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CONSERVATION TILLAGE EFFECTS ON SOIL PROPERTIES AND CORN YIELDS IN CENTRAL MICHIGAN

By

Michael James Staton

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ABSTRACT

CONSERVATION TILLAGE EFFECTS ON SOIL PROPERTIES
AND CORN YIELDS IN CENTRAL MICHIGAN

By

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No-tillage alters soil properties, sometimes inhibiting crop growth. The effects of plowing on no-tillage soil properties were evaluated. No-tillage plots were plowed after five and six years.

Plowing improved the physical and chemical condition of the no-till soil. Bulk density was decreased, while porosity and saturated hydraulic conductivity were increased. Acidic and high nutrient layers were mixed throughout the plow layer.

Zone tillage is increasing in Michigan. The effects of zone tillage on soil physical properties and corn yields were evaluated. Plots were subsoiled in the row and then planted as no-tillage for one and two years with controlled traffic to determine any residual tillage effects.

Zone tillage improved soil physical properties but not corn yields. Bulk density and soil strength were reduced while porosity and saturated hydraulic conductivity increased. The bulk density and total porosity effects of zone tillage persisted for two years.

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INTRODUCTION

No-tillage corn production has been increasing in the United States in recent years. No-tillage planting systems involve chemical weed control and planters which can place seed directly into an untilled soil. This system is well suited for soils that have no physical limitations to crop growth. Soane and Pidgeon (1975) state that when soil physical properties are not limiting to crop growth, tillage is required for seed placement only.

Soil physical and chemical properties are known to change under no-tillage. No-till has been shown to increase soil bulk density (Gantzer and Blake, 1978), increase soil strength (Van Ouwerkerk and Boone, 1970; and Hill et al., 1985a), and alter the soil's pore size distribution (Van Ouwerkerk and Boone, 1970; and Hill et al., 1985b). Acidic surface layers develop (Shear and Moschler, 1969; Blevins et al., 1977; and Dick, 1983) and nutrients become stratified (Triplett and Van Doren, 1969; Shear and Moschler, 1969; Fink and Wesley, 1974; Juo and Lal, 1979; and Hargrove, 1985) under no-tillage. These soil properties can inhibit crop production. Periodic plowing has been implemented to alleviate some of these undesirable soil properties of no-till.

Soil compaction is a widespread phenomenon in the United States (Voorhees, 1977a). Cohron (1971) states that vehicle traffic is the largest single source of compaction in agricultural soils. Compaction from agricultural vehicles can extend down to 30 cm (Voorhees, 1978).

Soil compaction at depth can increase soil strength, decrease air-filled porosity (Grable, 1971), and restrict water flow (Warkinten, 1971). Russell and Goss (1974) showed that soil strengths of 20 kPa caused barley root elongation to be reduced by 50 percent. Vomocil and Flocker (1961) stated that when air-filled porosity falls below 10 percent, no gas exchange occurs between the soil and the atmosphere. Soil compaction can reduce soil-water recharge which can cause moisture stress to occur when rainfall is limiting.

Subsoiling has been shown to alleviate soil compaction below the normal depth of plowing (Campbell et al., 1974). Zone tillage (under-the-row subsoiling) is used extensively on the coastal plain soils and is increasing in Michigan.

Normally, subsoiling should be performed when the soil is dry in order to achieve the maximum loosening (Spoor and Godwin, 1978). This condition rarely occurs in Michigan. Zone tillage is a costly operation and doesn't always increase yields.

The objectives of this study were to: 1) quantify changes in soil physical and chemical properties when no-till soils are periodically plowed; 2) determine the impact of wheel traffic on soil physical properties of no-tillage and conventional tillage; 3) determine the plant responses to the soil physical and chemical changes which occur following plowing; 4) determine if satisfactory soil loosening can be achieved by spring subsoiling operations; 5) determine if the loosened zone created by subsoiling will persist for one or two years after the initial subsoiling operation was performed; and 6) measure the effects of zone tillage on corn production and yields.

Chapter 1

LITERATURE REVIEW

Soil physical and chemical properties affect crop growth and yield. These soil properties can be manipulated by tillage to create a more favorable growing environment. Soil properties and how tillage can improve them to favor plant growth will be the subjects of this review.

Soil Compaction

Definition

Soil compaction is defined as the compression of an unsaturated soil which results in a reduction of the air-filled volume (Hillel, 1982). This phenomenon is so widespread in American agriculture that it can be considered a natural resource (Voorhees, 1977a). This review will discuss the causes and effects of compaction on soil properties and plant growth as well as its alleviation.

Causes

The forces which cause compaction can be divided into two catagories: internal and external (Cohron, 1971). Internal forces can be thought of as natural forces which occur within the soil. External forces are those which are applied externally to the soil. This review will concentrate on the external forces.

Three external forces are responsible for the compaction of agricultural soils: raindrop impact, vehicle traffic, and tillage operations. Each of these forces creates a distinct compact layer in the soil (Warkentin, 1971).

Raindrop impact applies a compressional force directly on the soil surface. This force causes aggregates to break down into their primary particles. These particles are rearranged and packed so that fine particles fill in the voids between larger particles. When the soil dries, it forms a surface crust.

Vehicle traffic is by far the largest single source of compressional forces in agricultural soils (Cohron, 1971). Soane et al. (1975) reported that 90 percent of the soil surface is compacted by wheel traffic during the preparation of a conventional seed bed for a cereal crop. Soil compaction from wheel traffic extends deeper into the soil profile than the surface crusting caused by raindrop impact. Voorhees (1978) found that wheel traffic compaction extended down to a depth of 30 cm in a Minnesota soil.

Tillage implements compress the soil as they pass through. The primary areas of compression occur just ahead of the tool and below the tool. Just as in the case of traffic-induced compaction, tilling the soil when it is too wet increases the severity of the compaction. Even subsoiling operations which are aimed at loosening a compacted layer can cause further compaction if the critical depth of the tool is exceeded or if conditions are too wet (Spoor and Godwin, 1978).

Compaction Effects on Soil Properties

Compaction reduces the total porosity of a soil (Voorhees, 1977a) and alters the size distribution of the pores in the soil (Warkentin, 1971). Hillel (1982) stated that the volume of soil occupied by large pores is reduced while the volume of small pores is increased by compaction. Russell (1973), as cited by Cannell and Jackson (1981), found that pores smaller than 60-30 um will remain filled with water at the soil's field capacity. It is pores of this size and smaller which predominate in a compacted soil. This alteration of the pore size distribution alters the soil's hydraulic, aeration, and strength properties.

Water is retained in the soil at field capacity by capillary and adsorptive forces exerted by the soil matrix. These combined forces make up the matric potential of the soil water. Capillarity is due to the water's surface tension and its contact angle with the solid particles (Hillel, 1982). This force is most important when matric suctions are less than one bar and adsorptive forces predominate when matric suctions exceed one bar (Hillel, 1982). In the capillary rise equation, the matric suction and the radius of pores which will retain water against this suction are related. This is an inverse relationship -- as suction increases, the pore radius decreases. Based on this equation, a compacted soil will retain less water at low matric suctions and more water at high matric suctions.

Compaction in the form of a surface crust will inhibit infiltration of surface water into the soil. A compacted soil layer at depth will restrict internal drainage of the overlying layers. These two conditions affect water transmission throughout the soil differently. Warkentin (1971) proposed the following theoretical explanations of how the location of the impermeable layer in the profile affects continuous water flow. When a compacted layer exists below a permeable layer, saturated flow will occur throughout the profile. When a surface crust forms over a more permeable layer, unsaturated flow can occur in the transition zone between the two layers. Warkentin (1971) stated that compaction reduces air-filled porosity and vapor movement.

Gaseous exchange between the soil and the atmosphere (aeration) occurs primarily in the air-filled pores (Grable, 1971). This process is accomplished primarily by diffusion. Diffusion is driven by partial pressure gradients. At an air-filled porosity of about 10 percent, this partial pressure gradient has been shown to be zero (Vomocil and Flocker, 1961). When the partial pressure gradient is zero, no gas exchange occurs between the soil and the atmosphere.

Vomocil and Flocker (1961) and Voorhees (1977a) state that compacting a soil leads to a larger volume of the soil comprised of small pores. These pores retain water at field capacity and restrict the diffusion of gases (Grable, 1971). Therefore, compaction inhibits aeration of the soil because of the altered pore size distribution of the compacted soil.

Chancellor (1971) defines soil strength as a measure of the resistance which must be exceeded in order to physically deform a soil. Soil strength is the property in soil which resists compaction. This property is affected by other soil properties: porosity, water content, soil texture, and number of particle-to-particle contacts. A soil is the most susceptable to compaction at high water contents. Water has a lubricating effect on the soil and reduces the friction in inter-particle contacts.

Soils which have a wide range of primary particle sizes are more susceptable to compaction than a soil with a uniform size of primary particles (Chancellor, 1971).

Compaction increases soil strength by decreasing porosity and by increasing the particle-to-particle contacts.

Voorhees (1977a) states that the cloddy surface created by plowing up a compacted soil can reduce wind and water erosion from harvest to planting. This is accomplished by improving infiltration, trapping wind-blown particles, and resisting raindrop impact. However, wheel tracks in the growing season reduce infiltration and increase surface runoff.

Compaction Effects on Plant Growth

Compaction alters the soil environment which in turn alters root growth. Specifically, it is the increase in soil strength and decrease in aeration which reduce root growth. The decrease of water recharge and storage associated with a compacted soil also contribute to reduced root growth.

The increased soil strength associated with soil compaction impedes root growth. This mechanical constrainment of the growing plant by the soil is termed mechanical impedance (Bowen, 1981).

Taylor and Burnett (1964) showed that root growth was prevented when the soil strength reached 25-30 bars (Critical Strength). Gerard et al. (1982) found that the critical strength was a function of clay content. They showed that critical strengths were as high as 70 bars for a coarse sand but dropped to 25 bars for a clay soil.

Wiersum (1957) showed that in a rigid system, plant roots were only able to enter pores that are of greater diameter than that of the root. The author also demonstrated that roots could move soil particles aside and enter pores smaller in diameter if the soil strength was low. Soil compaction mechanically impedes root growth by reducing pore size and by increasing soil strength.

When a surface crust forms on a bare soil surface after planting but before emergence, plant stands will be reduced (Bowen, 1981). Bowen (1981) cites work he did in 1966 to quantify the soil strength limits on cotton seedling emergence. He found that there was no mechanical impedance when crust strength was 70 kPa. But when strength increased above 75 kPa, the percentage of seedlings that emerged was reduced. At strengths of 200 kPa, no emergence occurred.

The metabolic energy required by roots is provided primarily by respiration. Root respiration consumes oxygen and produces carbon dioxide. In order for this process to occur at metabolic rates, the soil atmosphere must be constantly replenished with oxygen, and carbon dioxide must be free to escape out of the soil and back into the atmosphere. Aeration refers to the process of gaseous exchange between the atmosphere and the soil. This process occurs primarily in the air-filled pores of the soil. Compaction reduces aeration by reducing the air-filled pore volume of the soil.

Letey et al. (1962) created low oxygen conditions in the root zone of green beans, sunflower, and cotton seedlings by flushing the soil with nitrogen gas. They found that low oxygen is the most damaging in the early growth stages following germination; that roots stop growing at low oxygen concentrations; and that there is a lag time in the recovery of root growth when oxygen has been replenished.

Alleviation of Soil Compaction

Tillage operations are often employed to alleviate soil compaction. Tillage is defined as the act of mechanically manipulating the soil to improve soil conditions which affect crop growth (Hillel, 1982). The historical objectives of tillage are to move the soil for seed placement, manage crop residues, modify the physical properties of the soil, add and mix soil amendments, and control weeds. The control of weeds has been the primary reason for tillage operations. Chemical weed control can be so thorough that there is no longer need to till the soil for weed control.

Soane and Pidgeon (1975) realized that with chemical weed control and planters which can insert seed into an untilled soil, it is the physical properties of a soil which determine the tillage requirement. They state that tillage affects soil strength, soil aeration, water status, and soil temperature. Letey (1985) states that these same soil physical properties affect crop growth. In a soil where these properties are limiting to crop growth, tillage would be required.

Soil below 30 cm is usually loosened by subsoiling operations which consist of shattering the soil using high draft rigid-tined implements referred to as subsoilers and deep chisels. These implements have a critical working depth where soil is displaced forwards, sideways, and upwards (crescent failure) (Spoor and Godwin, 1978). When the critical depth is exceeded, the soil is displaced only laterally and forwards (lateral failure) causing compaction to occur beneath the base of the tine. The soil is fractured at a 45-degree angle from the surface of the soil to a point above the base of the tine. This forms a "Y"-shaped cross section of loosened soil.

Subsoiling when the soil is dry has been recommended to achieve the maximum soil shattering. Spoor and Godwin (1978) support this view, saying that as the soil becomes more plastic, the critical depth becomes shallower, resulting in less disturbance of the soil at the same operating depth.

Cooper (1971) disagrees, reporting that a very compact soil will fracture equally well at soil moisture contents from field capacity to the wilting point.

Because of the localized loosening of the soil and the cost of subsoiling, zone tillage -- planting crop rows directly over the loosened area -- has become widely practiced. Zone tillage is also referred to in the literature as under-the-row subsoiling. Zone tillage is used extensively on the coastal plain soils in the southeastern United States. The soils here are coarse textured and contain a dense A2 horizon which restricts root elongation and water movement. Rainfall is limiting and poorly distributed throughout the growing season (Campbell et al., 1974).

Conventional tillage systems consist of primary tillage, commonly moldboard plowing the soil in either the spring or the fall of each cropping season. Moldboard plowing loosens the soil by shearing, lateral movement, and inversion. The surface of the soil is left free of plant residues. Secondary tillage is then performed in the spring to create a uniform seed bed, to increase seed-soil contact, and to break up large clods (Soane and Pidgeon, 1975). This system requires large time, labor, and fuel inputs and offers no protection against wind and water erosion.

