), root temperature is lower than air temperature during the growing season and is subject to less variation in temperature compared to the ambient air. Root temperature optimum is less than top optimum. Roots are less adaptive to temperature extremes and therefore are more sensitive to sudden fluctuations (Nielsen, 1974). The optimal growth of the roots of many plants appears to be around 20°C which corresponds to the optimum temperature for nutrient absorption (Nielsen and Humphries, 1966). High temperatures increase root branching (Nielsen and Cunningham, 1964; Garwood, 1968) and lower temperatures encourage new root formation (Nielsen, 1974). At optimum temperature, cell division is more rapid but of shorter duration than at lower temperature (Nielsen, 1974). Effects on meristematic activity are frequently the most obvious consequences of unfavorable temperature. At cooler temperatures, the roots are whiter, thicker in diameter and less branched than at warmer temperature (Ketellapper, 1960; Brouwer and Hoagland, 1964; Nielsen and Cunningham, 1964). For example, Ketellapper (1960) reported that the roots of _Phalaris tuberosa_ became thick and less branched with decreasing temperature. Root yields of corn and bromegrass were found by Nielsen et al. (1961) to increase with increase in soil temperature from 5 to 25°C.

Root growth of creeping bentgrass was highly correlated with soil temperature at the 15 cm depth (Beard and Daniel, 1966). Beard and Daniel (1966) also observed that new roots were produced after a very sharp drop in temperature, suggesting that lower temperature either initiates root elongation or is required for the elongation of new roots from bentgrass crowns. In an experiment with bermudagrass cuttings in growth chambers, Burns (1972) observed that total root length, average length of root, number of roots and roots per node were less when the cuttings were grown under lower temperature (27/15$^{o}$C vs 32/24$^{o}$C). His results also showed that root branching was 67% less at low temperatures.

Mosher and Miller (1972) grew corn in the greenhouse under controlled conditions and reported that soil temperature was the primary factor that affected the differential directional growth of corn radicle during the winter and summer. The angle of radicle growth varied from 30$^{o}$ from horizontal at 18$^{o}$C to 61$^{o}$ from the horizontal at 36$^{o}$C. They suggested that the roots grew more horizontally at low temperature but turned and grew vertically as the soil warmed up. Pearson et al. (1970) showed that the root elongation rate of cotton increased with increasing soil temperature. It reached a maximum rate at 32$^{o}$C, then fell sharply with a further increase in temperature. Case et al. (1964) reported a higher root yield of oats at 15$^{o}$C than at 25$^{o}$C. Woolley (1963) showed that the root dry matter of spring wheat increased with increasing temperature from 7 to 32$^{o}$C.

Work on the influence of soil and root temperature on root growth of soybeans is scanty. Earley and Cartter (1943) reported that the root growth of Hudson Manchu and Dunfield soybeans tended to show an increase with increasing root temperature from 2$^{o}$ to about 27$^{o}$C. They also observed that light intensity was important in determining the magnitude of root response to increasing root temperature.

Soil moisture and top growth

Plants obtain their moisture from the soil. If the soil moisture is limiting, plant water status, estimated by measuring the leaf water potential, may not be adequate. Therefore, there is a direct relationship between soil water and plant water. The importance of water to the plant is well-known. Water is involved directly or indirectly in every facet of plant growth. So if the plant is subjected to water stress, many of the important physiological as well as morphological processes are affected although not to the same degree. Plant size is reduced by water stress and reduced cell turgor is the most important reason for it (Kramer, 1969). In his review on corn, Duncan (1975) states that moisture stress affects the length of internodes probably by inhibiting the elongation of developing cells. However, only the two or three internodes in the elongation phase during the period of moisture stress are affected. Namken (1965) found that an afternoon relative leaf water content of 0.64-0.66 significantly reduced the growth of cotton. Suppression of height and leaf growth when water potential is one bar below that at wilting has been reported for various plants (Slatyer, 1957; Lawlor, 1969; Jordan, 1970) including soybeans (Boyer, 1970). Slatyer (1969) concluded that the effect of stress on growth tends to be more pronounced in those tissues which are in rapid stages of development. Primordia initiation and cell enlargement are particularly susceptible.

Cell division seems to be affected less by water deficiency than cell elongation (Kramer, 1969). By imposing water stress at different stages of growth for soybeans in large cylinders, Shaw and Laing (1966) found that yield was reduced if stress occurred during the reproductive stages. If stress occurred during midflowering and early podding, for example, substantial pod abortion from lower nodes was observed. This loss, however, appeared to have been compensated for by higher bean set in the upper nodes and greater seed size in the lower nodes (Shibles et al., 1975).

Soil moisture and root configuration

Soil moisture profoundly affects root distribution in the soil. A number of published reports (Weaver, 1926; Newman, 1966b; Allmaras and Nelson, 1971; Allmaras et al., 1973; Durrant et al., 1973; Ellis et al. 1977; Russell, 1977) show that roots proliferate more in regions where soil moisture is adequate provided other environmental conditions are not limiting. Depth of root penetration into the soil is most affected by inadequate soil moisture. Weaver (1926), in his extensive investigations, showed that if the upper part of the profile is kept wet by rain or irrigation, the root system of most deep-rooted crops will be concentrated on the upper part of the profile. This observation has also been made in the case of corn (Allmaras and Nelson, 1971), soybeans (Mayaki et al., 1976), warm season forage species (Doss et al., 1960) and spring wheat (Ellis et al., 1977). The fact that root distribution follows closely the soil water depletion zone is the basis for the use of soil moisture depletion in estimating the extent of root distribution. For example, Long and French (1967), Draycott and Durrant (1971) did not make any direct measurements on the roots but speculated on the distribution based on the water depletion in the profile. Durrant et al. (1973) related root growth of sugar beet, potato and barley in the field to changes in soil moisture measured with a neutron probe. Maximum depth of water depletion seems to coincide with the maximum rooting depth of soybeans (Allmaras et al., 1975; Stone et al., 1976).

However, the relationship between roots and soil moisture is not strictly that of more moisture, more roots. As Kramer (1969) has observed, too much moisture in the soil reduces soil air and hence may restrict root growth. Experiments with water tables (Stanley, 1978; Reicosky et al., 1972) have shown that roots are normally concentrated in the layer just above a stationary water table. Very few or none of the roots penetrated into the water table. This is not true for some species, e.g., rice (<u>Oryza sativa</u> L.) whose roots are adapted to growing under flooded conditions.

One aspect of root-water relations which has attracted the attention of researchers concerns the water potential at which root elongation into the soil is first inhibited and that at which it stops altogether. Published results show that there is still an unresolved controversy over this issue. Hendrickson and Veihmeyer (1931) observed only a few millimeters of growth for bean and sunflower roots in soil at or below permanent wilting point during a 78-day period. Hunter and Kelley (1946) found that corn roots grew in air-dry soil with estimated potentials of -275 to -900 bars but Trouse (1972) did not observe any root growth in a soil where the water content was 1% below wilting point. He worked with sugar cane and corn. Newman (1966b) found that root growth of flax was first reduced at about -6 or -7 bars water potential. At -15 bars, root growth was reduced to 20% of the initial. At -20 bars, it was reduced to 10% and some growth occurred below -20 bars. In an experiment to determine the growth of corn and tomato roots in soils at various water potentials, Portas and Taylor (1976) reported that some growth occurred at water potentials more negative than -40 bars. They concluded that root growth probably stops at water potentials between -50 to -100 bars, although root tips may still remain alive in air-dry soil provided they are only 3 to 4 mm from moist layers. It appears that roots can survive in water potentials far below the wilting point although their activity is very much reduced.

Effect of mulches on crop growth

It has been shown that mulches modify the temperature and the water status of the soil and the influence of soil temperature and soil moisture on top and root growth has been discussed. It is expected then that mulches will have some influence on plant growth as a result of this modifying ability. Results of many workers support this view.

Effect of mulch on top growth The effect of mulch on plant growth depends on the optimum temperature for that plant. If the soil temperature at which the plant is growing is higher than the optimum, mulching tends to have beneficial effect. If, on the other hand, this soil temperature is lower than the optimum, mulching tends to have detrimental effect on top growth.

Jones et al. (1969) working in Virginia reported that mulched plots gave significantly greater average plant height and higher dry matter and yield of corn than unmulched plot.

Moody et al. (1963) also working in Virginia reported a significant increase in growth and yield of corn in mulched compared to the unmulched plots. Other investigations in places where the prevailing soil temperature is higher than the optimum have also shown the beneficial effect of mulches on plant growth. This was demonstrated on corn and soybeans in Texas (Adams, 1970), on corn in India (Chaudhary and Prihar, 1974), on potato in India (Grewal and Singh (1974), on corn in West Africa (Lal, 1974a) and on tea in Japan (Maehara, 1976).

Where the prevailing soil temperature is lower than the optimum for a particular crop, mulching has often resulted in detrimental effects. Anderson and Russell (1964) in Canada studied the effects of wheat straw mulch at various rates on spring and winter wheat for 9 years. They reported that rates of 4480 to 5600 kg/ha or more significantly depressed mean yields. Plant heights under mulch were less than those in the unmulched plots. Similar depressive effect of mulch in northern temperate latitudes has been observed in Iowa and Minnesota on corn (Van Wijk et al., 1959; Burrows and Larson, 1962).

Effect of organic mulch on crop growth--phytotoxicity of residues used as mulch material     The use of mulch for soil and water conservation is well-known and has been reviewed. Also discussed is the depression of yield by mulching which is attributed to lowering of soil temperature in a region where the soil temperature is either optimal or suboptimal. The reduction in yield through mulching can sometimes not be adequately explained by the soil temperature effect. This fact prompted McCalla and his colleagues in Nebraska to search for other effects. Their results together with those of other workers have firmly established the fact that crop residues used as mulch material sometimes contain toxic substances inhibitory to plant growth. This section will focus on the findings dealing with this phytotoxicity problem.

Guenzi and McCalla (1962) extracted wheat and oat straw, soybean and sweet clover hay, corn and sorghum stalks, bromegrass and sweet clover stems with hot and cold water and showed that these residues contained water soluble substances that inhibited the germination and growth of sorghum, corn and wheat. LeTourneau et al. (1956) showed that water extracts from 23 common weed and crop species inhibited germination and growth of wheat seedlings. In a study of the effect of decomposing plant material on plant growth under field conditions, Patrick et al. (1963) showed that the majority of the toxic material was confined to the decomposing residue and was not in the surrounding soil. Lettuce roots in direct contact with the decomposing residues showed injury but the organism isolated from these lesions were mostly nonpathogenic. In addition, they showed that phytotoxicity was most severe after 10 to 25 days of decomposition and diminished with increasing periods of decomposition. Guenzi et al. (1967) extracted wheat, oat, corn and sorghum residues with water and found that the residues contained water soluble materials toxic to the growth of wheat seedlings. The order of increasing toxicity was wheat, oat, corn, and sorghum residues. They also found that after 8 weeks of exposure to field environmental conditions, wheat and oat residues essentially contained no water soluble toxic components. Corn and sorghum required 22-28 weeks of decomposition before their water soluble substances were relatively nontoxic. Sorghum residues contained the most poisonous material, reducing root growth of wheat seedlings by 75%. Wheat straw contained the least poisonous material, causing only 6% reduction. Some of these toxic substances have been identified and include coumarin which has been shown (McCalla and Duley, 1948, 1950) to be present in appreciable quantities in sweet clover residues. Other toxic compounds are ferulic, p-coumaric, syringic, vanillic and p-hydroxybenzoic acids which have been quantitatively estimated in corn, sorghum, wheat and oat residues (Guenzi and McCalla, 1966a).

The above phenolic acid substances have been found to occur also in soil solutions (Guenzi and McCalla, 1966b) although their concentrations appear to be relatively low compared with the concentrations required for phytotoxic effects on plant growth (McCalla and Norstadt, 1974). This does not preclude their concentrations from becoming higher under some soil conditions. Also, combinations of many other phytotoxic substances occur in low concentrations in the soil and may have direct and indirect effects on plant growth, particularly under suboptimal growth conditions or during usually sensitive normal growth stages (McCalla and Norstadt, 1974).

Microorganisms in the soil produce phytotoxic substances. About 40% of all soil microorganisms isolated and studied produced organic substances which reduce plant growth (McCalla and Norstadt, 1974). Some of these substances have been identified as oxalic acid and patulin (McCalla et al., 1963). Studies on patulin (Ellis and McCalla, 1970), produced by *Penicillium urticae*, show that where this substance was applied at seeding, germination, tillering, winter survival and yield of winter wheat under field conditions were significantly reduced. Application after seeding had little effect as the plants rapidly overcame the toxic effects. When patulin was applied in one dose of 650 $\mu$moles per kg of soil at certain stages of growth of spring wheat, Ellis and McCalla (1973) showed that internodal elongation and dry matter as well as floret number, kernel weight and number as well as total yield of the wheat were markedly reduced. From the results of these experiments, McCalla and Norstadt (1974) concluded that wheat is susceptible to patulin at germination, stem elongation, and heading and flowering periods.

No work involving soybean growth response to phytotoxins in crop residues has been done to the author's knowledge.

## Objectives

It is evident from the previous review that mulching can have beneficial effects, particularly in soil moisture conservation. Mulching has been practiced and is encouraged in areas where soil erosion is a problem. The beneficial effect of mulches in regions where the soil temperature is superoptimal has been discussed. The detrimental effects where temperature is suboptimal for crop growth has also been mentioned.

Roots are the principal organs responsible for the absorption of water and nutrients for the survival of the plant. It is only now that roots are receiving the attention they deserve in scientific inquiry. The roots of most common crops are not well-understood, neither are the factors affecting their functions well-grasped. Soybean is among the crops whose roots are least studied. Neglected also is the effect of mulches on the roots and their performance. This study was initiated therefore:

1. To determine the variation of the root length and the root mass densities of soybeans with time and depth during the season.
2. To find out the effect of varying amounts of surface applied corn stalk mulch on root length and root mass densities of soybeans.
3. To determine the effect of varying amounts of surface applied corn stalk mulch on plant height, dry matter of top, leaf area index, stages of development and p plant water status of field grown soybeans.
4. To determine the patterns of soil moisture and soil temperature distribution with time and depth as affected by different rates of mulch.
5. To determine if soybean seed yield is affected by varying amounts of mulch.

# MATERIALS AND METHODS

The experiment was conducted during two growing seasons (1976 and 1977) on Ida silt loam soil (fine, silty, mixed calcareous mesic family of Typic Udorthents) located at the Western Iowa Agricultural Experimental Farm, Castana, Iowa. Physical properties and pH of the soil are shown in Tables 1 and 2.

## Plot Layout

The experimental field faced west, sloped about 8% and measured 38.4 m long and 35.4 m wide. The area was laid out in randomized block design with four replicates. Replicates 1 and 2 occupied the lower portion of the slope and 3 and 4 the upper portion (Figure 1). Each replicate, 19.2 m long and 17.7 m wide, consisted of 5 plots, each 17.7 m long and 3.0 m wide, to which treatments were randomly applied. Two adjacent plots were separated by an interplot space 0.75 m wide. Five rows of soybeans were planted in each plot. Each row was 17.7 m long and separated from one another by an interrow space 0.75 m wide.

## Planting and Treatment Application

'Wayne' soybeans (Glycine max (L.) Merr.), which had been inoculated, were planted on the 11th of May 1976 and 24th of May 1977. Prior to the 1977 planting, the experimental area

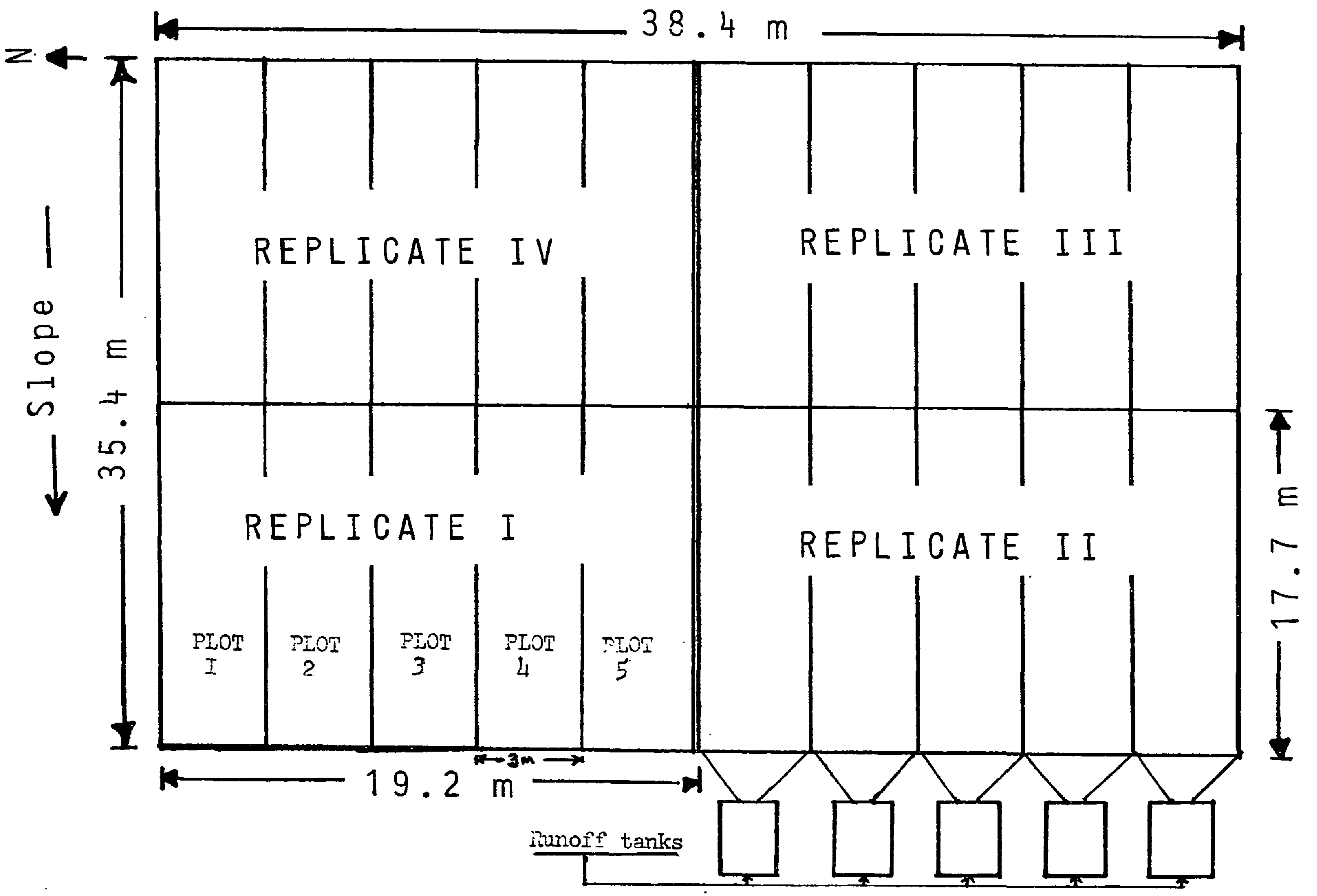
Table 1. Physical properties and pH of Ida silt loam by depth increments

| Depth (cm) | Clay (0-2 μ) % | Fine (2-20 μ) % | Coarse (20-50 μ) % | Sand (>50 μ) % | Bulk density $g/cm^3$ | pH 1:1 $H_2O$ |
|---|---|---|---|---|---|---|
| 0-22.5 | 14.3 | 24.3 | 52.8 | 8.6 | 1.25 | 7.5 |
| 22.5-37.5 | 13.4 | 25.7 | 52.5 | 8.4 | 1.20 | 7.7 |
| 37.5-55 | 15.8 | 24.7 | 46.5 | 13.0 | 1.25 | 7.8 |
| 55-80 | 11.5 | 24.6 | 55.1 | 8.8 | 1.24 | 7.8 |
| 80-97.5 | 12.1 | 21.0 | 56.8 | 10.1 | 1.26 | 7.8 |
| 97.5-117.5 | 10.5 | 23.8 | 56.7 | 8.9 | 1.27 | 7.8 |
| 117-5-135 | 13.2 | 26.2 | 48.8 | 11.8 | 1.29 | 7.8 |
| 135-152.5 | 12.3 | 26.6 | 51.8 | 9.3 | 1.29 | 7.9 |

Table 2. Volumetric water holding capacity of Ida silt loam by depth increments

| Depth (cm) | WHC % 1/3 AT | WHC % 15 AT | Avail. water % |
|---|---|---|---|
| 0-30 | 27.2 | 13.1 | 14.1 |
| 30-60 | 26.6 | 13.2 | 13.4 |
| 60-90 | 30.1 | 12.6 | 17.5 |
| 90-120 | 29.4 | 11.2 | 18.2 |
| 120-150 | 28.2 | 11.2 | 17.0 |

Figure 1. Layout of the experimental plots


38.4 m
N
Slope
35.4 m
REPLICATE IV
REPLICATE III
REPLICATE I
REPLICATE II
PLOT I
PLOT 2
PLOT 3
PLOT 4
PLOT 5
3m
19.2 m
17.7 m
Runoff tanks

was sprinkler irrigated to field capacity. There was no preplant tilling or plowing. Apart from the possible effect of tractor movement during planting, the field was undistrubed. After planting, Basagran, Roundup, and Amiben herbicides were sprayed at the recommended rates. Weed control by the herbicides was not entirely satisfactory and, subsequently, weeds were hand removed.

The treatments consisted of coarsely chopped and dried corn stalk material applied at different rates immediately following planting. The corn stalk, to be referred to subsequently as mulch, was collected the previous growing season but left in a wagon where it was protected from rain until use. The appropriate amount of mulch was weighed on a spring balance, dumped at the center of the plot area, and then raked to uniform thickness over the entire plot area. The mulch was secured with strings to prevent its scattering by wind. The treatments, as shown below, were applied on the same day.

| | |
|---|---|
| Treatment 1 | no mulch |
| Treatment 2 | 4484 kg/ha |
| Treatment 3 | 8968 kg/ha |
| Treatment 4 | 13452 kg/ha |
| Treatment 5 | 17936 kg/ha |

## Measurement of Soil Temperature

Soil temperature was measured with thermocouples starting about 15 days after planting (or mulch application) during 1976 and 1977 seasons. Measurements were made only in treatments 1 and 5, both in replicate 4.

The thermocouples (copper-constantan), protected against corrosion by dipping the fused ends in an epoxy resin, were buried at seven[1] different depths (0, 15, 30, 45, 60, 90, 200 cm) in the interrow and at the same depths within the row. The thermocouples were connected to two potentiometer instrument recorders, one for treatment 1 and the other for treatment 5. The temperatures at the various depths in the two locations were continuously recorded on a chart and subsequently read out. During the 1977 season, however, the temperatures, in addition to being recorded on a chart, were read directly from the recorders by means of the pointers. Readings were taken at 0800, 1200, and 1800 hours daily. The average daily temperatures at the different depths were taken as the average of the three daily readings at those depths. Air temperature was measured by a weather station located about 200 meters west of the experimental site.

## Measurement of Soil Moisture

Soil moisture was measured at weekly intervals throughout the season beginning on June 8, 1976 and June 1, 1977. Prior to planting and application of treatments during 1977, soil samples were taken on May 12 to determine the soil moisture before planting. Both pre- and post-planting soil moisture

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[1]In 1976, we had a problem with one of the recorders and the depths were altered to 0, 15, 30, and 45 cm starting on July 13.

determinations were made on soil samples taken with the 2.5-cm diameter auger at 7 different depths (0-15, 15-30, 30-60, 60-90, 90-120, 120-150, 150-180 cm) from each of 2 locations. The locations were (a) halfway between the rows and (b) within the rows. These locations will subsequently be referred to as interrow (or between the row) and within row (or in the row) locations, respectively. Samples were taken from these locations in the three middle rows of the five rows which made up a treatment plot. All the treatments of a replicate were sampled but on each sampling date, however, only 2 out of the 4 replicates were sampled. Replicates 1 and 3 were sampled together on one date and 2 and 4 together on the following date.

Soil samples were stored in soil moisture cans in the field and then taken to the lab where the wet weights were recorded. The samples were then dried at 105$^{o}$C for 24 hours and the dry weights obtained. The difference between the wet weight and the dry weight of a sample was taken as the weight of the moisture in the sample. This weight was converted to percent soil moisture based on the dry weight of the soil. Volumetric soil water content (SWC) was calculated from the percent soil moisture of each depth by multiplying by the bulk density of that depth divided by 100. For example, if depth A has a percent soil moisture of 17 and its bulk density is 1.25, then

$$\text{SWC of A} = 17/100 \times 1.25$$
$$= 0.75 \times 1.25 \ cm^3/cm^3$$
$$= 0.2125 \ cm^3/cm^3$$

## Stage of Development Measurement

Stages of development were recorded according to the method of Fehr and Caviness (1971) for 5 plants from each treatment. Stage of development measurements were made at weekly intervals starting on June 10 and continuing to August 27 during 1976 and from June 9 to August 23 during 1977. The measurements were made in all 4 replicates. From the values of the 5 plants, the stage of development for the treatment was calculated.

## Plant Height

Plant heights were also measured weekly in the 4 replicates, usually during the stage of development determination. Five plants from the 3 innerrows of each treatment were measured. The height from the soil surface to the apical bud was recorded in cm.

## Leaf Area, Leaf Dry Weight, Stem Dry Weight, Petiole Dry Weight, and Pod Dry Weight

Plant samples were taken at weekly intervals for the measurement of the leaf area, leaf dry weight, stem dry weight, petiole dry weight and pod dry weight. On any sampling date, samples were taken from all the treatments in the 4 replicates. Each sample, taken from the 3 innerrows of each treatment, consisted of 5 plants. The plants were separated into leaves, stems, and petioles. The combined leaf area for the 5 plants was determined using a LICOR portable leaf area meter (Lambda Instruments Corporation, Lincoln, Nebraska). The leaves, stems and petioles were separately bulked and stored in paper bags. They were then dried at 65°C in a forced draft oven and the dry weights obtained. The combined dry weights of leaf, stem, and petiole were taken as the shoot dry weight.

## Root Measurements

Two different methods were used to obtain root samples at fortnightly intervals during the 2 growing seasons. Sampling was started on June 22 (42 days after planting) in 1976 and on June 22 (31 days after planting) in 1977. During the 1976 season, root samples were obtained with the 10-cm diameter, 15 cm long bucket auger. Sampling was done at 2 locations--interrow and within row--in each treatment of 2 replicates. In each location, samples of soil and roots were taken at 0-15, 15-30, 30-45, 45-60 depth intervals. Each sample was soaked in water overnight. The soil suspension was transferred into a fine mesh sieve. The soil was washed off leaving the roots (both old and new) on the sieve. The new roots were then separated using tweezers and stored in a mixture of isopropyl alcohol and water for root length and root dry weight determinations. On 2 dates during the season, however, the modified external frame method, as described below, was used to obtain root samples.

During 1977 season, root samples were obtained at fortnightly intervals by a modified external frame method of Nelson and Allmaras (1969). Because of the labor involved (Böhm et al., 1977), only treatments 1, 3 and 5 were sampled. On any sampling date, only 1 replicate was sampled. Five plants growing close together were randomly selected from any of the 3 inner rows of a treatment plot. The plants at close proximity to those selected ones were hoed out. Two trenches, each 180 cm deep, were made with a trenching machine across the row on either side of the plants. The block of soil separated by the trenches was 30 cm thick. A frame which is a plywood board, lined on the outside with metal frames, was lowered inside each of the trenches.

The frames were adjusted so that the 5 plants in the row were centered between the edges of the frames. Each frame measured 100 cm in width and 180 cm in length. The frames were wedged into the soil block by wooden wedges. Soil was scooped out from either side of the block. These operations resulted in isolation of a block of soil, 180 cm deep, 100 cm wide and 30 cm thick with 5 soybean plants in a row centered on the block.

The tops of the plants were cut and stored for dry weight determinations. The soil block was lifted from the trench and carried from the field with a tractor. Metal pins were inserted in the holes on the plywood. These pins marked depth intervals. The first 60 cm from the surface were marked out into 7.5 cm depth intervals. Beyond 60 cm, all subsequent depth intervals were 15 cm apart. After the insertion of the pins, the soil block was immersed in a tank of water. An overhead sprinkler arrangement helped in washing off the soil, though most of the washing was done with a tractor mounted sprayer. The soil was washed off leaving the roots and some debris. The debris and old roots were carefully removed. The roots were sectioned according to the depth intervals marked out by the pins, i.e., the first 60 cm were sectioned into 7.5 cm intervals and the rest into 15 cm intervals.

The root samples were stored in a mixture of isopropyl alcohol and water for subsequent determination of the root length and root dry weight.

Depth of root penetration was determined either by locating the deepest root tip in the soil block during washing or by digging deeper for root tip in the field if the roots had grown beyond the depth of sampling. In either case, the depth of the root tip from the surface was measured with a tape measure.

Determination of root length and root dry weight: The root length was measured with an instrument whose principle of operation is based on the line intercept method of Newman (1966a). It is similar to the root length machine described by Rowse and Phillips (1974) except that a laser beam light source is used. In this machine, which was locally constructed (J. Andrews, Department of Agricultural Engineering, Iowa State University, Ames, Iowa), a laser tube is mounted in such a way that a fine laser beam strikes the underside of a glass tray. The glass tray, with roots on it, is moved from one side to another by means of an electric motor. During the movement, the laser beam intercepts the roots. The number of intercepts is displayed on a panel. The root length is calculated from the standard curve of known string length and number of intercepts.

To determine root length, small root samples were put on the tray. The roots were separated and spread out so that there was no overlapping. To prevent drying out of the roots during counting, water was added to the tray and a clean sheet of glass was placed over the roots. At the end of each run, the measured root sample was transferred into a beaker, dried at 38$^{o}$C and the dry weight was recorded.

## Leaf Water Potential

On July 21 and again on August 4 during 1976, and July 14 during 1977 season, plant water potential was determined for all the treatments in replicate 2 using the pressure bomb method (Scholander et al., 1965). Measurements were taken from 0735 to 2007 hours. A total of 12 readings were taken every 2 hours. The 12 readings were treated as replicates since it was assumed that the leaf water potential differences would not be significant during this period. Leaf samples for water potential determinations were taken from each of the treatments within every 10 minutes and from about the same height in the canopy.

## Measurement of Runoff

Runoff was measured in all treatments in replicate 2 during the two seasons. Because of the scanty rainfall in 1976, no runoff occurred. This was not the case in 1977 during which measureable runoff occurred after precipitation.

Runoff from each plot was collected in a tank by means of a collector constructed with plywood. Neither the tank nor the collector was covered at the top. The runoff was therefore corrected for the amount of water that could have collected directly in the tank and collector.

When a runoff occurred, the height of the suspension in the tank was recorded at about 7 different locations in the tank and the average of the 7 readings was taken as the height of the suspension. From the dimensions of the tank and the amount of precipitation, the amount of runoff in each treatment was calculated.

## Yield Measurements

Yield measurement was obtained by harvesting from the 3 middle rows of each treatment. The harvest length consisted of two rows, each 6.09 m long. Because of limitation in plot size, samples for yield as well as those for measurement of shoot attributes were taken from the same area in each plot.

The pods were machine threshed and the seeds were weighed. The moisture content of each sample was obtained with a moisture meter. The weight was converted to kg/ha at a corrected moisture content of 13%.

# RESULTS AND DISCUSSION

## The Shoot System

### Plant height as affected by mulch rates

Plant height is one of the easily measured growth parameters in the field and, because of this, it has often been used as an indication of plant vigor.

Plant height is therefore a valuable growth parameter and it is useful to know how mulching affects it under field conditions. Figure 2 shows the variations of plant height with time as affected by the various treatments during the growing seasons of 1976 and 1977. The relationship is generally sigmoid in nature. The greatest rate of increase in plant height occurred between 58 and 86 days after planting in 1976 and 46 to 80 days in 1977. There was relatively little increase in height either before or after these periods. The maximum heights attained under the various treatments were different for the two growing seasons. In 1976, they were 68, 65, 62, 62, and 62 cm for treatments 1, 2, 3, 4, and 5, respectively. Though the maximum heights differed in both years, the length of time it took to attain them seems to be the same--92 days after planting.

The effect of the mulch rates on the overall mean heights is shown in Table 3a and Figure 3. It is evident that mulches

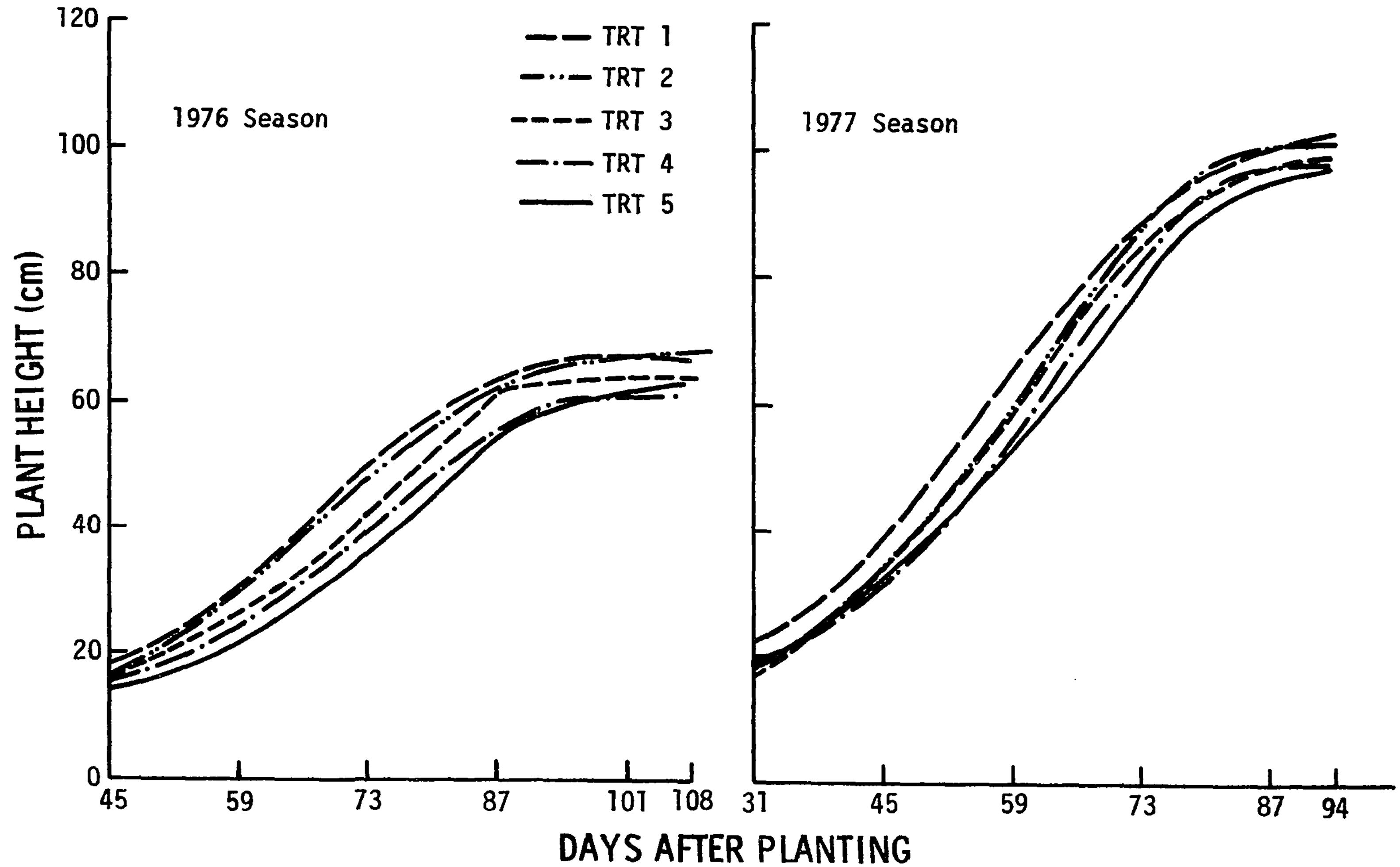



Figure 2. Variation of plant height with time as affected by mulch rates during 1976 and 1977 seasons

decreased plant height in 1976. The amount of decrease seems to be linearly related to the mulch rates up to 13452 kg/ha mulch. In 1977, there was a decrease in plant height with the application of 4484 kg/ha mulch, but no further effect on plant height was observed when the mulch rate was increased. These observations are confirmed by statistical analyses which show a highly significant ($P<0.01$) treatment effect in 1976 and no significant ($P>0.05$) effect in 1977. The regression equations for the various treatments are presented in Tables 3b and 3c.

Reduction of plant height with application of organic mulches has been reported in places where the soil temperature under mulch is lower than the optimum temperature for the growth of the crop. Where the soil temperature under bare soil is higher than the optimum for the growth of the crop, mulching enhances growth and increases plant height. Experimental evidence (Allmaras et al., 1964; Anderson and Russell, 1964; Burrows and Larson, 1962; Adams, 1970; Jones et al., 1969; Grewal and Singh, 1974; Lal, 1974a) support these observations. The reduction in plant height with mulch rates in any one growing season is due to the lowering of soil temperature at the early part of the season by mulch and hence the reduction in growth in the mulched plots compared to the bare plots. The same conclusion is reached in experi-

Table 3a. Variations of plant height (PTHT), leaf area indices (LAI) and shoot dry matter (SHDWT) with rates of mulch during 1976 and 1977 seasons

| Mulch rate kg/ha | Mean[a] | | | | | |
|---|---|---|---|---|---|---|
| | 1976 | | | 1977 | | |
| | PTHT | LAI | SHDWT[b] | PTHT | LAI | SHDWT |
| 0 | 50.9 | 2.85 | 70.08 | 67.74 | 4.68 | 102.90 |
| 4484 | 48.6 | 2.66 | 65.07 | 61.57 | 4.19 | 85.39 |
| 8968 | 45.4 | 2.36 | 55.38 | 62.19 | 4.41 | 89.99 |
| 13452 | 42.4 | 2.18 | 50.35 | 60.97 | 4.30 | 85.98 |
| 17936 | 41.3 | 2.19 | 51.63 | 59.97 | 4.59 | 88.87 |

[a]Each mean value is that of 32 observations taken over the entire season.

[b]Dry weight of all the shoot components excluding pods.

ments conducted in the north central states of the U.S. (Burrows and Larson, 1964; Willis et al., 1957; van Wijk et al., 1959).

The large difference between the plant heights in 1976 and 1977 is due to the difference in precipitation which resulted in lower soil moisture content during most of the 1976 season than during 1977. Total precipitation during the season was 141 mm in 1976. This is small compared to the total of

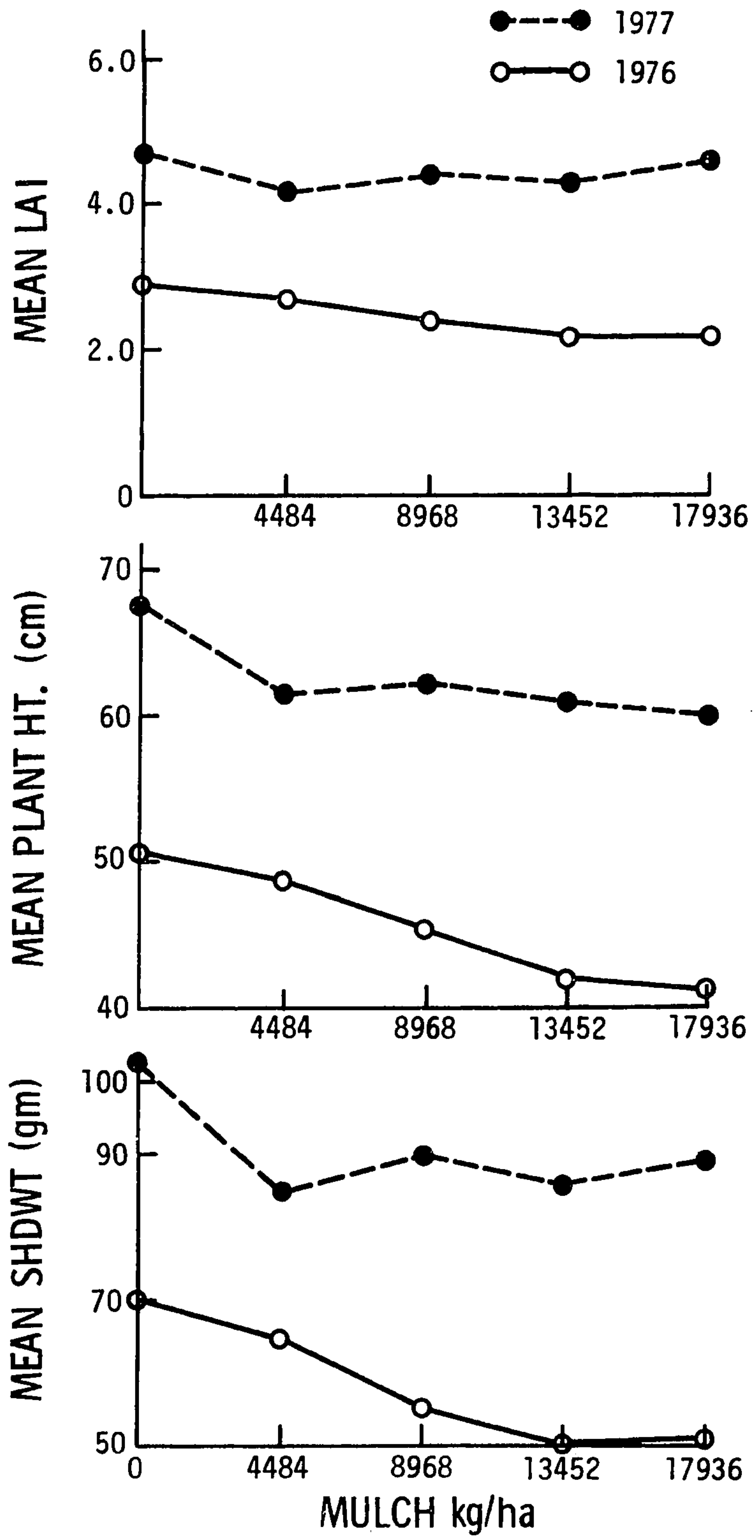



Figure 3. Effect of mulch rates on plant height, LAI, and shoot dry matter during the 1976 and 1977 seasons

Table 3b. Regression equations of plant height, leaf area index, and shoot dry matter as they vary with time (X) and treatment during the 1976 growing season

| Variable | Treatment kg/ha | Regression equation | $R^2$ |
|---|---|---|---|
| Plant height (cm) | 0 | $Y = 2.228 + 12.439X - 0.556X^2$ | 0.95** |
| | 4484 | $Y = -0.864 + 12.580X - 0.551X^2$ | 0.97** |
| | 8968 | $Y = 0.467 + 10.844X - 0.417X^2$ | 0.95** |
| | 13452 | $Y = 1.364 + 9.316X - 0.295X^2$ | 0.95** |
| | 17936 | $Y = 3.056 + 7.601X - 0.117X^2$ | 0.96** |
| Leaf area index | 0 | $Y = -0.761 + 1.069X - 0.064X^2$ | 0.84** |
| | 4484 | $Y = -0.923 + 1.009X - 0.054X^2$ | 0.81** |
| | 8968 | $Y = -0.788 + 0.838X - 0.041X^2$ | 0.86** |
| | 13452 | $Y = -0.639 + 0.657X - 0.023X^2$ | 0.89** |
| | 17936 | $Y = -753 + 0.638X - 0.017X^2$ | 0.88** |
| Shoot dry matter (g) | 0 | $Y = -7.625 + 12.104X - 0.206X^2$ | 0.93** |
| | 4484 | $Y = -11.749 + 11.922X + 0.253X^2$ | 0.91** |
| | 8968 | $Y = 2.391 + 3.330X + 0.887X^2$ | 0.94** |
| | 13452 | $Y = 6.773 - 0.803X + 1.245X^2$ | 0.94** |
| | 17936 | $Y = 1.917 - 0.034X + 1.292X^2$ | 0.96** |

**Significant at the 1% level.

Table 3c. Regression equations of plant height, leaf area index, and shoot dry matter as they vary with time (X) and treatment during the 1977 growing season

| Variable | Treatment kg/ha | Regression equation | $R^2$ |
|---|---|---|---|
| Plant height (cm) | 0 | $Y = 2.309 + 14.912X - 0.434X^2$ | 0.96** |
| | 4484 | $Y = 0.433 + 13.321X - 0.240X^2$ | 0.97** |
| | 8968 | $Y = -1.910 + 13.831X - 0.316X^2$ | 0.97** |
| | 13452 | $Y = 2.164 + 11.287X - 0.082X^2$ | 0.96** |
| | 17936 | $Y = 3.773 + 10.298X - 0.012X^2$ | 0.98** |
| Leaf area index | 0 | $Y = -0.055 + 1.270X - 0.056X^2$ | 0.88** |
| | 4484 | $Y = -1.099 + 1.574X - 0.088X^2$ | 0.79** |
| | 8968 | $Y = -1.122 + 1.482X - 0.070X^2$ | 0.87** |
| | 13452 | $Y = -0.814 + 1.194X - 0.038X^2$ | 0.94** |
| | 17936 | $Y = -1.130 + 1.440X - 0.057X^2$ | 0.87** |
| Shoot dry matter (g) | 0 | $Y = 10.710 + 7.354X + 1.864X^2$ | 0.93** |
| | 4484 | $Y = -0.019 + 8.219X + 1.496X^2$ | 0.91** |
| | 8968 | $Y = -2.993 + 8.721X + 1.622X^2$ | 0.92** |
| | 13452 | $Y = 5.594 + 2.094X + 2.278X^2$ | 0.96** |
| | 17936 | $Y = -0.652 + 8.304X + 1.637X^2$ | 0.93** |

**Significant at the 1% level.

463 mm which fell during the 1977 season. The predominant factor responsible for the taller plants in 1977 is the high soil moisture content. Soil temperature could have had some effect but its effect is minor compared to that of soil moisture. A recent investigation by Lal (1974b) tends to confirm this observation. Lal(1974b), in an experiment where maize (corn) was grown in constant as well as fluctuating root temperatures at two moisture suctions, showed that growth was greater at 250 cm $H_2O$ suction than at 750 cm suction. This was true in constant as well as fluctuating root temperature regimes, the latter approximating field conditions.