When the physical properties of the soil are not limiting to plant growth, tillage is not required and seeds can be placed directly into the untilled soil. The only tillage operation is opening the slit for seed placement. This system leaves the soil surface covered with residues. The no-tillage system is attractive to producers for several economic reasons. Because residues are left intact on the soil surface, soil erosion hazards are significantly reduced. This allows crops to be grown on land previously considered unsuitable because of high erosion hazards. Time, labor, and fuel inputs are all reduced under the no-till system.

The location of the compacted layer in the soil profile dictates what type of tillage implement is used. Surface crusts can be broken up with a rotary hoe. Compaction occurring in the plow layer can be alleviated by moldboard plowing. Compaction occurring beneath the plow layer is the most difficult to alleviate. It is the loosening of this type of soil compaction which will be addressed in this review.

Subsoiling effects on Plant and Soil Properties

Subsoiling has been shown to reduce the strength of compacted soils. Busscher et al. (1986) conducted research on a loamy sand soil in South Carolina in order to determine the residual effects of subsoiling on soil strength. They found that deep chiseling significantly reduced the soil strength immediately following tillage. However, after one year, the strength returned to a level where roots were restricted.

Chaudhary et al. (1985) measured a loamy sand soil in India. They found that subsoiling significantly decreased soil strength. However, the bulk density of the soil was not significantly affected. This was attributed to the fact that in coarse textured soils, strength is due to inter-particle friction and not due to the density of the soil. Subsoiling relieved this inter-particle friction on these soils.

Compaction at depth causes poor internal drainage of the soil. This creates a perched water table above the compact layer and restricts subsoil recharge. This can cause flooding of young plants early in the season and drought stress to occur in plants later in the season.

Trouse (1983) conducted research comparing under-the-row subsoiling with conventional tillage for 15 years on coastal plain soils. He found that shattering the compacted layer increased water availability by two mechanisms. First, roots were able to penetrate deeper and extract subsoil moisture. Secondly, moisture could enter the subsoil via the loosened areas and recharge the soil supply.

Mukhtar et al. (1985) measured infiltration rates as affected by subsoiling. The experiment was conducted in Iowa on two soils -- a silty clay loam and a silt loam. A double ring infiltrometer was used to measure one-minute and 30-minute cumulative infiltration. The subsoiled treatment had significantly higher one-minute and 30-minute cumulative infiltration rates than conventional tillage or no-tillage.

When a root-restricting layer such as that found in the A2 of the coastal plain soils is shattered, root growth is increased (Campbell et al., 1974; Trouse, 1983; and Box and Langdale, 1984). This increased root growth allows a larger volume of soil to be explored for water and nutrients. Chaudhary et al. (1985) found that in coarse textured soils in India, subsoiling increased both rooting depth and rooting density.

Grain yields are increased in areas where a root restricting-layer exists and the rainfall is limiting (Trouse, 1983; and Box et al., 1984). Therefore, the effect subsoiling has on crop yields is a function of the soil's hydraulic properties and the climatic conditions which occur during the growing season (Trouse, 1983).

Sene et al.(1985) measured soil physical properties to determine the yield response to subsoiling. They found that when aggregate mean weight diameter was greater than one mm, aggregation and texture were correlated to relative yield increases. When peds were not less than one mm, the fraction of very coarse sand became very important and was highly correlated to relative increases.

Comparison of Conventional and No-tillage Soil Properties

No-tillage crop production methods are increasing in use where soil physical properties are not limiting to crop growth. Soil physical and chemical properties have been shown to change under no-till due to the lack of plowing. There has been much concern about how these changes in soil physical and chemical properties will affect crop growth. Many studies have been conducted to measure these changes in soil properties and their effects on crop growth. The results of which will be reported in this review.

The bulk density of a soil is the ratio of the mass of the oven dried soil to its total volume (Hillel, 1982). Many researchers found that no differences in bulk density occurred between no-till and conventional tillage soils (Shear and Moschler, 1969, Blevins et al., 1983 and Hill and Cruze, 1985). However, there are some reports that bulk density is increased under no-tillage (Gantzer and Blake, 1978). Soane and Pidgeon (1975) reported that a dense soil layer develops around 12 cm deep in no-till soils.

Based on the capillary model, the pore size distribution of a soil determines the percentage of the total porosity which will retain water at field capacity. Thus, aeration and soil water status are determined largely by the soil's pore size distribution.

Hill et al. (1985b) conducted experiments in Iowa on loam and clay loam soils to determine tillage effects on soil water retention and pore size distribution. They reported that no-till soils had a different pore size distribution than that of a conventional tillage soil. Conventional tillage had a larger amount of its pore volume in pores larger than 15 um while no-tillage had a larger amount of its pore volume in pores smaller than 15 um. Van Ouwerkerk and Boone (1970) reported that on medium textured soils in the Netherlands, no-tillage produced a more uniform pore size distribution than conventional tillage.

Blevins et al. (1971) researched the effects of no-tillage on soil moisture in Kentucky. The authors found that no-tillage had significantly higher volumetric water contents than conventional tillage at the zero to eight cm depth. No-tillage consistantly had higher volumetric moisture contents to a depth of 45 cm. Gantzer and Blake (1978) reported similar results on a clay loam soil in Minnesota.

This trend for no-tillage soils to have higher water contents is primarily due to the residue cover on the soil surface. The residues trap surface waters, reducing runoff and increasing infiltration. They also reduce the radient energy at the soil's surface which reduces water losses due to evaporation. No-till soils have a greater ability to store water against loss by deep percolation because of the increase in the volume occupied by small pores (Blevins, 1971).

Saturated hydraulic conductivity (Ksat) measures the soil's ability to conduct water when fully saturated. Gantzer and Blake (1978) found that conventional tillage had higher Ksat values than no-till when measured in the spring. Blevins et al. (1983) reported that on a silt loam soil in Kentucky, Ksat was not significantly different between no-till and conventional tillage.

Research has shown that soil strength is significantly increased by no-tillage (Van Ouwerkerk and Boone, 1970 and Hill et al., 1985a).

However, Hill et al. (1985a) showed that the cone index values were low and should not inhibit root growth.

No-tillage has been shown to lead to a reduction in the volume of soil occupied by air-filled pores (Van Ouwerkerk and Boone, 1970; Gantzer and Blake, 1978; and Bauder et al., 1981). Because gas exchange occurs primarily in the air-filled pores, aeration is reduced in no-till soils at field capacity.

Soil pH is defined as the negative log of the H^+ ion activity in the soil. Soil pH has been shown to be significantly lower at the surface of no-till soils when compared to conventional tillage (Shear and Moschler, 1969; Blevins et al., 1977; and Dick, 1983). This difference is primarily attributed to the surface broadcasting of acidifying nitrogen fertilizers (Blevins et al., 1977; and Letaw et al., 1984). Dick (1983) studied a silty clay loam soil and a silt loam soil in Ohio. He found that the no-till soil had the lowest pH throughout the plow layer. He also concluded that acidic surface conditions can be alleviated by broadcast applications of lime, but acidity at depth cannot.

Tillage affects volumetric moisture content, temperature, aeration, and placement of microbial substrates. These factors regulate the types of microorganisms which predominate in the soil environment. The numbers, types, and activities of microorganisms are important because of their regulatory effects on soil carbon and nitrogen levels.

Microbial populations under no-tillage and conventional tillage were compared by Linn and Doran (1984) at five locations in 1980 and six locations in 1981 across the United States. They found that no-till soils had larger populations of both aerobic and anaerobic microorganisms in the 0 to 7.5 cm depth. At the 7.5 to 15 cm and 15 to 30 cm depths, conventional tillage had the higher microbial populations. In the 7.5 to 30 cm depth, anaerobic microbes comprised a larger percentage of the total population in no-tillage than in conventional tillage. Aerobic microorganisms predominated in conventional tillage soils due to the existance of a smaller volume of water-filled pores.

Organic carbon content is higher in the surface of no-till soils compared to conventional tillage soils (Blevins et al., 1977; Juo and Lal, 1979; and Dick, 1983). This buildup of organic carbon results from crop residues accumulating on the soil surface. Dick (1983) discusses three mechanisms which contribute to organic carbon buildup at the surface of no-till soils. He states that the absense of plowing decreases the soil-residue interaction, reduces soil erosion, and decreases the rate of biological oxidation.

It has been reported that no-tillage yields were lower than conventional tillage when nitrogen (N) fertilizers are applied at low rates. Blevins et al. (1977) reported lower N plant uptake for no-tillage at zero or low rates of N fertilizer application. This reduced efficiency of N fertilizer in no-tillage has been attributed to higher rates of denitrification, increased leaching, increased microbial immobilization, and reduced mineralization.

Denitrification is the biochemical conversion of nitrates and nitrites to nitrogen gas (Tisdale and Nelson, 1985). This conversion is carried out by anaerobic bacteria when oxygen is limiting in the soil.

Denitrification rates were found to be consistantly and significantly higher in no-till soils by Rice and Smith (1982). Their experiment was conducted on a Maury silt loam (well-drained soil) in Kentucky. The authors stated that higher moisture contents under no-tillage cause anaerobic conditions to persist. Linn and Doran (1984) showed that at 7.5 to 30 cm, no-till soils contained a higher percentage of facultative and total anaerobes than conventional tillage.

Microbial immobilization of soil N occurs when a high C/N ratio is present. The microbial populations increase due to the high concentration of carbohydrates. Nitrogen is used to build the new cells of the microbes and becomes unavailable to plants.

Rice and Smith (1984) studied three silt loam textured soils in Kentucky in order to measure short-term immobilization under no-tillage and conventional tillage. They found that on two of the three soils, no-tillage had twice as much immobilization after seven days. These findings resulted from the higher C/N ratio occurring in no-till soils. The authors reported that immobilization plays a larger role in the availability of fertilizer N than leaching or denitrification in no-till soils.

Mineralization of soil N is the opposite of immobilization. It is the conversion of organic N to mineral N which is available to plants. Rice et al. (1986) measured the soil N availability after long-term no-tillage and conventional tillage corn production on a silt loam soil in Kentucky. They found that conventional tillage led to greater N mineralization in the initial years. However, after five to 10 years of cropping, no-tillage mineralization rates were equal to those of conventional tillage. Plowing accelerates decomposition of crop residues by increasing soil-residue interaction and soil aeration. This decomposition of crop residues enhances N mineralization. After five to 10 years, many of the microbial substrates have been depleted in conventional tillage while they have been accumulating in no-tillage.

Nitrification is the last step in the process of mineralization. This step involves the conversion of ammonium to nitrate by aerobic bacteria collectively referred to as the nitrobacteria. Rice and Smith (1983) showed that nitrification was reduced in no-till soils. Tisdale and Nelson (1985) list six factors which affect nitrification: supply of ammonium, population of nitrobacteria, soil pH, soil aeration, soil moisture, and temperature. No-tillage has been shown to affect each one of these factors.

Both phosphorus (P) and potassium (K) are immobile nutrients in the soil. When these nutrients are broadcast applied, they accumulate in the surface five cm of no-till soils (Shear and Moschler, 1969; Triplett and Van Doren, 1969; Fink and Wesley, 1974; Juo and Lal, 1979; and Hargrove, 1985). Eckert and Johnson (1985) found that P accumulated at the surface of no-tillage plots which received no P fertilizer applications. Plant roots extracted P from deeper in the soil and deposited it on the surface as plant residues.

Hargrove (1985) conducted research to determine the influence of tillage on nutrient uptake and yield of corn on a sandy loam soil in Georgia. He reported that P and K did accumulate at the surface of no-tillage. However, he found that P and K concentrations in the ear leaf and above ground whole plants were equal or greater for no-tillage. Rubidium (Rb) was used to determine the activity of the roots in the different tillage systems. It was concluded that plant roots under no-tillage had the highest Rb uptake.

Triplett and Van Doren (1969) found that on a silt loam soil in Ohio, P and K uptake were equal or higher in no-tillage. Plant uptake of P and K in no-till soils is a function of the increased root growth in this nutrient-rich layer. Grain yields were higher under no-till for all six years of the experiment.

Eckert and Johnson (1985) conducted research in Ohio to compare crop and soil response to placement of P fertilizer. Equal rates of P fertilizer were applied by surface broadcasting and by subsurface banding. The authors reported that banding increased yields and fertilizer use efficiency while reducing the accumulation of P in the soil surface.

Summary

When soil physical properties are limiting to crop growth, tillage is required to improve these properties. Tillage can alleviate soil compaction whether at the soil surface or as deep as 45 cm.

If soil properties are not limiting to crop growth, then tillage is not required. No-tillage crop production methods on such soils have produced good results. However, no-till -- when practiced over long periods of time -- does alter the soil's physical and chemical properties. Some of these changes produce a soil environment that is less than ideal for plant growth. Periodic plowing of no-till soils becomes necessary to improve conditions for plant growth.

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Chapter 2

Changes in Soil Physical and Chemical Properties Associated with Periodic Plowing in No-till Corn

INTRODUCTION

No-tillage crop production is increasing throughout the United States. Optimistic estimates indicate that 60 to 80 percent of the total crop acreage will be planted to no-till in the next 20 years. No-till significantly reduces soil erosion on sloping fields. No-till also reduces time, labor, and fuel inputs required for seed bed preparation.

The absense of plowing causes a unique soil environment to form under no-tillage. These changes in soil physical and chemical properties have been well documented and there is concern about how these properties will affect plant growth.

No-till has been shown to affect soil physical properties. Gantzer and Blake (1978) showed that soil bulk density was higher under no-till. Hill et al. (1985b) reported that no-till increased the volume of soil occupied by pores smaller than 15 um. Van Ouwerkerk and Boone (1970) found that no-till produced a more uniform pore size distribution than conventional tillage. Blevins (1971) and Gantzer and Blake (1978) found that volumetric water contents were higher under no-till. Saturated hydraulic conductivities were shown to be significantly lower for no-till by Gantzer and Blake (1978). Air-filled porosity was found to be reduced in no-till soils (Van Ouwerkerk and Boone, 1970; Gantzer and Blake, 1978; and Bauder et al., 1981).

Because gas exchange occurs in the air-filled pores, the process of aeration can be inhibited in no-till soils. Hill et al. (1985a) and Van Ouwerkerk and Boone (1970) found that soil strength was increased by no-till. However, Hill et al. (1985a) showed that the cone index values were low and should not inhibit root growth.

Tire traffic is the leading cause of soil compaction in agricultural soils (Cohron, 1971). Compaction has been shown to inhibit root growth through mechanical impedance and aeration stress (Taylor and Burnett, 1964; and Letey et al., 1962). Wheel traffic-induced compaction could be a problem in no-till soils due to the absence of annual soil loosening provided by plowing.

Extended periods of no-tillage can lead to significant changes in soil chemical properties. Acidic surface conditions have been shown to develop in no-till soils (Shear and Moschler, 1969; Blevins, et al., 1977; and Dick, 1983). Blevins et al. (1977) attributes this process to the broadcast application of acidifying nitrogen fertilizers. Blevins et al. (1977), Juo and Lal (1979), and Dick (1983) reported accumulated organic carbon at the surface of no-till soils. Nitrogen (N) cycling has been shown to be affected by no-tillage. At low application rates, fertilizer N availability was found to be reduced in no-till by Blevins et al. (1977). Rice and Smith (1982) found that no-till had consistantly higher rates of denitrification. Microbial immobilization was also found to be higher in no-till (Rice and Smith, 1984). Rice et al. (1986) showed that N mineralization was higher for conventional tillage in the initial years (five to 10 years). After this time, mineralization rates were similar between no-tillage and conventional tillage. Phosphorus (P) and potassium (K) have been shown to accumulate near the surface of no-till soils when surface broadcast (Shear and Moschler, 1969; Triplett and Van Doren, 1969; Fink and Wesley, 1974; Juo and Lal, 1979; and Hargrove, 1985).

Periodic plowing has been recommended to alleviate some of the adverse conditions which develop under no-till. Plowing mixes the stratified nutrients and organic carbon into the plow layer. Woody perennial weeds can be controlled better by plowing. Acidic surface conditions can also be alleviated by plowing.

The objectives of this research were to: 1) quantify changes in soil physical and chemical properties when no-till soils are periodically plowed; 2) determine the impact of wheel traffic on the soil physical properties of no-tillage and conventional tillage; and 3) determine the plant responses to the soil physical and chemical changes which occur following plowing.

MATERIALS AND METHODS

The experiment was originally initiated in 1981 to assess the effect of rye cover management in no-tillage compared to conventional tillage. The site was located at the Michigan State University experimental farms in East Lansing, Michigan. The soil at this site was a Conover loam (Fine-loamy, Mixed, Mesic, Udollic Ochraqualf). This soil is somewhat poorly drained. However, this site was tile drained.

There were four tillage treatments from 1981 to 1985 (Table 1): 1) fall plowed and spring secondary tillage in each year (CT); 2) no-till with 90 percent rye cover killed at planting except three to four inches between rows (NTR1); 3) no-till with 90 percent of the rye cover crop killed at planting (NTR2); and 4) no-till with 100 percent rye cover crop killed at planting (NT). In the spring of 1986, the NTR2

Table 1. Descriptions of the tillage treatments.

Tillage Code	Tillage Treatments		
	---------------- Year	-----------------	
	1981-1985	1986	1987
CT	CT	CT	CT
NTP6	NTR1	NT	CT
NTP5	NTR2	CT	NT
NT	NT	NT	NT

treatment was plowed (NTP5) in addition to the CT treatment. The NTR1 and NT treatments were no-tilled in 1986. In the fall of 1986, the CT treatment and the NTR1 treatment were plowed (NTP6). The NTP5 treatment was returned to no-tillage for the 1987 field season as was the NT treatment from 1986. In 1986, soil measurements were made only on the CT, NTP5, and NT treatments. In 1987, measurements were made on CT, NTP5, NTP6, and NT.

Due to a wet fall in 1985, CT and NTP5 were spring plowed on April 18 for the 1986 field season. The CT and NTP6 treatments were plowed in the fall of 1986 for the 1987 field season. The depth of plowing was 20 cm for both years. Secondary tillage was performed in the spring and consisted of one pass of a disk and one pass of a spring-tined field cultivator.

In 1986, pioneer 3744 variety seed corn was planted on May 3. In 1987, pioneer variety 3737 was planted on April 28. In both years planting was done with a Buffalo no-till planter seeded to an intended population of 65,000 seeds per hectare.

Fertilizers and rates were the same in 1986 and 1987. A liquid starter fertilizer of 13 kg N ha^{-1} and 19 kg P ha^{-1} as ammonium polyphosphate was banded near the row at planting. Fertilizer N at a rate of 168 kg N ha^{-1} was broadcast as ammonium nitrate prior to seedling emergence.

Weed control in 1986 was achieved by broadcasting 4.7 liter alchlor ha^{-1}, 2.3 liter atrazine ha^{-1}, and 2.3 liter cyanazine ha^{-1}. In 1987, the alachlor and cyanazine were increased by 1.17 liter ha^{-1}. In 1986 and 1987, 2.3 liter ha^{-1} of paraquat were broadcast applied to the no-till plots.

Plant emergence was monitored by counting the number of plants emerged in 40 feet of row.

Ear leaf samples were taken in 1986 when half of the plants were silking. Fifteen leaves located opposite and below the ear were chosen at random to form a composite sample. The leaves were washed in sodium lauryl sulfate, rinsed in distilled deionized water, dried, and ground for N analysis.

Grain was harvested by hand from two 30-foot rows from each plot. The grain was subsampled for moisture and N analysis. Grain moisture was determined using a moisture meter. Stover from 20 random plants was chopped and weighed from each plot in 1986 and subsampled for moisture and N analysis. In 1987, all the plants from the harvest area were chopped, weighed, and subsampled for moisture and N analysis.

Ear leaf, grain, and stover tissue samples were digested using a Kjeldahl procedure (Bremner and Mulvaney, 1982). The N in the digest was determined analytically on the Lachet flow injection analyzer.

Inorganic nitrogen content was determined from composite samples, taken in the spring prior to fertilizer applications. In 1986, the sampling depths were 0 to 5 cm, 5 to 15 cm, and 15 to 30 cm. Six punch probe cores made up a composite sample. The soils were sampled on six dates: 4/14, 4/22, 4/24, 4/27, 5/1, and 5/5. In 1987, the sampling depths were 0 to 5 cm, 5 to 10 cm, and 10 to 20 cm. Eight punch probe cores made up a composite sample. The sampling was performed on six dates: 4/10, 4/13, 4/17, 4/20, 4/23, and 4/30.

Soil samples were frozen after sampling. The samples were thawed, sieved, and mixed thoroughly. Ten grams of moist soil were combined with 100 ml of 1.0 N KCl and shaken for one hour (Keeney and Nelson, 1982). The extract was then filtered through Whatman #2 filter paper. The filtrate was analyzed colorimetrically for NO_3^- and NH_4^+ on the Lachet flow injection analyzer. Duplicate extractions were performed on each sample and blanks were included to determine the filter paper's contribution of NO_3^-. The blanks were averaged and subtracted from the samples.

Soil pH, organic carbon, phosphorus, and potassium were determined from composite samples taken on April 10, 1987. The sampling depths were 0 to 5 cm, 5 to 10 cm, 10 to 15 cm, and 15 to 20 cm. Soil pH was determined using a glass electrode and a 1:1 soil-water slurry. Organic carbon was determined using the method of Snyder and Trofmow (1984). Phosphorus was extracted with Bray extract and analyzed on a Brinkman PC 800 Fiberoptic probe colorimeter. Potassium was extracted using 1.0 N NH_4OAc and extracted K was determined by atomic absorption.

Soil physical properties (bulk density, total porosity, pore size distribution, moisture characteristic curve and saturated hydraulic conductivity) were determined on 7.6 cm x 7.6 cm intact soil cores. Soil cores were taken at two depths: 0 to 7.5 and 7.5 to 15 cm. In 1986, both the wheel-tracked and non-wheel-tracked areas were sampled. In 1987, only the non-trafficed area was sampled on July 14. Cores were taken on two dates in 1986: June 21 and September 16.

The cores were saturated from the bottom for 48 hours. Saturated hydraulic conductivity (Ksat) was determined using the constant head method of Klute (1965). The cores were then resaturated and weighed. Moisture retention for 1, 2, 3, 4, and 6 kPa of matric suction were determined by the blotter paper method (Leamer and Shaw, 1941). The water retention at 10, 33.3, and 100 kPa of matric suction were determined using pressure plates (Richards, 1965). The pore size distribution was calculated by applying the capillary model to the moisture characteristic curve (Vomocil, 1965). Bulk density was determined on a mass per volume basis after oven drying the cores for 48 hours at 105 degrees C.

In 1986, the experimental design for the core samplings was a split plot with tillage as the main plots and tire traffic as the sub-plots. In 1987, the experimental design for the core samplings was a randomized complete block. The treatments were replicated four times in all years of the experiment. Analysis of variance was employed to detect significant differences between treatment means. Duncan's Multiple Range Test was used to separate and rank the treatment means.

RESULTS AND DISCUSSION

Physical Properties

The bulk density data from 6/21/86 and 9/16/86 are presented in Figure 1. The NT treatment had the highest bulk density (D_b) values of all treatments at both the 0 to 7.5 cm depth and the 7.5 to 15 cm depth. At the 0 to 7.5 cm depth, D_b values for NT were 1.43 g cm^{-3} on 6/21 and 9/16. At the 7.5 to 15 cm depth, D_b values for NT ranged from 1.48 g cm^{-3} on 6/21 to 1.55 g cm^{-3} on 9/16. Plowing a no-till treatment (NTP5) decreased these values by .20 g cm^{-3}.

The 1987 bulk density data is presented in Figure 2. Again, the NT treatment had the highest D_b at both the 0 to 7.5 cm depth and the 7.5 to 15 cm sampling depth. At the surface, all four bulk density treatment means were significantly different from each other. These means were ranked in the following order: NT> NTP5> CT> NTP6. At the 7.5 to 15 cm depth, NT and NTP5 (the two no-till treatments in 1987)

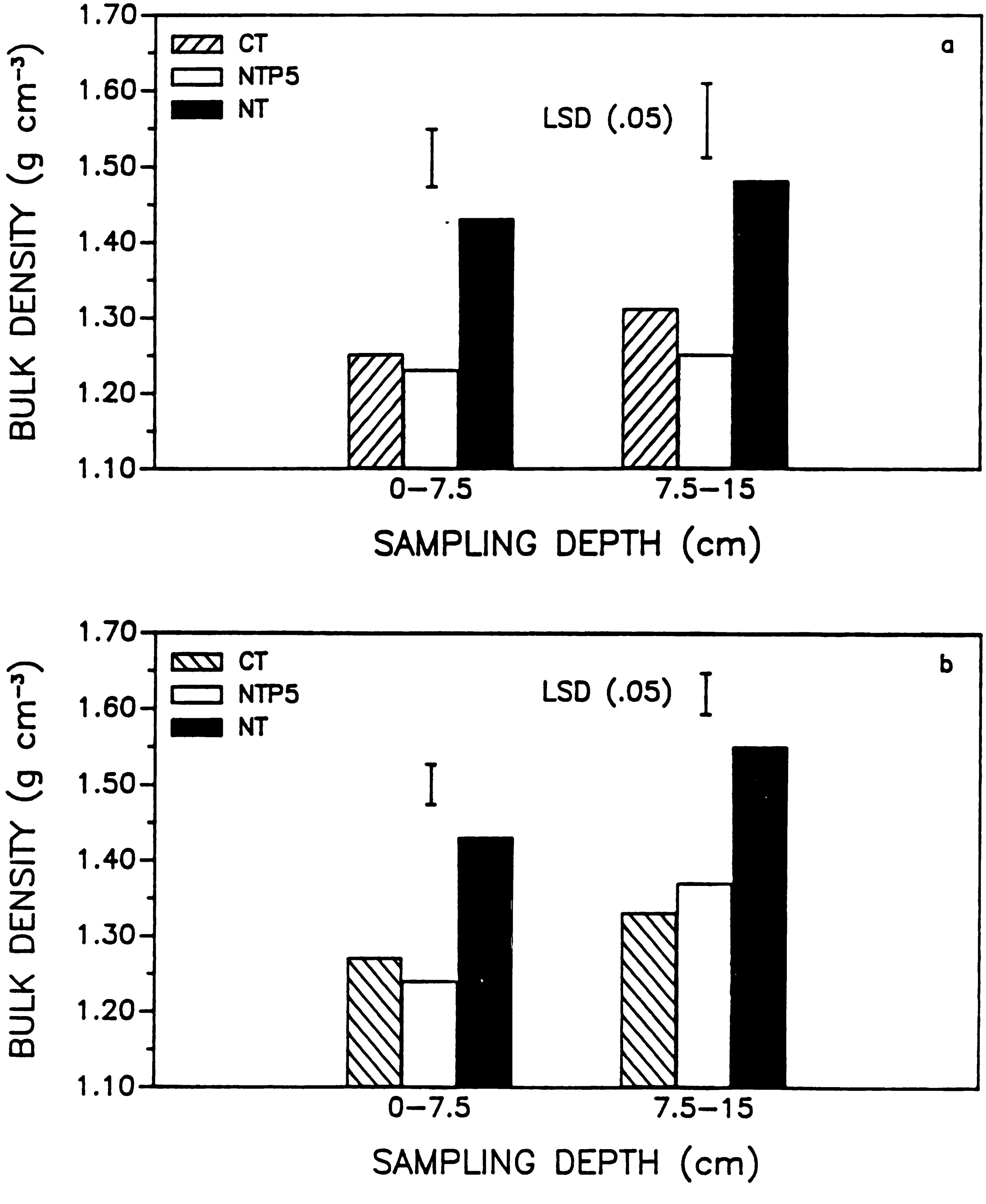

Figure 1. Tillage effects on soil bulk density from between the tire tracks on 6/21/86 (a) and 9/16/86 (b).