<u>Shoot dry matter accumulation as affected by mulch rates</u>

Accumulated dry matter is a balance between total photosynthates produced and that used in respiration. Dry matter, therefore, has been employed in the growth analysis of various crop communities (Weber et al., 1966; Watson, 1952; Koller et al., 1970). Since it is an important component of growth, knowledge of its variation with different rates of mulch is desirable. Figure 4 shows the variation of shoot dry matter[1] (DM) with time as affected by the treatments. It is evident that mulch affected DM accumulations differently during the two growing seasons. While the general trend of dry matter variations with time is about the same for both years, the absolute values of accumulated DM differ. The trend is for dry

[1]The weight of pods and seeds are not included.

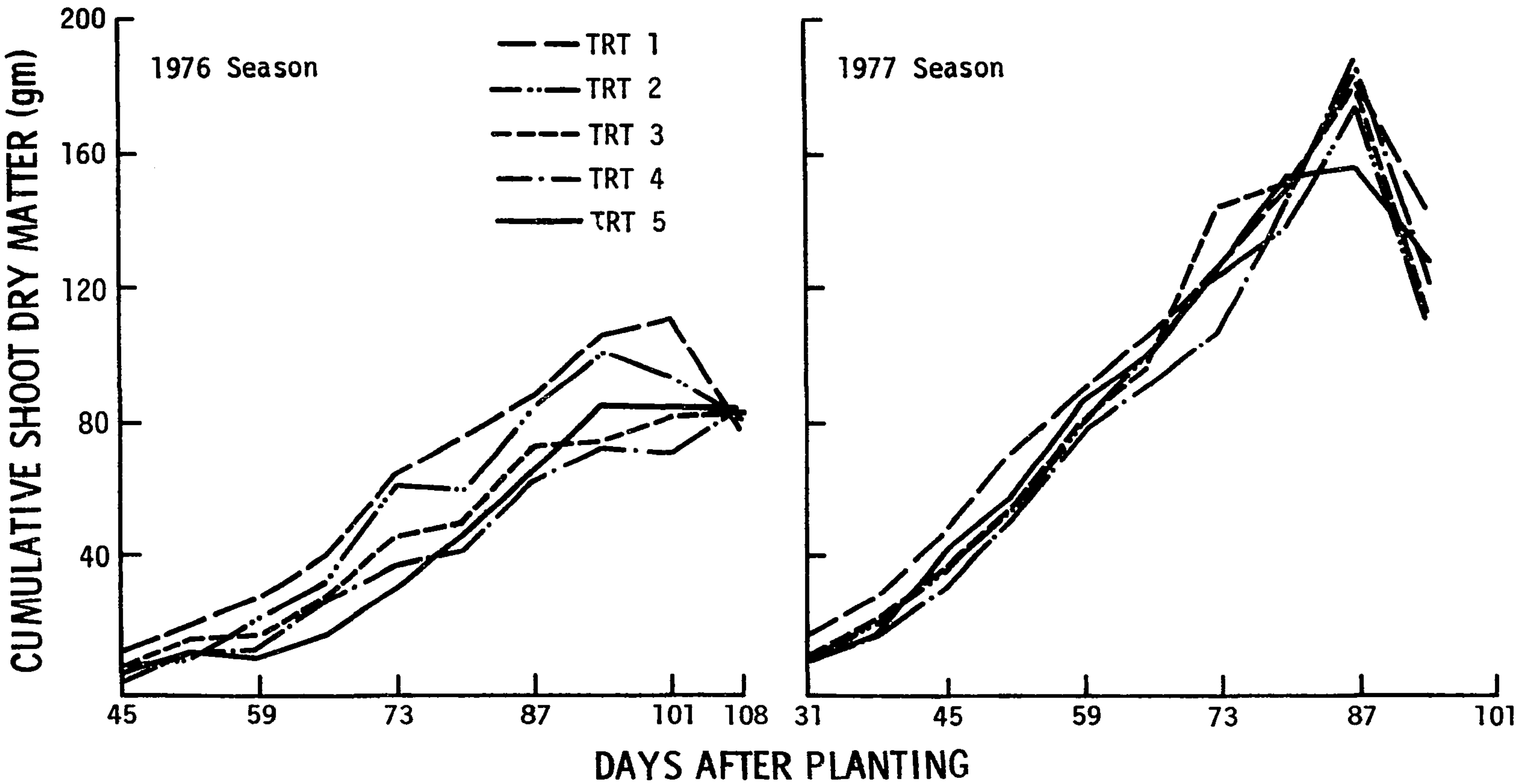



Figure 4. Variation of shoot dry matter with time as affected by mulch rates during 1976 and 1977 seasons

matter to increase slowly during the early part of the season and then increase rapidly to a maximum, declining thereafter. The period of rapid increase in DM occurred between 59 and 94 days after planting in 1976 and between 37 and 87 days after planting in 1977. These periods correspond to stages V8 to V15, R4 in 1976 and V8, R0.8 to V20, R5 in 1977. The maximum and the mean DM accumulated varied between the two growing seasons and within any one season they varied with the treatments. The maximum DM values in 1976 were 114, 100, 85, 85, and 86 g for treatments 1, 2, 3, 4, and 5, respectively. In 1977 they were 184, 176, 182, 190, and 185 g for treatments 1 through 5, respectively. The mean DM values (Table 3a) also differed for the two seasons, ranging from 50.3 g for treatment 2 to 109.9 g for treatment 1 in 1977. One other aspect of DM for the two seasons needs to be pointed out. Not only is there a gradual decline from maximum DM in 1976 but the DM of the various treatments declined to about the same value during stage V16, R6, 108 days after planting. In contrast, the decline from maximum DM in 1977 is sharp and the DM in the various treatments declined to different values at last sampling date (94 days after planting corresponding to stage V20, R6).

Of more interest is the nature of the effect of the different rates of mulch on DM production during the growing seasons. From Table 3a and Figure 3, it can be ascertained that mulching did depress DM production. As small as 4484 kg/ha of mulch decreased DM production by 7.1% in 1976 and 16.6% in 1977. Increased amounts of mulch beyond 4484 kg/ha had no further effect on DM in 1977, but increasingly decreased it in 1976 up to a rate of 13452 kg/ha. These results are confirmed by the highly significant ($P<0.01$) treatment effects in 1976 and the lack of significance in treatments in 1977. Tables 3b and 3c present the regression equations for the curves of the various treatments.

The effect of mulch on dry matter production depends on its effect on the soil temperature relative to the optimum soil temperature for plant growth. If soil temperature is above the optimum, then mulch, by decreasing the soil temperature, will increase the dry matter production. This is the case with some crops in southern latitudes. Lal (1974a) working in the tropics and Jones et al. (1969) working in the southern U.S. reported that mulching increased dry matter production.

On the other hand, where the soil temperature is suboptimal, mulches will further decrease it and will result in decreased dry matter production. A number of workers (Jones et al. 1969; van Wijk et al., 1959; Moody et al., 1963; Burrows and Larson, 1962), working in the northern latitude of the U.S., have reported decreased dry matter production in plants from mulched plots. Their findings are consistent with the one from the present work which also was done in the northern part of the U.S. Reduction in soil temperature during the early part of the season by mulching is the probable reason for the decrease in dry matter production. The large difference in DM between the 1976 and 1977 season is, however, attributed predominantly to soil moisture which was inadequate in 1976 and normal in 1977.

<u>Leaf area index as affected by rates of mulch</u>

Growth analysis technique is traditionally the preferred method of quantitatively analyzing crop growth. Leaf area, as a component in this technique, is valuable in estimating the amount of surface available for photosynthesis and hence dry matter production. In fact, differences in dry matter accumulation arise mainly from variations in leaf area (Watson, 1952). Leaf area is also an important component in the study of transpiration since most of the water lost in transpiration escapes through the leaves. In soybeans, which use a large amount of water, water consumption is dependent, among other variables, on leaf area (Shibles et al., 1975). Leaf area is, in addition, an important component in certain mathematical models to study movement of water from soil through the plants. It is therefore important to know the influence of mulch rates on leaf area.

In Figure 5, leaf area index (LAI) is plotted against time as functions of mulch rates. Leaf area index is defined as the leaf area over a certain area of ground. In Figure 3, it is $m^2$ leaf area/$m^2$ of ground. The trend of LAI with time

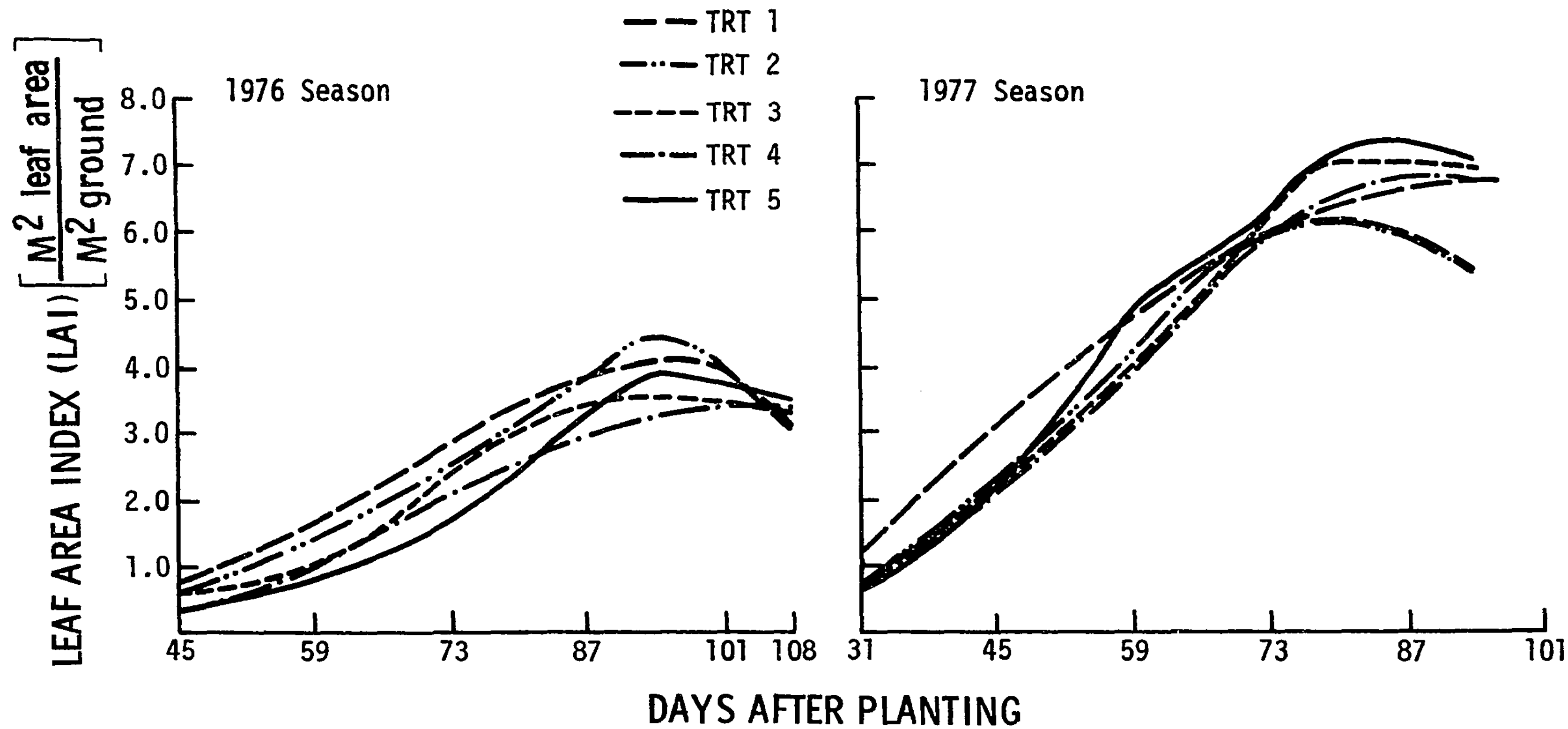



Figure 5. Variation of leaf area index (LAI) with time as affected by mulch rates during 1976 and 1977 seasons

follows that well-established in literature (Watson, 1952; Weber et al., 1966; Koller et al., 1970; Sivakumar, 1977). The LAI increases to a maximum and then declines. In 1976, it took about 94 days after planting, compared to about 82 days in 1977, to attain these maxima in the various treatments. The highest rates of LAI increases, indicating rapid rates of leaf expansion, occurred between 59 and 87 days after planting in 1976 and from 37 to about 66 days in 1977.

The effects of the different rates of mulch on the mean maximum LAI's is shown in Table 3a. During the 1976 season, the maximum LAI's ranged from 3.53 for treatment 3 to 4.57 for treatment 2. In contrast, the maximum LAI's are higher for 1977, ranging from 6.75 for treatment 2 to 7.46 for treatment 4. There is also a significant difference in mean LAI's for both seasons as shown in Table 3a.

More interesting, however, is the effect of mulch rates on LAI during both growing seasons. Increased rates of mulch decreased mean LAI's during 1976 season but seemed to have no effect in 1977. This is confirmed by the significant ($P < 0.01$) and the nonsignificant treatment effects during 1976 and 1977 seasons, respectively. The regression equations for the curves of the various treatments are presented in Tables 3b and 3c.

Leaf expansion is a function of leaf water potential which indirectly is related to soil water potential. If the soil water potential is low (i.e., lower water content) the plant may be subjected to stress (Slatyer, 1969) and the leaves may lose turgor, hence stop enlarging (Slatyer, 1957, 1969). Restriction of water supply reduces leaf area (Watson, 1952) while leaf elongation is decreased with increasing soil moisture stress (Wadleigh and Gauch, 1948).

The effect of mulch on leaf area in this study cannot be attributed to soil moisture content. It was stated above that leaf expansion and elongation are directly related to leaf turgor pressure which, in turn, is related to the water status in the leaf. If leaf water content is high, leaf expansion will proceed at the normal rate. It follows then that mulched plots should have equal or higher leaf areas than bare plots because the plants in the mulched plots should have higher leaf water potentials (i.e., higher water content), especially when soil moisture is limiting. That the leaf water potential in the mulched plot is higher than that in the bare plot is confirmed by measurements taken on August 4, 1976 and July 15, 1977 (see Figures 30 and 31). If the plants under mulch have higher leaf water content and yet lower leaf area, then some other soil factor other than moisture could be responsible. The most likely factor is soil temperature but the manner in which soil temperature affects leaf area is not clear. It is established that leaf expansion is very sensitive to air temperature. The relationship between the air temperature and the soil temperature as affected by mulch cover could be responsible for the Lower LAI under mulch.

In summary, then, it can be stated that the large difference in LAI between the 1976 and 1977 seasons is due to more soil moisture being available to the plants in 1977 than in "dry" 1976. This is also confirmed by leaf water potential as well as soil moisture measurements. In any one season, however, the reduction in LAI with increasing mulch rates is due to some factor related to soil temperature.

Relationship among leaf area, plant height and shoot dry matter

In field-grown soybeans, the leaves are mostly the organs responsible for carrying on the process of photosynthesis. Provided other factors, both environmental and internal, are not limiting, the amount of photosynthates produced can be directly related to the amount of leaf surface on which light is intercepted. The amount of photosynthates produced will also determine the rate of stem elongation and the amount of dry matter left over after respiration. Theoretically, therefore, leaf area, plant height and shoot dry matter should be related. They are indeed related as confirmed by the high correlation coefficients (Table 4) for the 1976 season.

Relationship between leaf area and plant height It is not enough to know that leaf area (LA) and plant height are related. More important is to establish the nature of this relationship and ascertain if it depends on mulch rates. To gain this information, LAI is plotted against plant height for both 1976 and 1977 seasons (Figure 6) and the regressions determined (Table 3b). Values for treatment 4 were not included on the plot but were utilized for the regression analysis. It is seen that there is a linear

Table 4. Correlation matrix of some soybean growth components during the 1976 season[a]

| | Plant height | LAI | DM | VS | RS |
|---|---|---|---|---|---|
| Plant height | 1.00 | 0.95 | 0.92 | 0.95 | 0.65 |
| LAI | | 1.00 | 0.89 | 0.89 | 0.34 |
| DM | | | 1.00 | 0.95 | 0.79 |
| VS | | | | 1.00 | 0.86 |
| RS | | | | | 1.00 |

[a]VS = index of vegetative growth; RS = index of reproductive growth.

relationship between plant height and LA and that this relationship appears to be unaffected by the mulch rates. It also tends to be less strong at higher LA and plant heights as can be discerned from the divergence of the points from the line at higher LAI and plant heights. It can be calculated from the graph that in 1976, 169 sq cm of leaf surface was associated with 1 cm of increase in plant height and vice versa. In 1977, this ratio is 225 sq cm for 1 cm of plant height and vice versa.

From Figures 2 and 5, it can be determined that higher plant heights and leaf areas are attained during the latter part of the season. It seems then that plant height can be estimated from leaf area and vice versa with greater precision during the early part of the season than during the later part. In 1976, this estimation could be valid up to

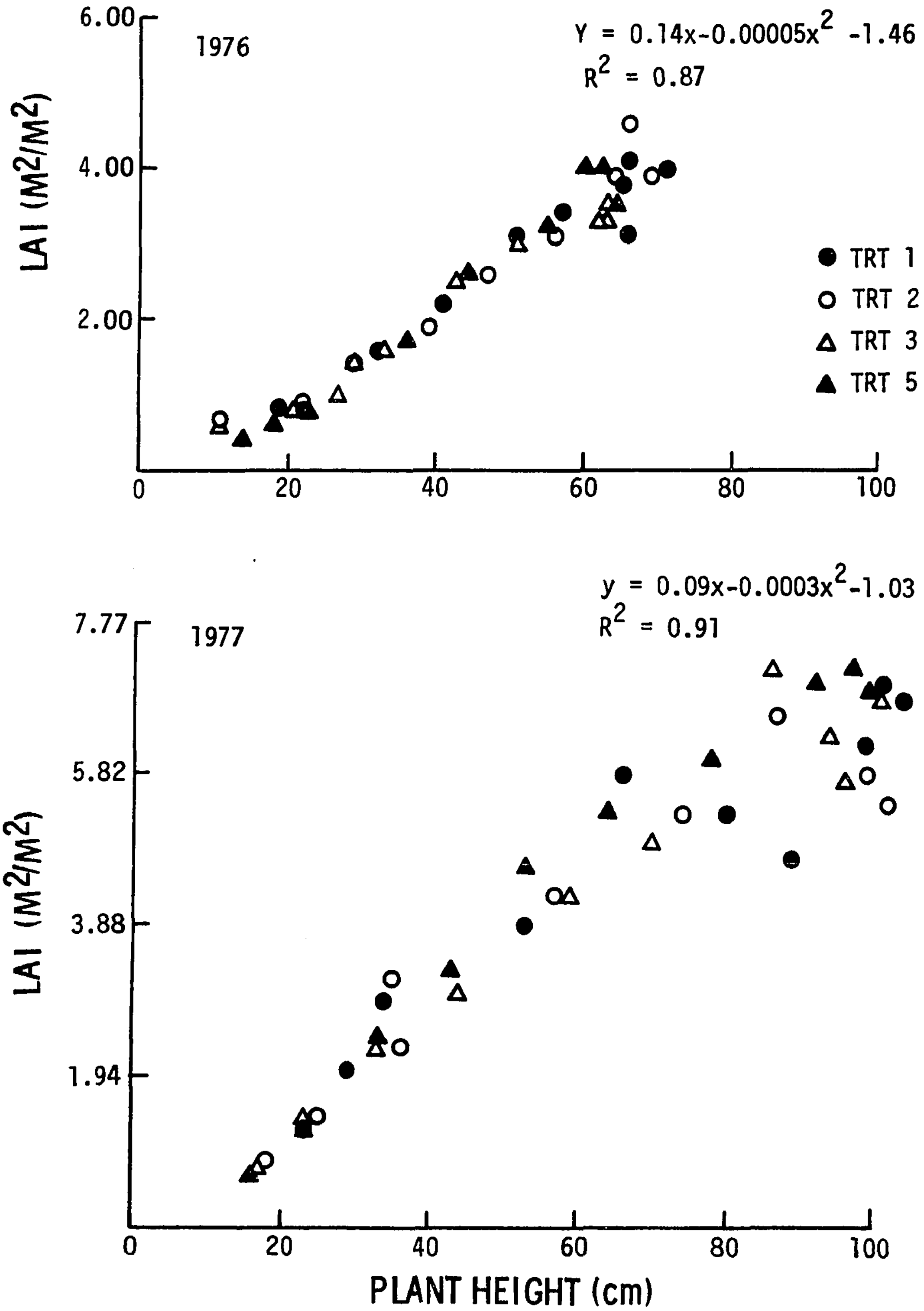



Figure 6. Relationship between plant height and LAI as affected by mulch rates during 1976 and 1977 seasons

about 80-93 days after planting. Beyond this period, the plant heights started declining in the various treatments (Figure 2). During the latter part of the 1977 season, there was an attack by grasshoppers which reduced the leaf area. This could be the reason for most of the points lying below the line at higher LAI's and plant heights (Figure 6). Because of this, it is not possible to estimate the length of time during which leaf area can be determined from plant height with a reasonable precision.

Relationship between shoot dry matter and leaf area Figures 7a and 7b are plots of leaf area (LA) vs shoot dry matter (DM) as affected by the different rates of mulch during the 1976 and 1977 seasons. It is clear from the graphs that mulching has no effect on the relationship between DM and LA. Shoot dry matter increases linearly with LA up to a certain value of DM. Beyond this value, the relationship deviates from linearity. This value is different for the two seasons. In 1976, the value where deviation from linearity occurs is about 60 g while in 1977 it is about 95 g. From the plot of DM vs time (Figure 4), it can be calculated that, in 1976, a shoot dry matter of 60 g was attained between 72 and 86 days after planting in the various treatments. It follows, then, that up to about 72 days after planting 113 sq cm of leaf area was associated with the production of 1 g of dry matter of shoot. In 1977, however, it took between 67 to 72 days after planting to produce a shoot dry matter of 95 g. It means

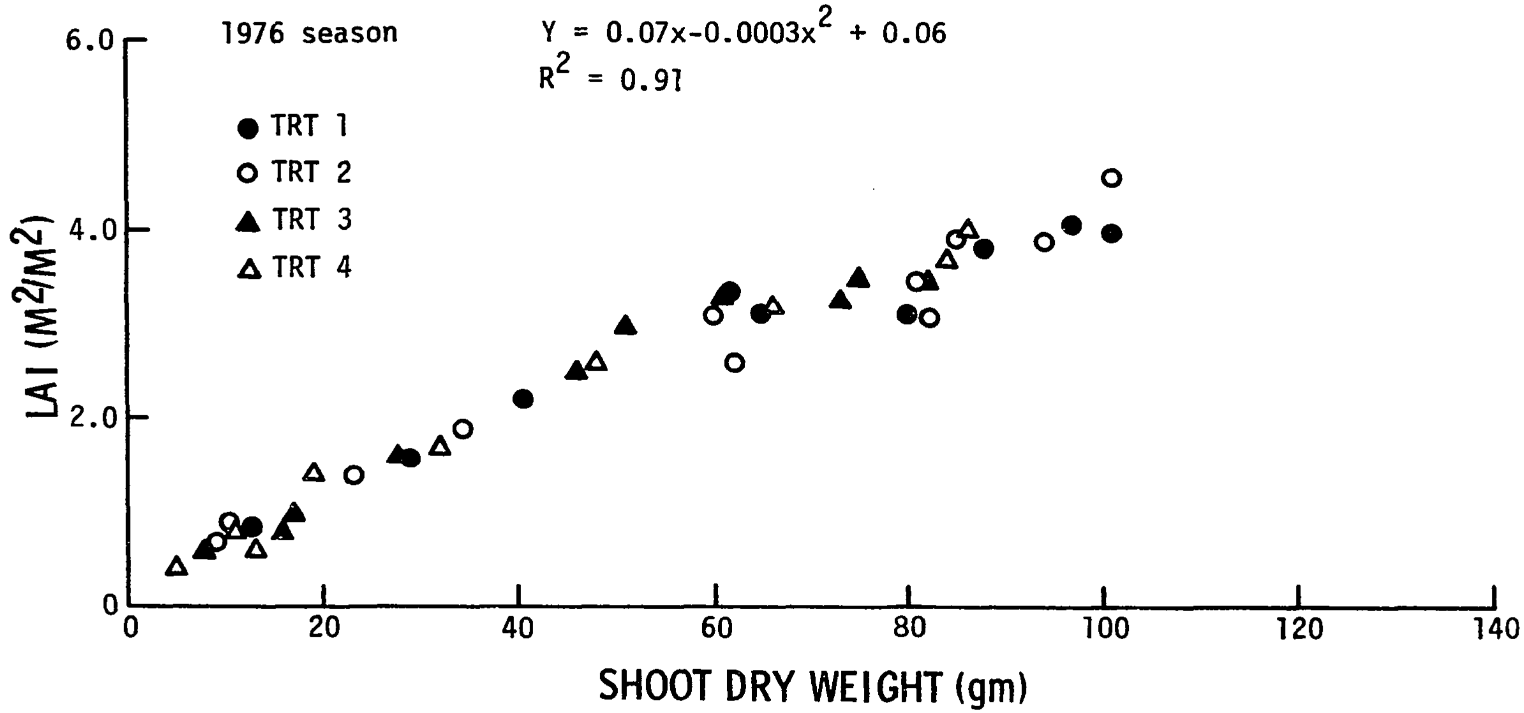



Figure 7a. Relationship between shoot dry matter and LAI as affected by mulch rates during 1976 season

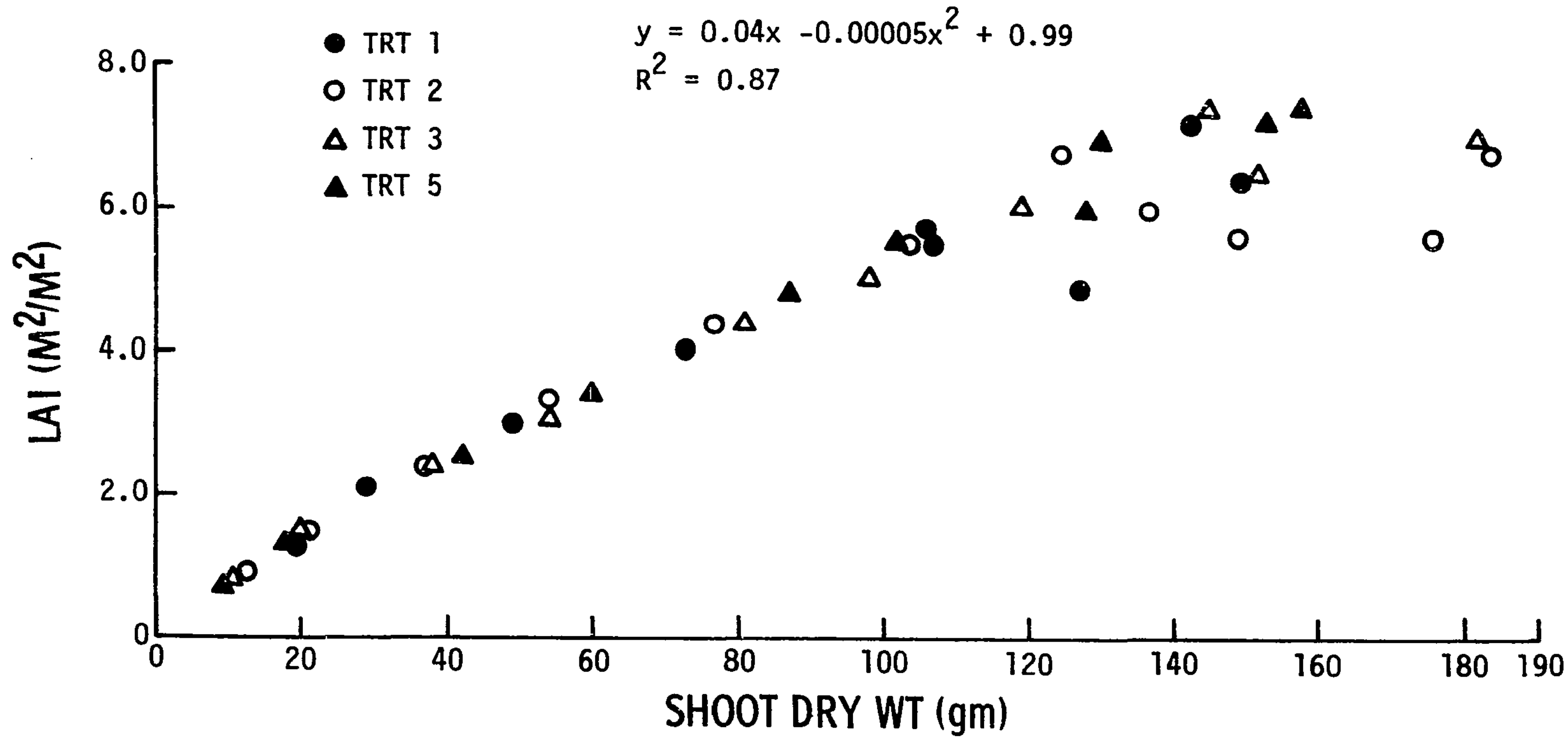



Figure 7b. Relationship between shoot dry matter and LAI as affected by mulch rates during the 1977 season

that up to 67 days after planting, 129 sq cm of leaf area was associated with production of 1 g of shoot dry matter. The deviation from linearity at higher values of DM and LA is probably due to the leveling off and decline in LA during the latter part of the season.

## Soil Moisture

### Soil moisture distribution with depth at selected times in the season

Figures 8 and 9 show the distribution of soil water content with depth at 4 dates during the 1976 and 1977 seasons. Generally, the pattern of distribution is the same for both seasons although certain differences occur as a result of the difference in seasonal precipitation. These differences in the pattern of profile soil moisture distribution will be pointed out where necessary. Because the 1977 graph illustrates the pattern better, it will be used to show how the soil moisture content varied in the profile as the season progressed.

At the beginning of the season when the roots had not developed appreciably, the soil moisture content was more or less uniformly distributed with depth in the profile although the mulched plots had more moisture, particularly at the 0-15 cm layer, than the unmulched plot. At this time, 8 days after planting, the water content in the 0-15 cm depth was 0.25 $m^3/m^3$ in the unmulched plot and 0.30 $m^3/m^3$ in the 17936 kg/ha plot.

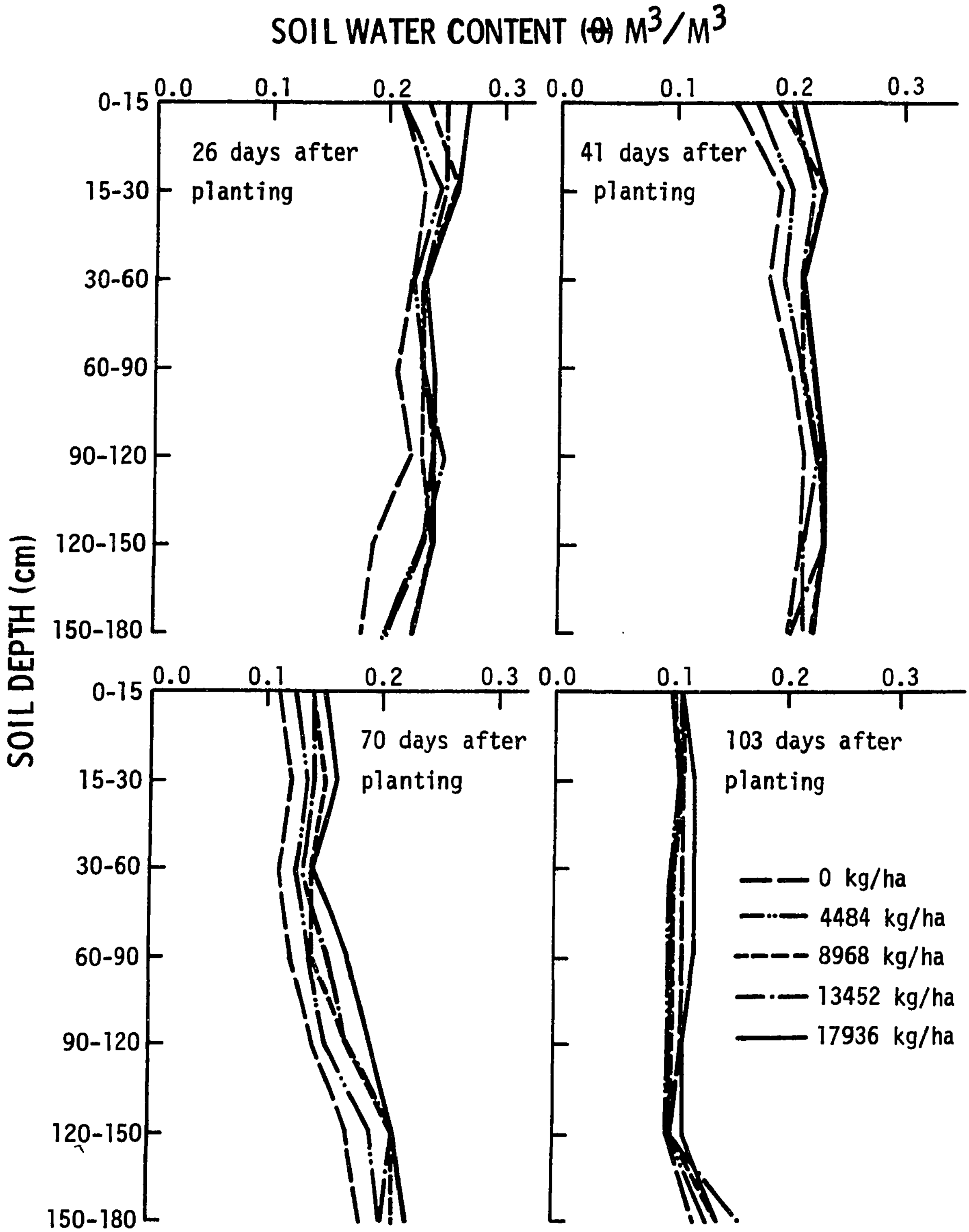



Figure 8. Effect of mulch on the variation of soil water content with depth at 4 dates during the 1976 season

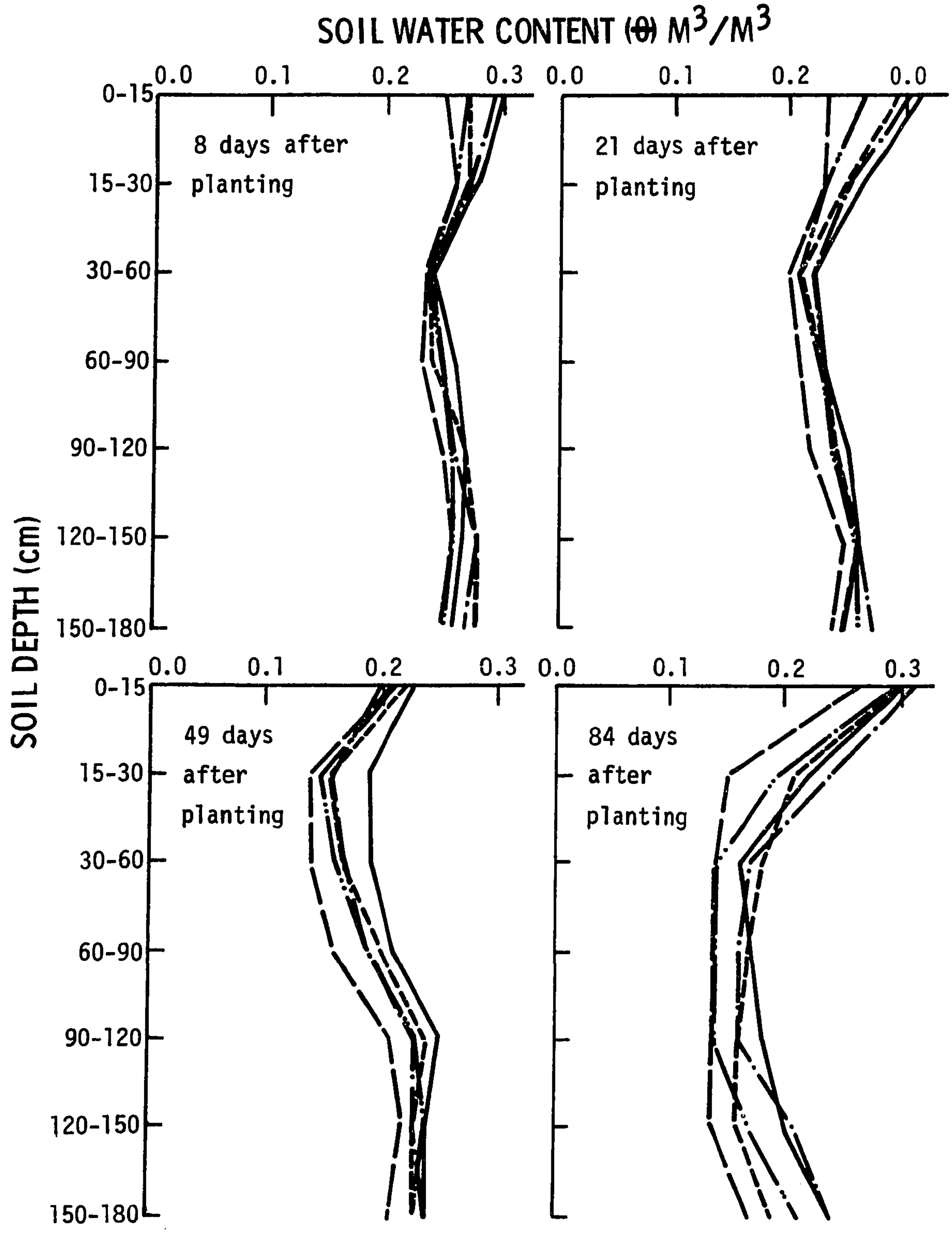



Figure 9. Effect of mulch on the variation of soil water content with depth at 4 dates during the 1977 season

As the season progressed and the roots developed further and penetrated deeper into the profile, the pattern of water content in the profile began to change. At 21 days after planting, the moisture content in the 15-30 cm and 30-60 cm layers had decreased from their previous values, obviously as a result of water extractions by the roots and a possible downward movement into the deeper layers in the profile. Meanwhile, the moisture content increased in the 0-15 cm depth in treatments 3, 4, and 5 and decreased in treatments 1 and 2. The increase was due to precipitation received before the samples were taken and the decrease was due to evaporation and also root extraction. Deeper down in the profile, there was little change in the moisture content.

As the season progressed further, moisture was further depleted from the surface down to about 90 cm in the profile. The decrease in the 90-180 cm profile is probably due to downward gravitational movement beyond the 180 cm depth or possibly due to upward movement into the zone of greatest moisture depletion. This zone ranges from about 15 to 90 cm depths. Here, the decrease in moisture content is mainly attributed to the extraction of water by the new proliferating root system. Meanwile at the 0-15 cm layer, the soil moisture content had decreased in all the treatments but was still higher than that in the 15-90 cm depth.

Towards the end of the season, at about 84 days from planting, the roots had penetrated deeper into the profile and depletion of soil moisture had extended to the 120-150 cm layer in all the treatments. As can be observed, there was an increase in the moisture content at this time in most of the layers as a result of precipitation. However, the pattern of distribution showed up quite clearly. The zone of soil moisture extraction had extended from the surface down to the 150 cm depth.

One observation in the 1976 graph (Figure 8) needs to be pointed out. At about 103 days after planting, the soil water content in the profile had been depleted essentially to a constant value from the surface down to the 150 cm depth. Because there was little or no precipitation to recharge the profile water, the roots practically depleted the soil moisture to a value between 0.10 and 0.14 $m^3/m^3$ in all the treatments. Because no further soil moisture samples were taken beyond this date, it is not certain if this 0.1 $m^3/m^3$ is a critical soil water content at which roots can no longer extract water from the soil. Reference to the moisture characteristic curve of this soil (Willatt and Taylor, 1978) shows that this water content corresponds to less than about -15 bars. It should also be pointed out that throughout the entire season, the moisture content in treatments 1 and 2 was less than in treatments 3, 4, and 5 in all depths. This does not mean that the mulch conserved water in the entire profile. The difference in the water content of the various treatments in the deeper part of the profile is due to the differences in the root distribution as will subsequently be discussed.