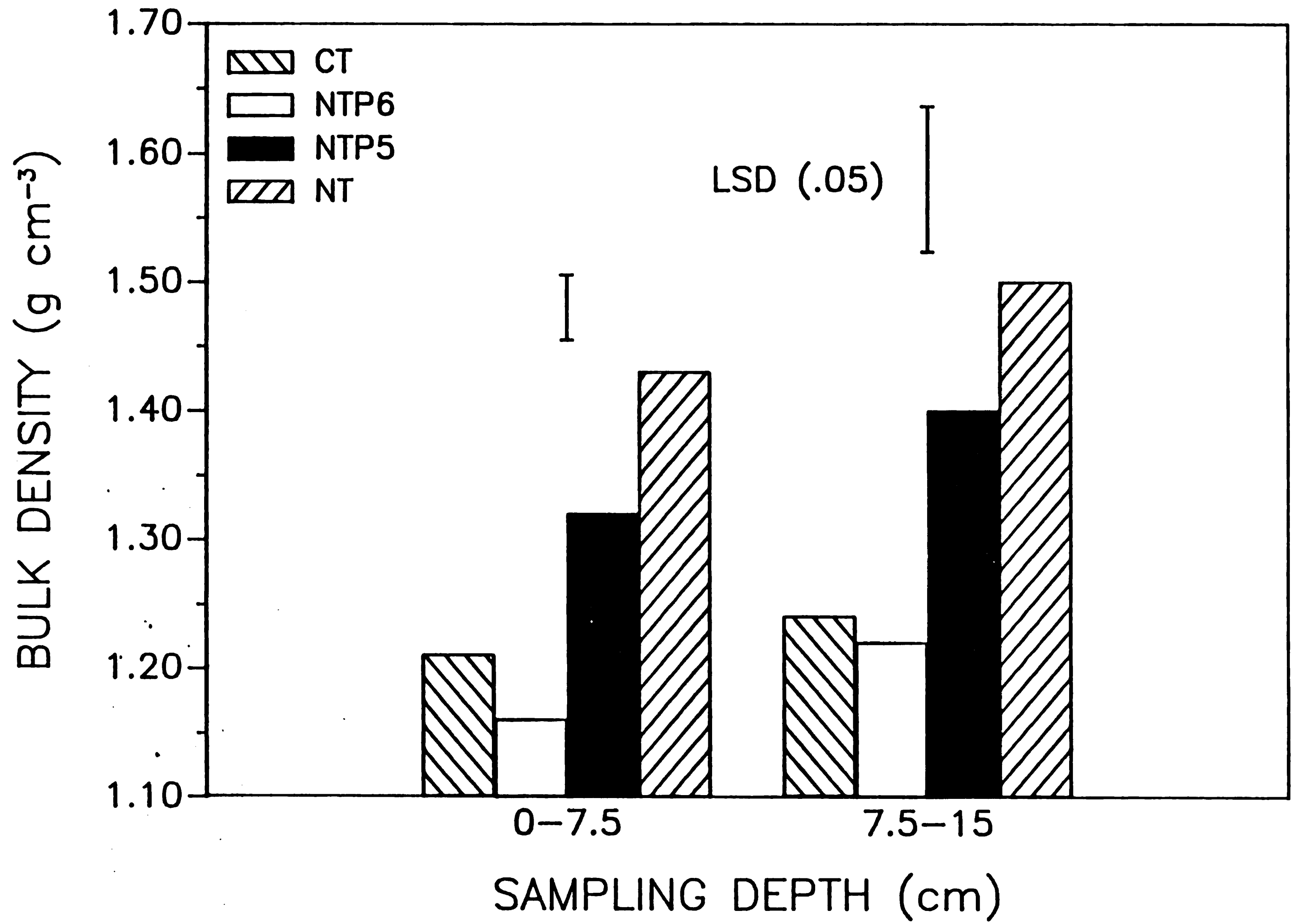

Figure 2. Tillage effects on soil bulk density from 7/14/87.

were significantly greater than those of the NTP6 and CT treatments (the two plowed treatments in 1987). The D_b values for the NT treatment at the 0 to 7.5 cm depth and the 7.5 to 15 cm depth were 1.43 g cm^{-3} and 1.50 g cm^{-3} respectively. Plowing reduced these values to 1.16 g cm^{-3} and 1.22 g cm^{-3} for the 0 to 7.5 cm depth and the 7.5 to 15 cm depth respectively in the NTP6 treatment.

The pore size distribution of the no-tillage soil was significantly affected by plowing in 1986 and 1987. The data from 6/21/86 and 9/16/86 are presented in figures 3 and 4 respectively. At both sampling depths, plowing increased the volume of soil occupied by pores whose radii were greater than 146 um by a factor of at least 1.5 for the three sampling dates. The volume of soil occupied by pores with radii between 146 and 24 um in the NTP5 treatment was double that of the NT treatment in 1986. This was true at the 0 to 7.5 cm depth and the 7.5 to 15 cm depth. In 1987 (Figure 5), the volume of pores in the size interval 146 to 24 um was increased 1.7 times by plowing (NTP6) when compared to continuous no-till (NT). With the exception of the 7.5 to 15 cm depth of the June 1986 sampling, plowing significantly decreased the volume of soil occupied by pores with radii less than 24 um compared to the NT treatment.

The pore size distribution of the no-tilled Conover loam was significantly affected by plowing. Plowing increased the volume of soil occupied by pores with radii greater than 24 um and decreased the volume occupied by pores with radii less than 24 um. This change in pore size distribution can in turn affect other soil properties: water retention and air-filled porosity.

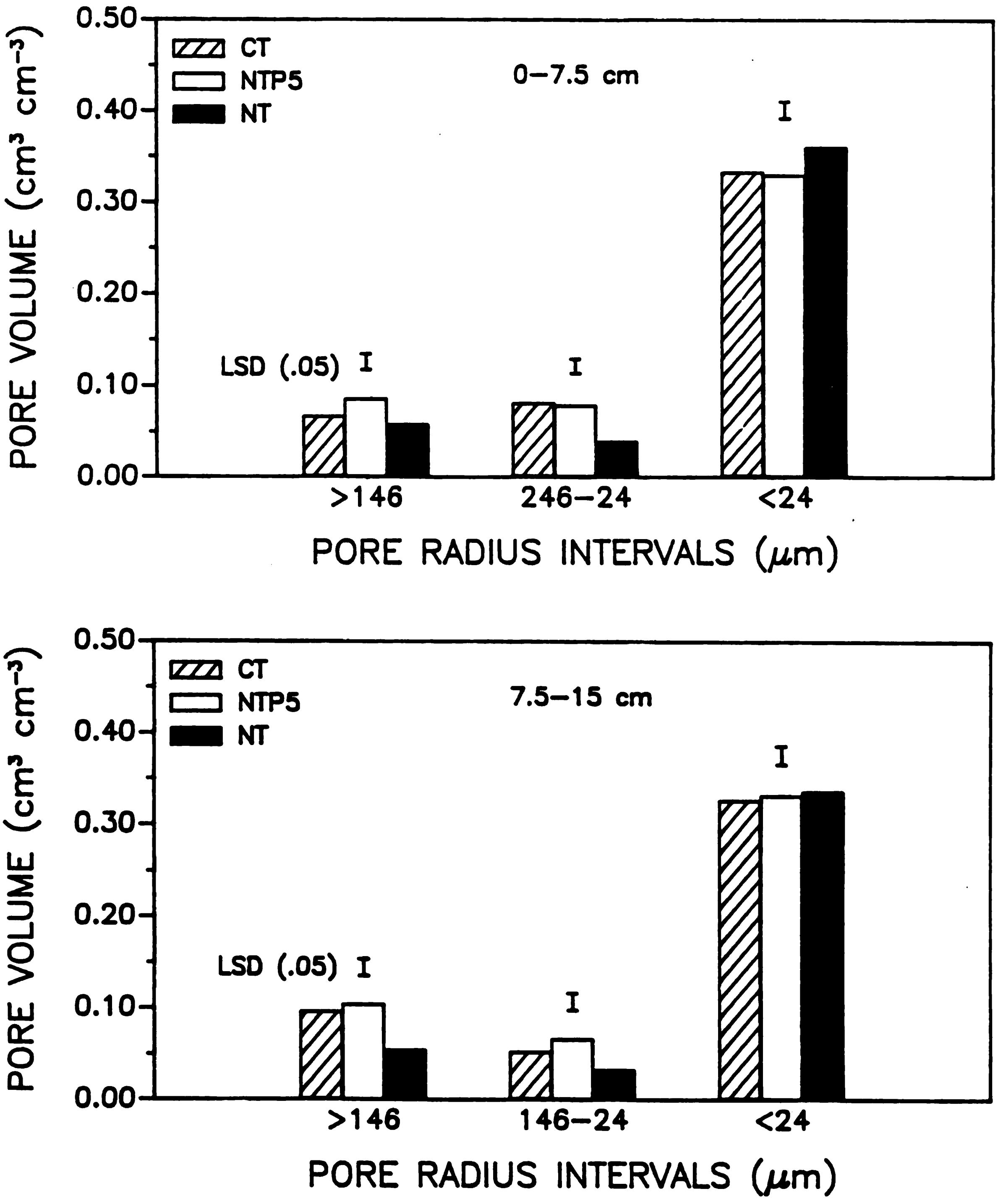

Figure 3. Tillage effects on the pore size distribution from 6/21/86.

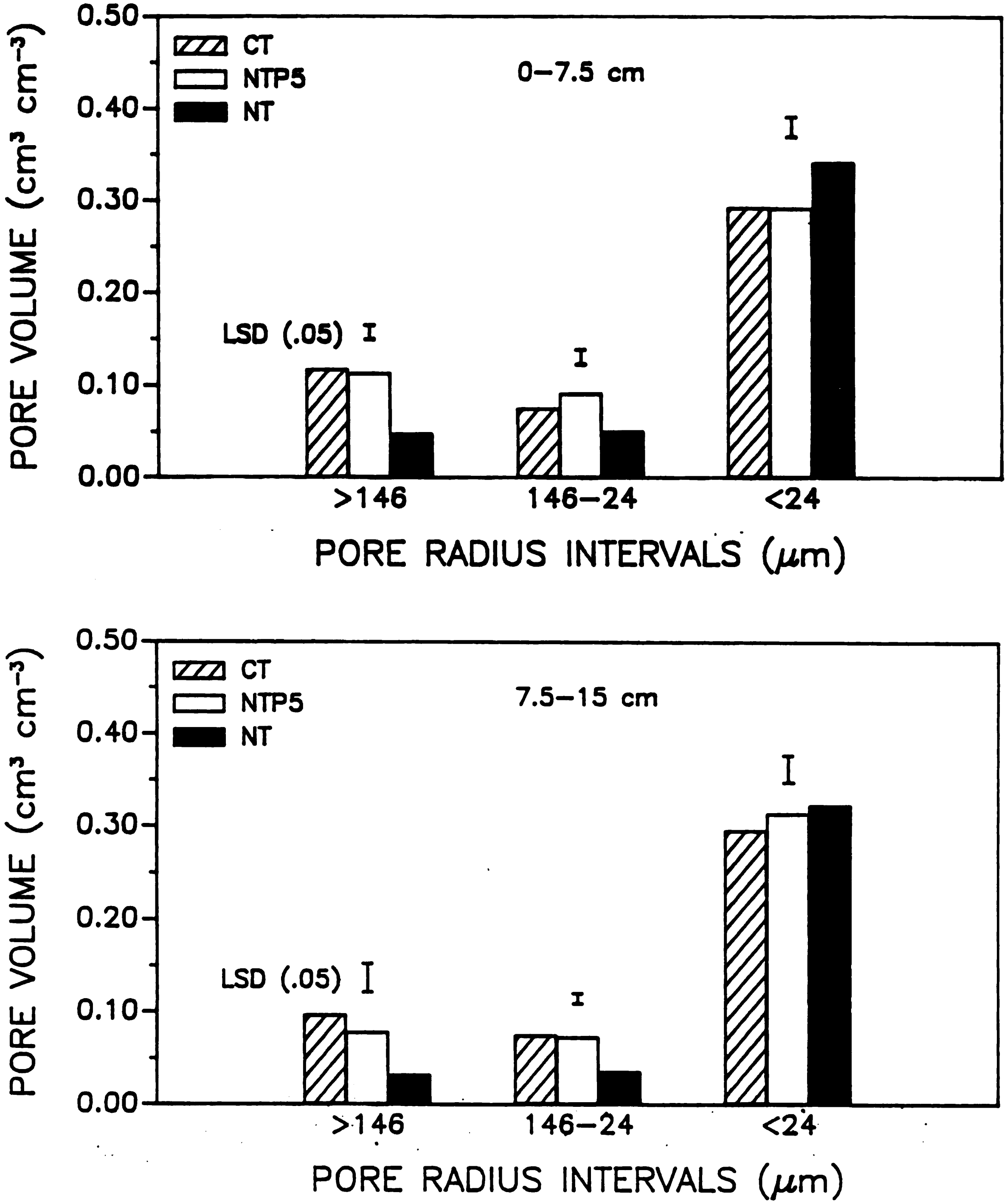

Figure 4. Tillage effects on the pore size distribution from 9/16/86.

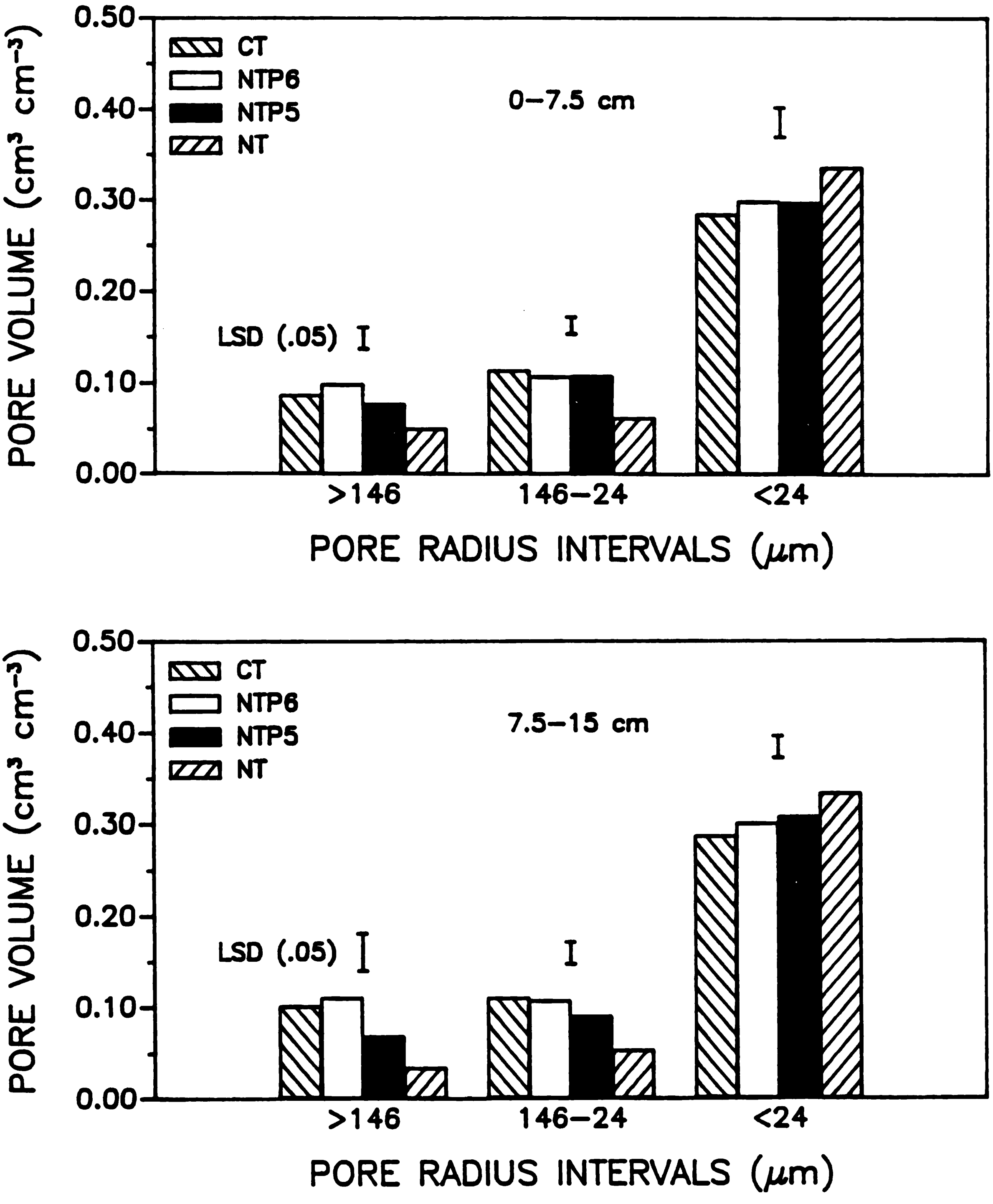

Figure 5. Tillage effects on the pore size distribution from 7/14/87.

The volume of water which drains at a given matric suction corresponds to the volume of soil occupied by pores with radii greater than those which will retain water by capillarity at that suction (Vomocil, 1965). In 1986, water retention curves were determined from intact soil cores at matric potentials of -1, -2, -3, -4, -6, -10, -33.3, and -100 kPa. The 6/21/86 data for the 0 to 7.5 cm and the 7.5 to 15 cm depths are presented in Figures 6 and 7 respectively. The 9/16/86 water retention curves for the 0 to 7.5 cm and the 7.5 to 15 cm depths are shown at the top of Figures 8 and 9 respectively. At both depths in 1986, the NTP5 and CT treatments had higher volumetric water contents at low matric suctions and lower volumetric water contents at high matric suctions than the NT treatment.

In 1987, the water retention curves were determined at matric potentials of -1, -2, -4, -6, and -33.3 kPa. The water retention curves for the 0 to 7.5 cm depth and the 7.5 to 15 cm depth are presented at the top of Figures 10 and 11 respectively. The CT, NTP5, and NTP6 treatments had higher volumetric water contents at high matric potentials and lower volumetric water contents at low matric potentials than the NT treatment.

The air-filled porosity (f_a) of the soil is a function of the pore size distribution also. Pores whose radii are from 30 to 60 um will remain filled with water at the soil's field capacity which occurs at a matric potential from -5 to -10 kPa (Cannell and Jackson, 1981). Foth (1978) states that the field capacity for medium and coarse textured soils corresponds to a matric potential of -6 kPa. Therefore, particular attention will be focused on the air-filled porosity of the tillage treatments at -6 kPa of matric potential.

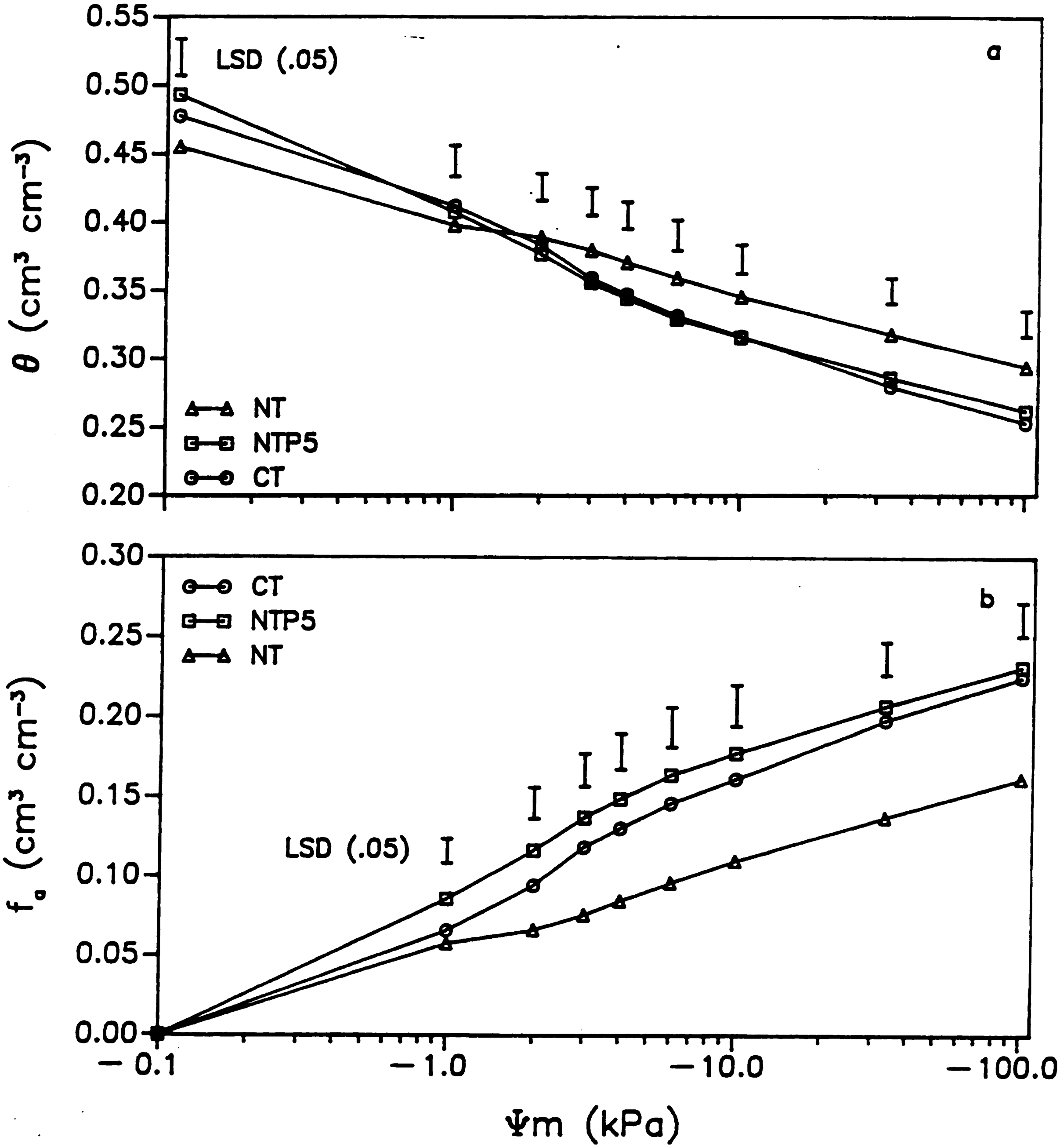

Figure 6. The effects of tillage on moisture retention (a) and air-filled porosity (b) at the 0 to 7.5 cm depth from 6/21/86.

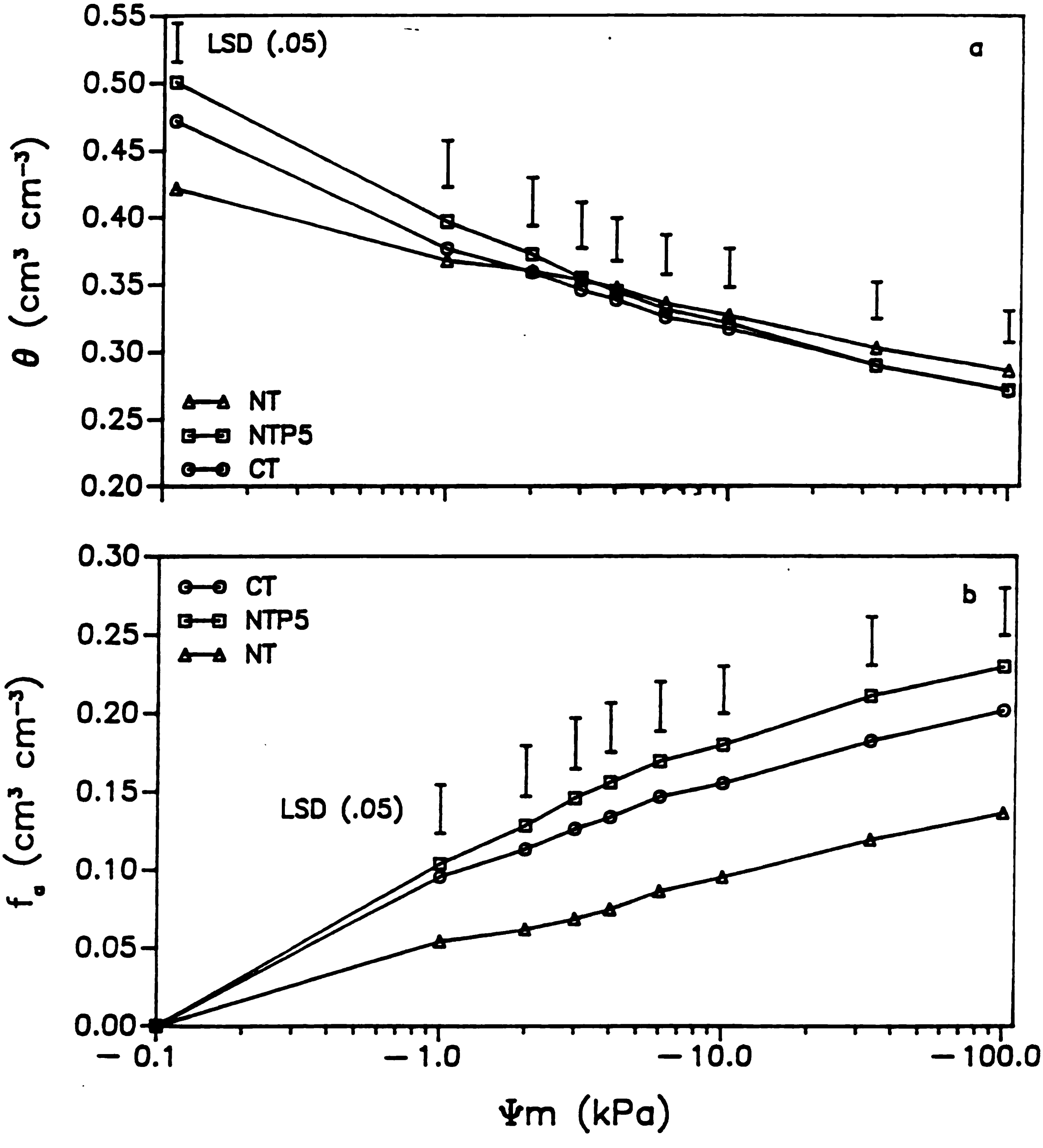

Figure 7. The effects of tillage on moisture retention (a) and air-filled porosity (b) at the 7.5 to 15 cm depth from 6/21/86.