Variation in soil water content at selected soil depths during the season

Figures 10a, 10b, and 11 depict the variations at 4 depths (0-15, 30-60, 90-120, and 150-180 cm) of soil water content during the 1976 and 1977 growing seasons. The distribution patterns at 3 mulch rates (0, 13452 and 17936 kg/ha) are presented but since they are largely similar, only that for the 0 mulch rate will be described. The patterns for 1976 and 1977 seasons differ essentially only in the 0-15 cm layer where the higher precipitation of 1977 constantly recharged the soil moisture, thus masking any effect of roots on soil moisture distribution in this layer. Because of this, the 1976 curves will be dwelt upon in illustrating the trend.

It can be seen that soil moisture content decreased in all depths during the season, but not in the surface layer when recharged by precipitation. The extent of the decrease and the time it started differed among the depths. Right from the time measurements started at about 26 days after mulch application, the water content in the surface to 15 and 30-60 cm layers decreased steadily. By the time the plants were 61 days old, i.e., about 71 days after planting, the water content in the 0-15 cm profile had decreased by 52% down to a constant value of about 0.11 $m^3/m^3$, which was only increased by precipitation received 96 days after planting. The moisture content in the 30-60 cm layer also decreased steadily reaching a

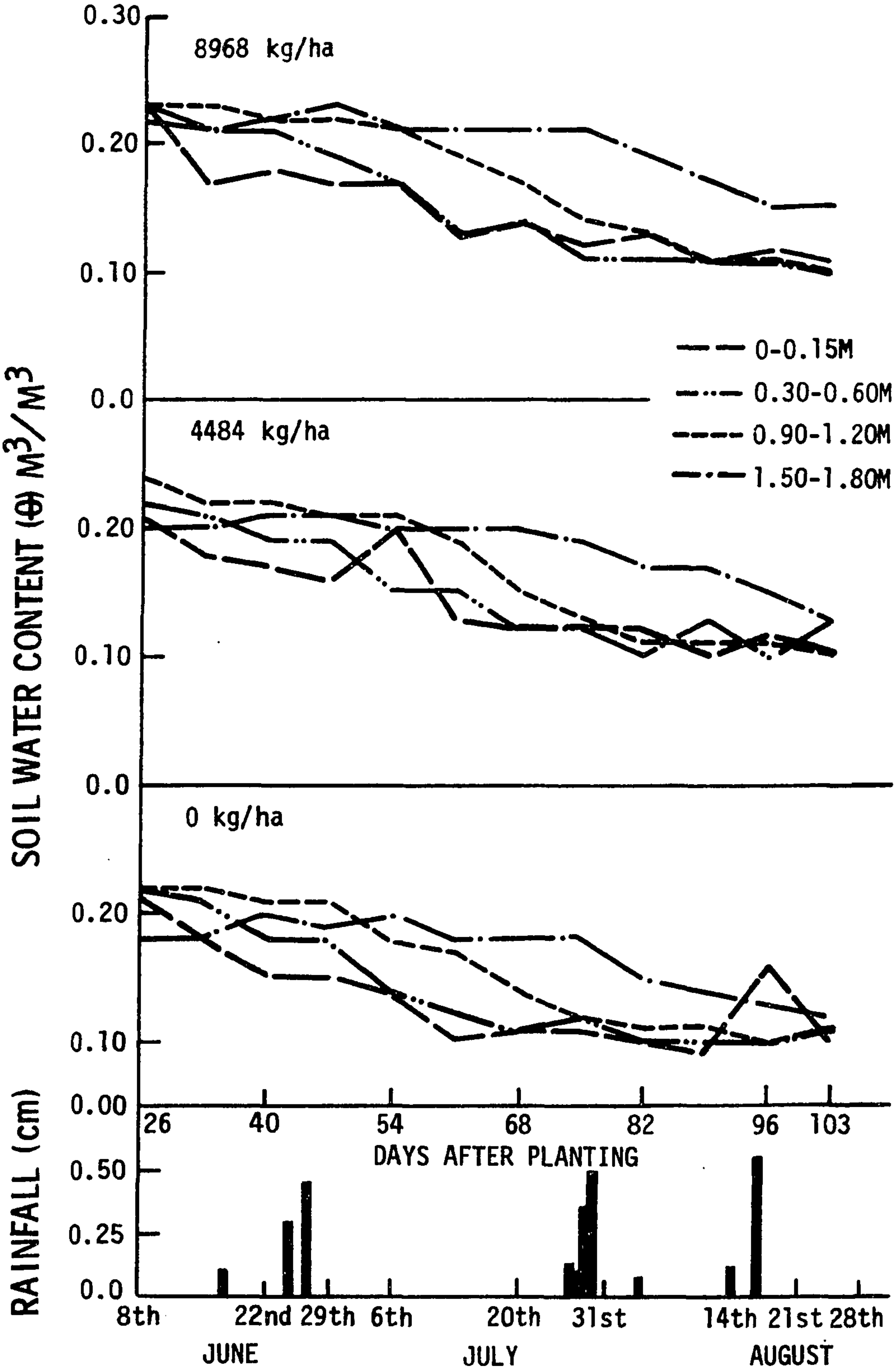



Figure 10a. Soil water content distribution with time at 4 depths during the 1976 season

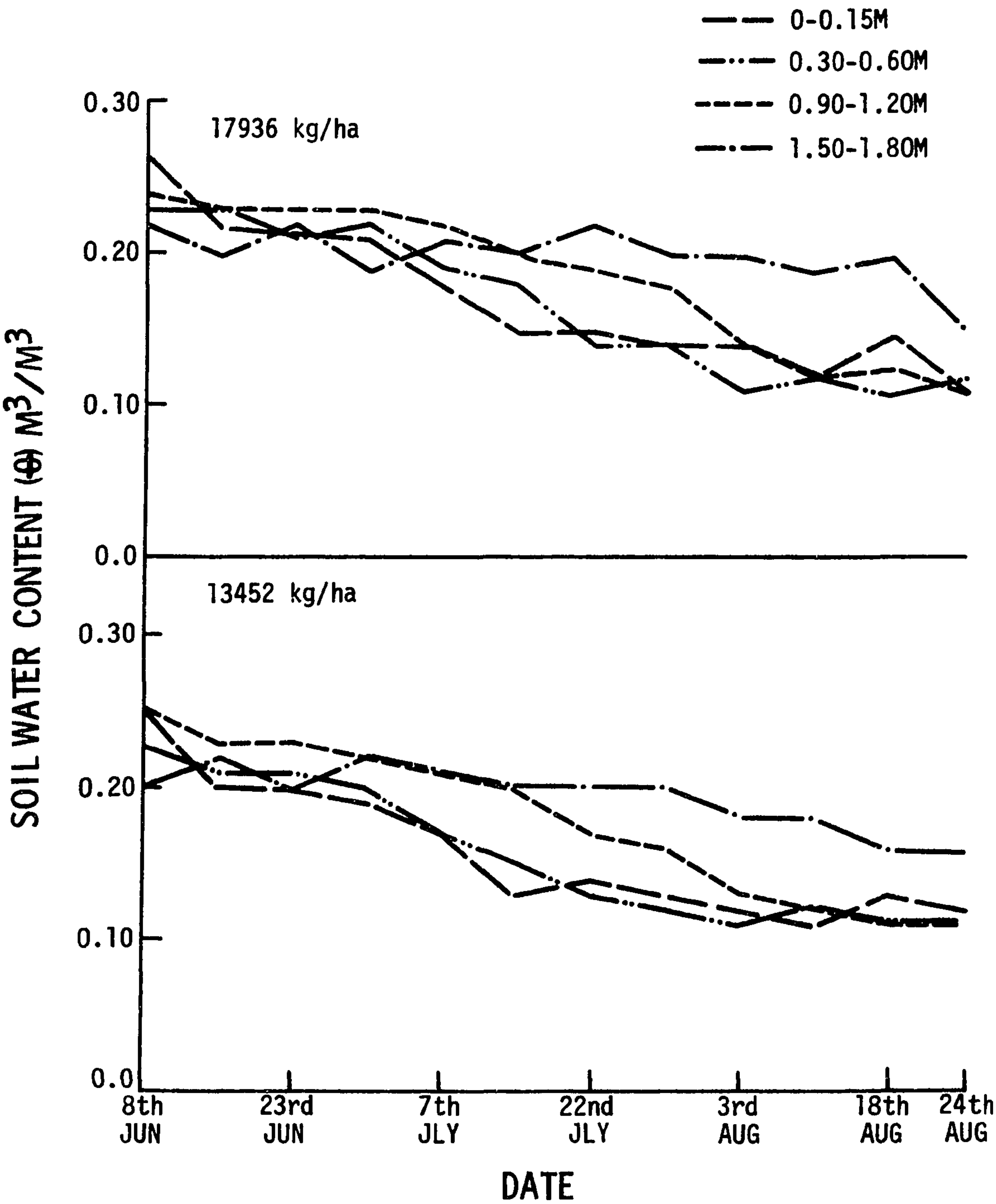
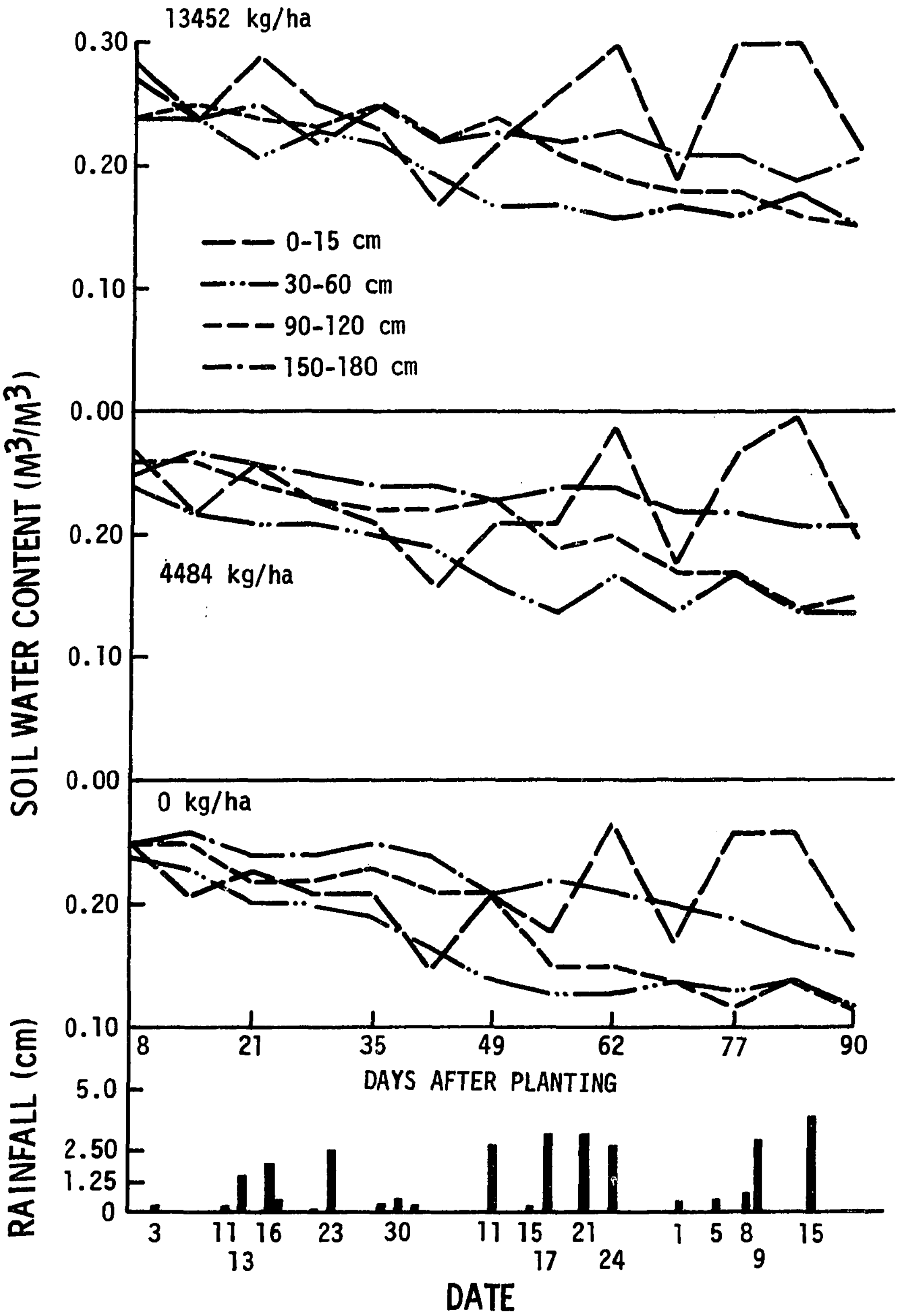



Figure 10b. Soil water content distribution with time at 4 depths as affected by mulch rates during the 1976 season

Figure 11. Variation of soil water content with time at 4 depths as affected by mulch rate and rainfall during the 1977 season


13452 kg/ha
0.30
0.20
0.10
0.00
0-15 cm
30-60 cm
90-120 cm
150-180 cm
SOIL WATER CONTENT (M3/M3)
4484 kg/ha
0 kg/ha
8
21
35
49
62
77
90
DAYS AFTER PLANTING
RAINFALL (cm)
5.0
2.50
1.25
0
3
11
13
16
23
30
11
15
17
21
24
1
5
8
9
15
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value of between 0.10 and 0.12 $m^3/m^3$ from an initial value of about 0.22 $m^3/m^3$, a decrease of about 50%. This decrease occurred in about 68 days after mulch application.

Meanwhile, the water content of the 90-120 and 150-180 cm layers did not decrease initially. In fact, the moisture content of the 150-180 cm depth increased during the early part of the season from 0.18 $m^3/m^3$ at the start of measurements to 0.20 $m^3/m^3$ about 54 days later. This increase is probably due to downward movement of water in the profile. The moisture content in the 90-120 cm depth was steady at 0.22 $m^3/m^3$ for 47 days after mulch was applied. However, it started declining thereafter, reaching a minimum constant value of about 0.11 $m^3/m^3$ 75 days after planting. The rate of this decrease was higher than in the 150-180 cm layer where the decrease started about 54 days after planting, continued at a gradual rate reaching a value (probably not the minimum) of 0.13 $m^3/m^3$ 103 days after planting.

It is important to point out the obvious trend depicted in the graph just described. This trend has also been observed by Garwood and Williams (1967) in an experiment with _Lolium perenne_ in southern England. Other workers (Jones et al., 1969; Moody et al., 1963; Lal, 1974a) have also reported higher soil moisture content during the entire season in the 0-15 cm layer than the 15-30, 30-60 cm layers. However, in none of the work just referenced was soil moisture content measured down to 180 cm depth throughout the season.

It is therefore appropriate to find an explanation for the patterns of soil moisture distribution shown in Figures 10a, 10b, and 11. Initially, the moisture was lowest in the deepest part of the profile and highest at the surface. By the time measurements were started, the moisture in the top layer had started decreasing due to evaporation and gravitational movement into deeper layers. The loss of moisture from the 0-15 and 30-60 cm layers meant a gain of moisture for the 90-120 cm layer. Apparently, the moisture gain did not extend to the 150-180 cm layer. The result was that the soil water content was highest in the 90-120 cm layer and this lasted up to 47 days after planting.

The extraction of moisture by the proliferating root system combined with the evaporation from the surface resulted in the early decline in water content in the 0-15 and 30-60 cm layers. As the root systems extended downwards into the profile, the moisture in each successive layer began to decline. This is well-illustrated in the figures where the moisture progressively declined in order from the surface down to the 180 cm depth. Stone et al. (1976) have also reported a decrease in available water and water potential as soybean root weight increased.

<u>Seasonal variation of water content as affected by mulch rates at 3 depths</u>

To find out how long mulch influenced soil moisture content during the season and at what depth in the profile this influence ceased to exist, if it did, the variations of soil moisture at 3 depths throughout the season were graphed and are presented in Figures 12a and 12b. The mulch did exert its influence throughout the season in the 0-15 cm depth, the higher the rate of mulch, the more moisture that was conserved. This influence is, however, more strongly expressed at the early part of the season than during the later part.

The apparent mulch influence at the deeper part of the profile is better explained as a result of root activities rather than the mulch itself. This root activity was discussed in the previous section.

Seasonal variation of soil moisture in the row-interrow locations

In situations where moisture is limiting, it is essential that maximum efficient use of soil moisture be made. To achieve this goal, it is important that the variations of soil moisture within and between crop rows be known. Also, as pointed out by Allmaras et al. (1973), the environment of the row and interrow locations may not be the same and roots respond differently to the variations in these environments (Allmaras et al., 1973; Allmaras and Nelson, 1971). It is important, therefore, to find out how the row and interrow soil moisture varied during the season. To do this, soil moisture samples were taken midway between the rows and within the rows during the season. Figures 13a, 13b, and Tables 5 and 6 present the results obtained from these measurements.

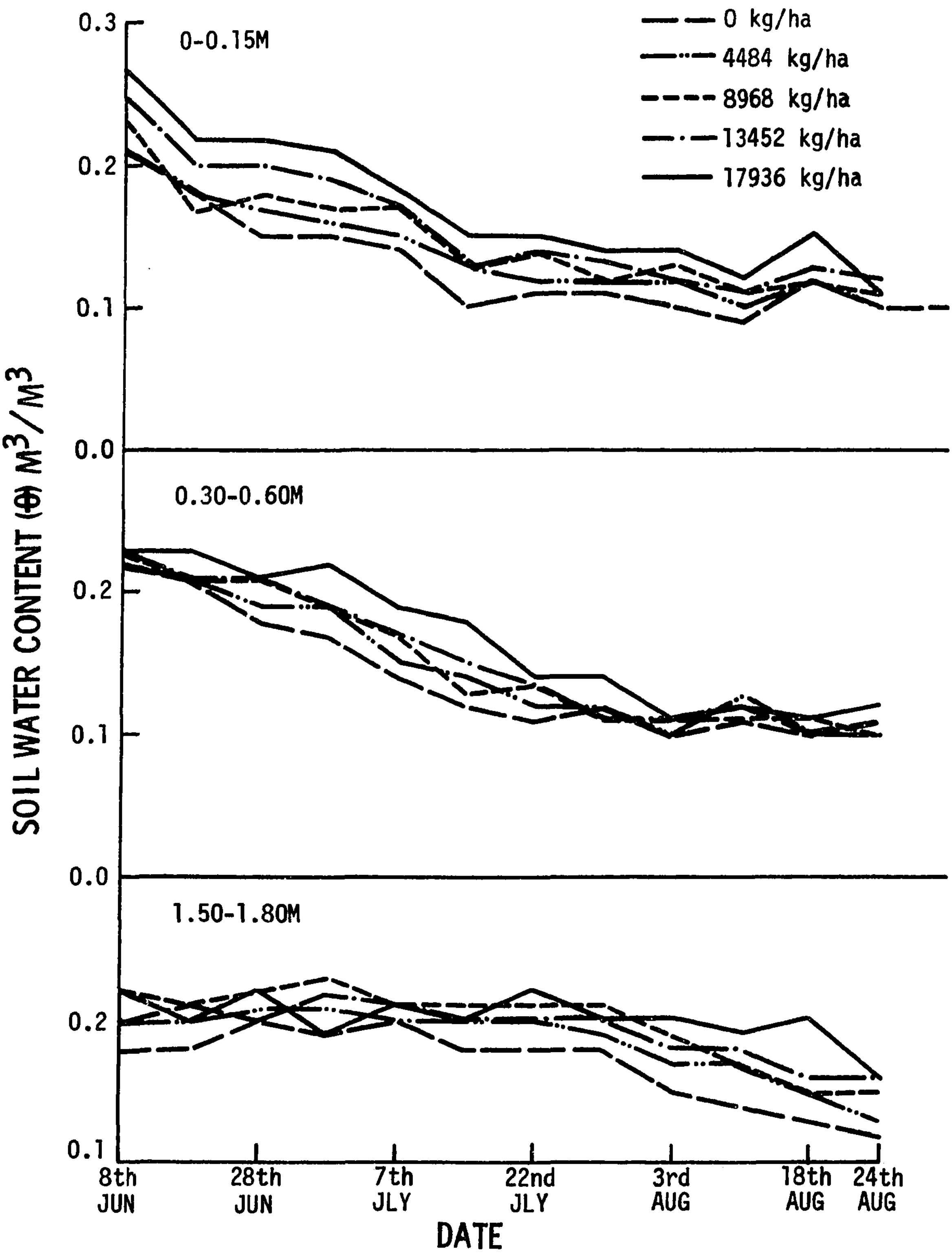



Figure 12a. Effect of mulch on soil water content at 3 depths during the growing season (June-August) in 1976

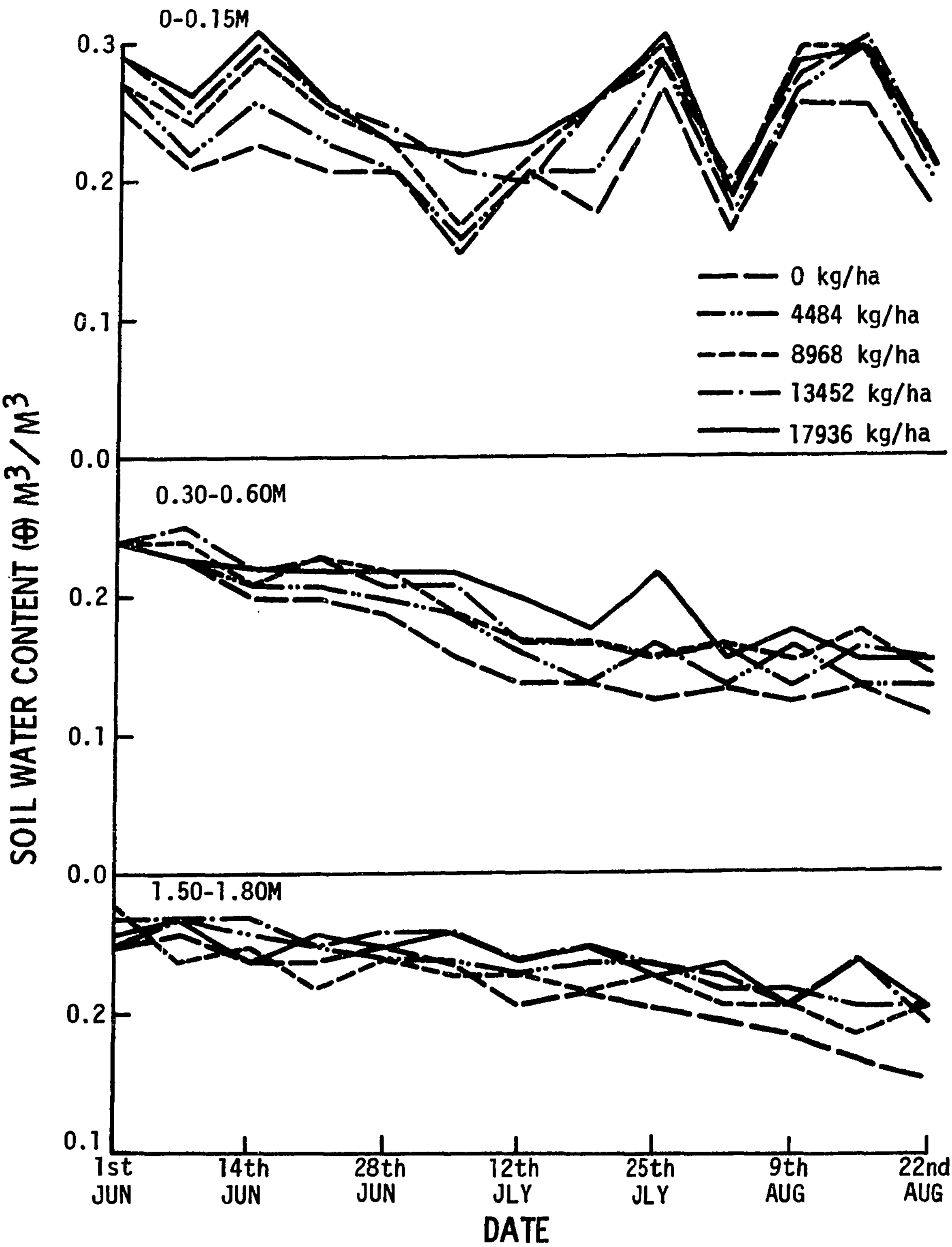



Figure 12b. Effect of mulch on soil water content at 3 depths during the growing season (June-August) in 1977

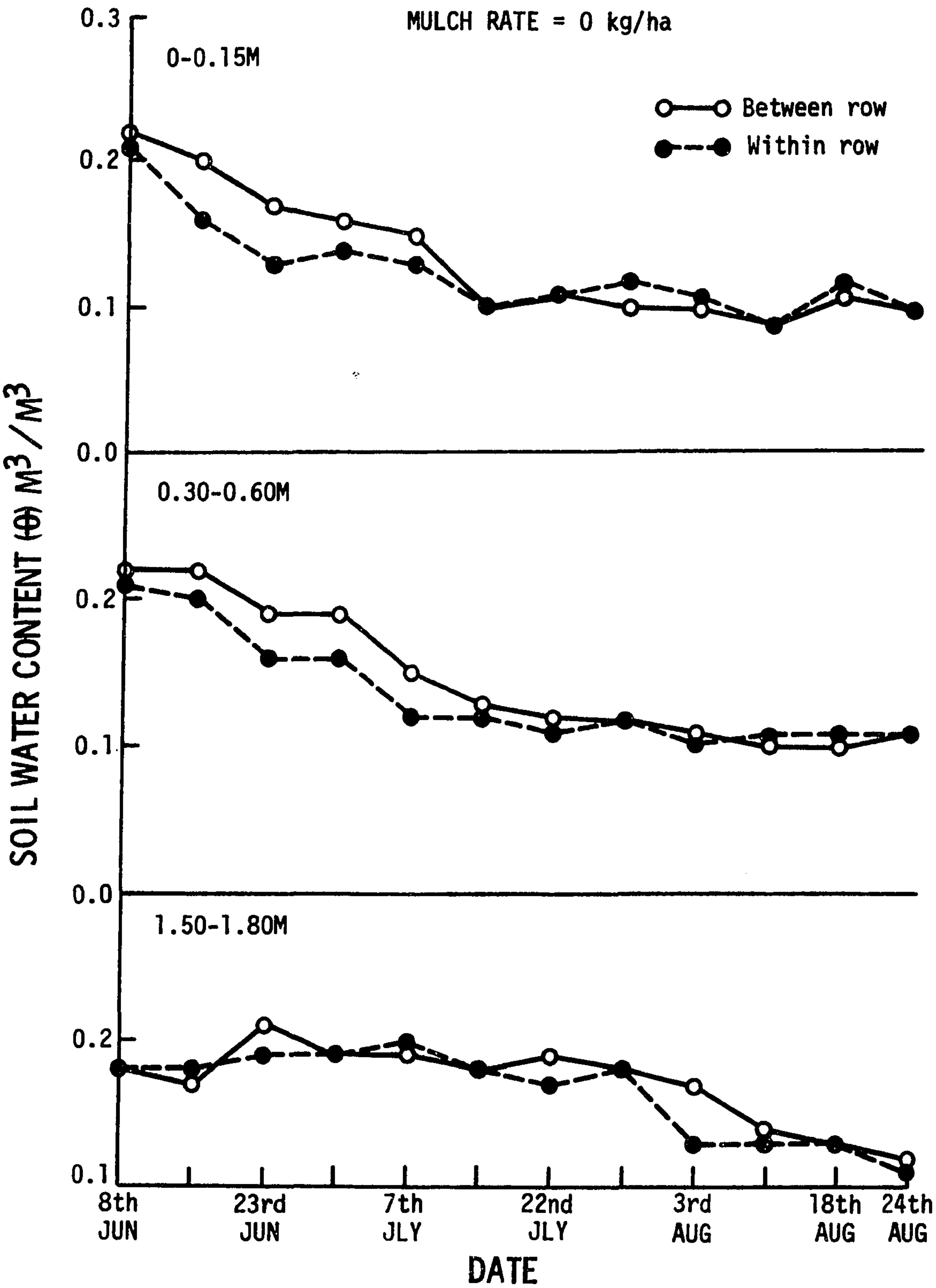



Figure 13a. Variation of soil water content with time at the row and interrow locations during 1976 season

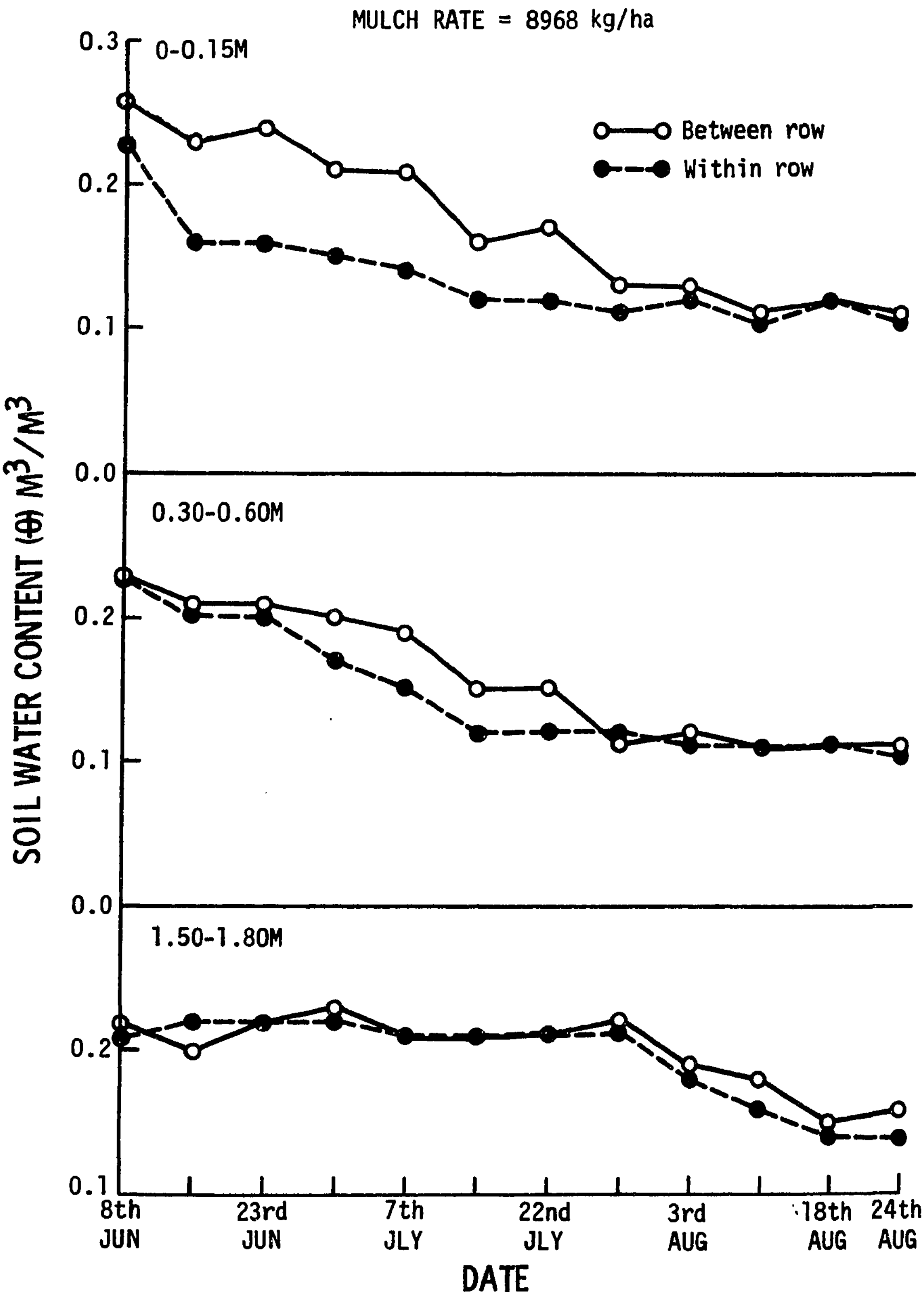



Figure 13a. (Continued)

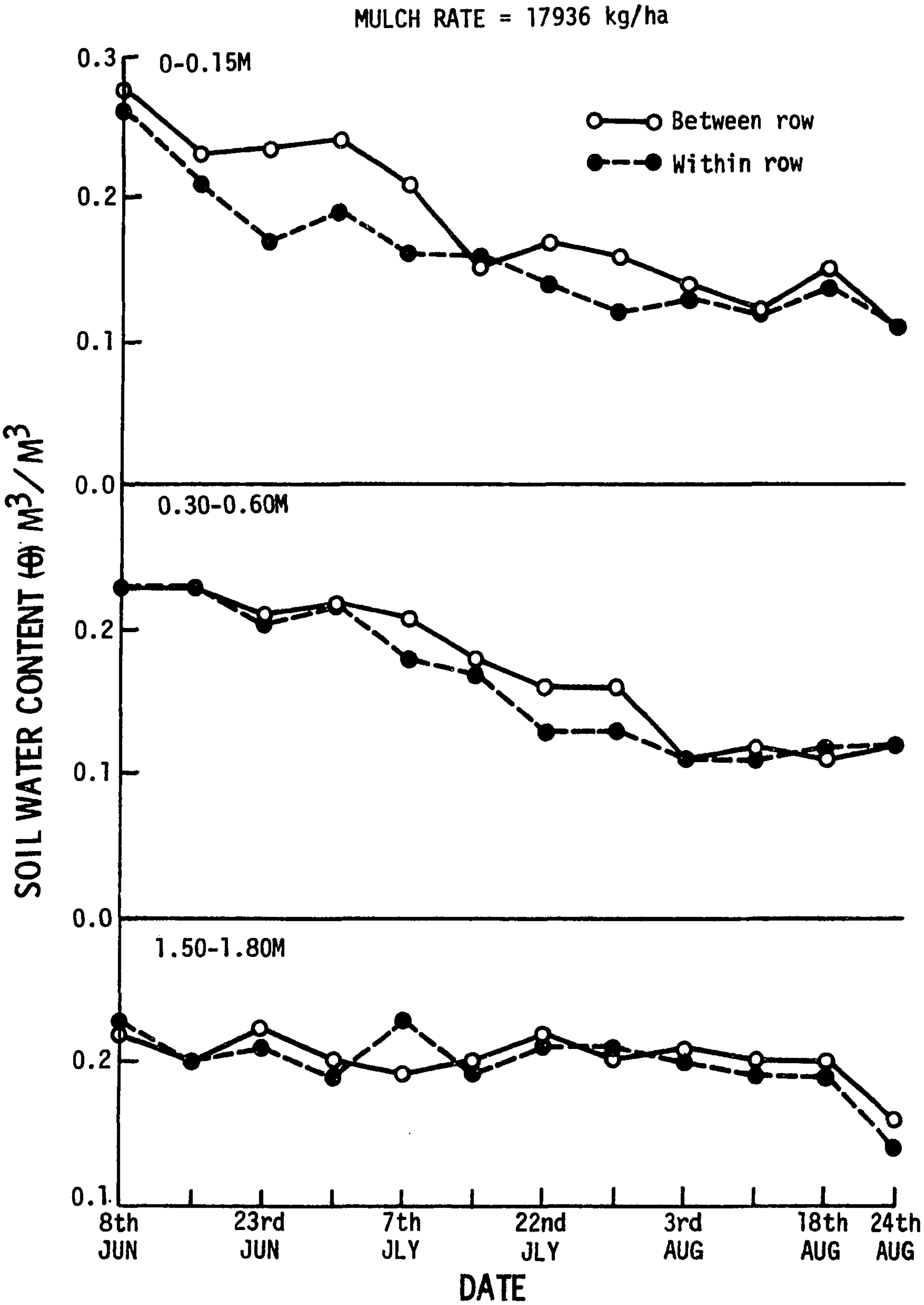



Figure 13a. (Continued)

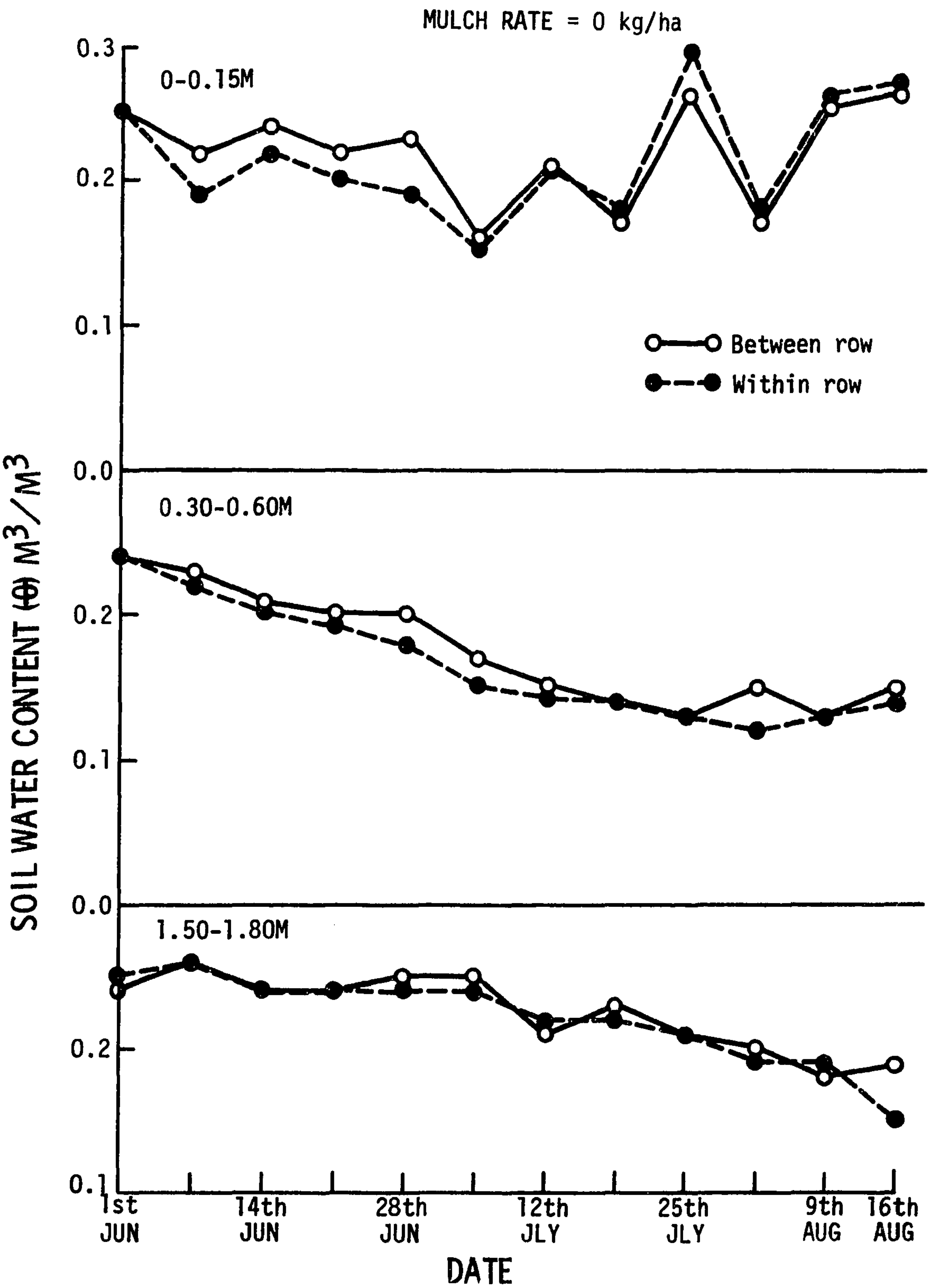



Figure 13b. Variation of soil water content with time at the row and interrow locations during 1977 season

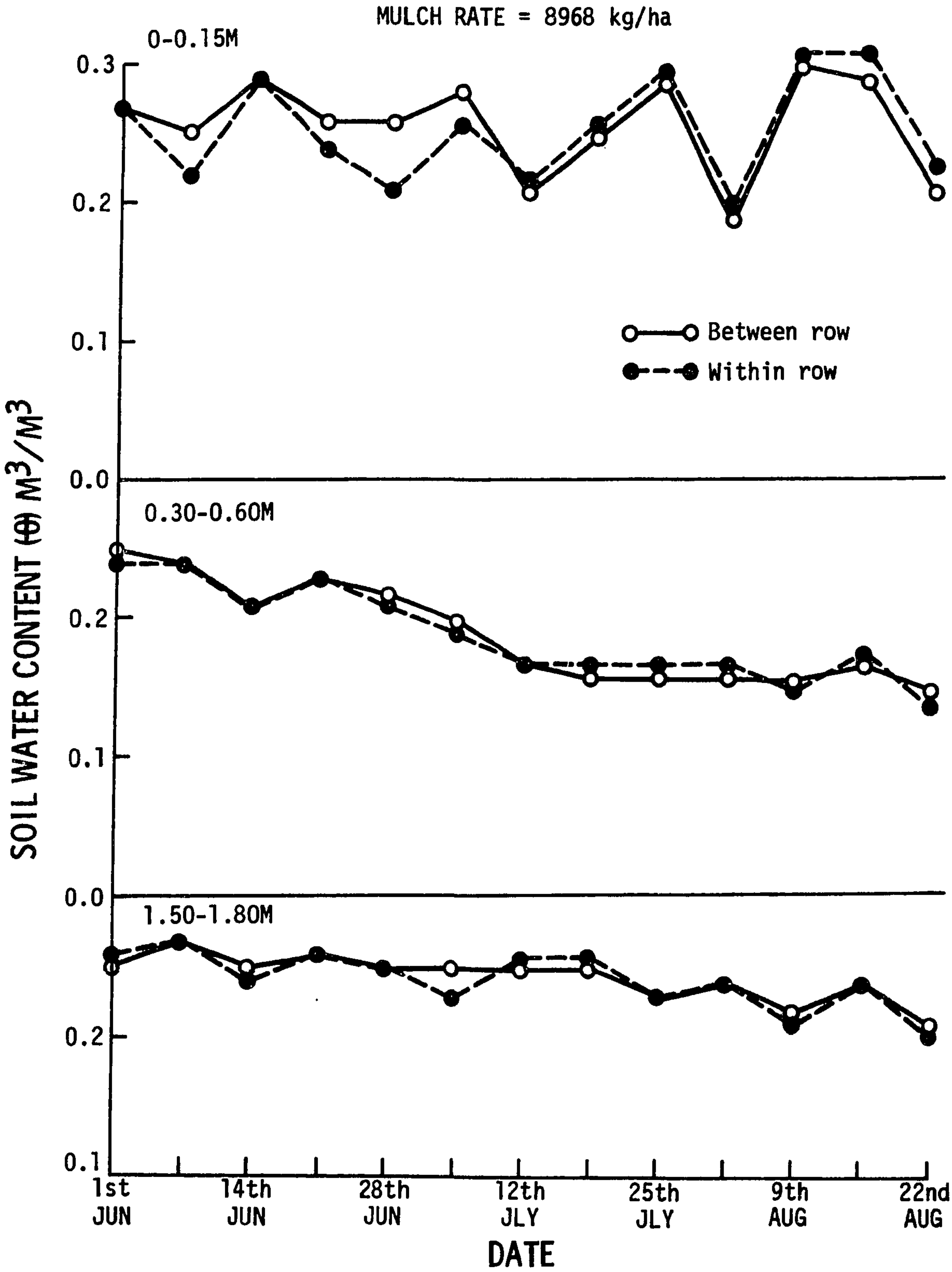



Figure 13b. (Continued)