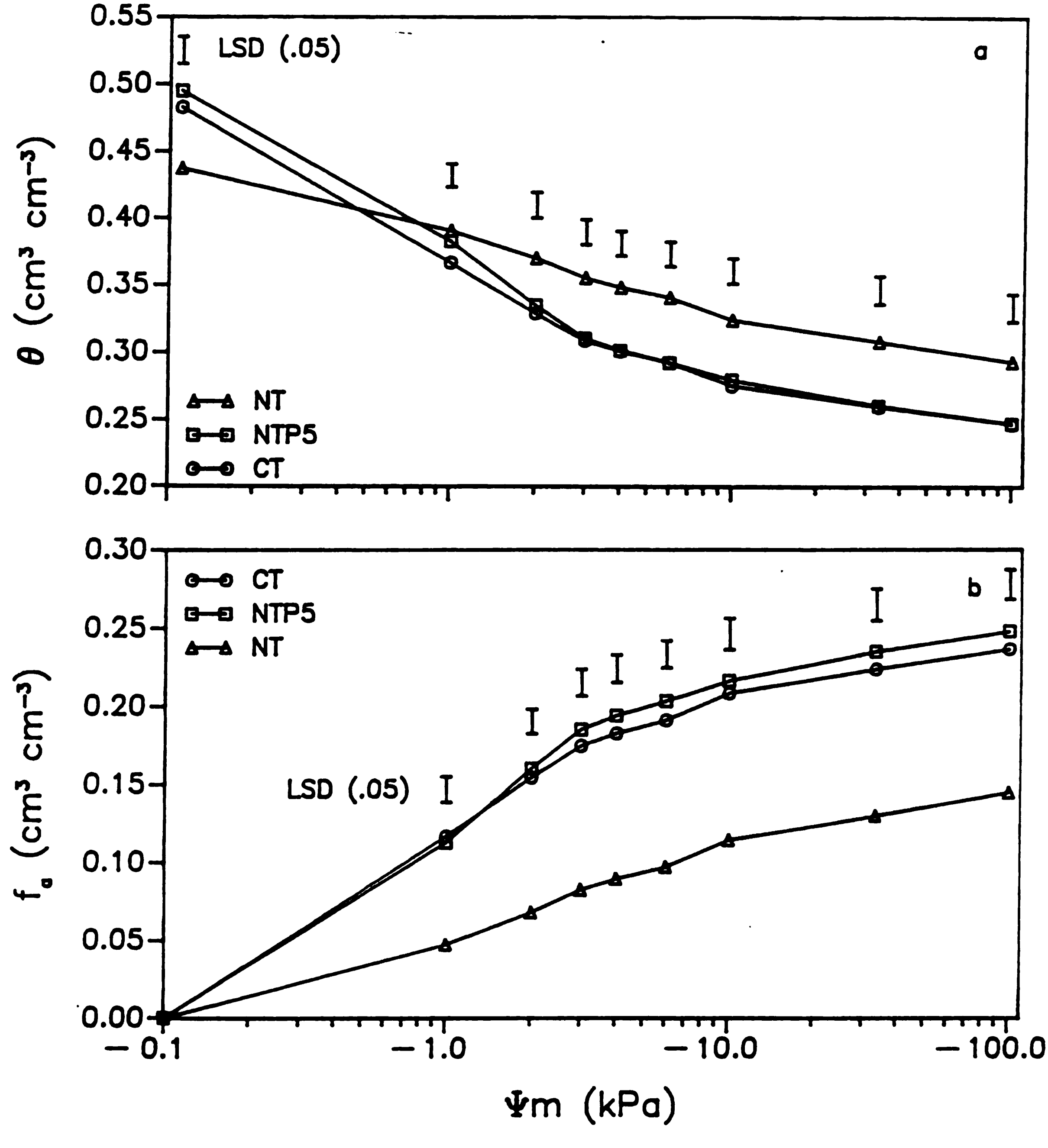

Figure 8. The effects of tillage on moisture retention (a) and air-filled porosity (b) at the 0 to 7.5 cm depth from 9/16/86.

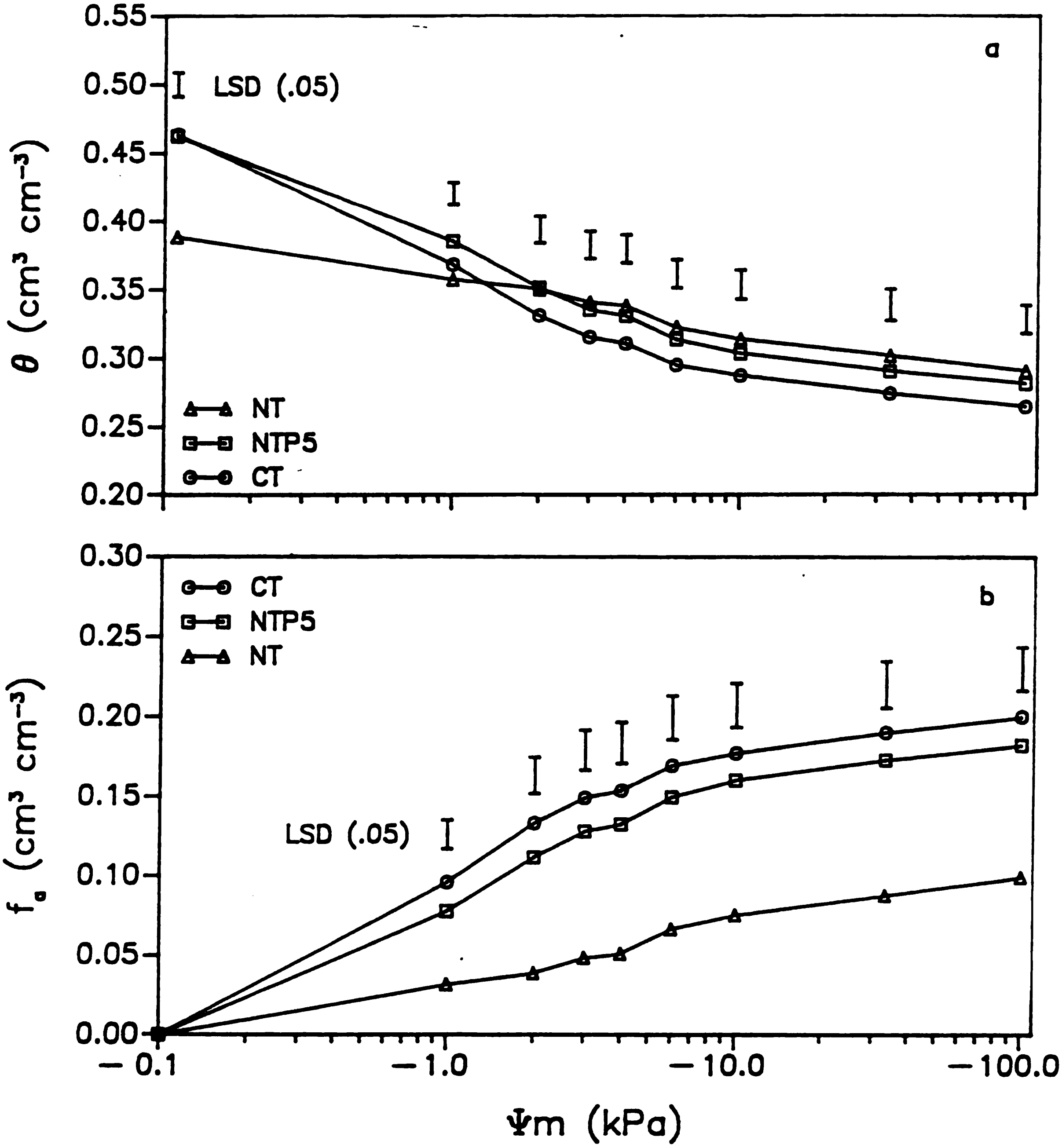

Figure 9. The effects of tillage on moisture retention (a) and air-filled porosity (b) at the 7.5 to 15 cm depth from 9/16/86.

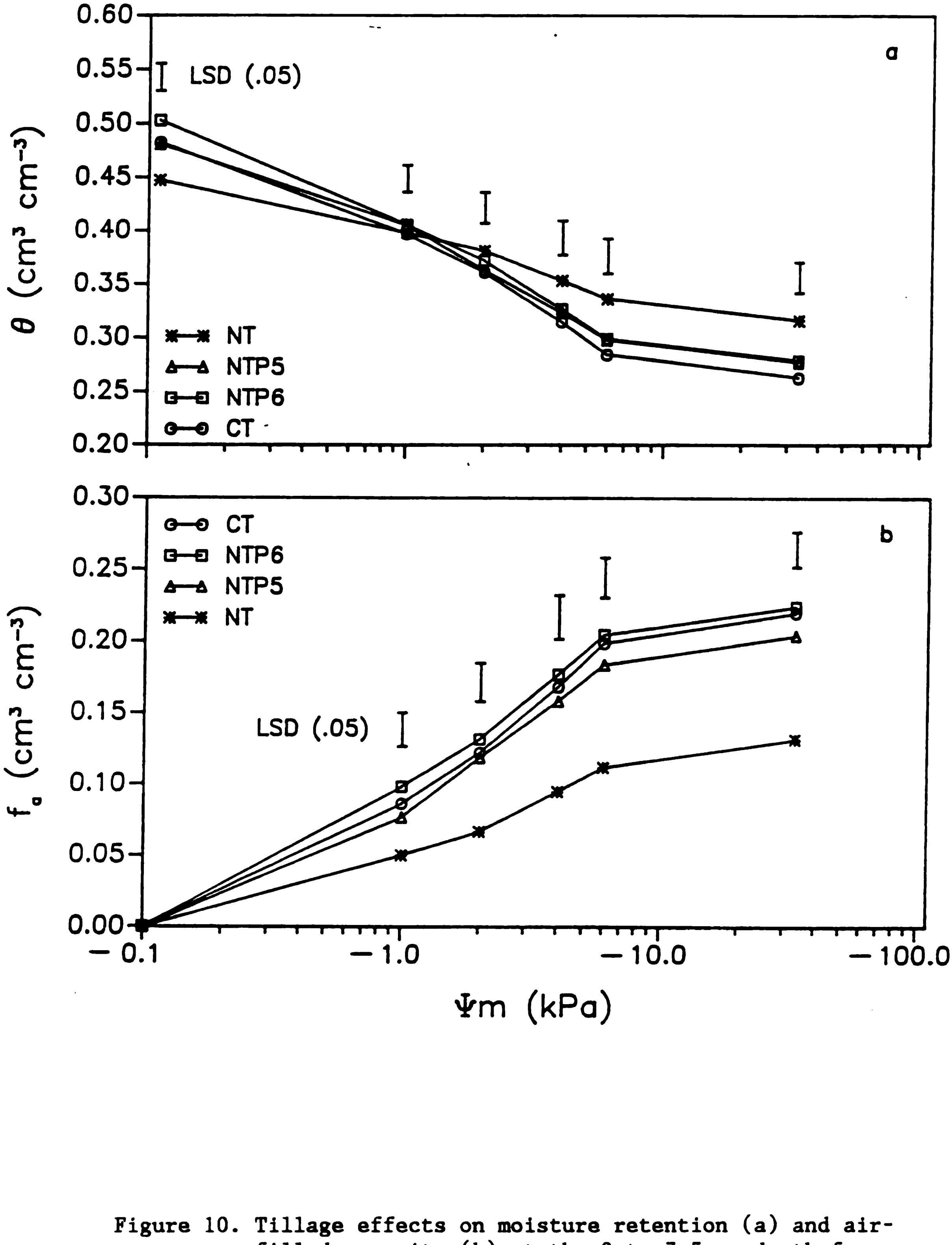

Figure 10. Tillage effects on moisture retention (a) and air-filled porosity (b) at the 0 to 7.5 cm depth from 7/14/87.

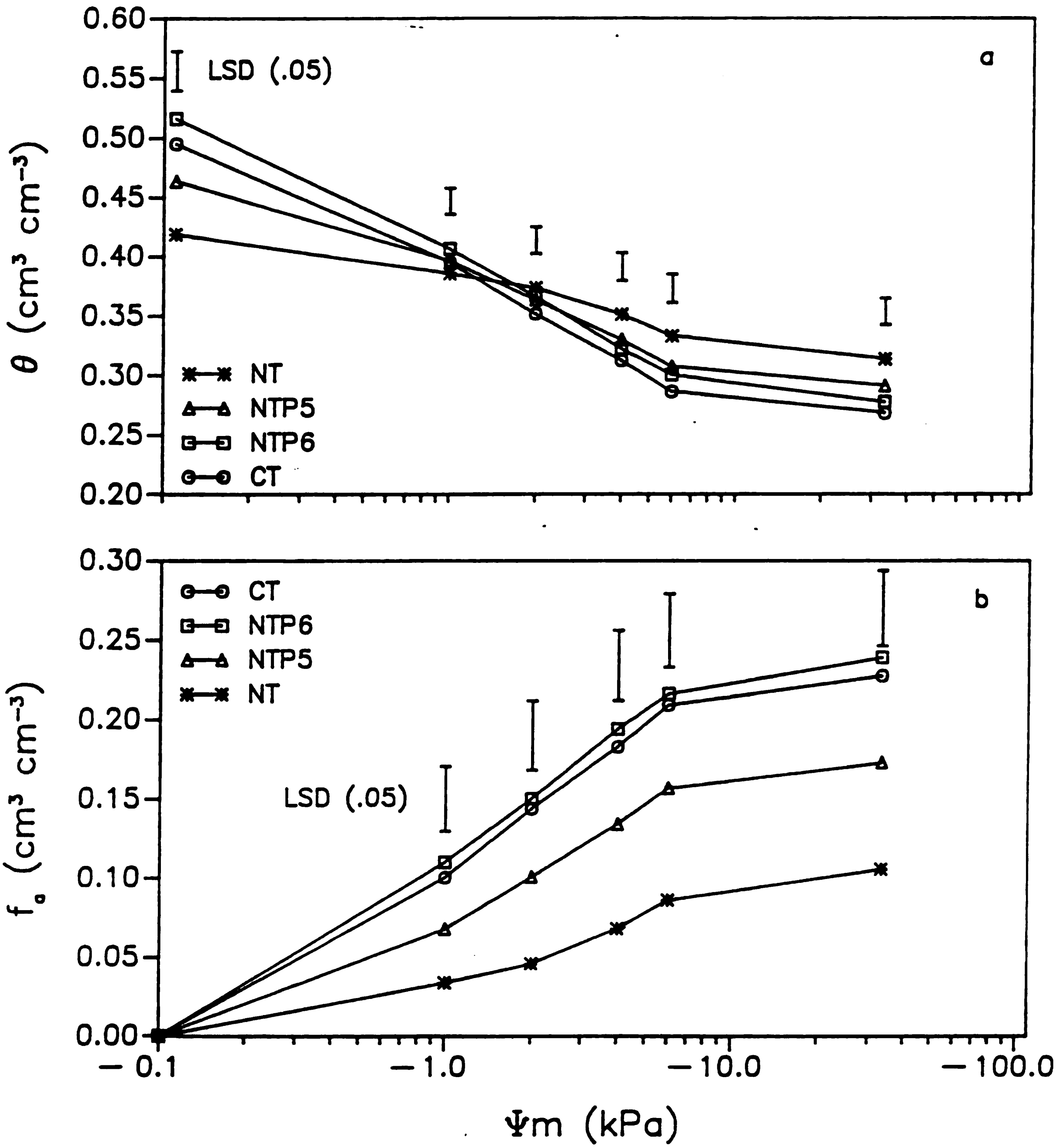

Figure 11. Tillage effects on moisture retention (a) and air-filled porosity (b) at the 7.5 to 15 cm depth from 7/14/87.