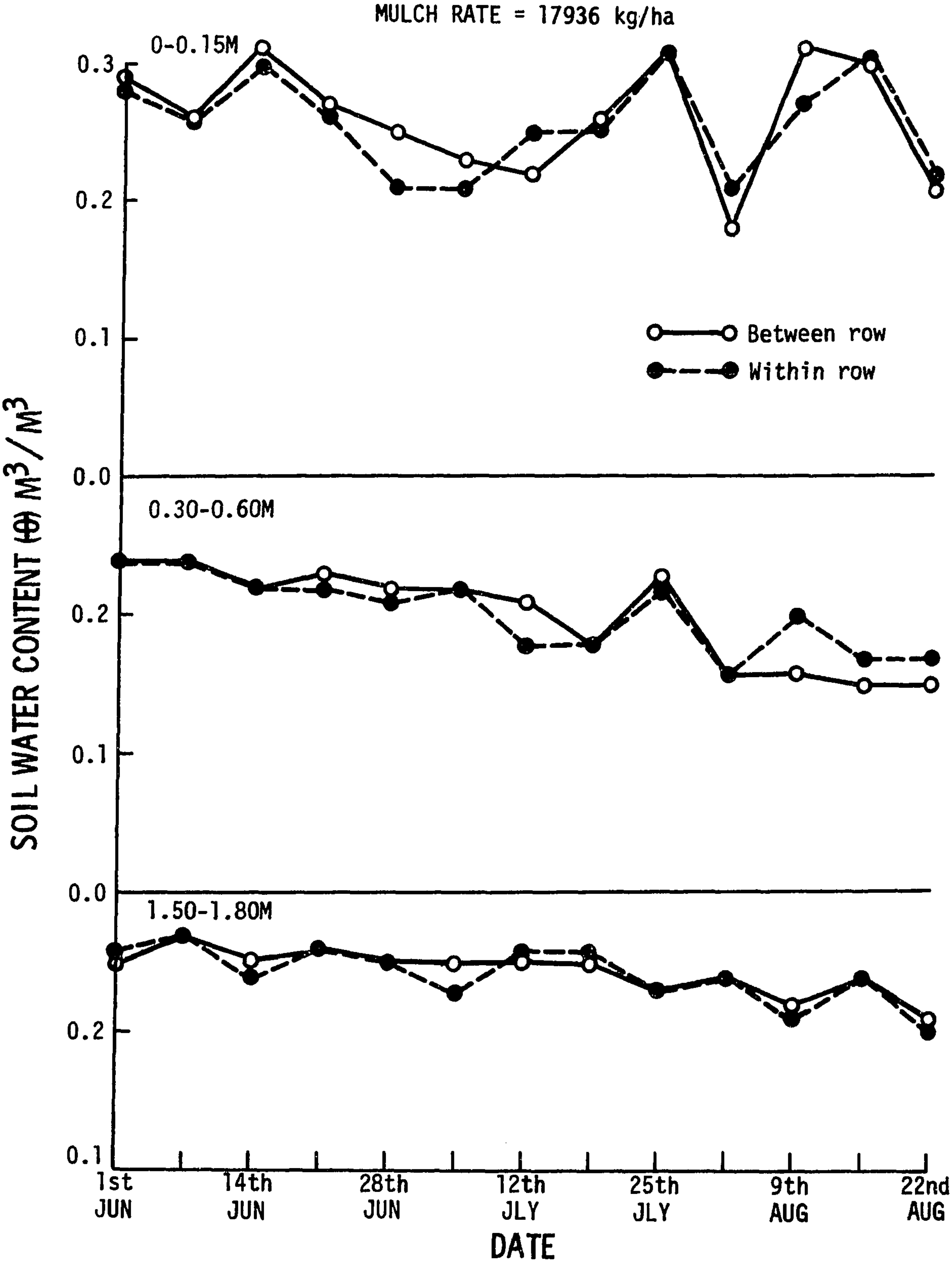



Figure 13b. (Continued)

Table 5. Distribution of soil water content with depth and time for row and interrow locations at 3 mulch rates during the 1976 season

| Soil depth cm | June 8 (26[a]) | | June 23 (41[a]) | | July 22 (70[a]) | | August 24 (108[a]) | |
|---|---|---|---|---|---|---|---|---|
| | Row | Interrow | Row | Interrow | Row | Interrow | Row | Interrow |
| | cm³/cm³ | | | | | | | |
| | | | | 0 kg/ha | | | | |
| 0-15 | 0.21 | 0.22 | 0.13 | 0.17 | 0.11 | 0.11 | 0.10 | 0.10 |
| 15-30 | 0.23 | 0.23 | 0.16 | 0.22 | 0.12 | 0.13 | 0.11 | 0.11 |
| 30-60 | 0.21 | 0.22 | 0.16 | 0.19 | 0.11 | 0.12 | 0.11 | 0.11 |
| 60-90 | 0.22 | 0.21 | 0.20 | 0.20 | 0.12 | 0.12 | 0.11 | 0.11 |
| 90-120 | 0.21 | 0.22 | 0.21 | 0.21 | 0.13 | 0.16 | 0.11 | 0.11 |
| 120-150 | 0.18 | 0.19 | 0.20 | 0.21 | 0.17 | 0.18 | 0.10 | 0.10 |
| 150-180 | 0.18 | 0.18 | 0.19 | 0.20 | 0.17 | 0.19 | 0.11 | 0.12 |
| | | | | 8968 kg/ha | | | | |
| 0-15 | 0.23 | 0.23 | 0.16 | 0.21 | 0.12 | 0.15 | 0.10 | 0.12 |
| 15-30 | 0.25 | 0.26 | 0.21 | 0.24 | 0.14 | 0.17 | 0.11 | 0.11 |
| 30-60 | 0.23 | 0.23 | 0.20 | 0.21 | 0.12 | 0.15 | 0.10 | 0.11 |
| 60-90 | 0.23 | 0.23 | 0.21 | 0.21 | 0.12 | 0.16 | 0.10 | 0.10 |
| 90-120 | 0.24 | 0.23 | 0.22 | 0.22 | 0.16 | 0.18 | 0.10 | 0.10 |
| 120-150 | 0.24 | 0.23 | 0.24 | 0.23 | 0.21 | 0.21 | 0.10 | 0.11 |
| 150-180 | 0.21 | 0.22 | 0.22 | 0.22 | 0.21 | 0.21 | 0.14 | 0.16 |
| | | | | 17936 kg/ha | | | | |
| 0-15 | 0.26 | 0.27 | 0.17 | 0.24 | 0.14 | 0.17 | 0.11 | 0.11 |
| 15-30 | 0.26 | 0.27 | 0.21 | 0.25 | 0.15 | 0.17 | 0.11 | 0.12 |
| 30-60 | 0.23 | 0.23 | 0.20 | 0.21 | 0.13 | 0.16 | 0.12 | 0.12 |
| 60-90 | 0.23 | 0.24 | 0.21 | 0.22 | 0.15 | 0.18 | 0.12 | 0.12 |
| 90-120 | 0.24 | 0.23 | 0.22 | 0.24 | 0.19 | 0.20 | 0.11 | 0.12 |
| 120-150 | 0.24 | 0.24 | 0.22 | 0.24 | 0.21 | 0.21 | 0.10 | 0.12 |
| 150-180 | 0.23 | 0.22 | 0.21 | 0.23 | 0.21 | 0.22 | 0.14 | 0.16 |

[a]Days after planting.

Table 6. Distribution of soil water content with depth and time for row and interrow locations at 3 mulch rates during the 1977 season

| Soil depth | June 1 (8[a]) | | June 14 (21[a]) | | July 12 (49[a]) | | August 16 (84[a]) | |
|---|---|---|---|---|---|---|---|---|
| cm | Row | Interrow | Row | Interrow | Row | Interrow | Row | Interrow |
| | $cm^3/cm^3$ | | | | | | | |
| | | | | 0 kg/ha | | | | |
| 0-15 | 0.25 | 0.25 | 0.22 | 0.24 | 0.21 | 0.21 | 0.27 | 0.26 |
| 15-30 | 0.26 | 0.26 | 0.22 | 0.23 | 0.15 | 0.14 | 0.15 | 0.15 |
| 30-60 | 0.24 | 0.24 | 0.20 | 0.21 | 0.14 | 0.15 | 0.14 | 0.15 |
| 60-90 | 0.23 | 0.24 | 0.21 | 0.21 | 0.15 | 0.16 | 0.13 | 0.15 |
| 90-120 | 0.24 | 0.25 | 0.21 | 0.23 | 0.21 | 0.21 | 0.14 | 0.14 |
| 120-150 | 0.27 | 0.26 | 0.25 | 0.25 | 0.22 | 0.22 | 0.14 | 0.14 |
| 150-180 | 0.25 | 0.24 | 0.24 | 0.24 | 0.22 | 0.21 | 0.15 | 0.19 |
| | | | | 8968 kg/ha | | | | |
| 0-15 | 0.27 | 0.27 | 0.29 | 0.29 | 0.22 | 0.21 | 0.31 | 0.29 |
| 15-30 | 0.26 | 0.27 | 0.25 | 0.25 | 0.17 | 0.16 | 0.23 | 0.20 |
| 30-60 | 0.24 | 0.25 | 0.21 | 0.21 | 0.17 | 0.17 | 0.18 | 0.17 |
| 69-90 | 0.24 | 0.24 | 0.22 | 0.23 | 0.19 | 0.20 | 0.19 | 0.14 |
| 90-120 | 0.27 | 0.27 | 0.24 | 0.25 | 0.23 | 0.24 | 0.18 | 0.15 |
| 120-150 | 0.28 | 0.28 | 0.26 | 0.26 | 0.23 | 0.24 | 0.16 | 0.15 |
| 150-180 | 0.27 | 0.28 | 0.25 | 0.25 | 0.24 | 0.24 | 0.19 | 0.19 |
| | | | | 17936 kg/ha | | | | |
| 0-15 | 0.28 | 0.29 | 0.30 | 0.32 | 0.25 | 0.22 | 0.31 | 0.30 |
| 15-30 | 0.27 | 0.27 | 0.26 | 0.26 | 0.19 | 0.20 | 0.24 | 0.20 |
| 30-60 | 0.24 | 0.24 | 0.22 | 0.22 | 0.18 | 0.21 | 0.17 | 0.15 |
| 60-90 | 0.27 | 0.24 | 0.24 | 0.22 | 0.21 | 0.21 | 0.18 | 0.16 |
| 90-120 | 0.28 | 0.26 | 0.26 | 0.25 | 0.24 | 0.25 | 0.18 | 0.18 |
| 120-150 | 0.26 | 0.27 | 0.26 | 0.26 | 0.24 | 0.24 | 0.21 | 0.19 |
| 150-180 | 0.26 | 0.25 | 0.24 | 0.25 | 0.26 | 0.25 | 0.24 | 0.24 |

[a]Days after planting.

Only the graph for 1976 will be discussed since the trend in 1977 is masked by the more frequent rainfall.

An examination of Figure 12a reveals some interesting trends. Soil moisture within the row is less than that between the row in all treaments. In the 0-15 cm layer, the average water content for samples taken at six time intervals in the row is 0.15, 0.22, and 0.19 $m^3/m^3$ and that between the row is 0.17, 0.16, and 0.21 $m^3/m^3$ for treatments 1, 3, and 5, respectively. The difference, however, did not last all season nor did it extend all the way down the profile (see Tables 5 and 6). In fact, in the 0-15 cm layer, it disappeared after 61, 82, and 82 days after mulch applications in treatments 1, 3, and 5, respectively. It also disappeared beyond certain depths which varied with the treatments (Tables 5 and 6). In treatments 1 and 3, these depths were 90 and 120 cm, respectively. In treatment 5, however, the difference seemed to extend all the way down to the last depth sampled (180 cm).

It should be noticed, however, that the largest differences between the two locations occurred in the upper part of the profile (0-15 cm) in all treatments during the 1976 season. In the "moist" 1977 season, little or no difference was observed between the row and interrow water content in all the treatments at all times and depths.

The nonuniformity in soil moisture content between the row and the interrow locations was also reported by Allmaras et al. (1973). Allmaras and Nelson (1971) placed different variants of mulch in the row and interrow positions and related corn root response to the different row, interrow environments created. Earlier, Nelson and Allmaras (1969) had attributed the different configurations of corn root development to the horizontal nonuniformity of soil moisture and temperature caused by row, interrow mulch placements. The finding in our study is different in that mulch was uniformly placed over the row and interrow locations at the same time and rate. There were no variants of mulch with respect to location of applications.

Since the soil environment under the mulch was the same in the row as the interrow prior to germination, the only possible factor that could have brought about the difference in soil moisture is the plant, specifically the roots. A comparison of Figures 13a and 13b with Figure 28, which shows the root length density distribution with time in the row and interrow positions, confirms the argument that the plant roots extracted more moisture from the row compared to the interrow locations at the early part of the season. This is true of the bare plot as well as the mulched plots.

Runoff

The effect of mulch rates on runoff from the various treatment plots is presented in Table 7. Mulches reduced runoff and the higher the rate, the more the reduction until

Table 7. The effect of mulch on runoff during the 1977 season

| Date | Precip. cm | 0 cm | 0 % | 4484 cm | 4484 % | 8968 cm | 8968 % | 13452 cm | 13452 % | 17936 cm | 17936 % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mulch rates (kg/ha) | | | | | | | | | |
| | | Runoff | | | | | | | | | |
| June 12 | 1.55 | 0.58 | 37.7 | 0.48 | 31.1 | 0.36 | 23.0 | - | - | - | - |
| 17 | 2.03 | 0.20 | 10.0 | 0.05 | 2.5 | 0.08 | 3.8 | - | - | - | - |
| 23 | 2.57 | 1.17 | 45.5 | 0.83 | 32.6 | 0.53 | 20.8 | - | - | - | - |
| July 11 | 2.87 | 1.09 | 38.1 | 0.33 | 11.5 | 0.36 | 12.4 | 0.08 | 2.6 | 0.05 | 3.3 |
| 21 | 3.38 | 0.66 | 19.5 | 0.36 | 10.5 | 0.41 | 12.0 | 0.05 | 1.5 | 0.0 8 | 2.3 |
| August 8 | 0.78 | 0.13 | 17.9 | 0.08 | 10.7 | 0.03 | 3.6 | 0.03 | 3.6 | 0.03 | 3.6 |

an application of 13452 kg/ha of mulch occurred. Beyond this rate, further increase in mulch did not seem to affect runoff. For example, when 17936 kg/ha of mulch was applied, the reduction in runoff did not differ significantly from that associated with the application of 13452 kg/ha. That surface applied mulch reduces runoff is well-established. This is explained as a result of the mulch cushioning the impact of raindrops, thus preventing surface sealing which would have reduced infiltration. Mulch therefore aids infiltration and hence reduces runoff. Mulch also slows the velocity of runoff water through creating small check-dams of material. These check-dams allow more time for infiltration and thus infiltration is increased.

## Soil Temperature

### Seasonal variation of soil temperature

The variations in average soil temperature during the season at the 0 and 15 cm depths are shown in Figures 14a and 14b. Mulching had its maximum effect at the early parts of the season. The mulched plot, as expected, had lower soil temperatures during this period at these depths. As the season advanced, however, the effect of mulch on soil temperature decreased. There was a considerable fluctuation in soil temperature during the two seasons. During the early part of the season (June 10-July 1, 1976 and June 8-July 6, 1977), the soil temperature in the 0 cm depth of the unmulched plot

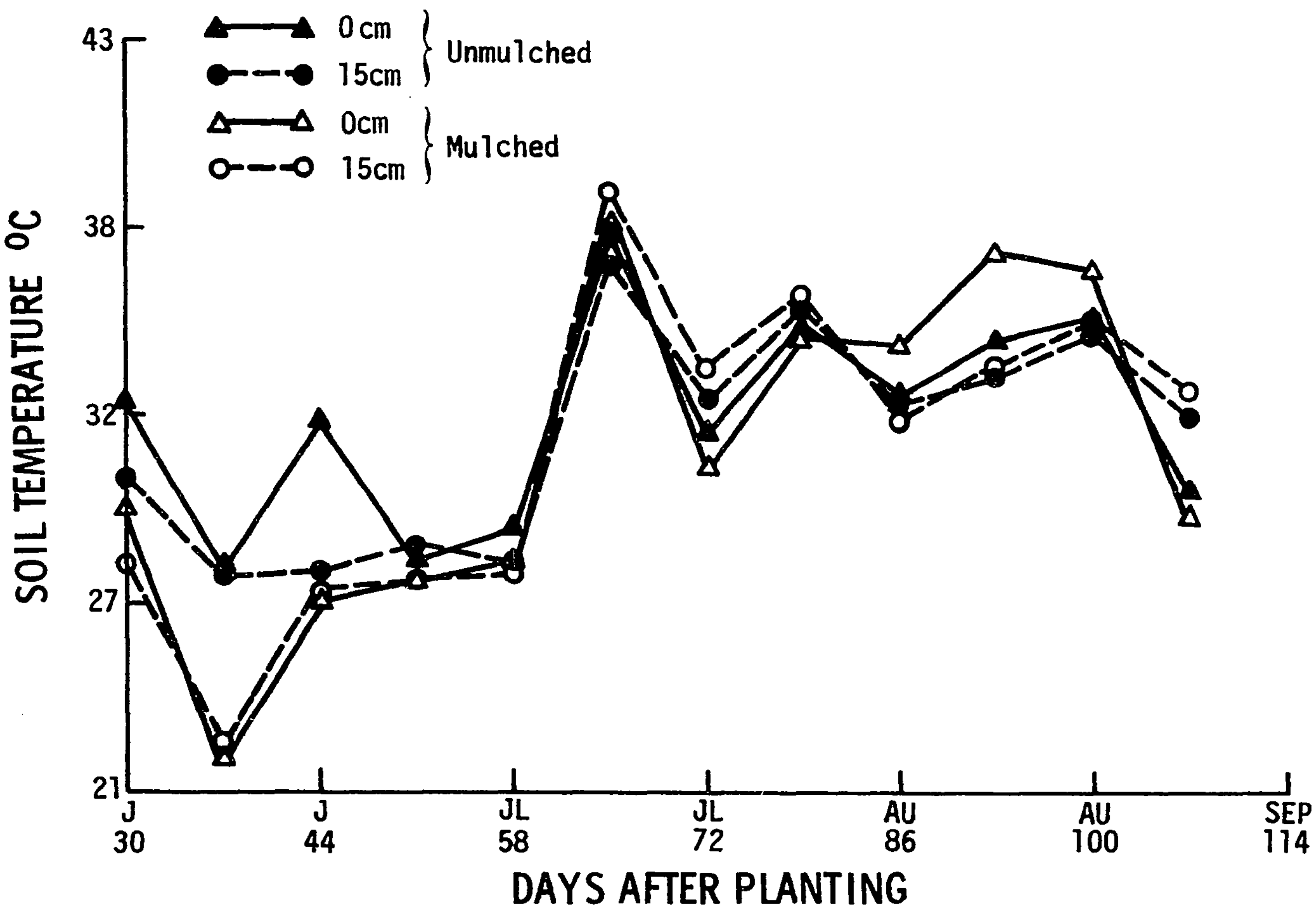



Figure 14a. Seasonal variation of average soil temperature at 2 depths as affected by mulching during 1976 season

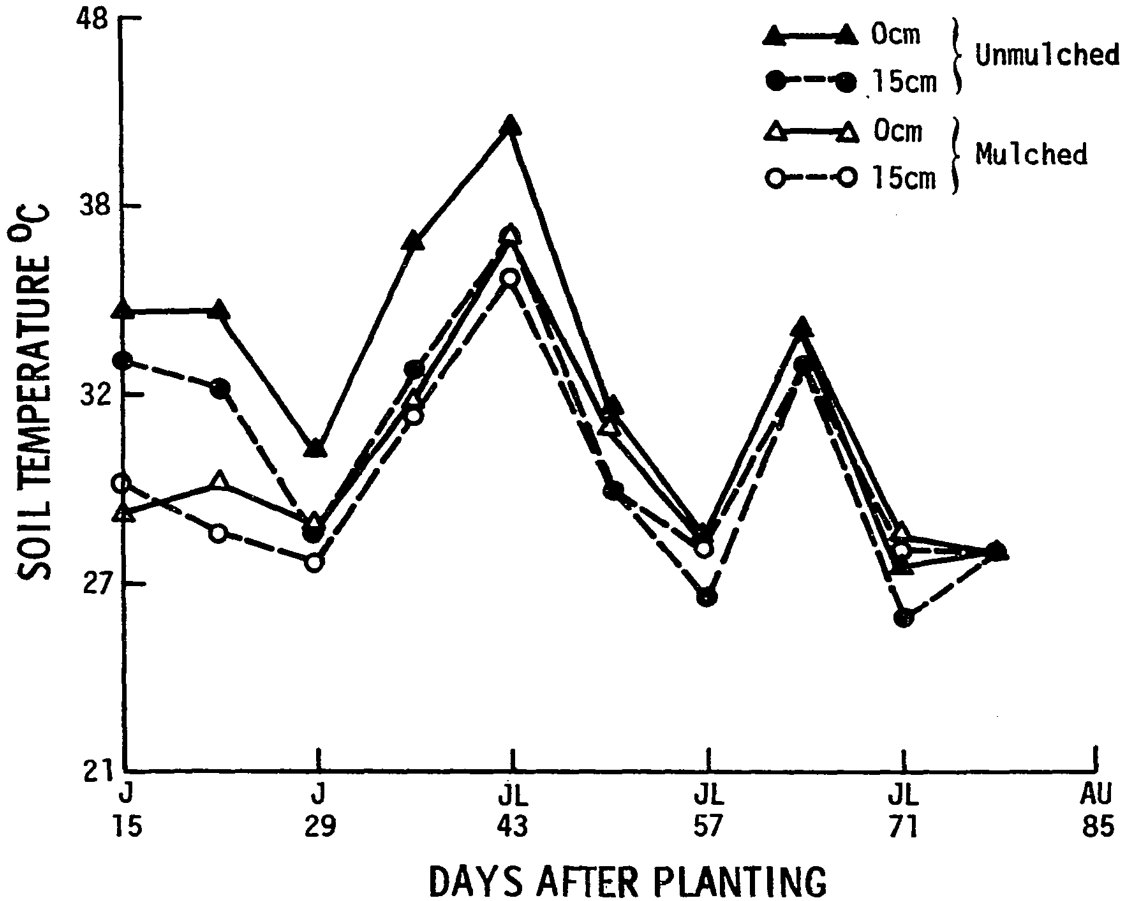



Figure 14b. Seasonal variation of average soil temperature at 2 depths as affected by mulching during 1977 season

was higher than that of the 15 cm depth of the same plot. But in the mulched plots, the soil temperature in these two depths did not differ in 1976 but appeared to differ in 1977 with the higher temperature occurring in the 0 cm depth.

The highest soil temperature in all the depths occurred on July 15, 1976 and July 6, 1977. The lowest temperature was recorded on June 17, 1976 and July 20, 1977. At the 0 cm depth in the unmulched plot, the maximum temperatures were 38$^{o}$C in 1976 and 40$^{o}$C in 1977. The minimum temperatures were 28$^{o}$C in 1976 and 31$^{o}$C in 1977.

In the mulched plot, the maximum temperatures were 38$^{o}$C in 1976 and 37$^{o}$C in 1977. The minimum temperatures were 22$^{o}$C and 28$^{o}$C for 1976 and 1977 seasons, respectively. The temperatures at 15 cm depth in both treatments during both seasons were generally lower than in the 0 cm depth.

Variation of soil temperature with depth at selected times

Figures 15a, 15b, 16a, and 16b show the variation of soil temperature with depth at selected times during the two seasons. It is clear that soil temperature decreased with depth in the mulched and unmulched plots. At the early part of the season (June 10, 1977 and June 8, 1977), the effect of mulching was substantially manifested. As expected, the mulched plot had lower temperature than the unmulched plot and this difference in soil temperature was evident at all depths in the profile. In 1976, for example, the temperature

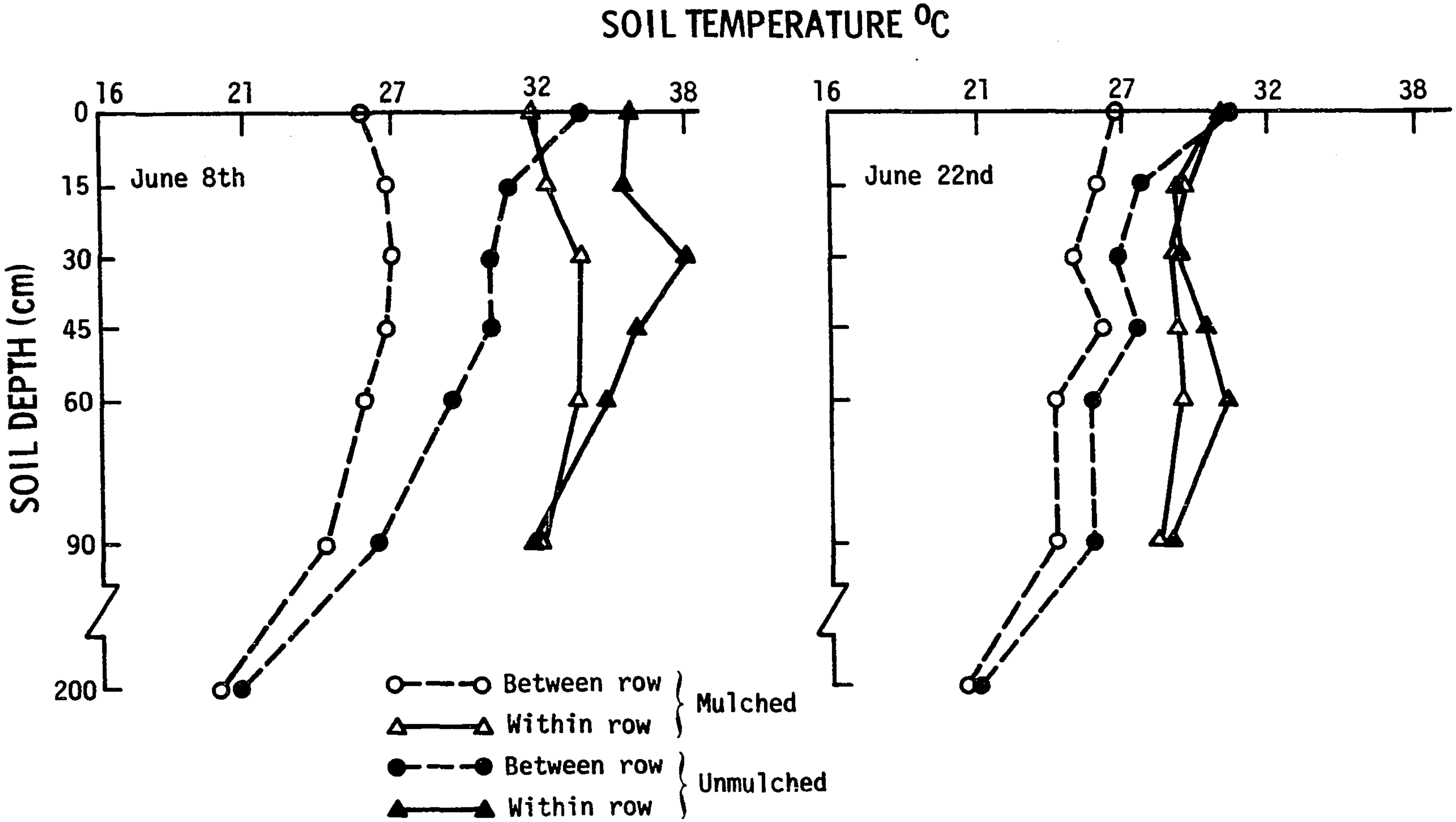



Figure 15a. Variation of soil temperature with depth at 4 dates as affected by mulching during 1977 season

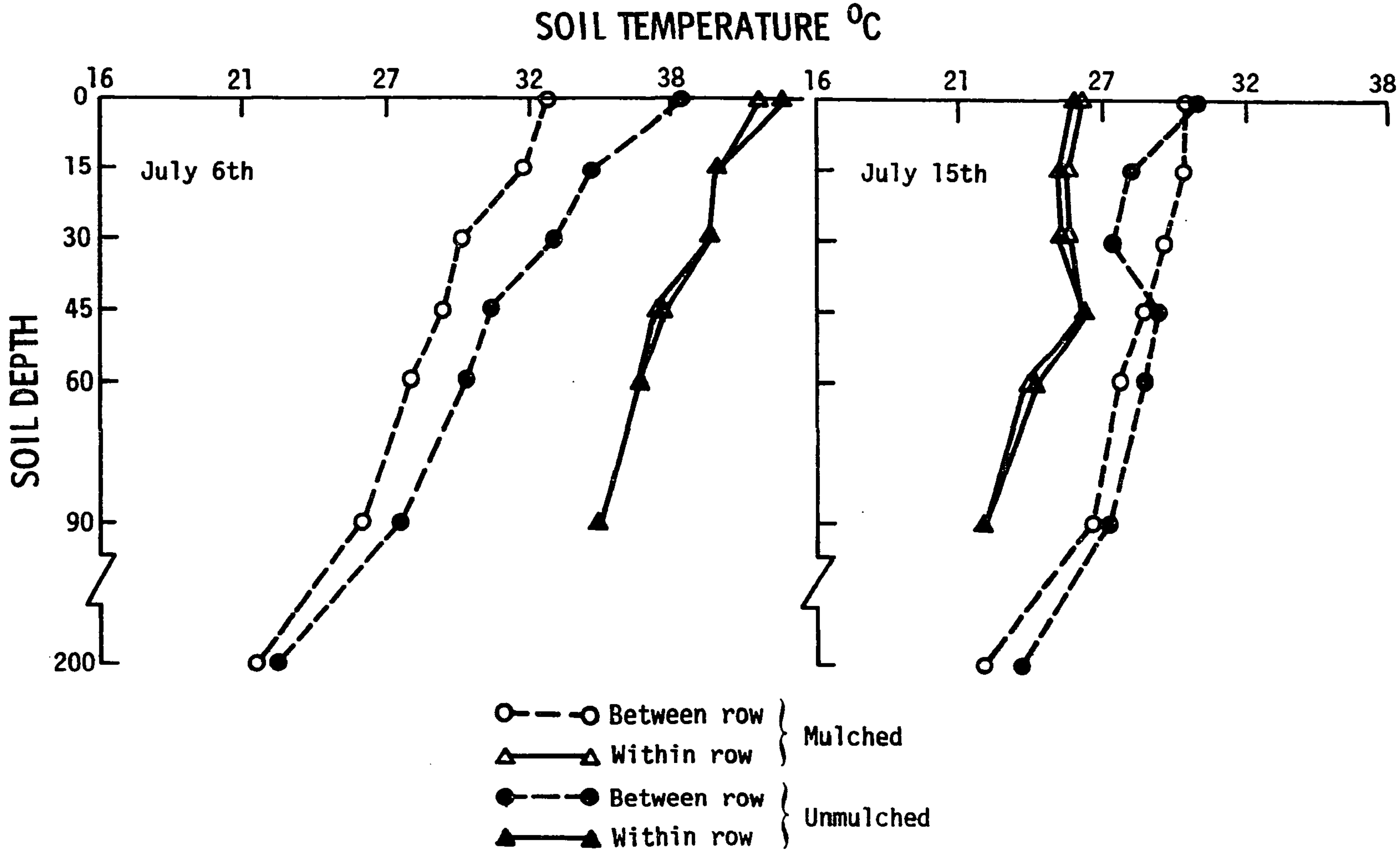



Figure 15b. Variation of soil temperature with depth at 4 dates as affected by mulching during 1977 season

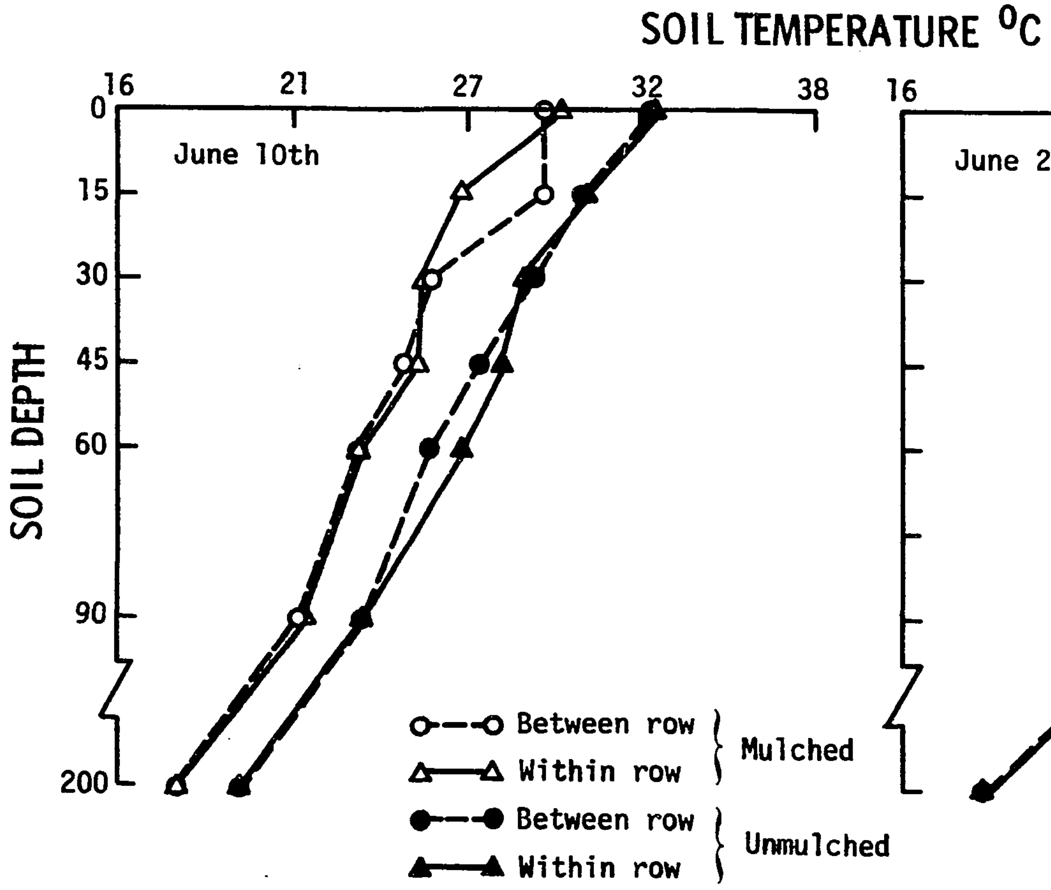



Figure 16a. Variation of average soil temperature with depth at 4 dates as affected by mulching during 1976 season

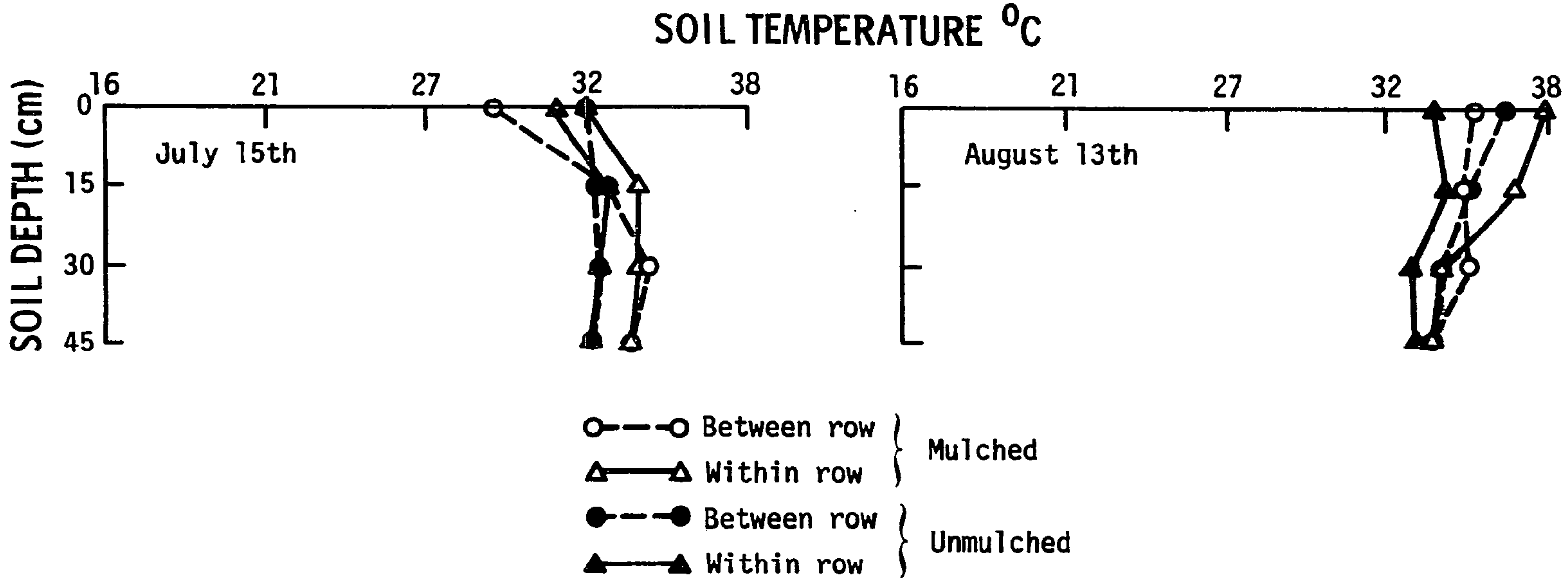





Figure 16b. Variation of average soil temperature with depth at 4 dates as affected by mulching during 1976 season

of the mulched plot ranged from about 29°C at the surface to 17°C at a depth of 200 cm. In the unmulched plot, the range was from 33 to 19°C. As the season advanced, the difference between the mulched and the unmulched plots decreased, probably as a result of canopy development as illustrated by soil temperatures measured on June 24 and July 15, 1976 and July 15, 1977.

<u>Variation of soil temperature in the row, interrow locations with depth at selected times</u>

The variation of soil temperature with depth in the row and interrow locations is revealing. During the "dry" 1976 season, there was little or no difference between the row and interrow soil temperature in both the mulched and unmulched plots at the early part of the season (June 19, 1976). But about the same period in "wet" 1977 season (June 8, 1977), the soil temperature in the row was higher than that between the row in both the mulched and unmulched plots.

To find out if this difference persisted during the season, the soil temperatures were plotted against time at the surface and 15 cm depths (Figure 17). From this plot, it is clear that in the mulched plot, the difference in temperature between the row and interrow locations appears to persist throughout the entire measurement period. This is true of the surface as well as the 15 cm depth. In the unmulched plot, however, this difference appears to be manifested mostly about the middle of the season (33-49 days after planting).

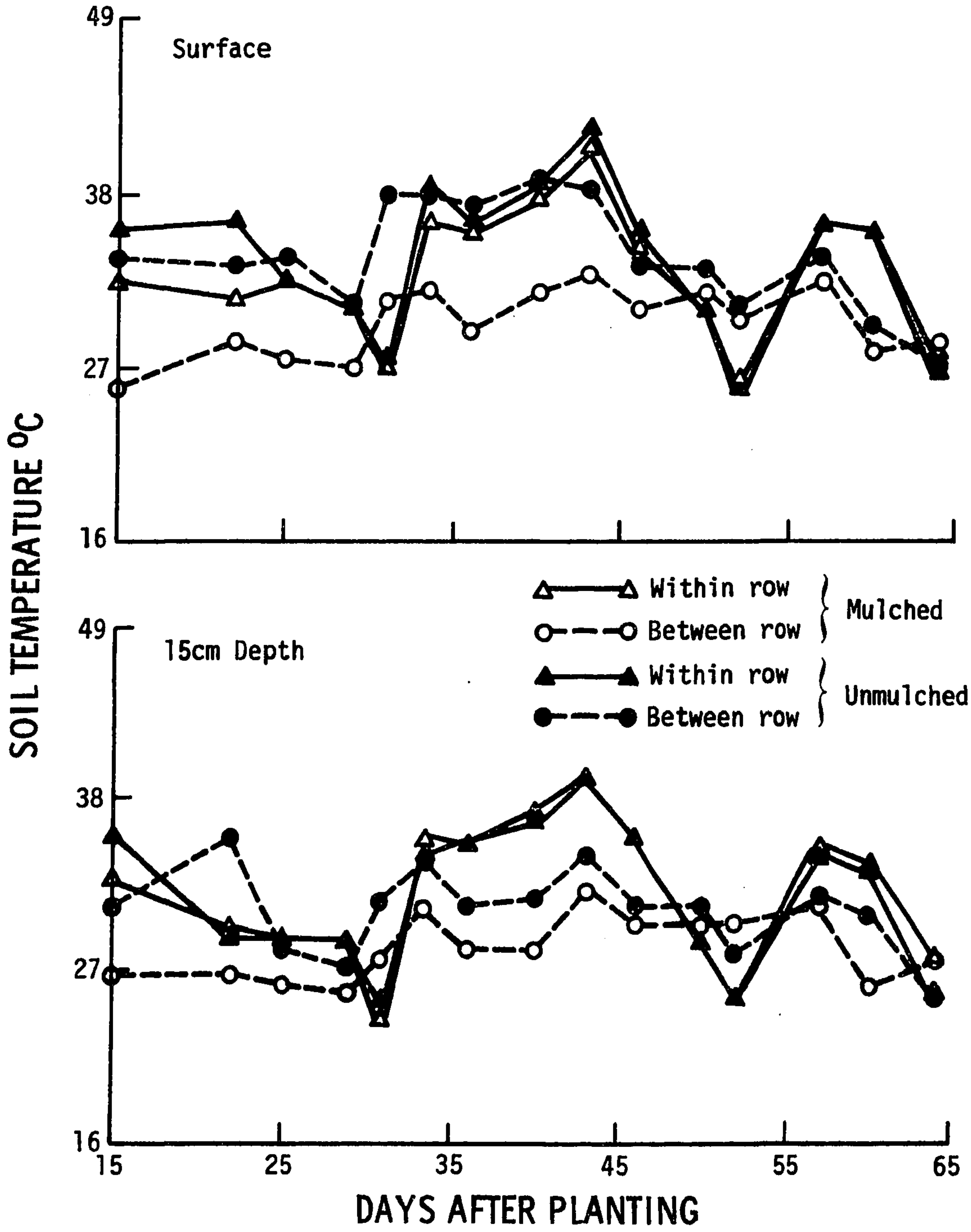



Figure 17. Seasonal variation of average soil temperature in the row and between the row as affected by mulching during the 1976 season

During this period, the temperature between the row was lower than that within the row.

Figure 17 also reveals that the interrow temperature in the mulched plot was lower than that in the unmulched plot. This difference narrowed with the advance in the season until little or no difference could be detected towards the end of the measurement period. This observation is expected. But what was not expected was the fact that there was little or no difference between the within row temperatures in the mulched and the unmulched plots.

It is also evident that the effect of mulch on the temperature of the soil and the variations between and within the rows tended to disappear with depth, especially late in the season. This observation has also been reported by other investigators and will be discussed subsequently.

That organic mulches applied on soil surfaces lower daytime soil temperature is well-established (McCalla and Duley, 1946; van Wijk et al., 1959; McCalla and Army, 1961; Burrows and Larson, 1962; Moody et al., 1963; Adams, 1970; Willis and Amemiya, 1973; Lal, 1974a; and others).

Direct solar radiation is the chief source of heat in the soil (Richards et al., 1952; Baver et al., 1972). Mulches reduce daytime temperature by reducing the amount of the solar radiation reaching the soil surface. This is done either by reflecting back some of the radiation in case of light-colored mulch or by insulating the soil surface from the radiation in case of mulches with low thermal conductivity (Baver et al., 1972). The lowering of the soil temperature in the above study is largely due to the reflectance property of the corn stalk mulch. The insulating effect is also a factor.

The recognition of difference in soil environment between the row and interrow locations has been reported in corn (Allmaras and Nelson, 1971; Allmaras et al., 1973) and wheat (Black, 1970). Studies of radiation and wind movement in soybean canopies (Perrier et al., 1970; Luxmoore et al., 1971) have also shown differences between the row and the interrow locations. A model has been proposed (Fuchs, 1972) to describe these changes. Since the soil temperature depends on the radiative exchanges between air and soil, soil temperatures can be variously influenced in the row and the interrow locations.

The fact that there was little or no difference between the within row temperatures in the mulched and unmulched plots can be attributed to the shading and reflective property of the developing canopy. The canopy shades the row from solar radiation, thus in effect, acts like a surface-applied mulch. The initial difference between the interrow temperature in the mulched and the unmulched plots and the shrinking of this difference as the season advanced can also be attributed to canopy development. When the canopies were not substantially developed, the interrow positions in the unmulched plot were not shaded. This resulted in the higher soil temperature in this location compared to that in the mulched plot. As the canopies closed and solar radiation striking the surface in the interrow locations was reduced, the soil temperature between the rows approached that in the row.

The observation that the soil temperature within the row was higher than that between the row in the mulched plot while there appeared to be little or no difference between them in the unmulched plot is difficult to explain. Since the possible difference between the row and interrow locations in the mulched plot has to do with root activities and soil moisture, particularly in the early stages of growth, the explanation may be found in this direction. This is more so as the difference in temperature between the row and interrow locations appears to disappear gradually as the season advanced. For example, there appears to be no difference between the two locations at the surface (Figure 17), beyond 50 days after planting. This disappearing trend of the row and interrow differences was also demonstrated earlier with root length density and soil moisture. Naturally, therefore, it can be speculated that the row-interrow soil temperature may have some relationship with soil moisture and root activities. This relationship may be found in the respiratory activities of the organisms in the rhizosphere which can release heat into the surrounding soil, hence raising its temperature. It is also possible that as a result of the lower moisture in the row, the soil was "heated" up faster in the row than between the row where the high specific heat of water kept the temperature lower. This is difficult, however, to justify because the shading action of the canopy would tend to keep low the radiation that reaches the row location.

## Roots

The importance of root configuration in the absorption of water and nutrients cannot be overemphasized. Allmaras et al. (1973) defined root configuration as the distribution of root elements among and within the various compartments of the root zone. Russell (1977) has pointed out that, as far as arable agriculture is concerned, the root system of the whole crop is of greatest interest. Recent investigations (Raper and Barber, 1970; Mitchell and Russell, 1971; Böhm et al., 1977) have described the root system of soybeans in the field.

Mulch tillage is often encouraged as a means of conserving moisture, particularly in areas of unreliable and scanty precipitation. But little work, as far as the author is aware, has been done on the effect of this tillage method on the root system of soybeans. Allmaras et al. (1975) investigated the effect of variants of mulches and tillage on corn root configuration and found that mulches, placed over the row or interrow at different times, affected the root configuration.

The root system is better studied quantiatively by defining two parameters: (a) root length density and (b) root mass density. Root length density is defined as the length of the root in a given volume of soil and the root mass density is also defined as the root dry weight in a unit volume of soil. As Rowse (1974) pointed out, the development and use of theories on water and nutrient uptake by plant roots depend on measurements of root length and knowledge of variations of this with depth and time. More informative, moreover, is the effect of mulching on this variation with time and depth. It was therefore decided appropriate to find out how the different rates of mulch affected the root length and root mass densities during the 1976 and 1977 growing seasons.

Variation of total root length density with time

Figure 18 shows the variation of total root length density with time in the different treatments during the 1977 season. Because the trend in 1976 is about the same as that of 1977, only the 1977 curves are presented and will be discussed. Perhaps it is best to discuss the curves based on the physiological stages of growth. To facilitate the discussion, stages of growth have been superimposed on the curves.

It is clear that from the time measurements were begun at stage V6 to about midway between the beginning of stage R2

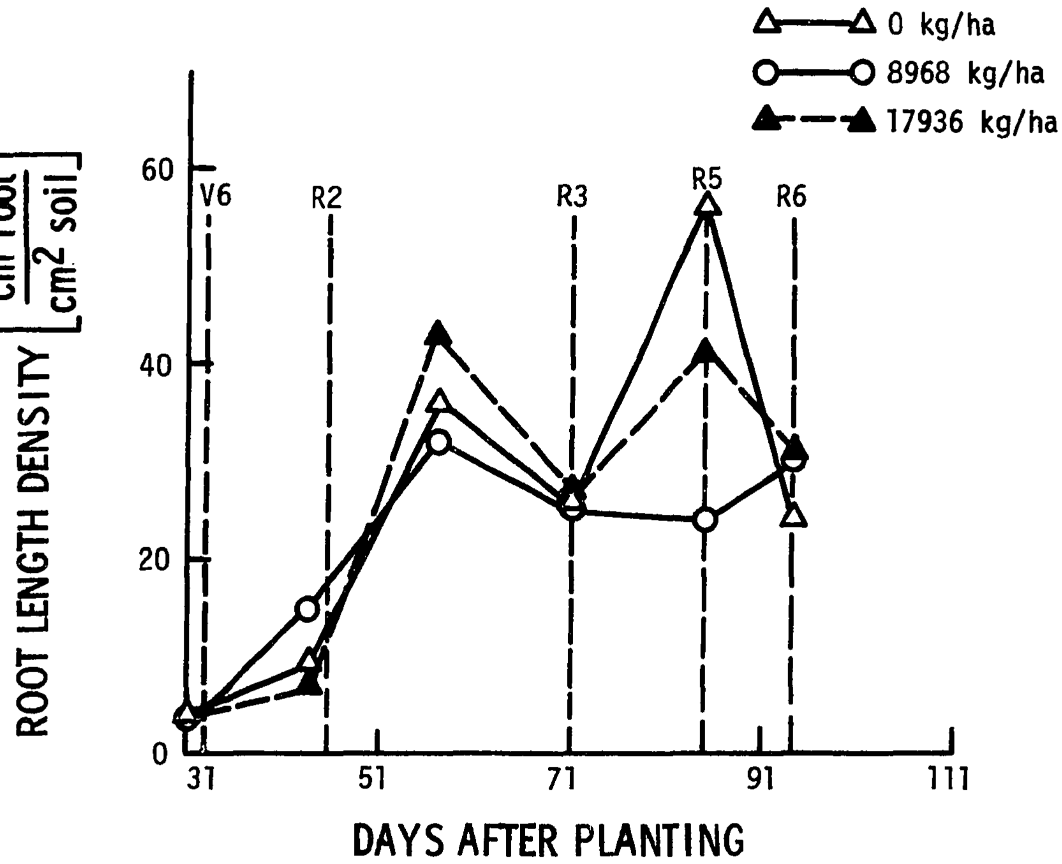



Figure 18. Variation of total root length density (summed over all depths) with time during 1977 season; root length density is defined here as cm of root per square cm of soil surface

and the beginning of stage R3, root length density increased in all the treatments. Beyond this stage, which is about 57 days after planting, root length density leveled off in treatment 3 while it fluctuated in treatments 1 and 5, decreasing, increasing, and then decreasing in that order. The variations in this type of experiment can be large and, because of the tediousness of obtaining the sample, more samples could not be obtained. So it is not clear if the wavy nature of this trend is real or not. If the midpoints of two successive data points are joined, thus obtaining smooth curves, it appears that root length density leveled off in treatments 1 and 5 just as it did in treatment 3. But a large amount of error could be involved in joining the midpoints because there are not enough replicates. This serves to underscore the problems of root research in the field. Despite these misgivings, it can generally be stated that root length density increased up to a point during the season.

With regard to the total root length density (RLV) at various stages of plant growth, Figure 18 shows that, at the early part of the season (between stages V6 and R2), RLV was higher in treatment 3 than in treatments 1 and 5. From stage R2 to R3, treatment 5 produced more RLV than treatments 1 and 3. Towards the end of the season (between stages R3 and R6) treatment 5 still produced more RLV than either treatments 1 or 3, but treatment 1, for the first time, had higher RLV than treatment 3.

When the total RLV during the entire season is considered with respect to the different mulch rates (Table 8), it appears that mulching affected root length density during the season, but statistically these differences are not significant at the 5% level.

<u>Distribution of root length density with time at selected depths</u>

Not only is a knowledge of the variation of total root length density with time vital, but also the distribution at each depth of the profile is important for efficient irrigation and fertilizer management practices. As has been noted by a number of researchers, the survival of the plant during droughts may well depend on the extent and depth of the root system. The distribution of the root length density (RLV) with time at 4 depths as affected by mulch rates during the 1977 season is shown in Figure 19.

When no mulch was applied (treatment 1) the pattern of distribution of RLV with time was similar in all the depths although the RLV in the different depths differed in magnitude, being highest in the 15-30 cm layer and lowest in the 45-60 cm layer.

During the growing season, RLV increased during 3 phases of growth and decreased during 2 phases in all the depths. It increased during growth stages V6 (31 days after planting) through R2a (45 days after planting) to R2b (57 days from planting). It also increased between R3 and R5 (71-85 days

Table 8. Effect of mulch on the total and mean RLV during the 1977 season; root length density (RLV) is cm root/cm$^2$ soil

| Days after planting | Total RLV, cm root/cm$^2$ soil | | |
|---|---|---|---|
| | 0 kg/ha | 8968 kg/ha | 17936 kg/ha |
| 31 | 3.94 | 3.17 | 3.77 |
| 44 | 8.61 | 14.70 | 6.85 |
| 57 | 35.97 | 31.67 | 42.78 |
| 71 | 26.32 | 25.30 | 27.30 |
| 85 | 55.56 | 24.31 | 41.01 |
| 94 | 24.43 | 30.38 | 31.26 |
| Mean | 28.81 | 21.59 | 25.50 |

after planting). It decreased between R2b and R6 (85-94 days from planting).

From the early to about the middle part of the season, in between growth stages V6 and R3, the 15-30 cm layer had the highest RLV followed in order by 135-150 cm, 105-120 cm and lastly, 45-60 cm layers. At the later part of the season, between stages R3 and R6, more roots had grown in the 105-120 and 45-60 cm layers than in the 135-150 cm layer. The result was that the RLV in the 105-120 cm layer was higher than that in the 135-150 cm layer.

When 8968 kg/ha of mulch (treatment 3) was applied, RLV in all the depths except the 45-60 cm was lower than in

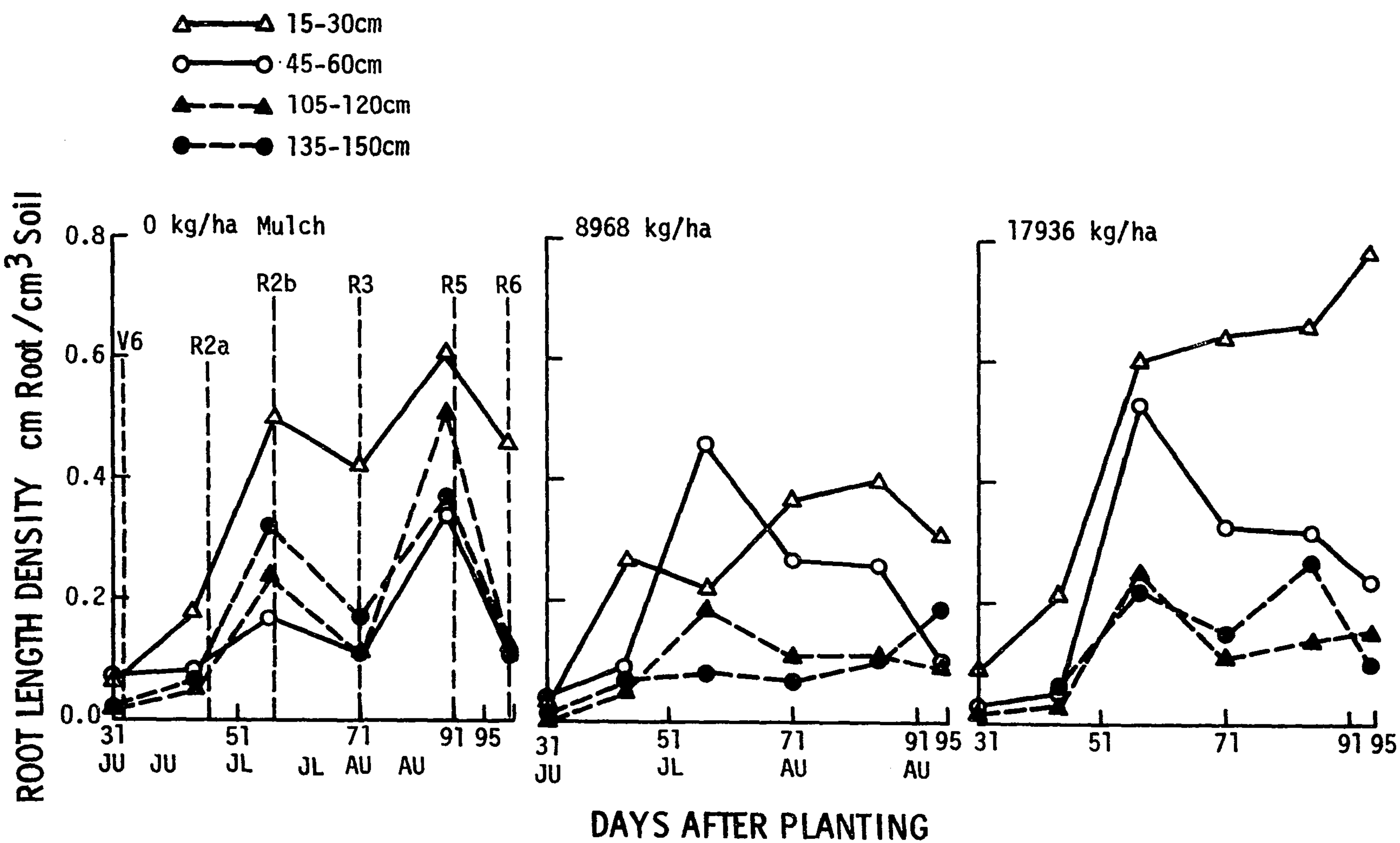



Figure 19. Variation of root length density with time at 4 depths during the 1977 season

treatment 1. The pattern of distribution with time was altered only at the two deepest layers. In the 135-150 cm layer, RLV was essentially the same during most of the season and tended to rise towards the end of the season even as it declined in the other layers. The highest RLV was found in the 15-30 cm layer except during a period (48-67 days after planting) when the RLV in the 45-60 cm was higher.

The distribution pattern of RLV when mulch was increased to 17936 kg/ha (treatment 5) is similar to that in treatment 1, although the 15-30, 45-60 cm layers produced more roots than the 105-120 and 135-150 cm layers. The highest RLV was found in the 15-30 cm layer and was still increasing by the time measurements were terminated at stage R6 (94 days after planting). The 45-60 cm layer had the second highest RLV which started declining after about 54 days after planting at stage R2b. The RLV in the last two and deeper layers appeared to be about the same during most of the season. The RLV in the 105-120 cm, 135-150 cm layers of treatment 5 was lower than that in the corresponding depths in treatment 1 but higher in treatment 3.

A general consideration of the graphs in Figure 19 shows that mulching decreased the root length density in the 15-30 cm depth when 8968 kg/ha was applied, but increased it when the amount was increased to 17936 kg/ha. At the lower depths in the profile, mulching decreased RLV but more so when 8968 kg/ha of mulch compared to 17936 kg/ha was applied.

Distribution of root length density with depth at selected times

When the root length density is plotted against depth, a better picture of root distribution in the entire profile is obtained. Figures 20, 21, and 22 show the distribution of root length density with depth at the indicated times. Figures 20 and 21 show the distribution obtained with two different methods of root sampling in 1976. In Figure 20, root samples were obtained with the 10 cm diameter bucket auger while in Figure 21, the samples were gotten by the external frame monolith method of Nelson and Allmaras (1969). During the 1977 season, the external frame method only was used in root samplings. The external frame method provides an opportunity to see the entire root system as it is while the precipitation (adequate in 1977 and scanty in 1976) provides an opportunity to see the root system under two contrasting environmental conditions.

During the early part of the season (Figure 22) about 31 days after planting (stage V6), the roots had not developed to any extent and were concentrated mostly at the 0-30 cm layer of the profile. There was little or no difference between the treatments.

As the seasons progressed, the RLV increased. At stage R2 (57 days after planting), root length density had increased substantially in all the layers and the effect of the treatments was more or less obvious. More roots were still

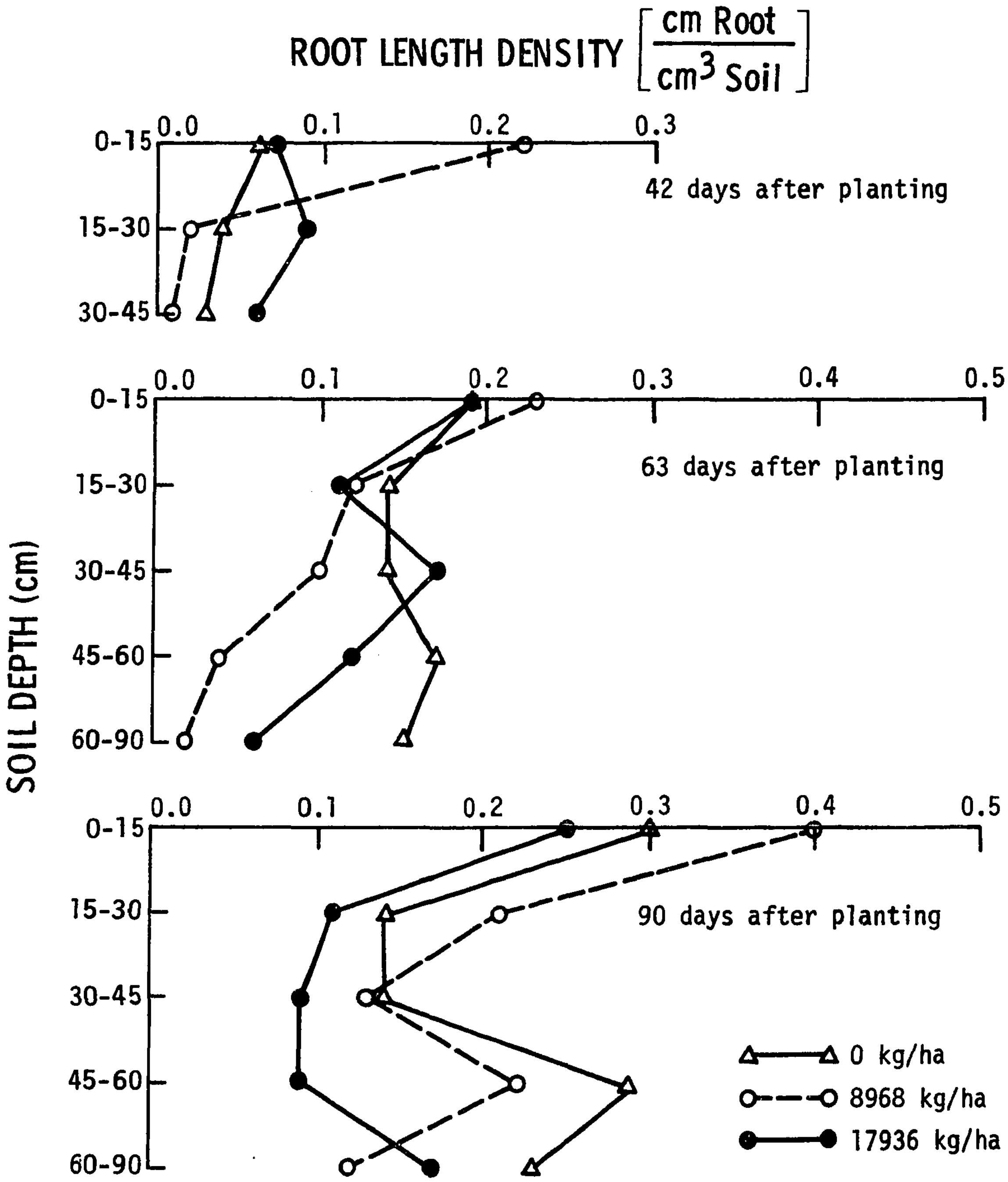



Figure 20. Distribution of RLV with depth at 3 dates during the 1976 season

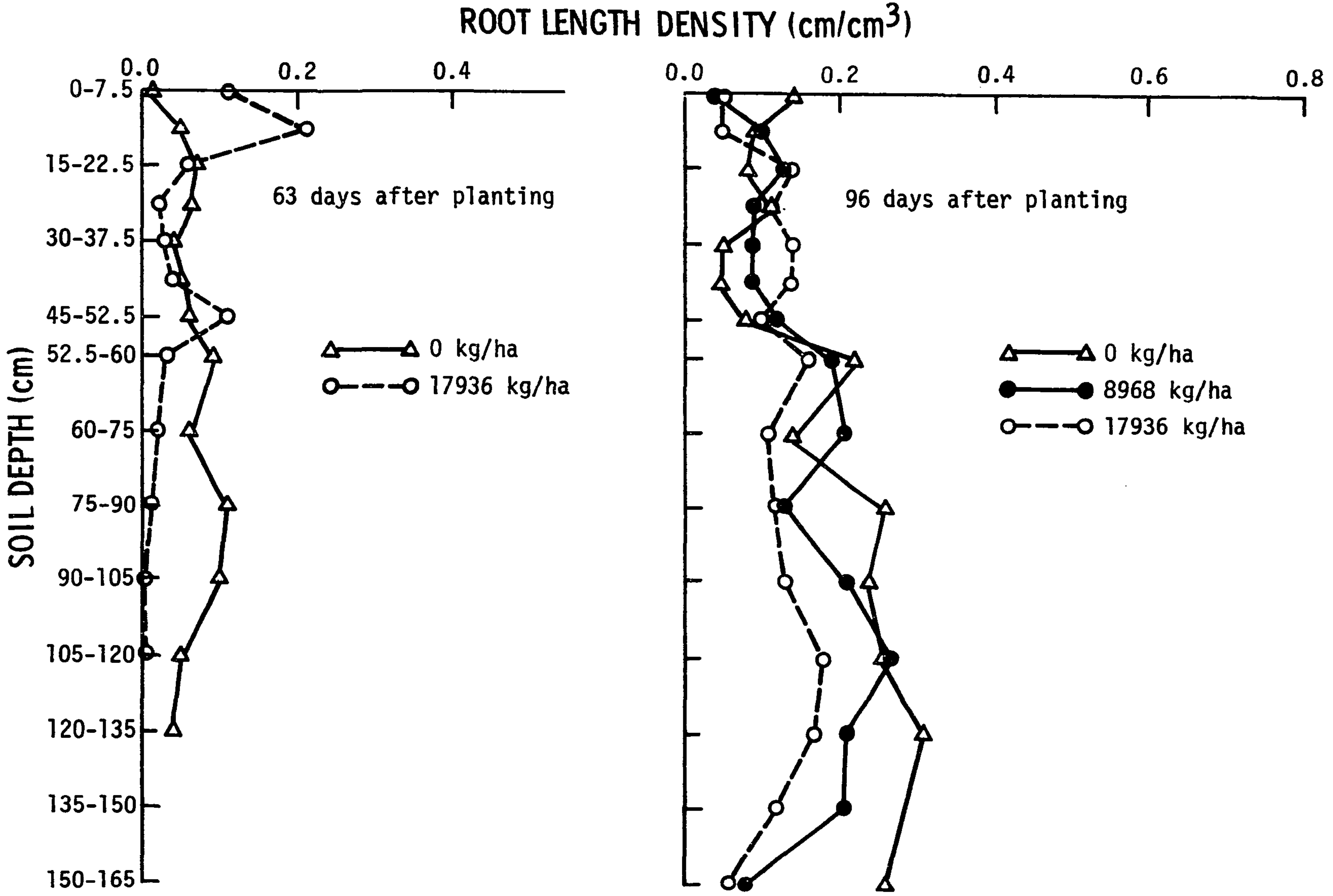



Figure 21. Distribution of root length density with depth during 1976 season

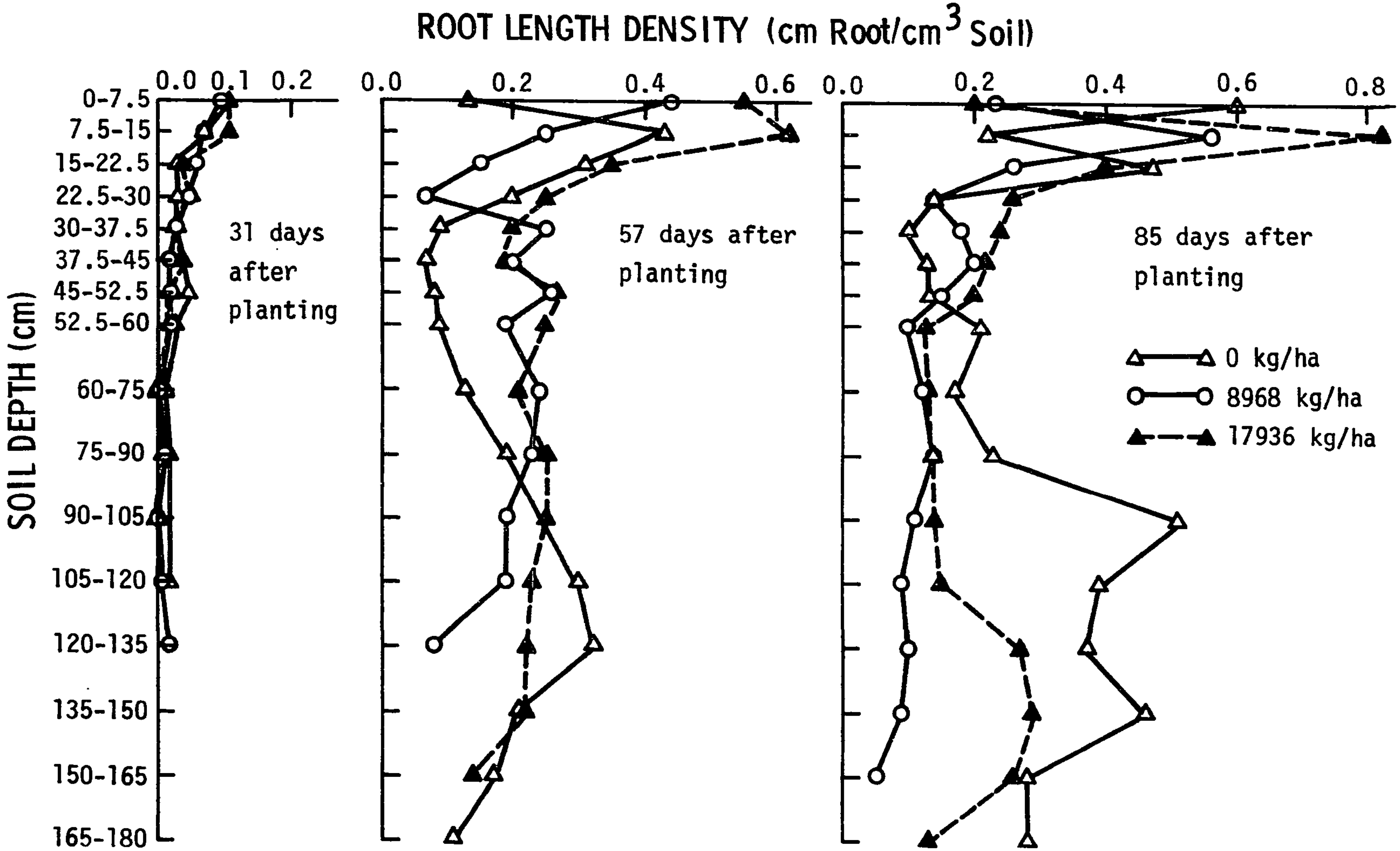



Figure 22. Distribution of root length density with depth at 3 dates during 1977 season

located in the upper 0-30 cm layer of the profile. The highest RLV in this layer was found in treatment 5 while the lowest was found in treatment 3. In the middle 30-105 cm layer of the profile, the RLV in treatments 3 and 5 remained essentially the same and was higher than in treatment 1. Lower down in the profile (90-180 cm layer) the root length density reached a maximum in treatment 1, remained about the same in treatment 5, but declined in treatment 3. The highest RLV in this layer occurred in treatment 1 and the lowest in treatment 3.

It is interesting to compare the root distribution in 1977 with that in 1976, taken about 63 days after planting (Figure 21). In 1976, the same pattern of distribution occurred, i.e., more roots in the upper 0-30 cm in the mulched plot and more roots down in the profile in the unmulched plots. But considerably less roots were found at all depths in the entire profile in 1976 than in 1977.

During the later part of the season, most root proliferation was taking place in the lower part of the profile (about 90-180 cm), particularly in treatment 1. Some root growth was taking place, however, at the 0-30 cm layer. Between 30 and 90 cm depth roots were not formed and some of those that were there died off. The result of these is that RLV increased slightly for treatments 3 and 5 in the 0-30 cm, decreased slightly for treatments 3 and 5 in the 30-90 cm layer, and increased substantially in the 90-180 cm layer for treatment 1. Comparison with the 1976 distribution from samples taken 96 days after planting (Figure 21) shows the effect of insufficient soil moisture on root distribution. Because of low water content, the RLV in the 0-60 cm layer was much lower than in 1977 and there appeared to be no mulch influence anymore. Root length density was about the same in all treatments. Deep down in the profile (60-180 cm) where some trace of moisture still remained, roots were formed but not to the extent of that of 1977. The RLV in treatments 1 and 3 appeared to be higher than in treatment 5.

Percentage distribution of roots in the profile

To still gain a further insight into the distribution of RLV, it is necessary to show what percent of RLV is in what layer at what period in the season. This type of information is presented in Table 9 and Figure 23. An examination of the table and graphs shows that the roots are concentrated in the upper part of the profile at the early part of the season. For example, at 31 days after planting when the plants were in stage V6, 52% of the total RLV was found in the 0-30 cm layer in treatment 1, 70% in treatment 3 and 68% in treatment 5. Deep down in the profile at 90-180 cm layer, however, the percentages were much lower: 14, 8 and 9% for treatments 1, 3 and 5, respectively. More of the roots were concentrated at the upper part of the profile in the mulched compared with the unmulched plots.

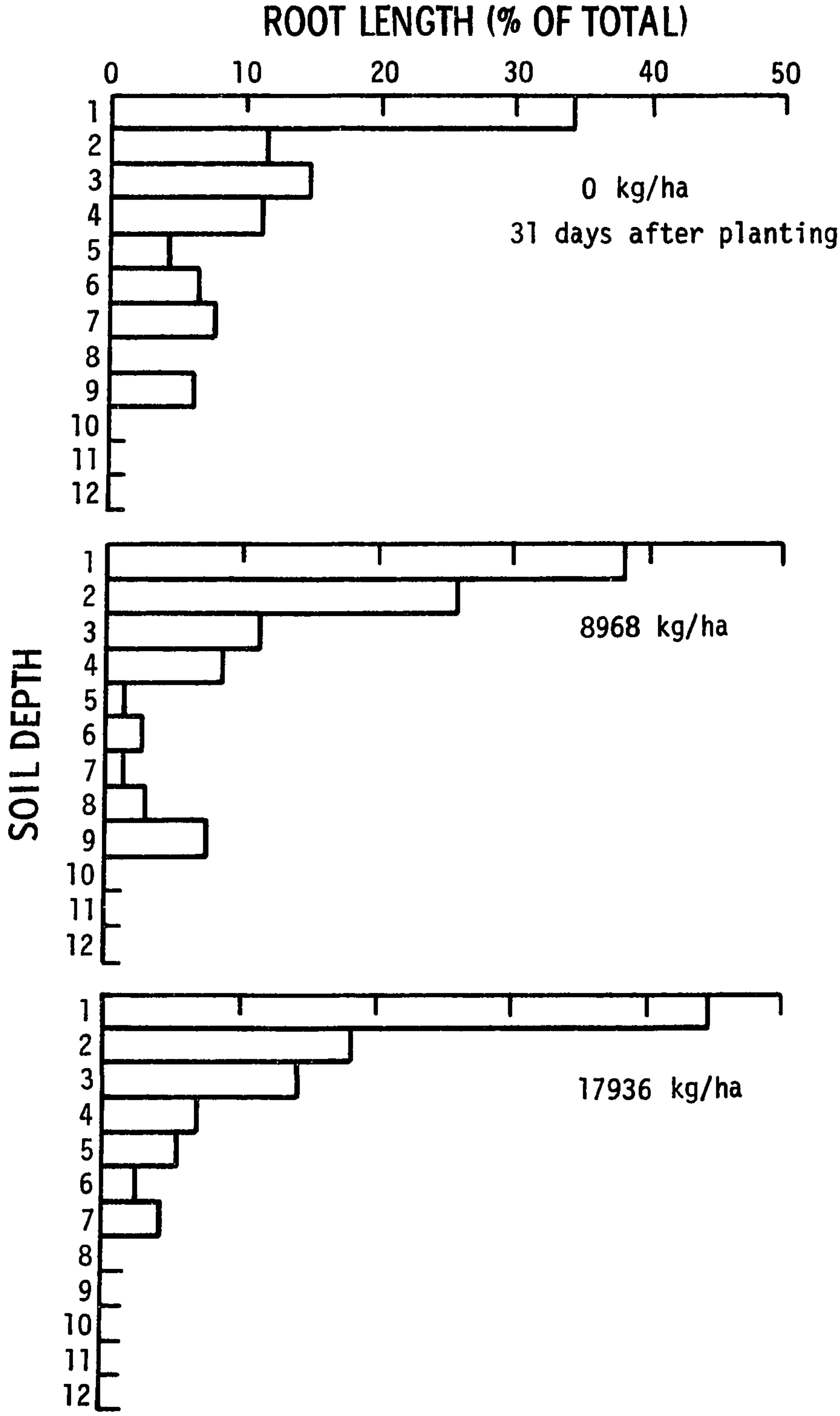
Table 9. Percentage distribution of root length density during the 1976 and 1977 seasons

| Days after planting | Root length density, % of total | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0-15 cm | | | 0-30 cm | | | 90-180 cm | | |
| | 0 | 8968 | 17936 | 0 | 8968 | 17936 | 0 | 8968 | 17936 |
| | --------kg/ha-------- | | | --------kg/ha-------- | | | --------kg/ha-------- | | |
| | | | | 1976 season | | | | | |
| 63 | 4.80 | - | 47.30 | 16.13 | - | 58.89 | 34.19 | - | 1.06 |
| 106 | 4.48 | 3.88 | 3.58 | 7.96 | 10.16 | 12.56 | 68.77 | 56.29 | 46.29 |
| | | | | 1977 season | | | | | |
| 31 | 39.51 | 41.79 | 48.59 | 52.40 | 69.74 | 68.46 | 14.63 | 8.46 | 8.65 |
| 57 | 18.22 | 25.16 | 27.98 | 34.64 | 33.17 | 42.19 | 54.71 | 33.84 | 35.98 |
| 85 | 18.13 | 31.24 | 25.70 | 31.05 | 47.04 | 42.28 | 56.91 | 27.74 | 37.82 |

Figure 23. Percentage distribution of roots at different layers during the 1977 season

Legend for depth:

| | | |
|---|---|---|
| 1 | = | 0.75 cm |
| 2 | = | 7.5-15 cm |
| 3 | = | 15-22.5 cm |
| 4 | = | 22.5-30 cm |
| 5 | = | 30-37.5 cm |
| 6 | = | 37.5-45 cm |
| 7 | = | 45-52.5 cm |
| 8 | = | 52.5-60 cm |
| 9 | = | 60-75 cm |
| 10 | = | 75-90 cm |
| 11 | = | 90-105 cm |
| 12 | = | 105-120 cm |


ROOT LENGTH (% OF TOTAL)
0
10
20
30
40
50
SOIL DEPTH
1
2
3
4
5
6
7
8
9
10
11
12
0 kg/ha
31 days after planting
8968 kg/ha
17936 kg/ha

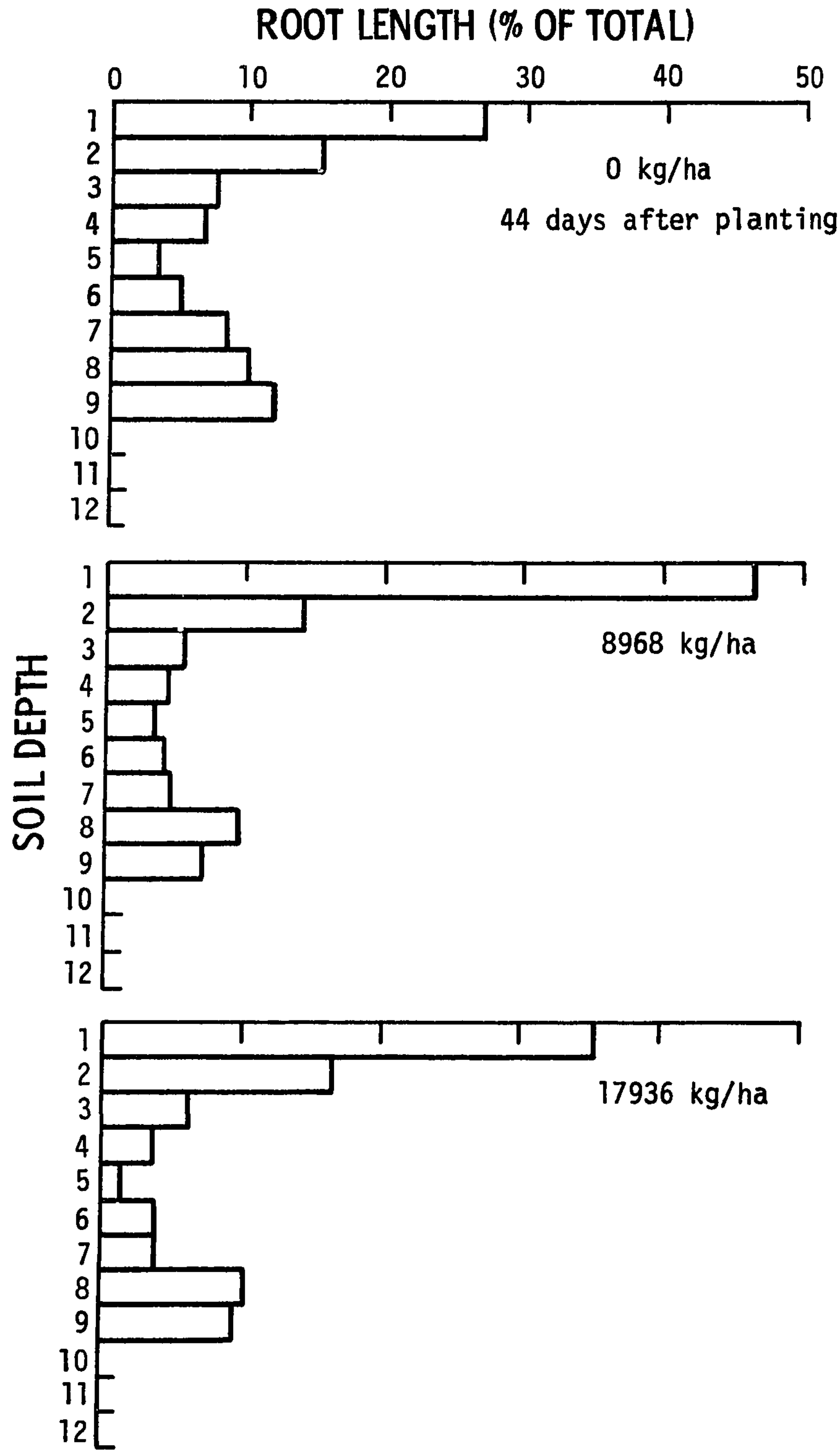



Figure 23. (Continued)

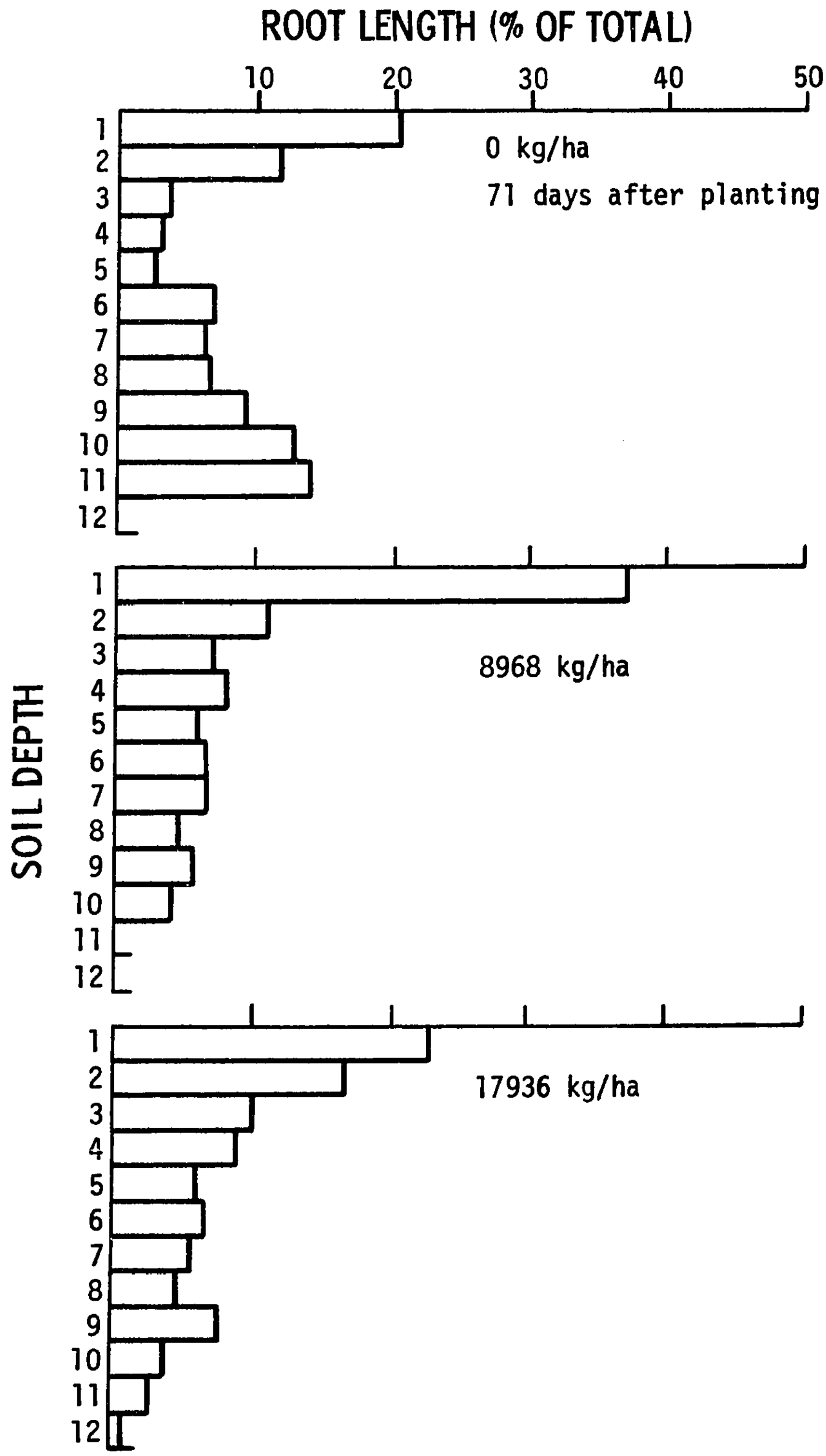



Figure 23. (Continued)

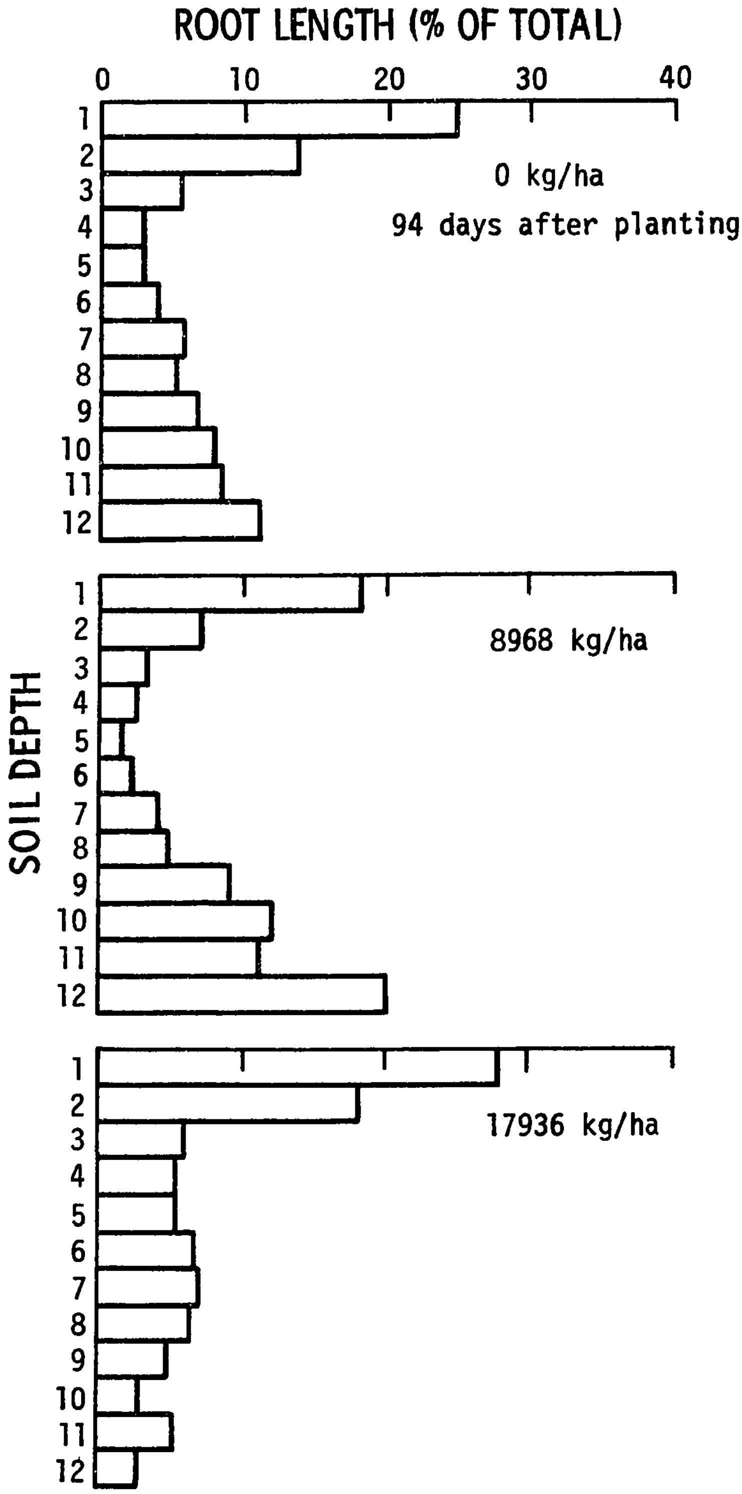



Figure 23. (Continued)

As the season advanced and the upper layers began to dry up, more roots began to proliferate deeper in the profile where moisture was adequate. When the plants were in stage R2 at about 57 days after planting, the percentage of the total root length in the 0-30 cm layer had dropped to 34, 33, and 42 in treatments 1, 3, and 5, respectively. Meanwhile, the percentage had gone up in the 90-180 cm layer to 54, 33, and 35% for treatments 1, 3, and 5, respectively.