The air-filled porosity data is presented in figures 6, 7, 8, 9, 10, and 11. On all dates and at all depths, plowing significantly increased the air-filled porosity over all matric potentials compared to the NT treatment.

In 1987, after returning to no-till for one year, the NTP5 treatment had a higher percentage of air-filled pores than the NT treatment. At the 0 to 7.5 cm depth, the NTP5, NTP6, and CT treatments were not significantly different. At the 7.5 to 15 cm depth, the NTP5 treatment had a significantly lower percentage of air-filled pores than the NTP6 treatment.

In 1986, the NT treatment contained fewer than 10 percent air-filled pores at both depths for the -6 kPa matric potential. When air-filled porosity is less than 10 percent, gas exchange and plant growth can be reduced (Vomocil and Flocker, 1961). The NTP5 treatment doubled the volume of air-filled pores at the -6 kPa matric potential over that of the NT treatment. This was true for both sampling depths.

In 1987, the NT treatment contained fewer than 10 percent air-filled pores only at the 7.5 to 15 cm depth for the -6 kPa matric potential. The volume of air-filled pores at -6 kPa was increased in the NTP6 treatment by a factor of 1.8 at the 0 to 7.5 cm depth and by a factor of 2.5 at the 7.5 to 15 cm depth over that of the NT treatment.

Plowing significantly increased the air-filled porosity over that of the continuous no-till (NT). But most importantly, it increased the volume of air-filled pores at the soil's field capacity. This would indicate that plowing may reduce the frequency and duration of aeration stresses.

The total porosity data for 1986 and 1987 are presented in tables 2 and 3 respectively. In 1986, the NTP5 treatment contained significantly more total pore volume than the NT treatment at the 0 to 7.5 cm and the 7.5 to 15 cm depths.

In 1987, the NTP6 treatment contained the highest percentage of pore space at both depths. However, at the 0 to 7.5 cm depth, the NTP6, NTP5, and CT treatments were similar and significantly higher than the NT treatment. At the 7.5 to 15 cm depth, NTP6 contained significantly more total pore volume than NTP5 and NT but not CT. However, NTP5 contained significantly more pore space than NT: .46 $cm^3\ cm^{-3}$ and .42 $cm^3\ cm^{-3}$ respectively.

Saturated hydraulic conductivity (Ksat) is a measure of the soil's ability to transmit water under saturated conditions. The 1986 data is presented in Table 2 and the 1987 data can be found in Table 3. The Ksat values were not significantly different between tillage treatments in the June 1986 sampling. However, plowing significantly increased the Ksat in the NTP5 treatment in September of 1986 over those of the NT and CT treatments at the 0 to 7.5 cm depth. In the 0 to 7.5 cm depth the Ksat values were 9.00 cm hr^{-1} for the NT treatment and 46.50 cm hr^{-1} for the NTP5 treatment. At the 7.5 to 15 cm depth, Ksat was 1.95 cm hr^{-1} and 9.60 cm hr^{-1} for NT and NTP5 respectively. These were significantly different. In 1987, the NTP5 treatment had significantly higher Ksat values than the NT treatment at the 0 to 7.5 cm depth but not at the 7.5 to 15 cm depth.

Ksat is correlated with the size of the soil pores. Large pores conduct more water under saturated conditions than small pores. Ksat is also a function of the continuity and tortuosity of the pores.

Table 2. Total porosity and saturated hydraulic conductivity (Ksat) from 6/21/86 and 9/16/86.

Tillage	Depth (cm)	Total Porosity ($cm^3\ cm^{-3}$)	Ksat ($cm\ hr^{-1}$)
		6/21/86	
	0-7.5		
CT		.48 ab	3.93 a
NTP5		.49 a	5.88 a
NT		.46 b	3.98 a
LSD (.05)		.03	2.36
	7.5-15		
CT		.47 b	4.08 a
NTP5		.50 a	8.26 a
NT		.42 c	8.70 a
LSD (.05)		.03	7.91
		9/16/86	
	0-7.5		
CT		.48 a	20.85 b
NTP5		.49 a	46.50 a
NT		.44 b	9.00 b
LSD (.05)		.02	17.10
	7.5-15		
CT		.46 a	16.35 a
NTP5		.46 a	9.60 a
NT		.39 b	1.95 b
LSD (.05)		.02	7.05

Means in each column which are not followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Table 3. Total porosity and saturated hydraulic conductivity (Ksat) from 7/14/87.

Tillage	Depth (cm)	Total porosity (cm^3 cm^{-3})	Ksat (cm hr^{-1})
	0-7.5		
CT		.48 a	26.2 ab
NTP6		.50 a	32.0 a
NTP5		.48 a	20.4 b
NT		.45 b	7.3 c
LSD (.05)		.03	8.4
	7.5-15		
CT		.49 ab	30.7 a
NTP6		.52 a	32.7 a
NTP5		.46 b	17.0 ab
NT		.42 c	3.4 b
LSD (.05)		.033	16.3

Means in each column which are not followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

During a rain or an irrigation event, the surface of the soil becomes saturated. The ability of water to infiltrate through this saturated soil layer is largely controlled by the Ksat of the soil. Plowing significantly increased the Ksat values compared to those of the continuous no-till.

Tire Traffic Effects on Soil Physical Properties

Wheel traffic significantly increased the bulk density of the plowed treatments at the 0 to 7.5 cm and the 7.5 to 15 cm depths (Figures 12 and 13). However, the bulk density of the NT treatment was not significantly affected by wheel traffic. Tire traffic increased D_b in the plowed treatments by at least .15 g cm^{-3} at all sampling dates and depths, with the exception of the 7.5 to 15 cm depth on 9/16/86 where the increase was .07 g cm^{-3}.

Pore size distribution was significantly altered by wheel traffic in the CT and NTP5 treatments. The NT treatment was not significantly affected by wheel traffic at either depth or sampling time or for any pore class. These trends are demonstrated by Figures 14 through 17. The volume of soil occupied by pores with radii greater than 146 um was cut in half in the CT and the NTP5 treatments at all sampling times and for both sampling depths. With the exception of the 0 to 7.5 cm depth of the 9/16/86 sampling, the pore volume occupied by pores with radii in the range from 146 to 24 um was significantly reduced in the CT and NTP5 treatments. This reduction was on the order of 25 percent. At both sampling depths, the volume of soil occupied by pores with radii less than 24 um was increased by wheel traffic in the CT and NTP5 treatments. Wheel traffic decreased the volume of soil occupied by pores larger than 24 um and increased the volume of soil occupied by

BULK DENSITY (g cm^{-3})

BULK DENSITY (g cm^{-3})

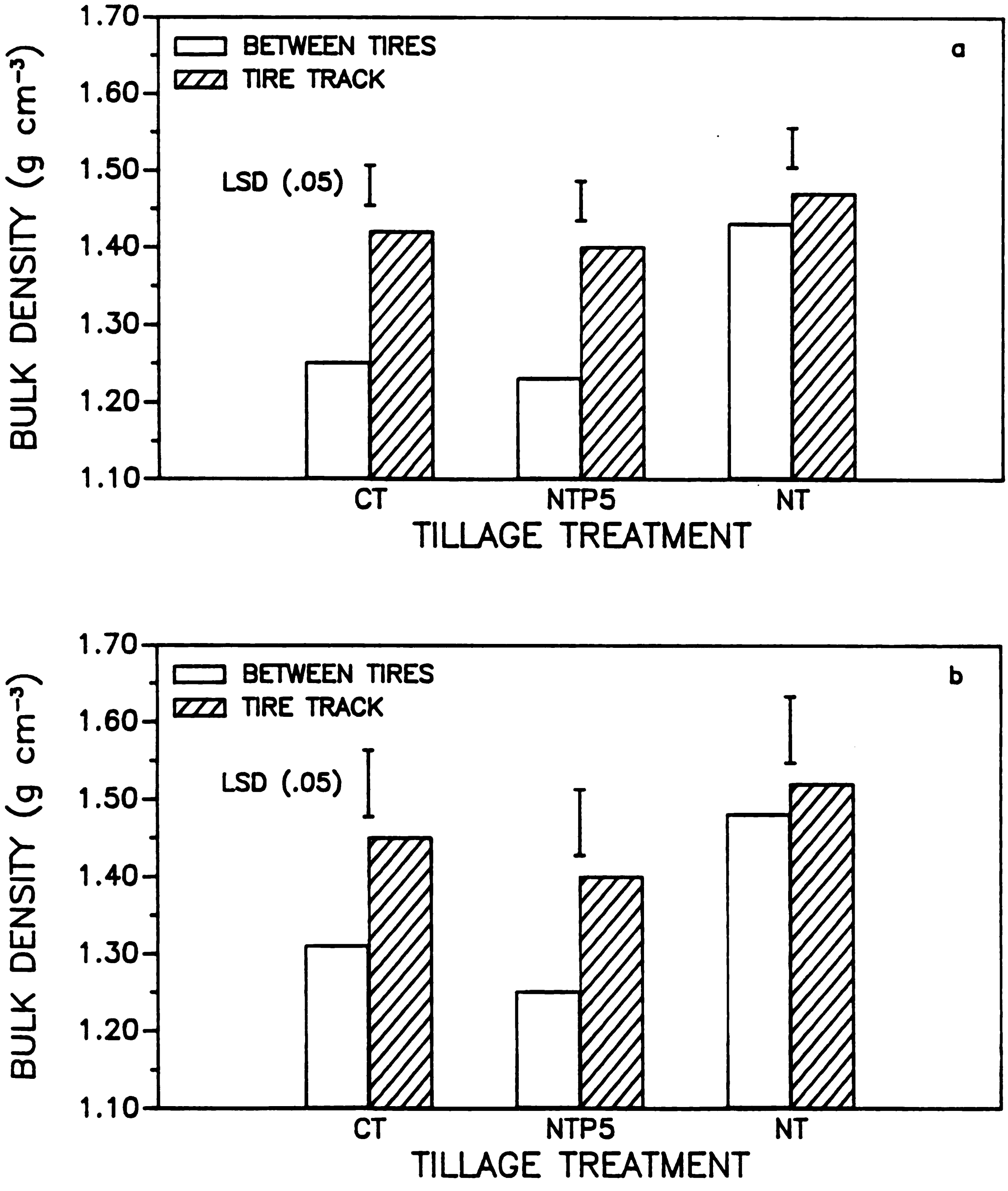

Figure 12. Tire traffic effects on bulk density at the 0 to 7.5 cm depth (a) and the 7.5 to 15 cm depth (b) from 6/21/86.