Root mass density

Root mass density (RMD) was defined earlier and like RLV it is an important parameter in the absorption of nutrients and water. The variation of total RMD with time is shown in Figures 24a and 24b. As expected, this variation is very similar to that of RLV described earlier. Root mass density did increase with increase in time. The increase was most rapid during the early part of the season. Root mass density was depressed most in treatment 3 while not being much different in treatments 1 and 5.

Figure 25 shows the percentage of total RMD at the different layers in the profile and Figure 26 and Table 10 show the distribution of RMD with depth. This is for three periods--31, 57, and 85 days after planting.

It can be seen from both Table 10 and Figure 26 that RMD was concentrated mostly in the upper part of the profile at the early stages of growth. For example, at stage V6 (31 days

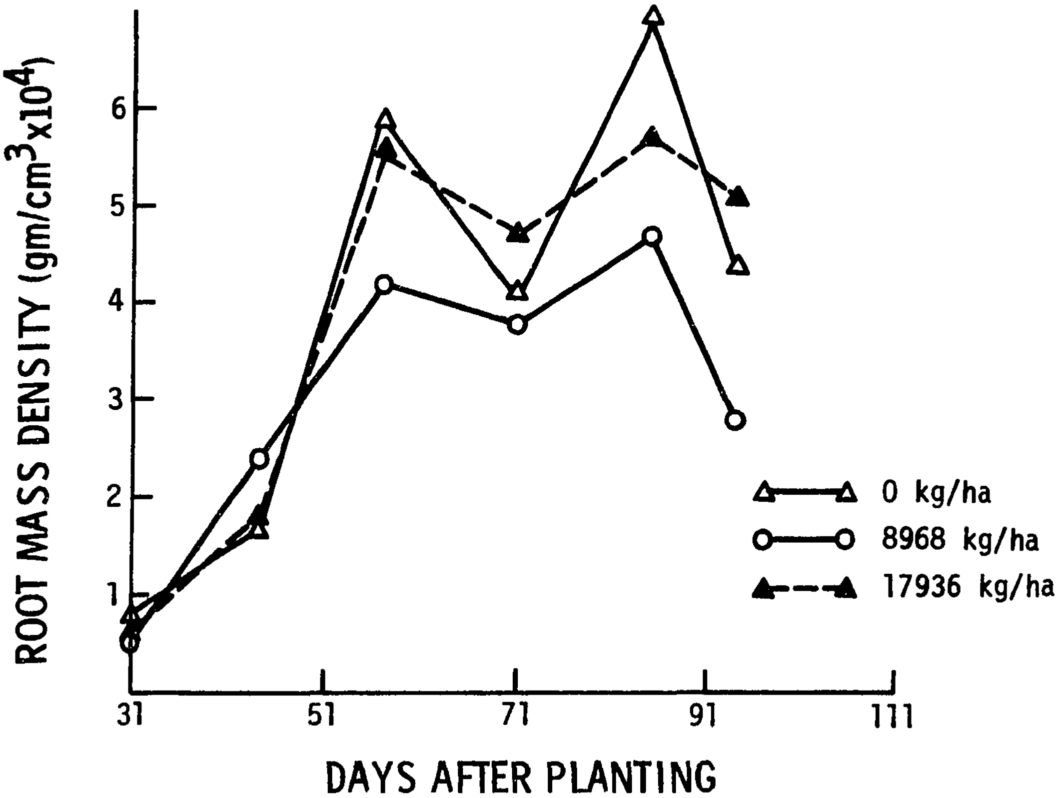



Figure 24a. Variation of root mass density with time during the 1977 season

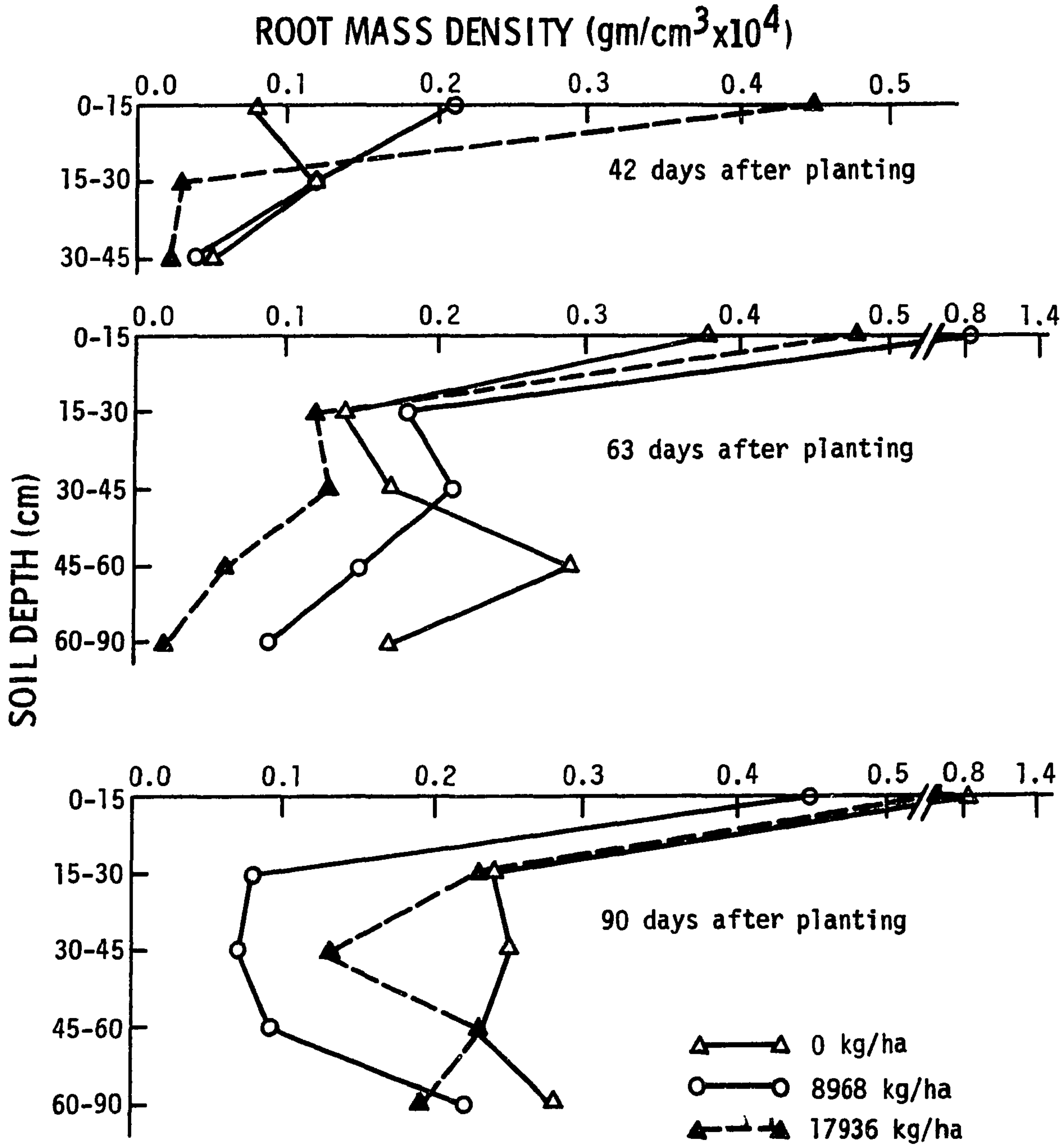
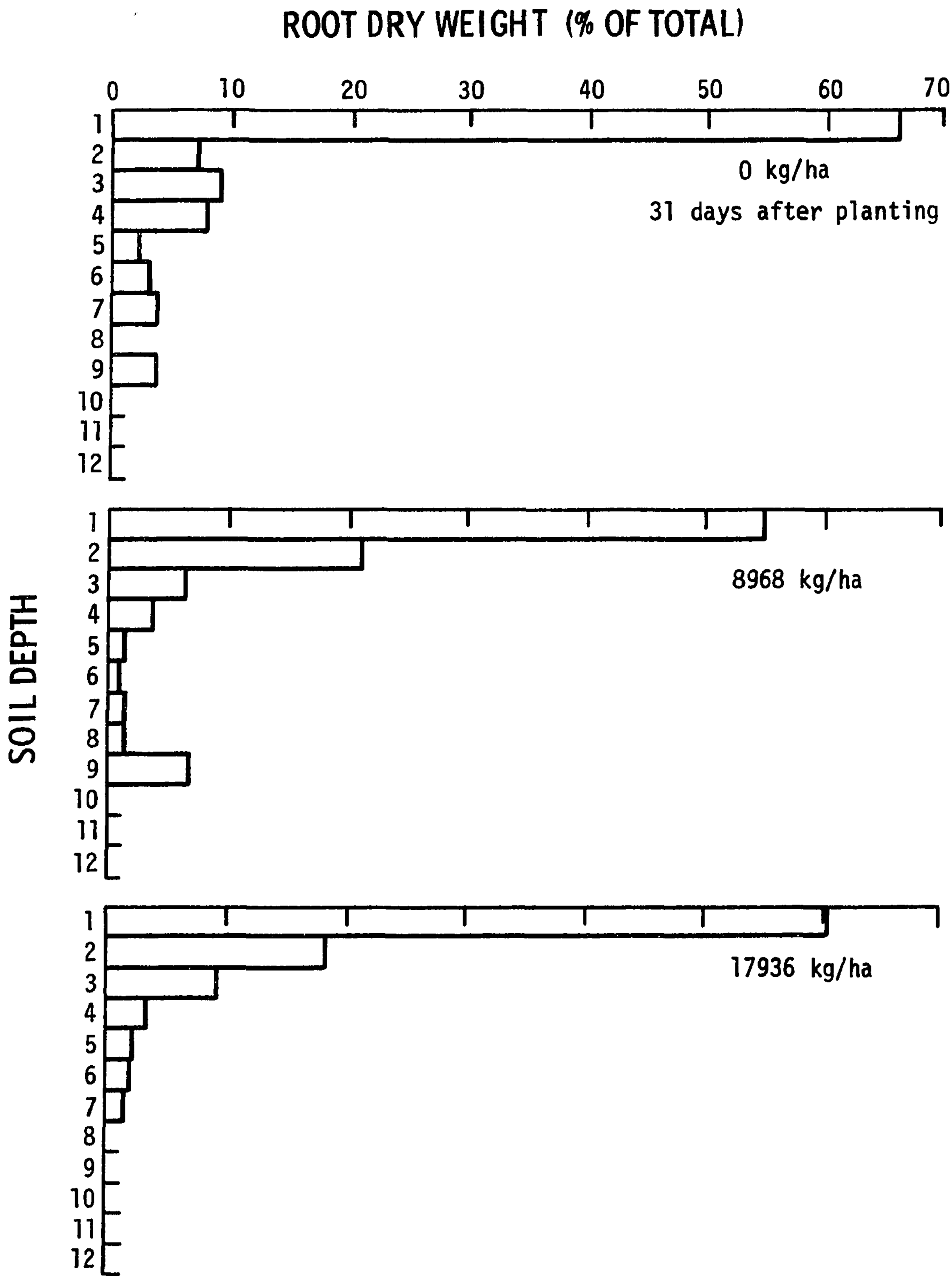



Figure 24b. Distribution of root mass density with depth at 3 dates during the 1976 season

Figure 25. Percentage distribution of root dry weight with depth during the 1977 season

Legend for depth

1 = 0-7.5 cm
2 = 7.5-15 cm
3 = 15-22.5 cm
4 = 22.5-30 cm
5 = 30-37.5
6 = 37.5-45 cm
7 = 45-52.5 cm
8 = 52.5-60 cm
9 = 60-75 cm
10 = 75-90 cm
11 = 90-105 cm
12 = 105-120 cm


ROOT DRY WEIGHT (% OF TOTAL)
0
10
20
30
40
50
60
70
SOIL DEPTH
1
2
3
4
5
6
7
8
9
10
11
12
0 kg/ha
31 days after planting
8968 kg/ha
17936 kg/ha

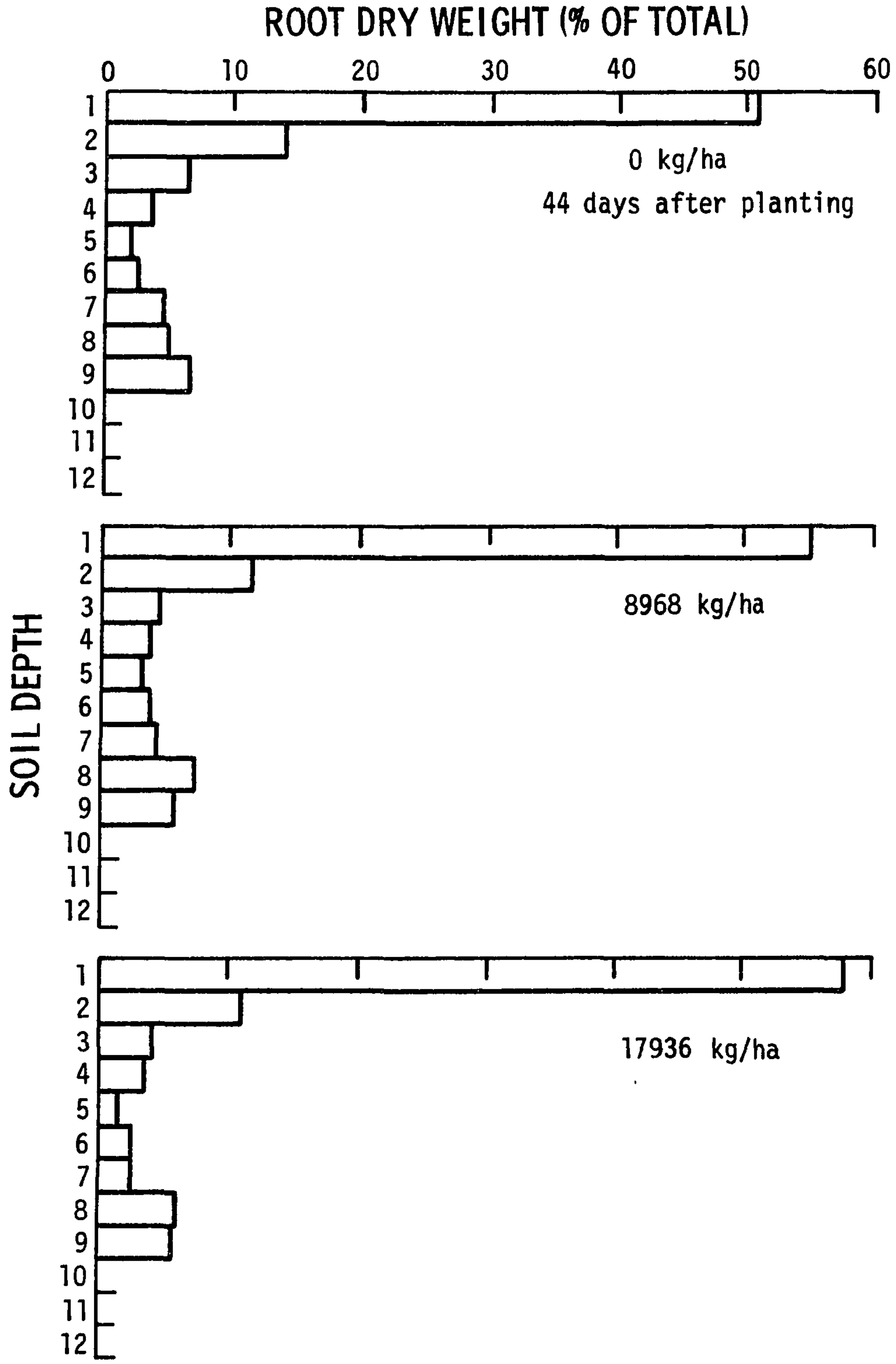



Figure 25. (Continued)

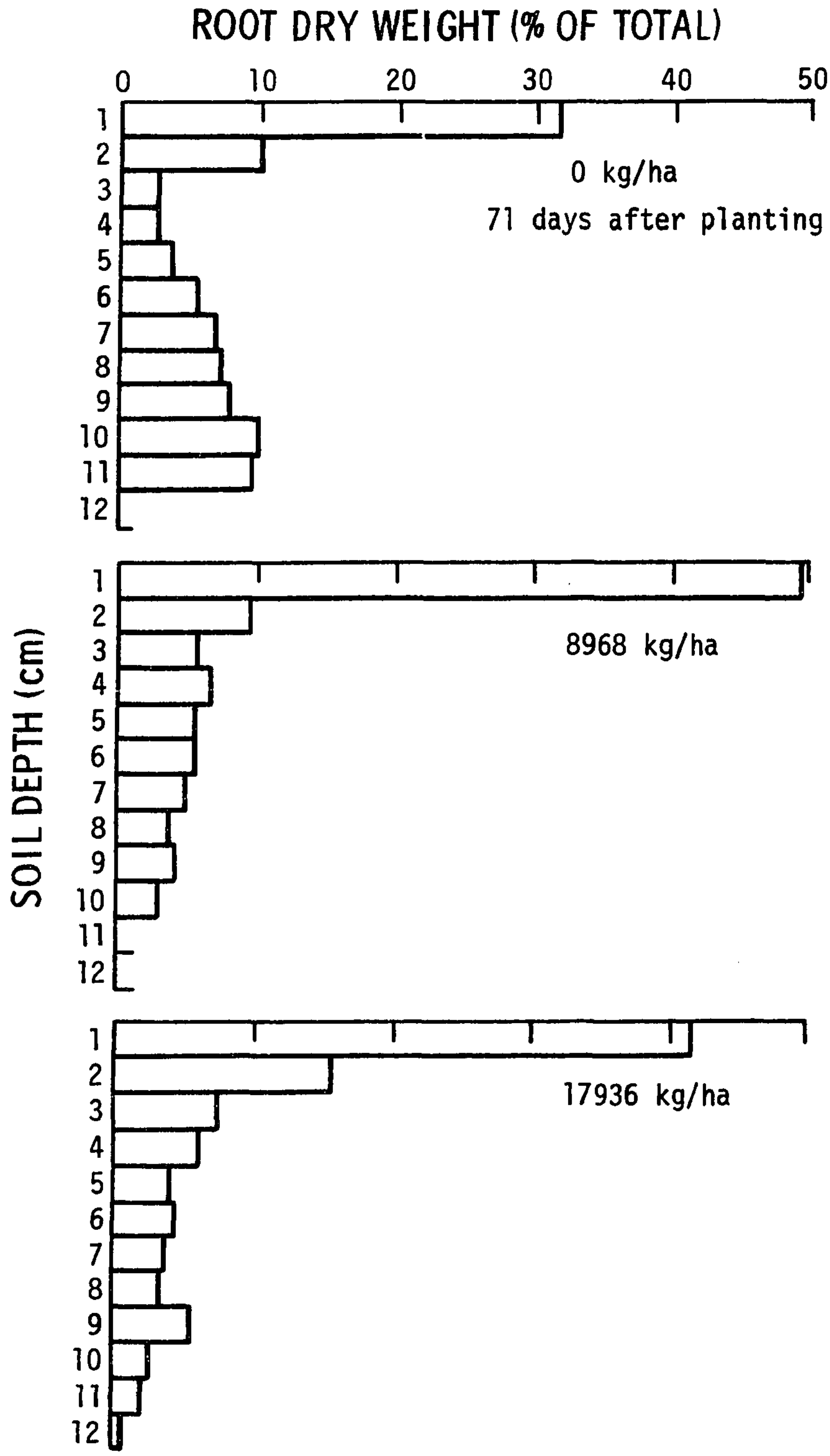



Figure 25. (Continued)

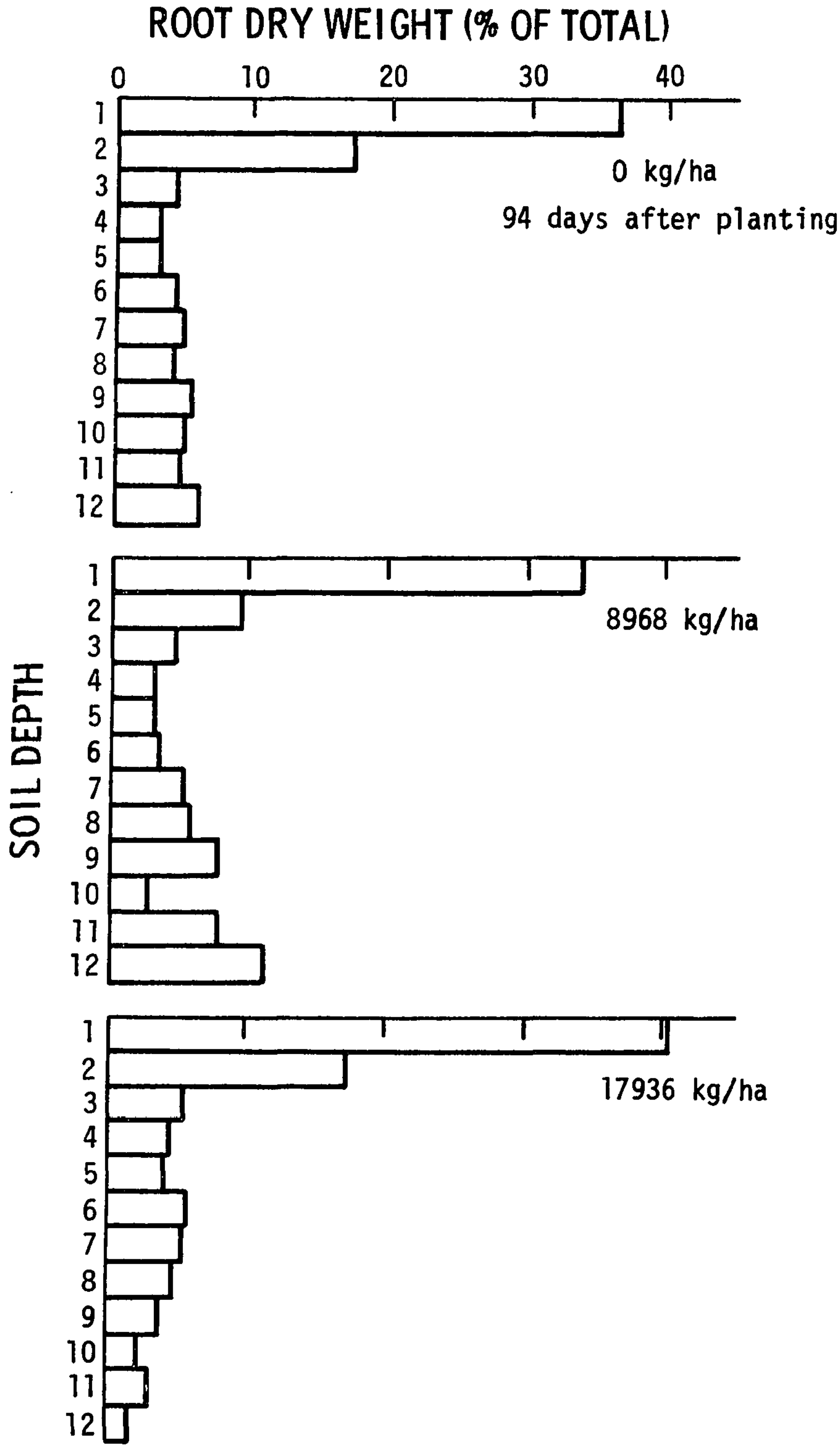



Figure 25. (Continued)

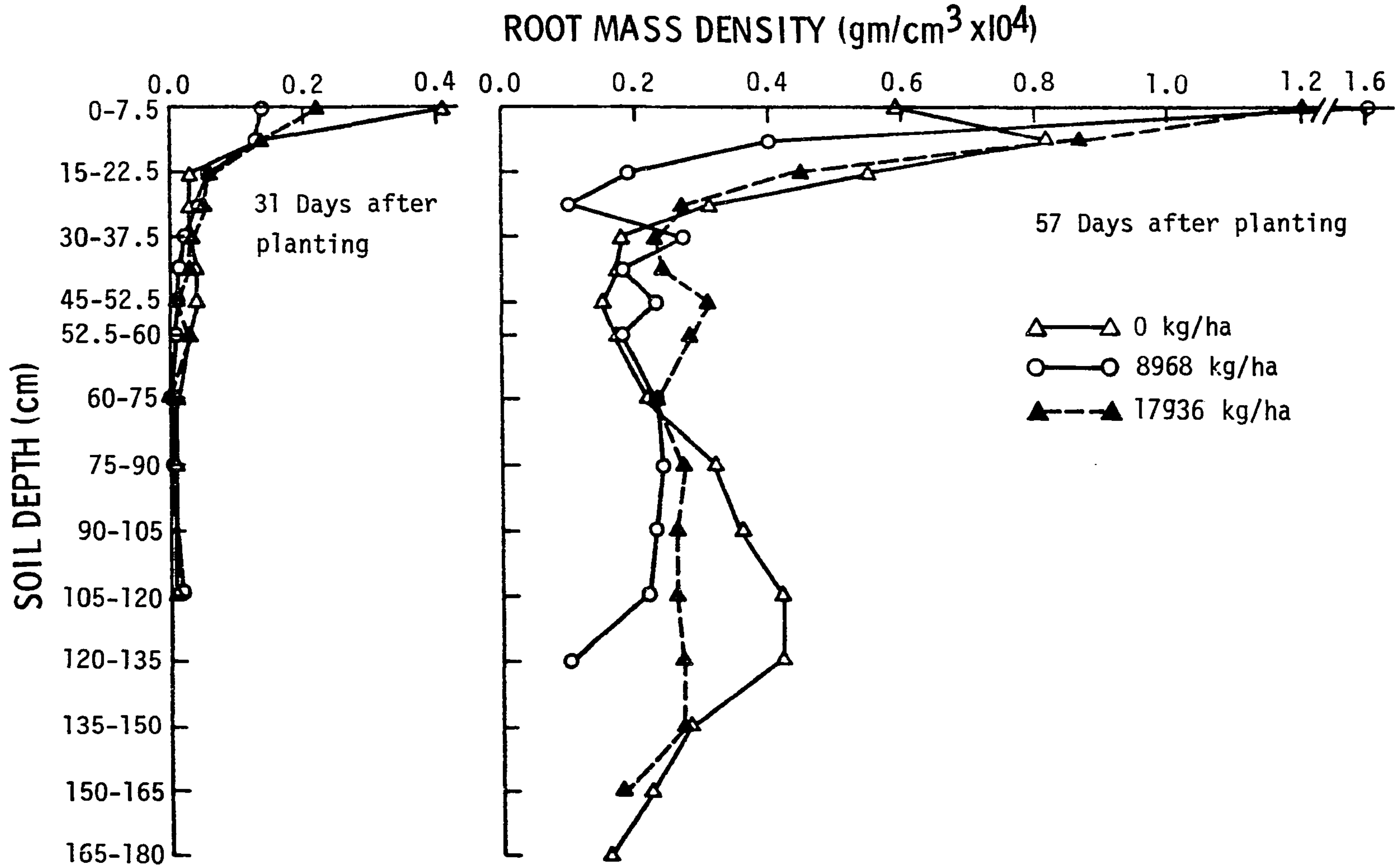



Figure 26. Distribution of root mass density with depth at 2 dates during 1977 season

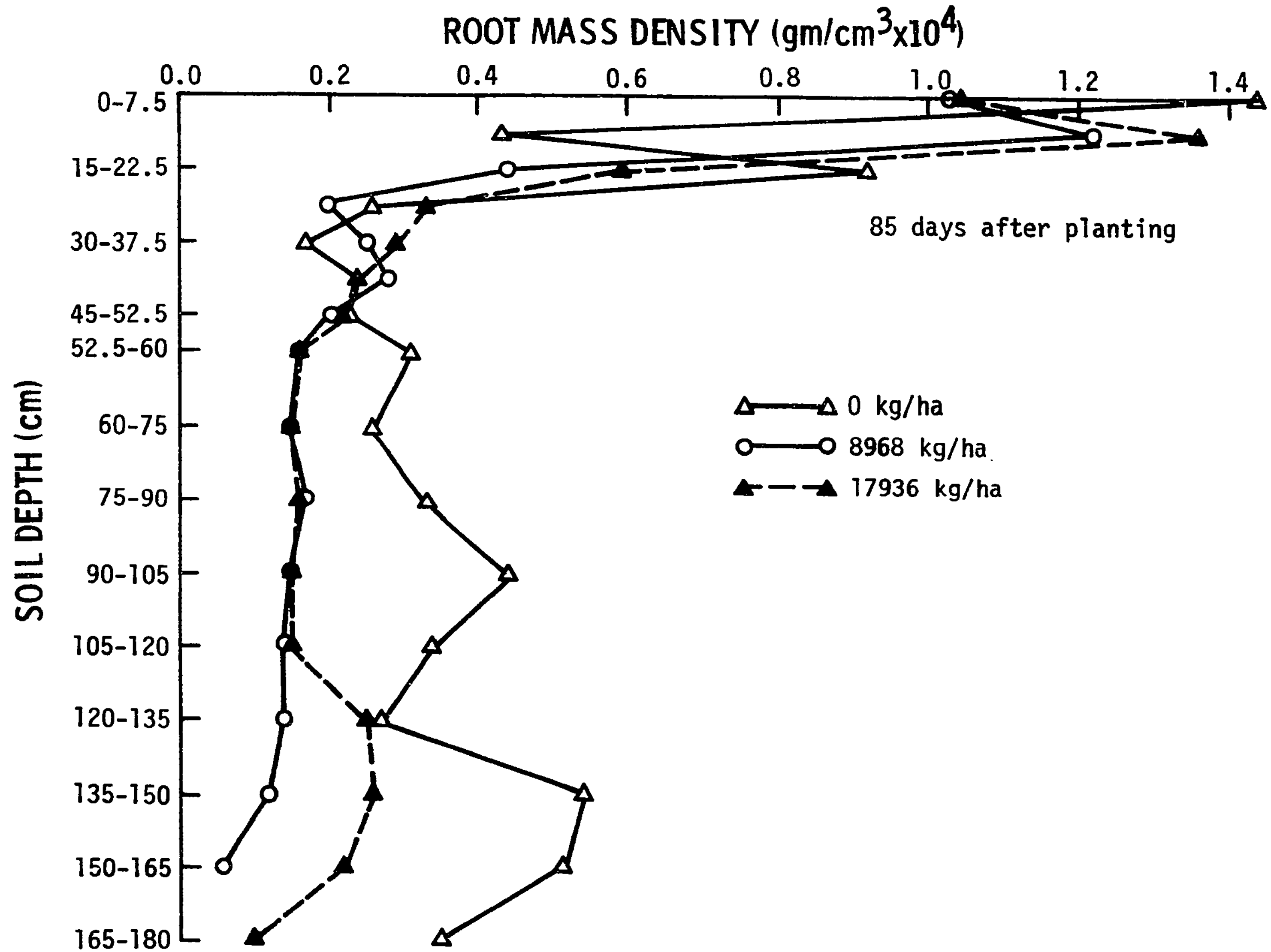



Figure 26. (Continued)

Table 10. Distribution of root mass density with depth at 3 dates during the 1977 growing season

| | Days after planting | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 31 | | | 57 | | | 85 | | |
| Depth | 0 | 8968 | 17936 | 0 | 8968 | 17936 | 0 | 8968 | 17936 |
| cm | --------kg/ha-------- | | | --------kg/ha-------- | | | --------kg/ha-------- | | |
| | 0.411 | 0.143 | 0.221 | 0.594 | 1.617 | 1.176 | 1.440 | 1.026 | 1.038 |
| | 0.126 | 0.131 | 0.142 | 0.827 | 0.403 | 0.873 | 0.483 | 1.218 | 1.362 |
| | 0.029 | 0.064 | 0.060 | 0.552 | 0.185 | 0.449 | 0.920 | 0.438 | 0.586 |
| | 0.030 | 0.042 | 0.050 | 0.310 | 0.104 | 0.274 | 0.263 | 0.201 | 0.381 |
| | 0.032 | 0.019 | 0.026 | 0.076 | 0.271 | 0.228 | 0.174 | 0.254 | 0.293 |
| | 0.042 | 0.014 | 0.028 | 0.165 | 0.184 | 0.242 | 0.237 | 0.276 | 0.242 |
| | 0.037 | 0.009 | 0.009 | 0.149 | 0.228 | 0.309 | 0.232 | 0.197 | 0.223 |
| | 0.027 | 0.010 | 0.034 | 0.171 | 0.178 | 0.277 | 0.311 | 0.158 | 0.100 |
| | 0.010 | 0.004 | 0.007 | 0.216 | 0.232 | 0.229 | 0.264 | 0.150 | 0.153 |
| | 0.013 | 0.003 | 0.006 | 0.317 | 0.243 | 0.272 | 0.332 | 0.171 | 0.158 |
| | 0.015 | 0.004 | 0.005 | 0.357 | 0.225 | 0.259 | 0.437 | 0.147 | 0.148 |
| | - | 0.004 | - | 0.415 | 0.224 | 0.255 | 0.338 | 0.142 | 0.151 |
| | 0.014 | 0.018 | - | 0.415 | 0.096 | 0.266 | 0.273 | 0.142 | 0.250 |
| | - | - | - | 0.284 | - | 0.274 | 0.535 | 0.124 | 0.257 |
| | - | - | - | 0.217 | - | 0.176 | 0.505 | 0.055 | 0.216 |
| | - | - | - | 0.156 | - | - | 0.354 | - | 0.101 |
| Total | 0.786 | 0.467 | 0.588 | 5.904 | 4.191 | 5.558 | 7.048 | 4.698 | 5.669 |

after planting), 73% of RMD was found in the 0-30 cm layer in treatment 1, 76% in treatment 3 and 78% in treatment 5. As the season advanced, the surface layers got drier resulting in the death of some roots while new roots were being formed deep down in the profile. This resulted in a decrease in RMD at the upper part of the profile. By the time the plants were at stage R5 (85 days after planting), the percentage of total RMD in the 0-30 cm layer had decreased to 53%, 42% and 57% for treatments 1, 3 and 5, respectively. Deep down in the profile, meanwhile, RMD had increased.

Discussion on root length and root mass densities

It has so far been shown that RLV and RMD were concentrated at the upper part of the profile especially during the early part of the season. It has also been shown that the percentage of total RLV and RMD in the upper part of the pro- profile at any given time is higher in the mulched than the unmulched plots. That more roots proliferated in deeper parts of the profile as the upper part was exposed to unfavorable conditions was also demonstrated. It is pertinent, therefore, to ask certain questions, the answers to which will help explain these observations. These questions are: (1) Why are more roots concentrated at the upper part of the profile at the early part of the season and why more under mulch than unmulched plots? (2) If a part of the root system is exposed to unfavorable environment, can the rest of the root system make up for this? (3) Why were there more roots at the upper 0-30 cm and lower 105-150 profile layers than at the middle (30-90 cm) layer late in the season? The answers to these questions are forthcoming, but before then, evidence will be presented to show that other investigators have also reported similar findings.

That roots are concentrated on the upper layers during the early part of the season and deeper down in the profile at late season has been shown by a number of investigators. Böhm (1977) used a modified trench profile method to estimate root length of Wayne soybeans in the field at selected dates during the season. He found that 79% of the roots in the profile were located in the 0-15 cm layer at the time the plants were in the V6 stage. When the plants had advanced to the V17, R5 stage, the percentage of the total roots in the 0-15 cm layer had decreased to 13-16%. Mitchell and Russell (1971) described the root development and pattern of field grown soybeans and obtained similar results. They reported that 31 days after planting, 93% of the total root weight was in the 0-15 cm zone. At 80 days after planting, only 86% of the total root weight was found in the 0-15 cm zone. Between 80-102 days after planting, they reported an accumulation of dry weight at the lower depths in the profile and also an increase in the 0-7.6 cm layer. This finding of Mitchell and Russell agreed very well with our finding as well as those of others (Mayaki et al., 1976; Sivakumar et al., 1977; Mengel and Barber, 1974; Böhm, 1977; and Welbank et al., 1974). The distribution of soybean roots with depth may be due to soil physical and chemical conditions or to varietal differences as has been shown by Raper and Barber (1970). However, the distribution described in this study is best explained based on other properties of the soil. Root configuration is influenced by nutrient concentrations in the soil. More roots tend to proliferate in zones where nutrients are more favorably concentrated (Weaver, 1926; Barley, 1970; Russell, 1977). Because the plots were unfertilized in 1976 and received only a small amount of phosphate in 1977, the influence of nutrients on the root configuration is thought to be very minimal.

The factors having the most profound influence on the root distribution in this study were soil temperature and soil moisture. The influence of soil temperature was exerted mainly at the early growth stage of the plant but the soil moisture influence was present throughout the entire season. Roots proliferate where soil moisture is favorably supplied (Weaver, 1926; Allmaras and Nelson, 1971; Chaudhary and Prihar, 1974; Allmaras et al., 1973; Klepper et al., 1973; Russell, 1977).

The distribution of roots in this study is explained largely on the soil moisture variations. At the early part of the season, there was adequate moisture in the profile but more in the mulched than in the unmulched plots. As a result, the root length density was more concentrated at the upper layers in the mulched than the unmulched plot (Figure 23). As the season progressed, however, and the top layers tended to "dry out", more roots were formed lower in the profile than in the upper part in all the treatments but the rate and magnitude of the proliferation in the deeper layers were higher in the bare than the mulched plots.

The question as to why roots were concentrated more on the top layers of the profile appears to have been answered. But the reason for more proliferation at the deeper part of the profile as the season advanced has to do with the concept called "compensatory" growth (Russell, 1977; Rowse, 1974; Lawlor, 1973; Crossett et al., 1975). According to this principle, if the growth of one part of the root system is reduced or inhibited, that of other root members which experience more favorable conditions is frequently enhanced.

Also, if a part of a root system is placed in an unfavorable environment while the rest experiences a favorable condition, the growth of the part in the unfavorable environment may be less than if the entire root system experiences the unfavorable environment. The compensatory mechanism is important in the survival of crops under unfavorable situations. The explanation of this mechanism is incomplete but, as Russell (1977) suggests, may be in the source-sink relationship. Unfavorable conditions in part of the root zone cause the reduction or removal of some sinks, thereby diverting available metabolites to the root members experiencing favorable conditions. Hormonal involvement may also be possible.

The pattern of RLV distribution with depth at various times during the season (Figures 21 and 22) shows very clearly the mechanism of compensatory growth. In 1977 (Figure 22), roots in the top (0-30 cm) and deeper (105-180 cm) layers in the profile experienced favorable soil moisture conditions while those in the 30-105 cm layer were being desiccated. The result was an increase in RLV in the top and deeper layers and a possible decrease in the middle layer of the profile. The distribution pattern in 1976 (Figure 21) compared to 1977 shows a good example of the importance of soil moisture in root configuration. Because of the scanty rainfall in 1976, the top 0-60 cm layer of the profile was depleted of moisture. Roots in this horizon were, therefore, placed under unfavorable conditions. Deep down in the profile, the roots in the 60-180 cm layer were placed in a better environmental condition and hence showed more growth to compensate for the reduced growth of those at the top 0-60 cm layer.

The questions raised earlier now appear to have been answered. Mulching appeared to have decreased RLV and RMD in treatment 3 (8968 kg/ha), but increased it in treatment 5 (17936 kg/ha). Work by Maehara (1976), on tea in Japan, showed that straw mulch increased the quantity of roots almost twice compared to the bare plot. Maehara also observed, as was the case in this study, that bare plots had more roots in the deep layer of the profile. He suggested that this might be due to the fact that the fertility of the surface layer was decreased owing to the long exposure under bare conditions. In our study, however, fertility is not considered a factor in the compensatory growth.

Depth of rooting and root elongation as affected by mulch rate

To find out if rooting depth and root elongation rate are affected by the different rates of mulch, the distance from the surface to the lowest visible root tip was measured each time root samples were taken. Figure 27 is a depiction of the various distances vertically covered by the deepest root tips at various times during the 1977 season. A look at the graph shows that roots grew much faster during the vegetative and early reproductive stages of the plant in all the treatments. Before the onset of bloom at stage V8, R1 (Fehr and Caviness, 1977), the rates at which the roots penetrated into the soil were 1, 2.3 and 3 cm per day for the 0, 8968 and 17936 kg/ha plots, respectively. At 45 days after planting, the rate was the same in all the treatments; but it varied beyond this stage, with the unmulched plot (treatment 1) showing the highest rate and treatment 3 the least. By the time the plants were at stage R3, which corresponds to the beginning of pod development, the rate of elongation had slowed substantially in treatment 1 but appreciably in treatments 3 and 5. At the onset of seed formation (stage R5), the roots

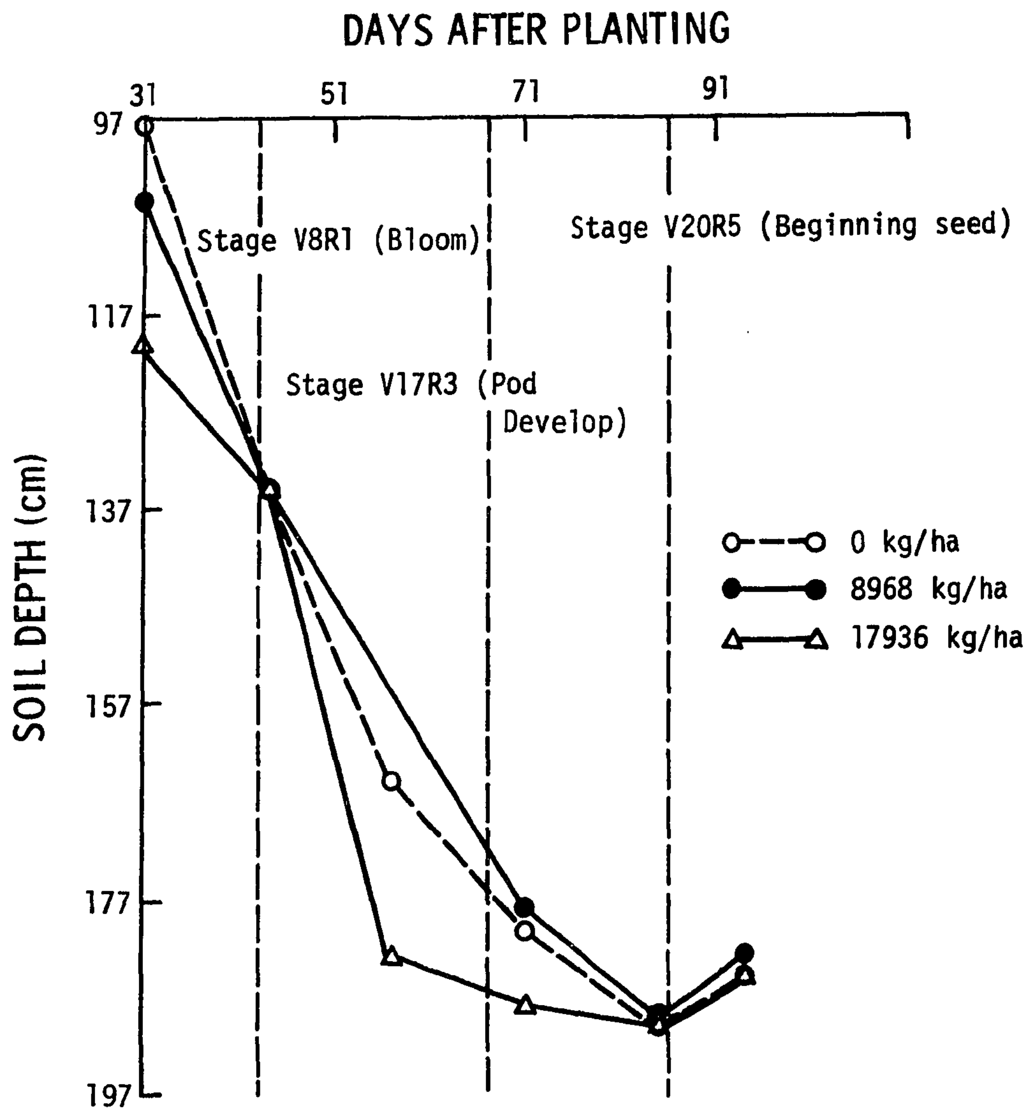



Figure 27. Root depth as affected by rates of mulch during the 1977 season

had stopped elongating in all treatments. By this time, 85 days after planting, they had penetrated 189 cm deep into the profile in all treatments. Rooting depth was not measured during the 1976 growing season.

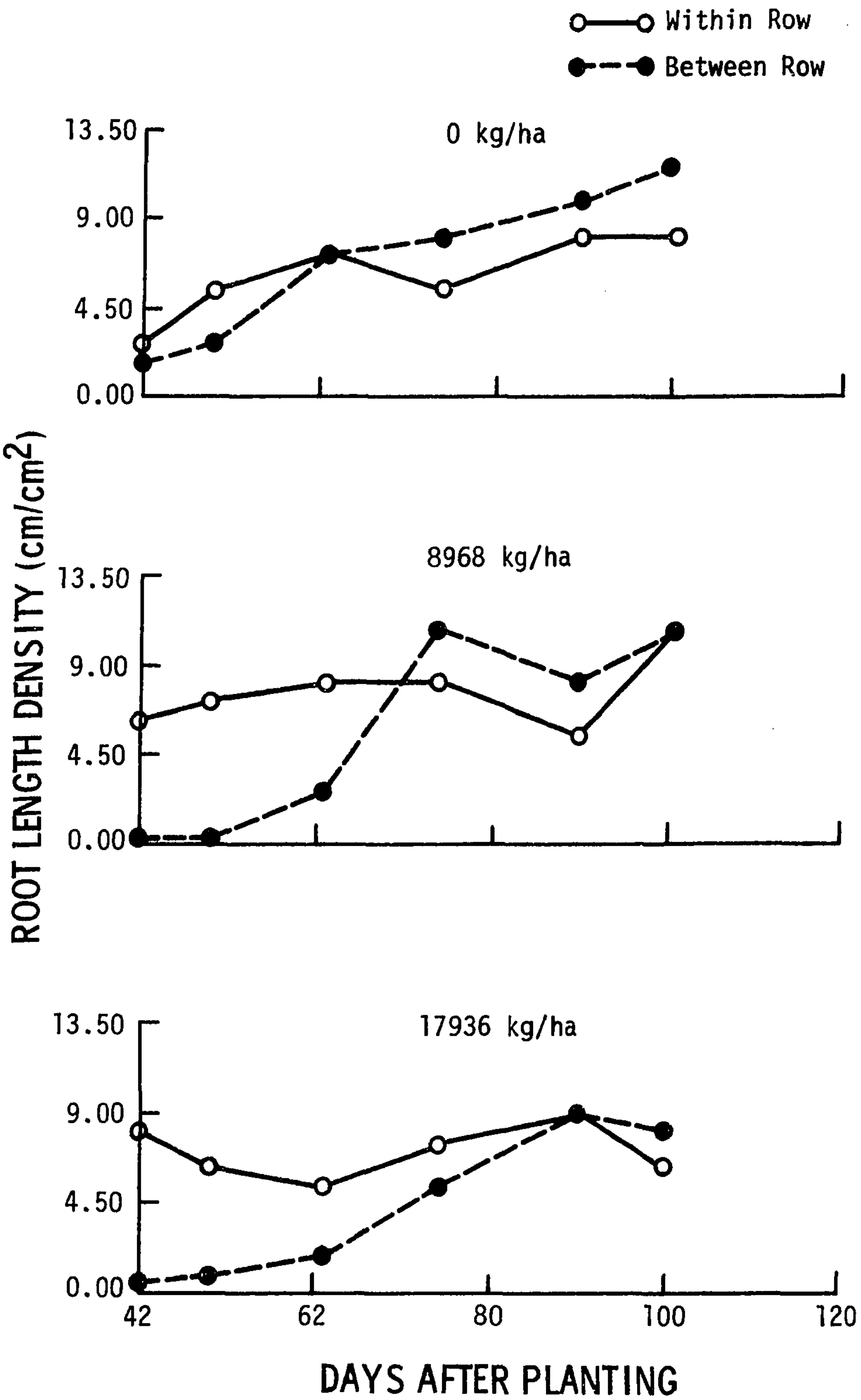
That root elongation should slow down before and during pod development ceasing altogether at the onset of seed development is expected. During those phases of growth, most of the photosynthates are diverted to the formation of pods and seeds and little or none goes to the roots for the purpose of elongation. This agrees with the view of Aung (1974) who stated that with the advent of flowering and fruiting, root growth slows and ceases abruptly due to shortage of photosynthates from the shoots.

Root extension, according to Russell (1977) starts to decrease at a water potential higher than that of wilting point. The water potential at wilting is generally considered to be about -15 bars (Kramer, 1969), but root extension starts to slow down at a potential as high (high water content) as -0.5 bar. Root extension may, however, continue at erratic potentials of -10 or lower as shown by Newman (1966b), Lawlor (1973) and Portas and Taylor (1976). Moisture however, seems not to be the cause of the difference in rate of extension of the roots in the bare and mulched plots, especially between 44 and 85 days after planting. Soil temperature is thought to be more important here. The reduced rate of extension at this period in the mulched plots is due to reduced soil temperature owing to mulching. That mulches reduced root elongation in the northern latitudes was shown by Van Wijk et al. (1959) and Burrows and Larson (1962) among others.

Differential growth of roots in the row and interrow locations

For an efficient irrigation as well as nutrient application management, it is necessary to know not only the total root configuration but also where the roots are located at a particular time during the season. The spatial orientation of the root members is very important for it can influence the efficiency with which soil water and nutrients are taken up. For slowly diffusible nutrients, uptake may well depend on how many roots are located in the zone of the nutrients. To gain information on the spatial arrangement of the roots, root samples were taken at intervals at two locations during the 1976 season. These locations were "within the row" and half-way between the rows. Figure 28 depicts the variation of the total RLV with time at these two locations during the season as affected by the various mulch treatments. The lower values as compared to Figure 18 is because of the scanty rainfall in 19 1976 and also the method of obtaining the root samples. In 1976, root samples were obtained with the 10 cm diameter bucket auger. An examination of the curves shows some interesting trends. Root length density was higher in the row than between the row at the start of sampling. This agrees with Barber's (1978) observations for soybeans. As the season progressed, more roots grew between the row than within the row. The result of this is that the difference in RLV between the row and

Figure 28. Variation of total root length density (summed over all depths) with time in the row and between the row during the 1976 season; root length density here is defined as cm of root per square cm of soil surface


Within Row
Between Row
0 kg/ha
8968 kg/ha
17936 kg/ha
13.50
9.00
4.50
0.00
ROOT LENGTH DENSITY (cm/cm2)
42
62
80
100
120
DAYS AFTER PLANTING

within the row narrowed with the advance in season. Eventually at a stage, the RLV between the row equalled that within the row and surpassed it. The time at which the RLV in the row and that between the row were equal varied with the treatments. For example, it took about 62 days after planting for both to be equal in the unmulched plot (treatment 1), 72 days when 8968 kg/ha of mulch was applied and about 90 days on application of 17936 kg/ha of mulch.

Another feature brought out in Figure 28 is that mulching tended to increase the difference between the RLV in the row and interrow positions. For example, at 52 days after planting, the difference between the row-interrow RLV's were 0.02, 0.07 and 0.06 for treatments 1, 3 and 5, respectively. One other point of interest in the graphs is the fact that the rate of increase with time of RLV was higher in the interrow than within the row position.

The reason for the behavior of roots as illustrated in Figure 28 is based on the soil moisture and the soil temperature in these locations. Allmaras and Nelson (1971) placed straw mulch either in the row or between the row of field grown corn for two seasons. In one season (1968) a straw mulch strip centered over the row decreased proliferation laterally at the early sampling date. In another season (1969), the effect of straw mulch centered over the row increased the lateral root proliferation. Straw mulch decreased average soil temperature in the 0-45 cm depth in 1969. Both years appeared to have adequate precipitation, although 1969 was wetter. Comparison of the result of Allmaras and Nelson (1971) with that obtained in the above study reveals that soil moisture had a predominant role in the pattern of root distribution in the row or interrow position. The mulch was uniformly applied so that soil temperature was equally influenced in the two locations at the beginning of the season when the roots had not developed. Soil moisture was adequate at this time in the two locations. It seems then that as the season advanced the roots extracted more moisture from within the row than between the rows. As the moisture in the row was depleted, root growth was reduced in the row and was compensated for by increased root growth in the interrow position.

Length of root per square centimeter of leaf area

The length of root for supplying water to unit leaf area is important in models involved with uptake of water by roots. As Eavis and Taylor (1978) observed, some models include the assumption that radial resistance to water flow through root tissue is a constant, independent of the flow rate. The validity of this assumption will affect transpiration and the status of water in the plant. To test this assumption, the root length relative to leaf area will have to be known. It is, therefore, useful to show how this ratio varies with time and how mulch rates affect this variation. The data for the 1977 season were used to calculate the root length per unit leaf area. Table 11 illustrates the trend.

In the check plot, the length of root that supplies water and nutrients to a unit leaf area ranged from 4 during the early part of the season to 10 late in the season. Generally this length was small in the early part of the season, but increased as much as 2-fold by late in the season.

When 8968 kg/ha of mulch (treatment 3) was applied, the trend compared to the bare plot was reversed. The ratio was higher during the early part of the season and then decreased during the latter part. It ranged from 4.5 to 8.3. When the mulch rate was further increased to 19736 kg/ha (treatment 5), the ratio remained about the same during the season except for an upward surge which occurred 57 days after planting. The ratio ranged from 5.0 to 12.5.

In contrast, Eavis and Taylor (1978) obtained root length/leaf area ratio ranging from 30-140 cm of root length per $cm^2$ of leaf in an experiment where the plants were grown in large containers. Sivakumar (1977) reported a value of 3 to 8 in field grown soybeans. The variations in the results can be attributed to differences in (a) the methods of obtaining the roots, (b) different people measuring the root lengths, and (c) factors that caused major deaths of roots in field situations.

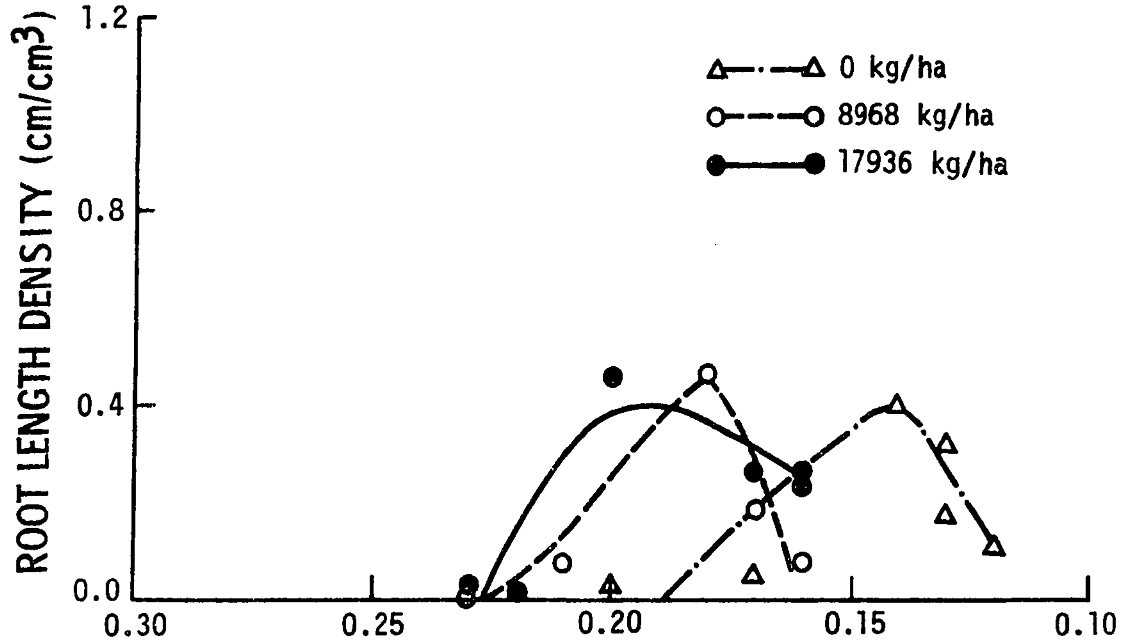
Table 11. Variation of root length/leaf area ratio with time as affected by mulch rates

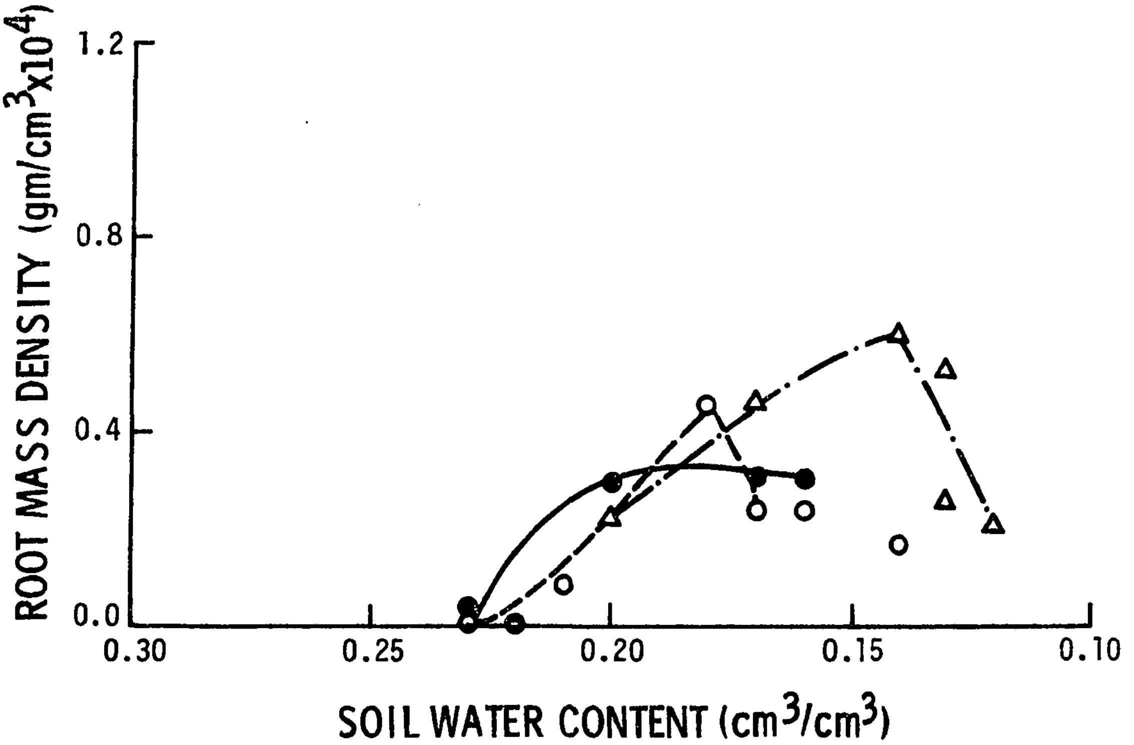
| Days after planting | Root length/leaf area, $cm/cm^2$ | | |
|---|---|---|---|
| | 0 | 8968 | 17936 |
| | kg/ha | | |
| 31 | 4.0 | 5.56 | 7.69 |
| 44 | 4.17 | 8.33 | 5.00 |
| 57 | 8.33 | 8.33 | 12.50 |
| 71 | 7.14 | 4.55 | 6.25 |
| 85 | 10.00 | 4.76 | 7.69 |

### Relationship between soil moisture content and root length density

For a more efficient utilization of available soil moisture by the root system, more information is needed than is available now. One type of required information is whether new roots are found in a particular layer when more moisture is made available to that layer. At what moisture content does the formation of new roots cease? To try to get some answers to the above questions, the moisture content at the 90-120 cm layer in the profile was plotted against the root length and root mass densities at that layer for the entire 1977 season. Figure 29 shows these plots as affected by the mulch rates. It is seen that root length density increased with decreasing water content up to a point and then sharply declined with further decrease in moisture content. This

Figure 29. Relationship between root length and root mass densities with soil water content at 90-120 cm soil depth


ROOT LENGTH DENSITY (cm/cm3)
1.2
0.8
0.4
0.0
0.30
0.25
0.20
0.15
0.10
0 kg/ha
8968 kg/ha
17936 kg/ha


ROOT MASS DENSITY (gm/cm3x10^4)
1.2
0.8
0.4
0.0
0.30
0.25
0.20
0.15
0.10
SOIL WATER CONTENT (cm3/cm3)

pattern is expected since the more that the root system is developed in a particular layer the more the moisture is extracted from that layer. Figure 29 also shows that when soil moisture content is depleted to a certain value, not only are new roots not formed but the existing roots start to die, leading to a decline in root length density. Böhm et al. (1977), Klepper et al. (1973), Russell (1977) have also observed dying of roots as the soil gets drier.

This soil moisture content at which new roots ceased to be formed varied with different rates of mulch application. It increased from 0.14 $cm^3/cm^3$ in treatment 1 to 0.18 and 0.19 $cm^3/cm^3$ in treatments 3 and 5, respectively. The maximum root length density attained did not seem to be affected by mulch rates. It was about 0.40 $cm/cm^3$ for treatment 1, 0.44 $cm/cm^3$ for treatment 3 and 0.40 $cm/cm^3$ for treatment 5.

The relationship of root mass density with soil moisture content follows the same pattern as that described above but there was more variation in the maximum root mass density as a result of the treatments. Maximum root mass densities are $0.60 \times 10^{-4}$, $0.46 \times 10^{-4}$, and $0.32 \times 10^{-4}$ g root/$cm^3$ soil for 0, 8968, 17936 kg/ha plots, respectively.

Taylor and Klepper (1974) observed a similar trend of root length variation as the soil dried in a particular layer of the profile. They found that where the water content in a particular soil layer decreased to about 0.06 to 0.07 $cm^3/cm^3$, root length of cotton ceased to increase in that layer. This is due probably to root die off as a result of dry soil water potential. This die off was thought to start at about -1 to -2 bars in the above experiment with cotton. In our study with soybeans, however, roots started dying off at a more negative soil water potential. This potential is influenced by the amount of mulch cover. In the 0 kg/ha plot (treatment 1), root die off started at -13 bars but when 8968 and 17936 kg/ha of mulch was applied, die off started to occur at -3.2 and -2.4 bars, respectively. The reason for the roots dying at higher water content in the mulched plots is not well-known. However, it can be speculated that soil moisture-soil temperature interaction may be an important factor.

Leaf water potential

Surface applied organic mulch, as has been established, conserves soil moisture. It follows that plants under mulch should have more moisture available to them, particularly during a drying cycle. If this available moisture is actually taken up by the roots of the plant, then plants under mulch should show less water stress or higher plant water potential (higher water content). To confirm or disprove this assertion, the water potential of the leaf was measured in all the treatments in replicate 2 at 85 days after planting in 1976 and 53 days after planting in 1977. Water potential of the leaf petiole has traditionally been used as an indicator of the plant water status and its diurnal variation as affected by mulch rates is shown in Figures 30 and 31.

A look at the figures shows an interesting contrast between the 1976 and 1977 growing seasons. During 1976 when little precipitation occurred, mulch exerted some influence on plant water status but where moisture was adequately available, e.g., 1977, mulch did not seem to have any effect on plant water potential. When it did have an effect, mulching tended to increase the plant water supply. This is illustrated in Figure 30 where the plants in the heavier mulched plots (treatments 3, 4 and 5) had higher water content (higher water potential) than those in the bare and lightly mulched plots (treatments 1 and 2).

The general trend follows that well-established in the literature. Plants tend to suffer some water deficit during the day and recover from the deficit at night. In 1976, the period of greatest deficit seemed to occur between 1255 and 1405 hours. The period in 1977 was about the same--1200 to about 1425 hours.

Soybeans use a large amount of water and estimates put their water requirement to be about 580 $g^{-1}$ dry matter (Kato, 1967; Shibles et al., 1975). It will be expected then that inadequate water supply in the soil will subject soybeans to water stress. That plants suffer from water deficit during the day and recover at night has been observed by a number of investigators (Slatyer, 1969, 1957; Crafts, 1968). Work on soybeans

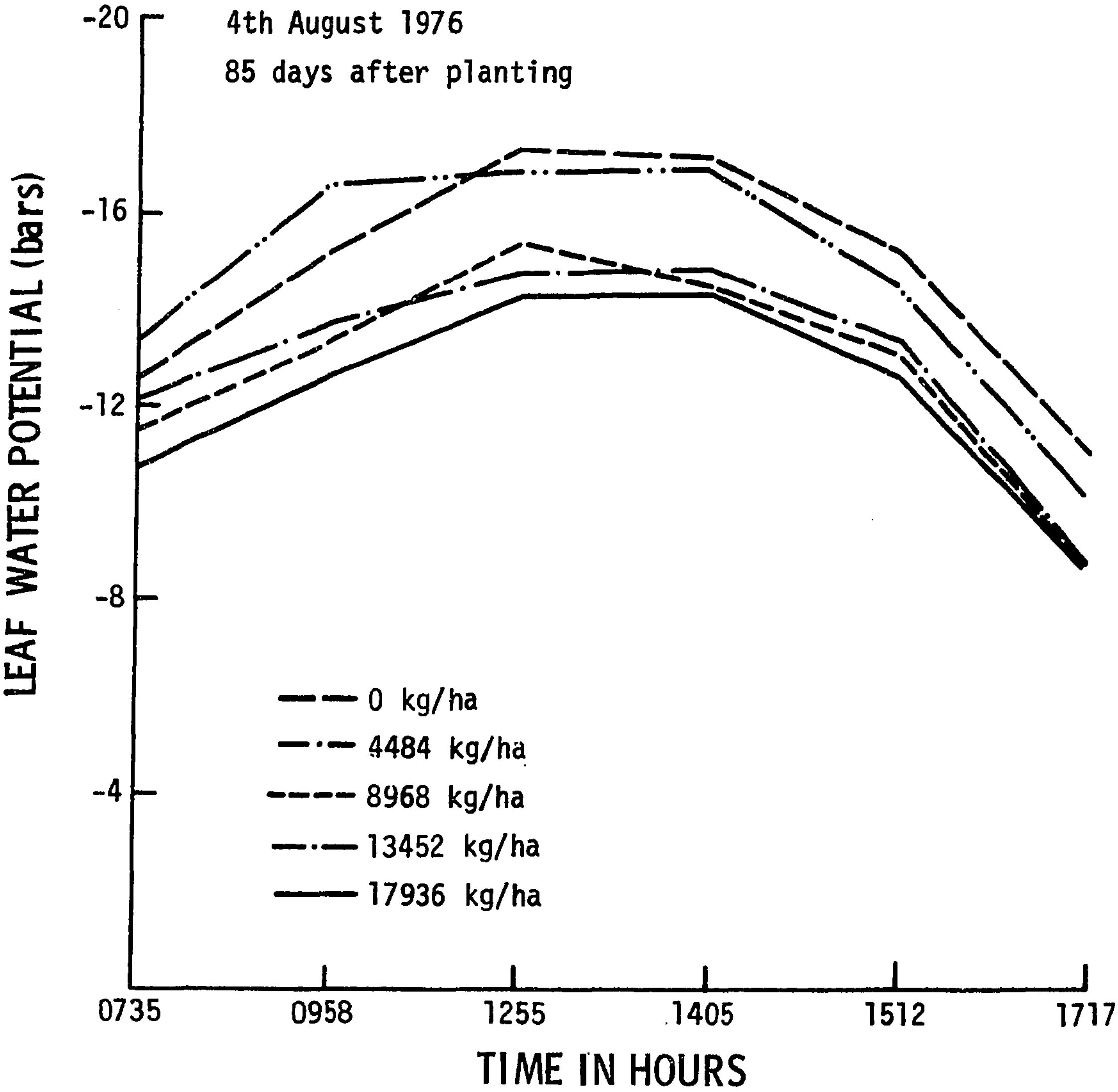



Figure 30. Diurnal variation in leaf water potential as affected by mulch rates during the 1976 season

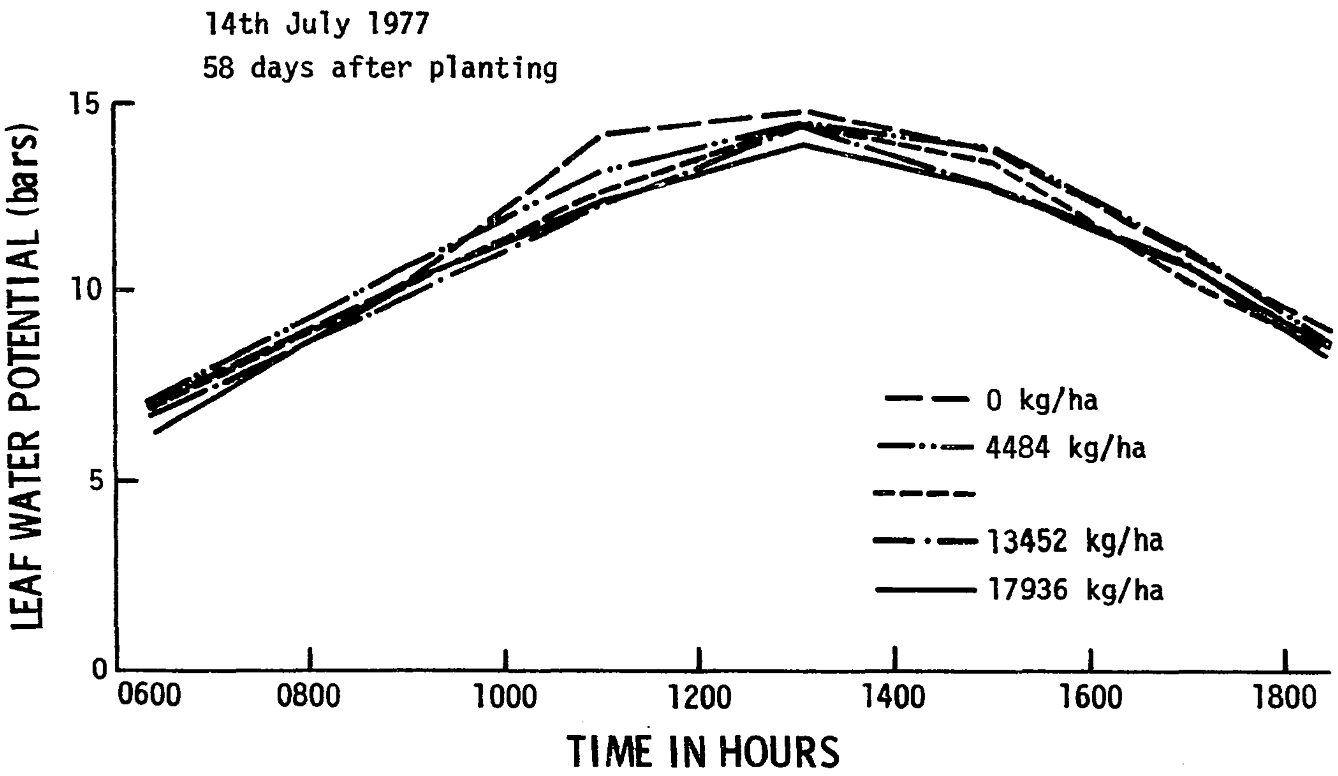



Figure 31. Diurnal variation in leaf water potential as affected by mulch rates during the 1977 season

(Chen et al., 1971; Shaw and Laing, 1966; Sivakumar, 1977) has also produced similar results.

The reason that plants suffer from water deficit during the day is because transpiration exceeds absorption and hence plants lose more water than they can absorb (Slatyer, 1969). This is the diurnal pattern when adequate moisture is present in the soil. When the soil moisture is limiting, the plant water status appears to be directly related to the amount of water in the soil. So mulching, by making more water available for absorption by reducing evaporation, increases the level of water in the plant.

Yield

The yield in kg/ha obtained during the two growing seasons is presented in Table 12 and the analysis of variance is shown in Table 13. It is clear that in 1976, mulching did not affect yield as evidenced by the nonsignificant difference between the different treatments. This is due to the scanty rainfall in 1976 which resulted in possible stressing of the plants during the reproductive phase. Shaw and Laing (1966) have shown that yield is markedly decreased if plants are stressed during the reproductive phase. The low yield value of 1976 indicates that the plants were stressed at critical periods during the season.

The yield in 1977 is significantly higher than in 1976 but as in 1976, mulching had no effect on yield as shown by

Table 12. Yield in kg/ha during the two growing seasons

| Kg/ha (mulch) | Yield (kg/ha)[a] 1976 | 1977 |
|---|---|---|
| 0 | 755 | 3032 |
| 4484 | 731 | 3115 |
| 8968 | 748 | 3071 |
| 13452 | 705 | 3022 |
| 17936 | 812 | 2958 |

[a]Mean of 4 observations.

Table 13. Analysis of variance for yield obtained during 1976 and 1977 seasons

| Source of variation | Degrees of freedom | F values | $P > F$ |
|---|---|---|---|
| | 1976 | | |
| Replicate | 3 | 2.24 | 0.14 |
| Treatment | 4 | 2.99 | 0.06 |
| | 1977 | | |
| Replicate | 3 | 2.27 | 0.13 |
| Treatment | 4 | 3.02 | 0.06 |

the nonsignificant treatment effects. This is possibly due to the fact that moisture was adequately available to all the treatments during most of the season and hence the plants did not come under water stress.

## SUMMARY AND CONCLUSIONS

Mulching has been used as a means of conserving soil moisture and reducing soil temperature where it is excessive for crop growth. To find out how mulching might be influencing crop performance, an experiment was initiated to investigate the effect of increasing rates (0, 4484, 8963, 13572, 17936 kg/ha) of surface applied corn stover mulch of the top and root growth of field grown soybeans at Castana, Iowa.

Data were collected during the growing seasons of 1976 and 1977. During each growing season, plant height, petiole dry weight, stem dry weight, leaf dry weight, and leaf area were obtained from samples taken at weekly intervals during the season. Soil moisture and soil temperature were also measured weekly while root samples were taken at fortnightly intervals. Root length density and root mass density were calculated from the root length and root dry weight of the samples. Runoff was measured in all the treatments on one replicate. The diurnal pattern of leaf water potential was also measured once during each growing season. The variation associated with the root samples is thought to be large. But despite this probability, analysis of the data obtained during the two seasons shows the following salient features of the experiment.

1. Soybean plants grew taller, accumulated more dry matter and leaf area and had higher yield during

1977 season compared to 1976. This difference is attributed to the difference in precipitation between the two seasons.

2. During any one growing season, mulch application decreased plant height, leaf area and dry matter of the shoot. This decrease appears to be significant when soil moisture is limiting but not when it is adequate. It is attributed to lowering of soil temperature by the mulch.
3. Soil moisture seems to have a profound influence on the root distribution of soybeans. Root distribution, on the other hand, seems to determine the pattern of soil moisture distribution.
4. Root systems increase in weight and in total root length up to a certain time during the season which corresponds to the onset of active pod and seed formation.
5. The influence of mulch on root distribution is unclear from the above experiment. At certain times, it decreased root length and root mass densities compared to the control. At other time, it seems to have no effect when the mulch rate is increased.
6. During the early part of the season, the root length density in the row is higher than that between the row. As the season advances, more roots proliferate in the interrow position compared to the row. This

root distribution is associated closely with soil moisture distribution in the row and interrow locations.

7. The length of root which supplies water and nutrients to 1 sq cm of leaf area is between 4-10 cm and was not affected markedly by mulch rates of 17936 kg/ha during the season.
8. In a year of insufficient rainfall and hence low soil water potential, mulched plants appear to have higher leaf water potential than unmulched plants. When soil water is adequate, mulching effect becomes unimportant.
9. Roots grow and proliferate up to a certain soil water content. If the soil becomes drier than this water content, the roots die off.
10. Roots of soybeans exhibit the phenomenon of compensatory growth. This compensation is better observed during periods when soil water contents differ among the various layers of the profile.
11. Soybean roots penetrated to a maximum depth of about 190 cm by 85 days after planting. The rate of penetration was influenced by the mulch during the early part of the season, with the unmulched plants showing greater downward root growth.

12. Greater percentages of the roots were concentrated in the upper parts of the profile during the early part of the season. Mulched plants showed more of this concentration than unmulched plants.

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## ACKNOWLEDGMENTS

I wish to express my sincere thanks to the members of my graduate committee, Drs. H. M. Taylor, L. C. Dumenil, R. B. Pearce and W. D. Shrader, for their kindness in agreeing to serve on this committee. I am particularly grateful to Dr. H. M. Taylor, my major professor, for his guidance throughout the study. The learning experience under him is invaluable.

My thanks also go to Mr. Donald Law, Mr. Gary Grindeland and the staff of the Western Iowa Agricultural Experiment Station for their help during the course of this study.

My appreciation goes to my wife, Nkechi, and my daughter, Chinedu, for their patience and encouragement throughout the duration of the study.

Finally, I wish to express my sincere gratitude to the Agronomy Department at Iowa State University for making this study possible through the assistantship granted to me.

# APPENDIX A

<u>Legend to Treatments</u>

Trt 1 = 0 kg/ha mulch

Trt 2 = 4484 kg/ha mulch

Trt 3 = 8968 kg/ha mulch

Trt 4 = 13452 kg/ha mulch

Trt 5 = 17935 kg/ha mulch

Table 14. Variation of plant height, leaf area index and pod dry weight with time as affected by mulch rates during 1976 and 1977 seasons

| Days after planting | Trt 1 | Trt 2 | Trt 3 | Trt 4 | Trt 5 |
|---|---|---|---|---|---|
| | | | 1976 | | |
| | | | Plant height (cm) | | |
| 45 | 14.0 | 16.3 | 16.1 | 15.6 | 14.3 |
| 52 | 21.8 | 22.0 | 21.0 | 18.5 | 18.4 |
| 58 | 32.3 | 28.7 | 27.0 | 24.0 | 23.1 |
| 65 | 40.8 | 38.7 | 33.3 | 31.4 | 29.4 |
| 72 | 51.0 | 47.4 | 42.6 | 39.5 | 36.5 |
| 79 | 57.4 | 55.7 | 51.5 | 47.5 | 44.1 |
| 86 | 65.3 | 64.2 | 62.3 | 56.0 | 55.2 |
| 93 | 66.1 | 66.0 | 63.3 | 60.5 | 60.2 |
| 98 | 71.8 | 69.6 | 64.4 | 61.1 | 62.2 |
| 108 | 66.0 | 66.0 | 63.5 | 61.7 | 63.9 |
| | | | Leaf area index ($m^2/m^2$) | | |
| 45 | 0.85 | 0.65 | 0.55 | 0.40 | 0.35 |
| 52 | 0.80 | 0.90 | 0.75 | 0.55 | 0.55 |
| 58 | 1.63 | 1.35 | 0.98 | 0.85 | 0.75 |
| 65 | 2.20 | 1.90 | 1.60 | 1.50 | 1.35 |
| 72 | 3.05 | 2.60 | 2.48 | 2.05 | 1.68 |
| 79 | 3.85 | 3.10 | 3.03 | 2.58 | 2.55 |
| 86 | 3.83 | 3.87 | 3.27 | 2.97 | 3.23 |
| 93 | 4.13 | 4.57 | 3.50 | 3.63 | 3.97 |
| 98 | 4.00 | 3.87 | 3.53 | 3.17 | 3.67 |
| 108 | 3.07 | 3.13 | 3.27 | 3.53 | 3.47 |
| | | | Pod dry weight (g) | | |
| 45 | - | - | - | - | - |
| 52 | - | - | - | - | - |
| 58 | -- | - | - | - | - |
| 65 | - | - | - | - | - |
| 72 | - | - | - | - | - |
| 79 | - | - | - | - | - |
| 86 | - | - | - | - | - |
| 93 | 14.6 | 13.1 | 11.2 | 9.5 | 11.0 |
| 98 | 24.8 | 24.6 | 19.7 | 15.1 | 20.0 |
| 108 | 44.1 | 42.1 | 44.2 | 47.5 | 45.3 |

Table 14. (Continued)

| Days after planting | Trt 1 | Trt 2 | Trt 3 | Trt 4 | Trt 5 |
|---|---|---|---|---|---|
| | | | 1977 | | |
| | | | Plant height (cm) | | |
| 45 | 23.3 | 18.3 | 16.5 | 18.8 | 17.5 |
| 37 | 29.0 | 24.5 | 23.3 | 22.3 | 22.5 |
| 46 | 34.0 | 35.5 | 32.8 | 31.8 | 33.3 |
| 52 | 52.8 | 34.8 | 43.8 | 41.8 | 42.8 |
| 59 | 66.3 | 57.0 | 59.0 | 55.5 | 53.0 |
| 65 | 79.8 | 73.8 | 69.8 | 67.8 | 63.7 |
| 73 | 89.0 | 87.0 | 85.5 | 78.0 | n78.0 |
| 79 | 98.8 | 99.3 | 93.8 | 96.3 | 92.3 |
| 87 | 104.0 | 101.7 | 101.3 | 99.3 | 97.0 |
| 93 | 100.7 | 102.3 | 96.3 | 98.3 | 99.3 |
| | | | Leaf area index ($m^2/m^2$) | | |
| 45 | 1.33 | 0.88 | 0.75 | 0.73 | 0.68 |
| 37 | 2.10 | 1.48 | 1.48 | 1.30 | 1.25 |
| 46 | 2.95 | 2.43 | 2.40 | 2.08 | 2.45 |
| 52 | 4.00 | 3.25 | 3.13 | 3.10 | 3.43 |
| 59 | 5.70 | 4.38 | 4.43 | 4.28 | 4.75 |
| 65 | 5.45 | 5.50 | 5.13 | 4.93 | 5.53 |
| 73 | 4.90 | 6.75 | 7.40 | 5.90 | 6.15 |
| 79 | 6.43 | 6.03 | 6.50 | 6.70 | 7.23 |
| 87 | 6.77 | 5.60 | 7.03 | 7.47 | 7.40 |
| 93 | 7.17 | 5.63 | 5.90 | 6.60 | 7.07 |
| | | | Pod dry weight (g) | | |
| 45 | - | - | - | - | - |
| 37 | - | - | - | - | - |
| 46 | - | - | - | - | - |
| 52 | - | - | - | - | - |
| 59 | 0.43 | - | - | - | - |
| 65 | 1.60 | 0.58 | 0.60 | 0.37 | 0.10 |
| 73 | 7.60 | 5.30 | 6.50 | 5.20 | 3.35 |
| 79 | 24.28 | 19.30 | 16.23 | 19.03 | 17.75 |
| 87 | 55.53 | 44.67 | 52.87 | 51.76 | 47.87 |
| 93 | 83.67 | 68.23 | 67.90 | 70.10 | 74.93 |

Table 15. Variation of petiole dry weight, stem dry weight and leaf dry weight with time as affected by mulch rates during 1976 and 1977 seasons

| Days after planting | Trt 1 | Trt 2 | Trt 3 | Trt 4 | Trt 5 |
|---|---|---|---|---|---|
| | | | 1976 | | |
| | | | Petiole dry weight (g) | | |
| 45 | 2.20 | 1.40 | 1.30 | 0.85 | 0.75 |
| 52 | 1.10 | 1.65 | 2.80 | 1.35 | 2.10 |
| 58 | 4.08 | 3.23 | 2.53 | 1.68 | 1.50 |
| 65 | 6.85 | 5.90 | 4.73 | 4.33 | 4.20 |
| 72 | 12.23 | 9.90 | 9.30 | 7.68 | 5.83 |
| 79 | 10.80 | 12.33 | 12.85 | 9.90 | 10.70 |
| 86 | 20.30 | 20.73 | 18.23 | 12.63 | 13.07 |
| 93 | 15.93 | 17.00 | 13.23 | 12.13 | 13.87 |
| 98 | 16.27 | 15.47 | 13.80 | 11.93 | 13.97 |
| 108 | 13.95 | 13.37 | 13.30 | 13.50 | 13.90 |
| | | | Stem dry weight (g) | | |
| 45 | 2.55 | 1.75 | 1.60 | 1.35 | 1.30 |
| 52 | 1.60 | 2.20 | 3.35 | 2.40 | 2.80 |
| 58 | 7.35 | 5.70 | 4.93 | 3.70 | 3.53 |
| 65 | 11.17 | 9.38 | 7.38 | 7.43 | 6.60 |
| 72 | 17.03 | 14.30 | 11.78 | 10.23 | 8.95 |
| 79 | 18.78 | 16.33 | 14.00 | 11.90 | 12.05 |
| 86 | 24.57 | 23.23 | 19.27 | 18.33 | 20.23 |
| 93 | 33.43 | 34.03 | 26.07 | 24.20 | 28.60 |
| 98 | 36.27 | 32.90 | 27.57 | 24.73 | 28.47 |
| 108 | 32.67 | 30.53 | 29.10 | 29.37 | 29.97 |
| | | | Leaf dry weight (g) | | |
| 45 | 8.10 | 6.10 | 4.95 | 4.00 | 3.45 |
| 52 | 3.60 | 6.20 | 9.75 | 6.90 | 7.85 |
| 58 | 17.30 | 13.85 | 12.40 | 8.43 | 5.63 |
| 65 | 22.00 | 19.15 | 15.82 | 16.00 | 11.20 |
| 72 | 36.10 | 37.93 | 25.10 | 20.25 | 16.98 |
| 79 | 35.28 | 31.53 | 32.07 | 26.17 | 24.98 |
| 86 | 43.90 | 41.07 | 35.40 | 31.90 | 33.20 |
| 93 | 47.77 | 49.77 | 39.70 | 37.57 | 43.10 |
| 98 | 49.23 | 45.53 | 40.57 | 35.67 | 41.10 |
| 108 | 37.77 | 38.37 | 38.33 | 41.40 | 37.10 |

Table 15. (Continued)

| Days after planting | Trt 1 | Trt 2 | Trt 3 | Trt 4 | Trt 5 |
|---|---|---|---|---|---|
| | | | 1977 | | |
| | | | Petiole dry weight (g) | | |
| 31 | 2.80 | 1.65 | 1.33 | 1.28 | 1.08 |
| 37 | 4.63 | 3.25 | 3.28 | 2.73 | 2.65 |
| 46 | 8.78 | 6.58 | 6.38 | 5.30 | 6.45 |
| 52 | 13.60 | 10.03 | 9.90 | 9.35 | 10.58 |
| 59 | 19.80 | 15.00 | 15.10 | 13.03 | 15.43 |
| 65 | 20.75 | 20.10 | 19.60 | 17.93 | 20.60 |
| 73 | 24.50 | 24.80 | 29.70 | 25.60 | 25.80 |
| 79 | 27.68 | 25.78 | 39.88 | 27.90 | 29.68 |
| 87 | 34.17 | 32.87 | 33.17 | 35.53 | 36.53 |
| 93 | 36.57 | 28.83 | 30.37 | 32.03 | 33.17 |
| | | | Stem dry weight (g) | | |
| 31 | 3.80 | 2.75 | 2.43 | 2.48 | 2.43 |
| 37 | 7.05 | 5.05 | 4.48 | 4.28 | 4.80 |
| 46 | 14.08 | 9.58 | 10.75 | 9.13 | 11.43 |
| 52 | 23.20 | 16.97 | 16.78 | 16.48 | 18.43 |
| 59 | 36.88 | 24.98 | 27.13 | 25.80 | 28.38 |
| 65 | 39.65 | 36.20 | 34.25 | 32.00 | 35.60 |
| 73 | 50.00 | 46.60 | 53.50 | 41.05 | 45.80 |
| 79 | 62.75 | 56.20 | 54.55 | 57.40 | 60.80 |
| 87 | 80.30 | 73.17 | 77.37 | 78.87 | 47.20 |
| 93 | 84.50 | 65.13 | 67.10 | 71.33 | 73.00 |
| | | | Leaf dry weight (g) | | |
| 31 | 11.93 | 8.10 | 6.75 | 6.68 | 6.00 |
| 37 | 17.63 | 13.03 | 12.35 | 10.95 | 10.93 |
| 46 | 25.80 | 20.50 | 20.85 | 17.98 | 24.63 |
| 52 | 36.53 | 27.53 | 27.73 | 26.83 | 31.10 |
| 59 | 59.45 | 37.08 | 38.50 | 38.33 | 42.95 |
| 65 | 47.25 | 47.30 | 44.05 | 42.13 | 46.87 |
| 73 | 53.00 | 53.65 | 61.95 | 51.15 | 56.50 |
| 79 | 59.85 | 54.60 | 57.65 | 58.18 | 63.10 |
| 87 | 69.80 | 69.67 | 71.83 | 75.83 | 74.30 |
| 93 | 69.83 | 54.70 | 60.87 | 63.63 | 66.97 |

# APPENDIX B

## Legend to Depth

| Depth (no.) | Depth (cm) |
|---|---|
| 1 | 0-7.5 |
| 2 | 7.5-15.0 |
| 3 | 15.0-22.5 |
| 4 | 22.5-30.0 |
| 5 | 30.0-37.5 |
| 6 | 37.5-45.0 |
| 7 | 45.0-52.5 |
| 8 | 52.5-60.0 |
| 9 | 60.0-75.0 |
| 10 | 75.0-90.0 |
| 11 | 90.0-105.0 |
| 12 | 105.0-120.0 |
| 13 | 120.0-135.0 |
| 14 | 135.0-150.0 |
| 15 | 150.0-165.0 |
| 16 | 165.0-180.0 |

Table 16. Percentage distribution of root length density with depth and time as affected by mulch rates during the 1977 season

| Depth (cm) | 31 days after planting | | | 44 days after planting | | | 57 days after planting | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 |
| 1 | 20.60 | 22.56 | 22.08 | 16.40 | 25.85 | 18.02 | 2.66 | 11.77 | 9.67 |
| 2 | 13.60 | 15.71 | 22.61 | 10.26 | 20.62 | 17.36 | 9.12 | 6.61 | 10.93 |
| 3 | 5.20 | 14.68 | 8.30 | 9.22 | 10.48 | 10.82 | 6.46 | 3.95 | 6.85 |
| 4 | 6.25 | 11.15 | 9.85 | 5.93 | 3.47 | 5.72 | 4.17 | 1.92 | 4.31 |
| 5 | 6.56 | 6.00 | 6.82 | 4.51 | 2.98 | 3.74 | 1.79 | 6.59 | 3.34 |
| 6 | 8.36 | 5.38 | 7.60 | 2.97 | 2.48 | 2.53 | 1.51 | 5.38 | 3.39 |
| 7 | 8.79 | 4.28 | 3.03 | 3.22 | 2.27 | 1.95 | 1.67 | 7.07 | 4.79 |
| 8 | 5.32 | 4.19 | 3.79 | 3.39 | 2.20 | 1.81 | 1.89 | 5.18 | 4.43 |
| 9 | 4.39 | 1.49 | 5.27 | 3.12 | 3.44 | 1.28 | 5.49 | 12.53 | 7.47 |
| 10 | 6.71 | 2.45 | 2.18 | 5.15 | 4.38 | 4.14 | 8.16 | 12.36 | 8.67 |
| 11 | 7.82 | 1.38 | 4.17 | 8.35 | 4.84 | 3.96 | 10.14 | 10.71 | 8.66 |
| 12 | - | 3.00 | - | 10.04 | 9.65 | 10.22 | 12.65 | 10.11 | 7.99 |
| 13 | 6.43 | 7.37 | - | 11.79 | 7.33 | 9.84 | 13.50 | 4.36 | 7.58 |
| 14 | - | - | - | - | - | - | 8.93 | - | 7.57 |
| 15 | - | - | - | - | - | - | 7.10 | - | 4.99 |
| 16 | - | - | - | - | - | - | 4.75 | - | - |

Table 16. (Continued)

| Depth (cm) | 71 days after planting | | | 85 days after planting | | | 94 days after planting | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 |
| 1 | 11.81 | 29.70 | 12.44 | 9.44 | 6.85 | 3.54 | 11.46 | 11.04 | 13.07 |
| 2 | 8.50 | 7.42 | 10.27 | 3.30 | 16.70 | 15.00 | 13.56 | 7.60 | 14.81 |
| 3 | 6.64 | 7.19 | 8.73 | 7.04 | 7.77 | 7.27 | 3.45 | 5.70 | 12.44 |
| 4 | 5.11 | 3.83 | 8.08 | 2.06 | 4.13 | 4.68 | 5.55 | 1.93 | 5.79 |
| 5 | 1.50 | 3.62 | 4.81 | 1.46 | 5.33 | 4.43 | 3.17 | 2.98 | 2.90 |
| 6 | 2.21 | 3.41 | 5.32 | 1.93 | 6.07 | 4.07 | 2.40 | 1.42 | 2.87 |
| 7 | 1.75 | 3.57 | 5.51 | 1.87 | 4.58 | 3.57 | 1.31 | 1.27 | 2.63 |
| 8 | 1.46 | 4.53 | 3.27 | 3.19 | 3.06 | 2.27 | 1.61 | 1.22 | 2.64 |
| 9 | 2.77 | 6.86 | 5.92 | 4.98 | 7.18 | 4.84 | 2.84 | 1.67 | 5.25 |
| 10 | 7.07 | 6.45 | 6.65 | 6.92 | 8.13 | 5.01 | 4.05 | 2.19 | 6.66 |
| 11 | 6.25 | 6.50 | 5.75 | 15.09 | 6.64 | 4.92 | 5.94 | 4.07 | 6.81 |
| 12 | 6.74 | 4.46 | 4.52 | 11.49 | 5.59 | 5.31 | 5.17 | 4.73 | 6.37 |
| 13 | 9.35 | 5.60 | 7.66 | 11.99 | 6.21 | 9.89 | 6.78 | 8.95 | 4.51 |
| 14 | 12.89 | 4.00 | 3.81 | 13.60 | 5.35 | 10.68 | 8.06 | 12.06 | 2.61 |
| 15 | 14.02 | - | 2.59 | 8.44 | 2.81 | 9.33 | 8.46 | 11.15 | 4.98 |
| 16 | - | - | 0.82 | 8.41 | - | 4.60 | 11.16 | 19.82 | 2.70 |

Table 17. Percentage distribution of root dry weight with depth as affected by mulch rates

| Depth (cm) | 31 days after planting | | | 44 days after planting | | | 57 days after planting | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 |
| 1 | 50.56 | 28.63 | 36.74 | 33.55 | 32.31 | 36.25 | 7.69 | 29.60 | 16.13 |
| 2 | 15.63 | 26.21 | 23.50 | 17.58 | 23.12 | 21.74 | 10.70 | 7.38 | 11.98 |
| 3 | 3.53 | 12.73 | 9.98 | 9.83 | 9.11 | 7.46 | 7.14 | 3.39 | 6.15 |
| 4 | 3.78 | 8.58 | 8.34 | 4.29 | 2.77 | 3.49 | 4.01 | 1.89 | 3.76 |
| 5 | 3.95 | 3.76 | 4.33 | 4.31 | 2.36 | 2.30 | 2.28 | 4.97 | 3.12 |
| 6 | 5.17 | 2.94 | 4.67 | 1.99 | 2.35 | 1.85 | 2.13 | 3.38 | 3.31 |
| 7 | 4.57 | 1.82 | 1.50 | 1.95 | 1.92 | 1.56 | 1.92 | 4.16 | 4.24 |
| 8 | 3.26 | 2.02 | 1.87 | 1.78 | 1.85 | 1.81 | 2.22 | 3.26 | 3.79 |
| 9 | 2.47 | 1.44 | 2.25 | 1.89 | 2.96 | 1.29 | 5.59 | 8.47 | 6.27 |
| 10 | 3.28 | 1.18 | 2.12 | 2.59 | 3.80 | 2.44 | 8.19 | 8.90 | 7.46 |
| 11 | 3.80 | 1.43 | 1.79 | 4.58 | 4.27 | 2.43 | 9.26 | 8.27 | 7.12 |
| 12 | - | 1.54 | - | 5.01 | 7.32 | 5.79 | 10.73 | 8.21 | 6.98 |
| 13 | 3.58 | 6.97 | - | 6.69 | 5.86 | 5.63 | 10.74 | 3.50 | 7.29 |
| 14 | - | - | - | - | - | - | 7.36 | - | 7.53 |
| 15 | - | - | - | - | - | - | 5.63 | - | 4.83 |
| 16 | - | - | - | - | - | - | 4.05 | - | - |

Table 17. (Continued)

| Depth (cm) | 71 days after planting | | | 85 days after planting | | | 94 days after planting | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 |
| 1 | 11.53 | 37.87 | 26.98 | 14.28 | 17.58 | 14.62 | 15.77 | 17.64 | 14.84 |
| 2 | 20.22 | 11.80 | 14.60 | 4.29 | 20.85 | 19.19 | 20.63 | 16.46 | 25.56 |
| 3 | 6.49 | 6.31 | 9.23 | 9.13 | 7.50 | 8.25 | 11.68 | 5.92 | 11.80 |
| 4 | 3.64 | 3.23 | 6.55 | 2.61 | 3.44 | 4.67 | 5.58 | 3.50 | 5.18 |
| 5 | 1.11 | 3.01 | 3.79 | 1.73 | 4.35 | 4.12 | 2.80 | 2.74 | 2.83 |
| 6 | 1.55 | 2.58 | 3.54 | 2.35 | 4.72 | 3.41 | 1.80 | 1.85 | 2.54 |
| 7 | 1.42 | 2.51 | 3.71 | 2.30 | 3.37 | 3.13 | 1.27 | 1.63 | 2.40 |
| 8 | 1.21 | 4.18 | 2.48 | 3.08 | 2.70 | 2.26 | 1.81 | 1.60 | 2.12 |
| 9 | 3.59 | 5.02 | 4.07 | 5.24 | 5.13 | 4.31 | 3.22 | 3.16 | 4.30 |
| 10 | 5.52 | 5.60 | 4.37 | 6.59 | 5.88 | 4.47 | 4.58 | 3.49 | 5.64 |
| 11 | 6.87 | 5.02 | 3.63 | 8.66 | 5.03 | 4.16 | 4.80 | 5.30 | 5.47 |
| 12 | 7.12 | 3.80 | 3.25 | 6.69 | 4.87 | 4.24 | 4.41 | 5.50 | 4.58 |
| 13 | 7.93 | 4.26 | 4.50 | 5.41 | 4.88 | 7.03 | 5.55 | 7.76 | 3.64 |
| 14 | 10.07 | 2.97 | 2.52 | 10.60 | 4.27 | 7.24 | 5.06 | 2.78 | 2.10 |
| 15 | 9.73 | - | 2.14 | 10.02 | 1.87 | 6.09 | 4.93 | 7.69 | 3.00 |
| 16 | - | - | 0.61 | 7.01 | - | 2.82 | 6.05 | 11.16 | 1.77 |

# APPENDIX C

## Legend to Depth

| Depth (no.) | Depth (cm) |
|---|---|
| 1 | 0-7.5 |
| 2 | 7.5-15.0 |
| 3 | 15.0-22.5 |
| 4 | 22.5-30.0 |
| 5 | 30.0-37.5 |
| 6 | 37.5-45.0 |
| 7 | 45.0-52.5 |
| 8 | 52.5-60.0 |
| 9 | 60.0-75.0 |
| 10 | 75.0-90.0 |
| 11 | 90.0-105.0 |
| 12 | 105.0-120.0 |
| 13 | 120.0-135.0 |
| 14 | 135.0-150.0 |
| 15 | 150.0-165.0 |
| 16 | 165.0-180.0 |

Table 18. Distribution of root length density with depth as affected by mulch rates during 1977 season

| Depth Depth (cm) | 31 days after planting ($cm/cm^3$) | | | 44 days after planting ($cm/cm^3$) | | | 57 days after planting ($cm/cm^3$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 |
| 1 | 0.109 | 0.096 | 0.111 | 0.200 | 0.504 | 0.226 | 0.126 | 0.440 | 0.551 |
| 2 | 0.072 | 0.067 | 0.114 | 0.125 | 0.405 | 0.218 | 0.432 | 0.251 | 0.623 |
| 3 | 0.027 | 0.062 | 0.042 | 0.112 | 0.206 | 0.136 | 0.306 | 0.148 | 0.351 |
| 4 | 0.032 | 0.047 | 0.050 | 0.072 | 0.069 | 0.072 | 0.197 | 0.072 | 0.245 |
| 5 | 0.034 | 0.026 | 0.034 | 0.055 | 0.059 | 0.047 | 0.085 | 0.247 | 0.197 |
| 6 | 0.044 | 0.023 | 0.038 | 0.036 | 0.049 | 0.032 | 0.072 | 0.202 | 0.194 |
| 7 | 0.046 | 0.018 | 0.015 | 0.039 | 0.045 | 0.024 | 0.079 | 0.263 | 0.273 |
| 8 | 0.027 | 0.018 | 0.019 | 0.041 | 0.043 | 0.023 | 0.090 | 0.194 | 0.252 |
| 9 | 0.011 | 0.003 | 0.013 | 0.019 | 0.034 | 0.008 | 0.130 | 0.235 | 0.213 |
| 10 | 0.018 | 0.005 | 0.005 | 0.031 | 0.043 | 0.026 | 0.194 | 0.232 | 0.247 |
| 11 | 0.021 | 0.003 | 0.011 | 0.051 | 0.047 | 0.025 | 0.240 | 0.191 | 0.247 |
| 12 | - | 0.006 | 0.011 | 0.061 | 0.094 | 0.064 | 0.299 | 0.189 | 0.228 |
| 13 | 0.017 | 0.016 | - | 0.072 | 0.072 | 0.062 | 0.330 | 0.082 | 0.216 |
| 14 | - | - | - | - | - | - | 0.211 | 0.746 | 0.216 |
| 15 | - | - | - | - | - | - | 0.113 | - | - |
| 16 | - | - | - | - | - | - | 0.113 | - | - |

Table 18. (Continued)

| Depth (cm) | 71 days after planting ($cm/cm^3$) | | | 85 days after planting ($cm/cm^3$) | | | 94 days after planting ($cm/cm^3$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 |
| 1 | 0.423 | 0.986 | 0.471 | 0.634 | 0.231 | 0.195 | 0.373 | 0.457 | 0.562 |
| 2 | 0.305 | 0.246 | 0.389 | 0.222 | 0.562 | 0.825 | 0.442 | 0.313 | 0.636 |
| 3 | 0.238 | 0.239 | 0.331 | 0.472 | 0.262 | 0.400 | 0.276 | 0.234 | 0.534 |
| 4 | 0.183 | 0.127 | 0.305 | 0.139 | 0.139 | 0.258 | 0.181 | 0.080 | 0.249 |
| 5 | 0.053 | 0.120 | 0.182 | 0.098 | 0.180 | 0.244 | 0.104 | 0.123 | 0.124 |
| 6 | 0.079 | 0.114 | 0.201 | 0.130 | 0.204 | 0.224 | 0.078 | 0.059 | 0.123 |
| 7 | 0.062 | 0.118 | 0.209 | 0.125 | 0.154 | 0.197 | 0.043 | 0.053 | 0.113 |
| 8 | 0.049 | 0.150 | 0.124 | 0.214 | 0.102 | 0.125 | 0.053 | 0.050 | 0.114 |
| 9 | 0.050 | 0.075 | 0.112 | 0.167 | 0.120 | 0.133 | 0.046 | 0.034 | 0.113 |
| 10 | 0.126 | 0.114 | 0.126 | 0.232 | 0.137 | 0.138 | 0.066 | 0.046 | 0.143 |
| 11 | 0.112 | 0.107 | 0.109 | 0.507 | 0.112 | 0.136 | 0.097 | 0.085 | 0.146 |
| 12 | 0.121 | 0.108 | 0.085 | 0.386 | 0.094 | 0.146 | 0.084 | 0.100 | 0.137 |
| 13 | 0.168 | 0.074 | 0.145 | 0.373 | 0.004 | 0.272 | 0.110 | 0.185 | 0.097 |
| 14 | 0.231 | 0.093 | 0.073 | 0.456 | 0.090 | 0.293 | 0.131 | 0.250 | 0.056 |
| 15 | 0.251 | 0.066 | 0.049 | 0.283 | 0.047 | 0.257 | 0.138 | 0.231 | 0.107 |
| 16 | - | - | 0.015 | 0.283 | - | 0.126 | 0.182 | 0.410 | 0.058 |

Table 19. Distribution of root mass density with depth as affected by mulch rates during the 1977 season

| Depth (cm) | 31 days after planting ($g/cm^3 x 10^{-4}$) | | | 44 days after planting ($g/cm^3 x 10^{-4}$) | | | 57 days after planting ($g/cm^3 x 10^{-4}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 |
| 1 | 0.411 | 0.143 | 0.221 | 0.680 | 0.877 | 0.753 | 0.594 | 1.617 | 1.176 |
| 2 | 0.126 | 0.131 | 0.142 | 0.357 | 0.627 | 0.451 | 0.827 | 0.403 | 0.873 |
| 3 | 0.029 | 0.064 | 0.060 | 0.200 | 0.247 | 0.155 | 0.552 | 0.185 | 0.449 |
| 4 | 0.030 | 0.043 | 0.050 | 0.087 | 0.075 | 0.072 | 0.310 | 0.104 | 0.274 |
| 5 | 0.032 | 0.019 | 0.026 | 0.088 | 0.064 | 0.048 | 0.176 | 0.271 | 0.228 |
| 6 | 0.042 | 0.014 | 0.028 | 0.040 | 0.064 | 0.048 | 0.176 | 0.271 | 0.228 |
| 7 | 0.037 | 0.009 | 0.009 | 0.040 | 0.052 | 0.033 | 0.149 | 0.228 | 0.309 |
| 8 | 0.027 | 0.010 | 0.034 | 0.036 | 0.050 | 0.037 | 0.171 | 0.178 | 0.277 |
| 9 | 0.010 | 0.004 | 0.007 | 0.019 | 0.040 | 0.014 | 0.216 | 0.232 | 0.229 |
| 10 | 0.013 | 0.003 | 0.006 | 0.027 | 0.052 | 0.025 | 0.317 | 0.243 | 0.272 |
| 11 | 0.015 | 0.004 | 0.005 | 0.046 | 0.058 | 0.025 | 0.357 | 0.225 | 0.259 |
| 12 | - | 0.004 | - | 0.051 | 0.099 | 0.660 | 0.415 | 0.224 | 0.255 |
| 13 | 0.014 | 0.018 | - | 0.068 | 0.079 | 0.059 | 0.415 | 0.096 | 0.266 |
| 14 | - | - | - | - | - | - | 0.284 | - | 0.274 |
| 15 | - | - | - | - | - | - | 0.217 | - | 0.176 |
| 16 | - | - | - | - | - | - | 0.156 | - | - |

Table 19. (Continued)

| Depth (cm) | 71 days after planting ($g/cm^3 x 10^{-4}$) | | | 85 days after planting ($g/cm^3 x 10^{-4}$) | | | 94 days after planting ($g/cm^3 x 10^{-4}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 | Trt 1 | Trt 3 | Trt 5 |
| 1 | 0.656 | 1.696 | 1.511 | 1.440 | 1.026 | 1.038 | 0.866 | 0.910 | 0.909 |
| 2 | 1.151 | 0.529 | 0.818 | 0.433 | 1.218 | 1.362 | 1.133 | 0.849 | 1.566 |
| 3 | 0.370 | 0.283 | 0.517 | 0.920 | 0.438 | 0.586 | 0.642 | 0.305 | 0.723 |
| 4 | 0.207 | 0.145 | 0.367 | 0.263 | 0.201 | 0.331 | 0.306 | 0.181 | 0.318 |
| 5 | 0.063 | 0.135 | 0.213 | 0.174 | 0.254 | 0.293 | 0.153 | 0.142 | 0.074 |
| 6 | 0.088 | 0.115 | 0.198 | 0.237 | 0.276 | 0.242 | 0.099 | 0.095 | 0.155 |
| 7 | 0.081 | 0.112 | 0.207 | 0.232 | 0.197 | 0.223 | 0.070 | 0.041 | 0.147 |
| 8 | 0.069 | 0.187 | 0.139 | 0.311 | 0.158 | 0.160 | 0.102 | 0.082 | 0.130 |
| 9 | 0.102 | 0.113 | 0.114 | 0.264 | 0.150 | 0.153 | 0.088 | 0.082 | 0.132 |
| 10 | 0.156 | 0.126 | 0.122 | 0.332 | 0.171 | 0.158 | 0.126 | 0.090 | 0.173 |
| 11 | 0.195 | 0.113 | 0.101 | 0.437 | 0.147 | 0.148 | 0.132 | 0.136 | 0.168 |
| 12 | 0.202 | 0.085 | 0.091 | 0.338 | 0.142 | 0.151 | 0.121 | 0.144 | 0.140 |
| 13 | 0.226 | 0.095 | 0.157 | 0.273 | 0.142 | 0.250 | 0.152 | 0.200 | 0.111 |
| 14 | 0.287 | 0.066 | 0.071 | 0.535 | 0.124 | 0.257 | 0.139 | 0.072 | 0.064 |
| 15 | 0.277 | - | 0.059 | 0.505 | 0.055 | 0.216 | 0.136 | 0.198 | 0.091 |
| 16 | - | - | 0.018 | 0.354 | - | 0.101 | 0.166 | 0.288 | 0.054 |

# APPENDIX D

## Legend to Depth

| Depth (no.) | Depth (cm) |
|---|---|
| 1 | 0-15 |
| 2 | 15-30 |
| 3 | 30-60 |
| 4 | 60-90 |
| 5 | 90-120 |
| 6 | 120-150 |
| 7 | 150-180 |

Table 20. Distribution of volumetric soil water content with depth and time as affected by mulch rates during the 1976 season

| | Trt 1 | | Trt 2 | | Trt 3 | | Trt 4 | | Trt 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth | Within row | Bet. row | Within row | Bet. row | Within row | Bet. row | Within row | Bet. row | Within row | Bet. row |
| | | | | | 26 days after planting | | | | | |
| 1 | 0.21 | 0.22 | 0.20 | 0.22 | 0.23 | 0.23 | 0.26 | 0.24 | 0.26 | 0.27 |
| 2 | 0.23 | 0.23 | 0.24 | 0.24 | 0.25 | 0.26 | 0.25 | 0.25 | 0.26 | 0.26 |
| 3 | 0.21 | 0.22 | 0.22 | 0.22 | 0.23 | 0.23 | 0.22 | 0.23 | 0.23 | 0.23 |
| 4 | 0.22 | 0.21 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.24 |
| 5 | 0.21 | 0.22 | 0.24 | 0.23 | 0.24 | 0.23 | 0.23 | 0.27 | 0.24 | 0.23 |
| 6 | 0.18 | 0.19 | 0.23 | 0.24 | 0.24 | 0.23 | 0.24 | 0.22 | 0.24 | 0.24 |
| 7 | 0.18 | 0.18 | 0.20 | 0.20 | 0.21 | 0.22 | 0.21 | 0.18 | 0.23 | 0.22 |
| | | | | | 41 days after planting | | | | | |
| 1 | 0.13 | 0.17 | 0.15 | 0.18 | 0.16 | 0.21 | 0.17 | 0.22 | 0.16 | 0.24 |
| 2 | 0.16 | 0.22 | 0.19 | 0.21 | 0.21 | 0.24 | 0.22 | 0.23 | 0.21 | 0.25 |
| 3 | 0.16 | 0.19 | 0.18 | 0.20 | 0.20 | 0.21 | 0.21 | 0.21 | 0.20 | 0.21 |
| 4 | 0.20 | 0.20 | 0.21 | 0.21 | 0.21 | 0.21 | 0.22 | 0.22 | 0.21 | 0.22 |
| 5 | 0.21 | 0.21 | 0.23 | 0.21 | 0.22 | 0.22 | 0.22 | 0.23 | 0.22 | 0.24 |
| 6 | 0.20 | 0.21 | 0.22 | 0.21 | 0.24 | 0.23 | 0.23 | 0.22 | 0.22 | 0.24 |
| 7 | 0.19 | 0.21 | 0.22 | 0.21 | 0.22 | 0.22 | 0.20 | 0.21 | 0.21 | 0.23 |
| | | | | | 55 days after planting | | | | | |
| 1 | 0.13 | 0.15 | 0.14 | 0.15 | 0.14 | 0.19 | 0.15 | 0.20 | 0.16 | 0.21 |
| 2 | 0.13 | 0.20 | 0.14 | 0.17 | 0.17 | 0.21 | 0.17 | 0.20 | 0.18 | 0.23 |
| 3 | 0.12 | 0.15 | 0.15 | 0.16 | 0.15 | 0.19 | 0.16 | 0.18 | 0.18 | 0.21 |
| 4 | 0.14 | 0.17 | 0.17 | 0.21 | 0.17 | 0.20 | 0.19 | 0.20 | 0.21 | 0.20 |
| 5 | 0.18 | 0.19 | 0.21 | 0.20 | 0.21 | 0.21 | 0.20 | 0.22 | 0.22 | 0.22 |
| 6 | 0.19 | 0.20 | 0.21 | 0.21 | 0.22 | 0.22 | 0.23 | 0.22 | 0.22 | 0.22 |
| 7 | 0.20 | 0.19 | 0.20 | 0.19 | 0.21 | 0.21 | 0.21 | 0.21 | 0.23 | 0.19 |

Table 20. (Continued)

| Depth | Trt 1 Within row | Trt 1 Bet. row | Trt 2 Within row | Trt 2 Bet. row | Trt 3 Within row | Trt 3 Bet. row | Trt 4 Within row | Trt 4 Bet. row | Trt 5 Within row | Trt 5 Bet. row |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 70 days after planting | | | | | |
| 1 | 0.11 | 0.11 | 0.11 | 0.13 | 0.12 | 0.15 | 0.12 | 0.16 | 0.14 | 0.17 |
| 2 | 0.12 | 0.13 | 0.12 | 0.14 | 0.14 | 0.17 | 0.13 | 0.16 | 0.15 | 0.17 |
| 3 | 0.11 | 0.12 | 0.12 | 0.12 | 0.12 | 0.15 | 0.12 | 0.14 | 0.13 | 0.16 |
| 4 | 0.12 | 0.12 | 0.12 | 0.14 | 0.12 | 0.16 | 0.12 | 0.17 | 0.15 | 0.18 |
| 5 | 0.13 | 0.16 | 0.13 | 0.17 | 0.16 | 0.18 | 0.15 | 0.19 | 0.19 | 0.20 |
| 6 | 0.17 | 0.18 | 0.17 | 0.20 | 0.21 | 0.21 | 0.20 | 0.22 | 0.21 | 0.21 |
| 7 | 0.17 | 0.19 | 0.20 | 0.20 | 0.21 | 0.21 | 0.20 | 0.21 | 0.21 | 0.22 |
| | | | | | 82 days after planting | | | | | |
| 1 | 0.11 | 0.10 | 0.11 | 0.13 | 0.12 | 0.14 | 0.11 | 0.13 | 0.13 | 0.14 |
| 2 | 0.11 | 0.11 | 0.11 | 0.11 | 0.12 | 0.13 | 0.11 | 0.12 | 0.12 | 0.14 |
| 3 | 0.10 | 0.11 | 0.10 | 0.10 | 0.11 | 0.12 | 0.11 | 0.11 | 0.11 | 0.13 |
| 4 | 0.11 | 0.11 | 0.10 | 0.11 | 0.10 | 0.11 | 0.11 | 0.11 | 0.11 | 0.13 |
| 5 | 0.11 | 0.11 | 0.11 | 0.11 | 0.12 | 0.14 | 0.13 | 0.14 | 0.13 | 0.15 |
| 6 | 0.13 | 0.15 | 0.15 | 0.17 | 0.17 | 0.18 | 0.17 | 0.19 | 0.17 | 0.19 |
| 7 | 0.13 | 0.17 | 0.17 | 0.18 | 0.18 | 0.19 | 0.18 | 0.18 | 0.20 | 0.21 |
| | | | | | 97 days after planting | | | | | |
| 1 | 0.12 | 0.11 | 0.12 | 0.13 | 0.12 | 0.13 | 0.13 | 0.14 | 0.14 | 0.15 |
| 2 | 0.12 | 0.11 | 0.12 | 0.11 | 0.12 | 0.12 | 0.11 | 0.12 | 0.12 | 0.16 |
| 3 | 0.11 | 0.10 | 0.10 | 0.10 | 0.11 | 0.11 | 0.11 | 0.10 | 0.12 | 0.11 |
| 4 | 0.10 | 0.11 | 0.10 | 0.10 | 0.11 | 0.10 | 0.11 | 0.10 | 0.12 | 0.12 |
| 5 | 0.10 | 0.10 | 0.11 | 0.11 | 0.11 | 0.10 | 0.11 | 0.11 | 0.14 | 0.12 |
| 6 | 0.11 | 0.11 | 0.12 | 0.12 | 0.11 | 0.12 | 0.14 | 0.15 | 0.15 | 0.15 |
| 7 | 0.13 | 0.13 | 0.15 | 0.15 | 0.14 | 0.15 | 0.16 | 0.15 | 0.19 | 0.20 |

Table 21. Distribution of volumetric soil water content with depth and time as affected by mulch rates during the 1977 season

| Depth | Trt 1 | | Trt 2 | | Trt 3 | | Trt 4 | | Trt 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Within row | Bet. row | Within row | Bet. row | Within row | Bet. row | Within row | Bet. row | Within row | Bet. row |
| | | | | | 8 days after planting | | | | | |
| 1 | 0.25 | 0.25 | 0.27 | 0.27 | 0.27 | 0.27 | 0.28 | 0.29 | 0.28 | 0.29 |
| 2 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.27 | 0.27 | 0.28 | 0.27 | 0.27 |
| 3 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.25 | 0.24 | 0.24 | 0.24 | 0.24 |
| 4 | 0.23 | 0.24 | 0.25 | 0.25 | 0.24 | 0.24 | 0.25 | 0.24 | 0.27 | 0.24 |
| 5 | 0.24 | 0.25 | 0.26 | 0.26 | 0.27 | 0.27 | 0.26 | 0.26 | 0.28 | 0.26 |
| 6 | 0.27 | 0.26 | 0.26 | 0.26 | 0.28 | 0.28 | 0.28 | 0.28 | 0.26 | 0.27 |
| 7 | 0.25 | 0.24 | 0.25 | 0.26 | 0.27 | 0.28 | 0.27 | 0.27 | 0.26 | 0.25 |
| | | | | | 21 days after planting | | | | | |
| 1 | 0.22 | 0.24 | 0.25 | 0.26 | 0.29 | 0.29 | 0.30 | 0.30 | 0.31 | 0.32 |
| 2 | 0.22 | 0.23 | 0.23 | 0.24 | 0.25 | 0.25 | 0.25 | 0.25 | 0.26 | 0.26 |
| 3 | 0.20 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.22 | 0.22 | 0.22 | 0.22 |
| 4 | 0.21 | 0.21 | 0.23 | 0.23 | 0.22 | 0.23 | 0.23 | 0.22 | 0.24 | 0.22 |
| 5 | 0.21 | 0.23 | 0.25 | 0.24 | 0.24 | 0.25 | 0.24 | 0.24 | 0.26 | 0.25 |
| 6 | 0.25 | 0.25 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.27 | 0.26 | 0.26 |
| 7 | 0.24 | 0.24 | 0.26 | 0.26 | 0.25 | 0.25 | 0.27 | 0.27 | 0.24 | 0.25 |
| | | | | | 35 days after planting | | | | | |
| 1 | 0.19 | 0.23 | 0.20 | 0.22 | 0.21 | 0.26 | 0.22 | 0.25 | 0.21 | 0.25 |
| 2 | 0.19 | 0.23 | 0.15 | 0.23 | 0.23 | 0.24 | 0.24 | 0.25 | 0.22 | 0.24 |
| 3 | 0.18 | 0.20 | 0.20 | 0.20 | 0.21 | 0.22 | 0.21 | 0.22 | 0.21 | 0.22 |
| 4 | 0.22 | 0.21 | 0.21 | 0.21 | 0.23 | 0.23 | 0.22 | 0.22 | 0.23 | 0.23 |
| 5 | 0.23 | 0.23 | 0.21 | 0.22 | 0.26 | 0.25 | 0.23 | 0.23 | 0.25 | 0.25 |
| 6 | 0.26 | 0.26 | 0.24 | 0.25 | 0.25 | 0.27 | 0.25 | 0.26 | 0.26 | 0.27 |
| 7 | 0.24 | 0.25 | 0.24 | 0.24 | 0.25 | 0.26 | 0.26 | 0.25 | 0.25 | 0.25 |

Table 21. (Continued)

| Depth | Trt 1 Within row | Trt 1 Bet. row | Trt 2 Within row | Trt 2 Bet. row | Trt 3 Within row | Trt 3 Bet. row | Trt 4 Within row | Trt 4 Bet. row | Trt 5 Within row | Trt 5 Bet. row |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 49 days after planting | | | | | |
| 1 | 0.21 | 0.21 | 0.22 | 0.21 | 0.22 | 0.21 | 0.20 | 0.21 | 0.25 | 0.22 |
| 2 | 0.15 | 0.14 | 0.16 | 0.16 | 0.17 | 0.16 | 0.15 | 0.17 | 0.19 | 0.20 |
| 3 | 0.14 | 0.15 | 0.16 | 0.17 | 0.17 | 0.17 | 0.18 | 0.17 | 0.18 | 0.21 |
| 4 | 0.15 | 0.16 | 0.19 | 0.19 | 0.19 | 0.20 | 0.19 | 0.19 | 0.21 | 0.21 |
| 5 | 0.21 | 0.21 | 0.22 | 0.23 | 0.23 | 0.24 | 0.23 | 0.23 | 0.24 | 0.25 |
| 6 | 0.22 | 0.22 | 0.24 | 0.24 | 0.23 | 0.24 | 0.23 | 0.24 | 0.24 | 0.24 |
| 7 | 0.22 | 0.21 | 0.24 | 0.23 | 0.24 | 0.24 | 0.26 | 0.24 | 0.26 | 0.25 |
| | | | | | 62 days after planting | | | | | |
| 1 | 0.29 | 0.26 | 0.29 | 0.28 | 0.30 | 0.29 | 0.30 | 0.29 | 0.31 | 0.31 |
| 2 | 0.18 | 0.16 | 0.24 | 0.18 | 0.25 | 0.22 | 0.26 | 0.22 | 0.28 | 0.25 |
| 3 | 0.13 | 0.13 | 0.17 | 0.16 | 0.17 | 0.15 | 0.17 | 0.15 | 0.22 | 0.23 |
| 4 | 0.13 | 0.13 | 0.17 | 0.o7 | 0.16 | 0.17 | 0.17 | 0.16 | 0.21 | 0.21 |
| 5 | 0.14 | 0.15 | 0.19 | 0.21 | 0.19 | 0.20 | 0.22 | 0.21 | 0.22 | 0.22 |
| 6 | 0.20 | 0.20 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.24 | 0.24 |
| 7 | 0.21 | 0.21 | 0.25 | 0.24 | 0.23 | 0.23 | 0.24 | 0.24 | 0.23 | 0.23 |
| | | | | | 77 days after planting | | | | | |
| L | 0.26 | 0.25 | 0.26 | 0.28 | 0.31 | 0.30 | 0.30 | 0.27 | 0.27 | 0.31 |
| 2 | 0.17 | 0.18 | 0.24 | 0.17 | 0.22 | 0.19 | 0.22 | 0.16 | 0.24 | 0.19 |
| 3 | 0.13 | 0.13 | 0.17 | 0.17 | 0.15 | 0.16 | 0.15 | 0.14 | 0.20 | 0.16 |
| 4 | 0.13 | 0.12 | 0.16 | 0.19 | 0.15 | 0.16 | 0.14 | 0.13 | 0.18 | 0.15 |
| 5 | 0.12 | 0.13 | 0.16 | 0.19 | 0.16 | 0.19 | 0.15 | 0.14 | 0.20 | 0.17 |
| 6 | 0.15 | 0.15 | 0.20 | 0.21 | 0.20 | 0.22 | 0.21 | 0.20 | 0.23 | 0.22 |
| 7 | 0.19 | 0.18 | 0.22 | 0.23 | 0.21 | 0.22 | 0.21 | 0.22 | 0.21 | 0.22 |