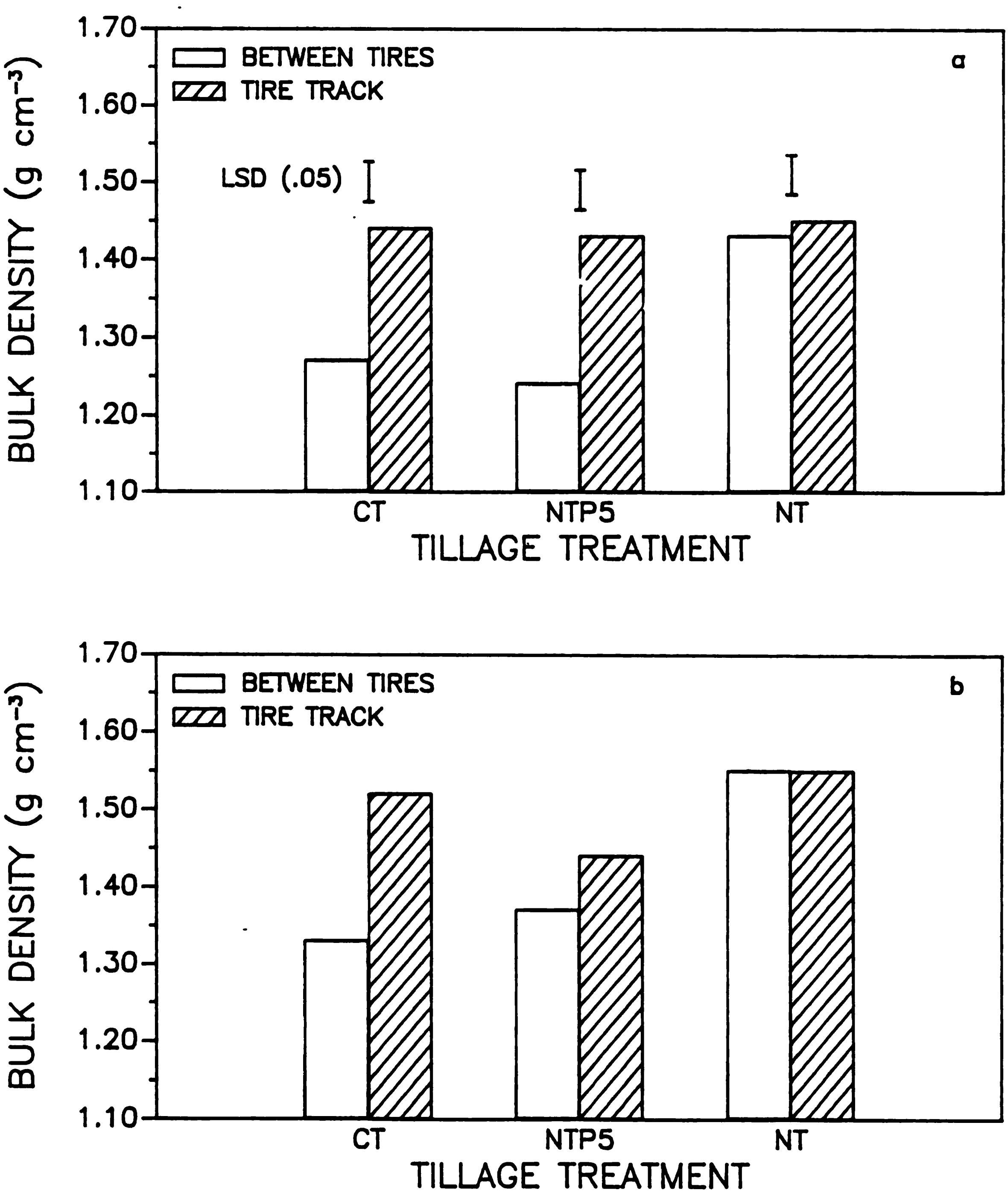

Figure 13. Tire traffic effects on bulk density at the 0 to 7.5 cm depth (a) and the 7.5 to 15 cm depth (b) from 9/16/86.

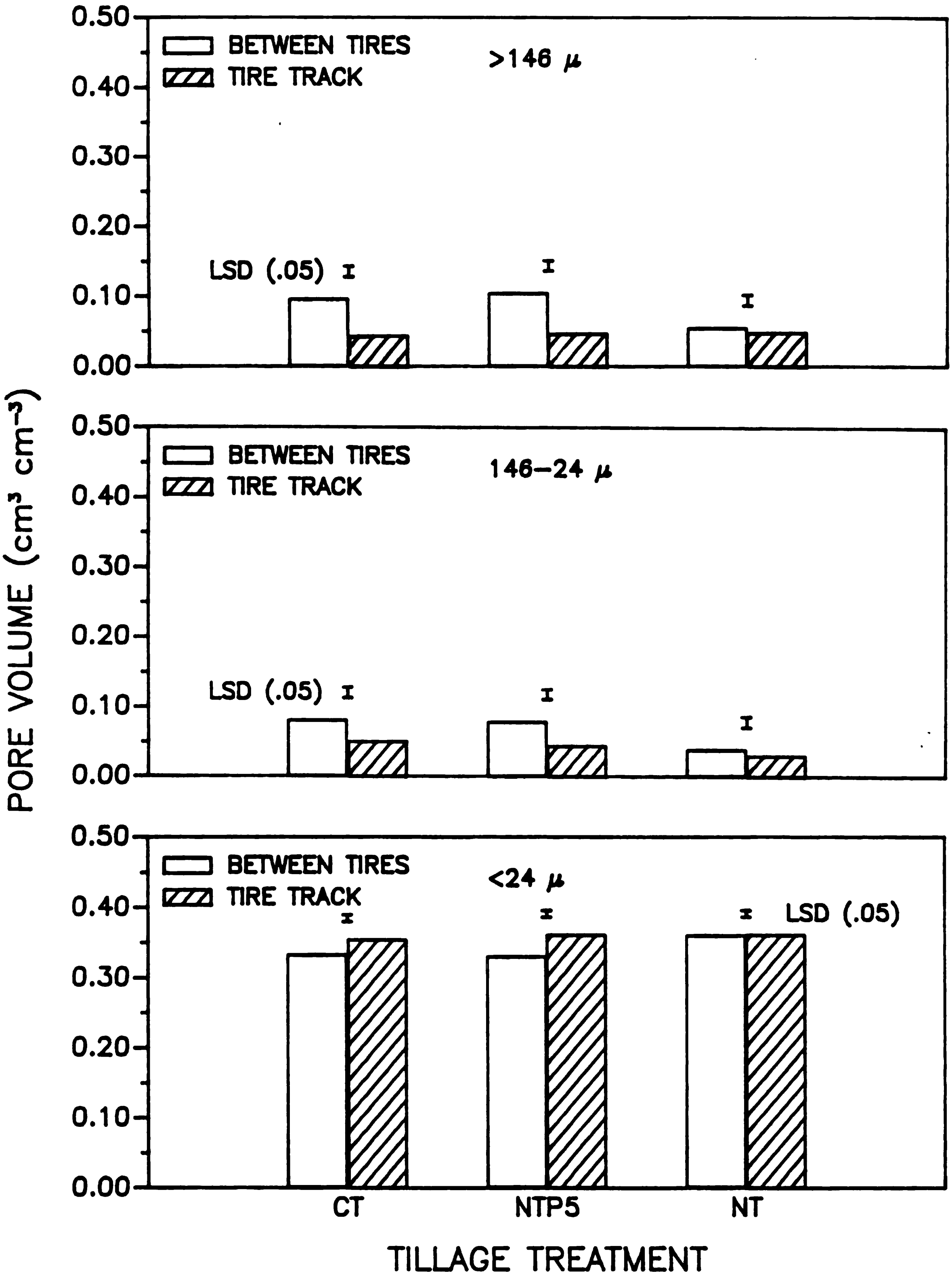

Figure 14. Tire traffic effects on the pore size distribution at the 0 to 7.5 cm depth from 6/21/86.

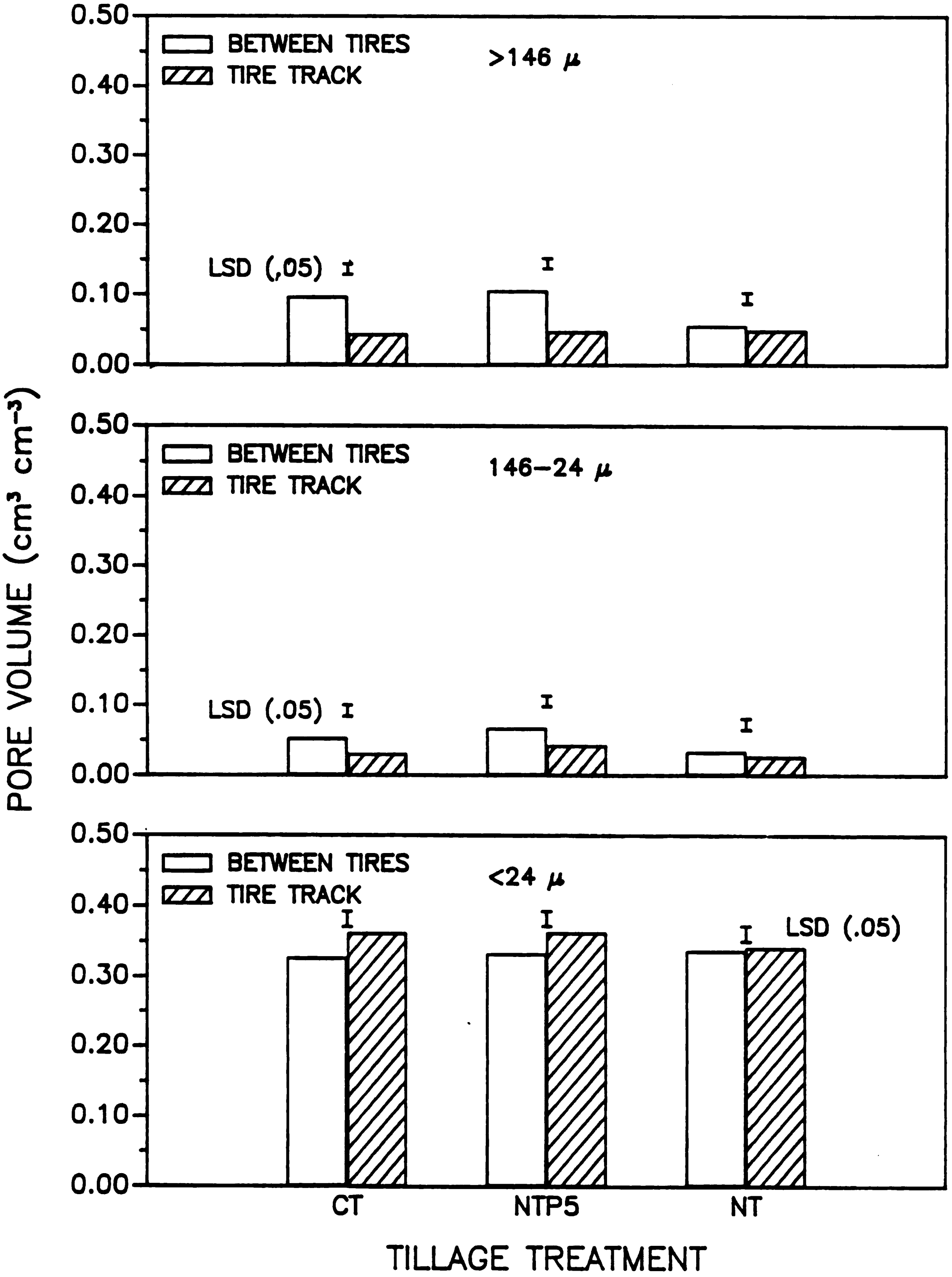

Figure 15. Tire traffic effects on the pore size distribution at the 7.5 to 15 cm depth from 6/21/86.

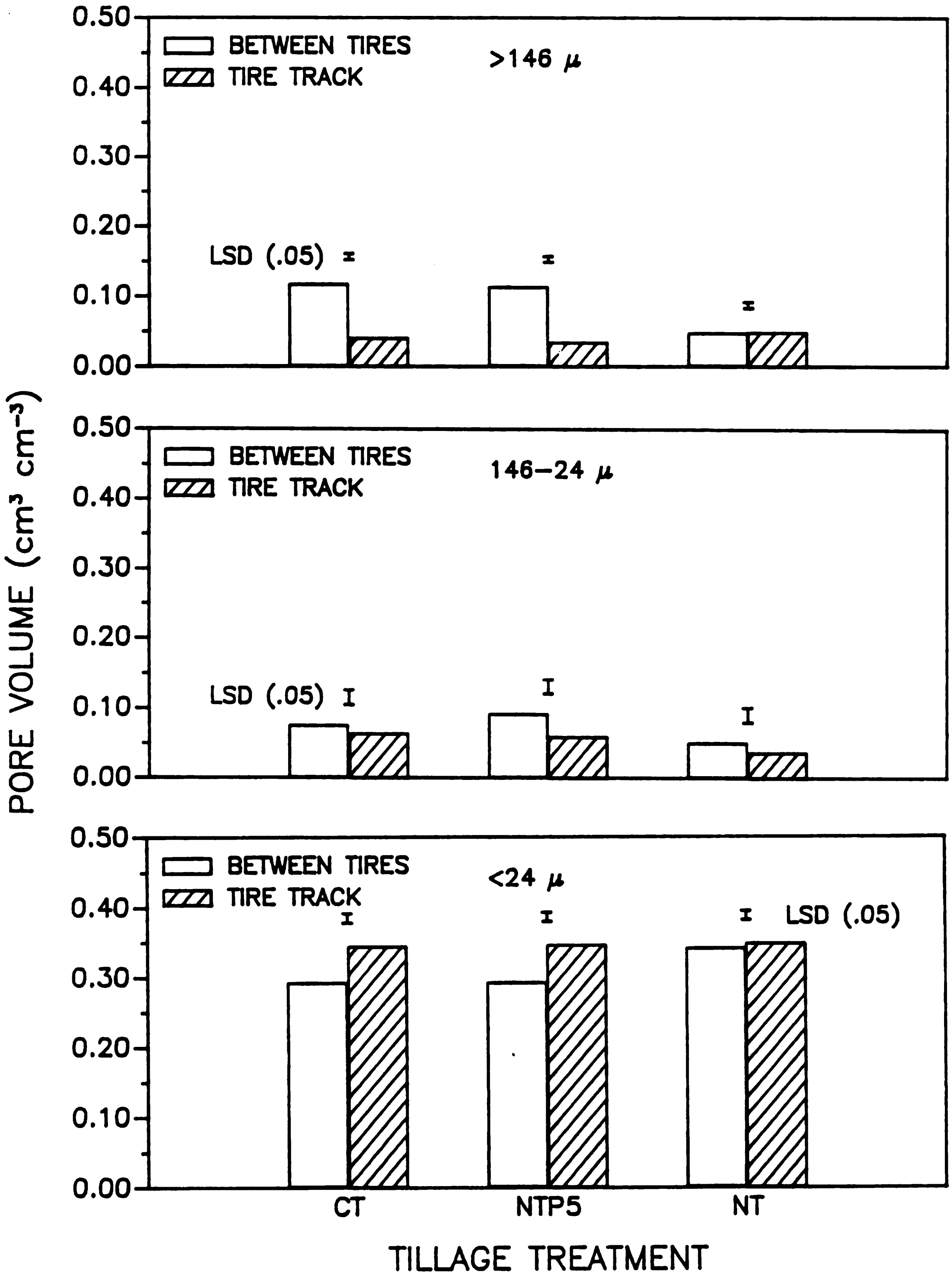

Figure 16. Tire traffic effects on the pore size distribution at the 0 to 7.5 cm depth from 9/16/86.

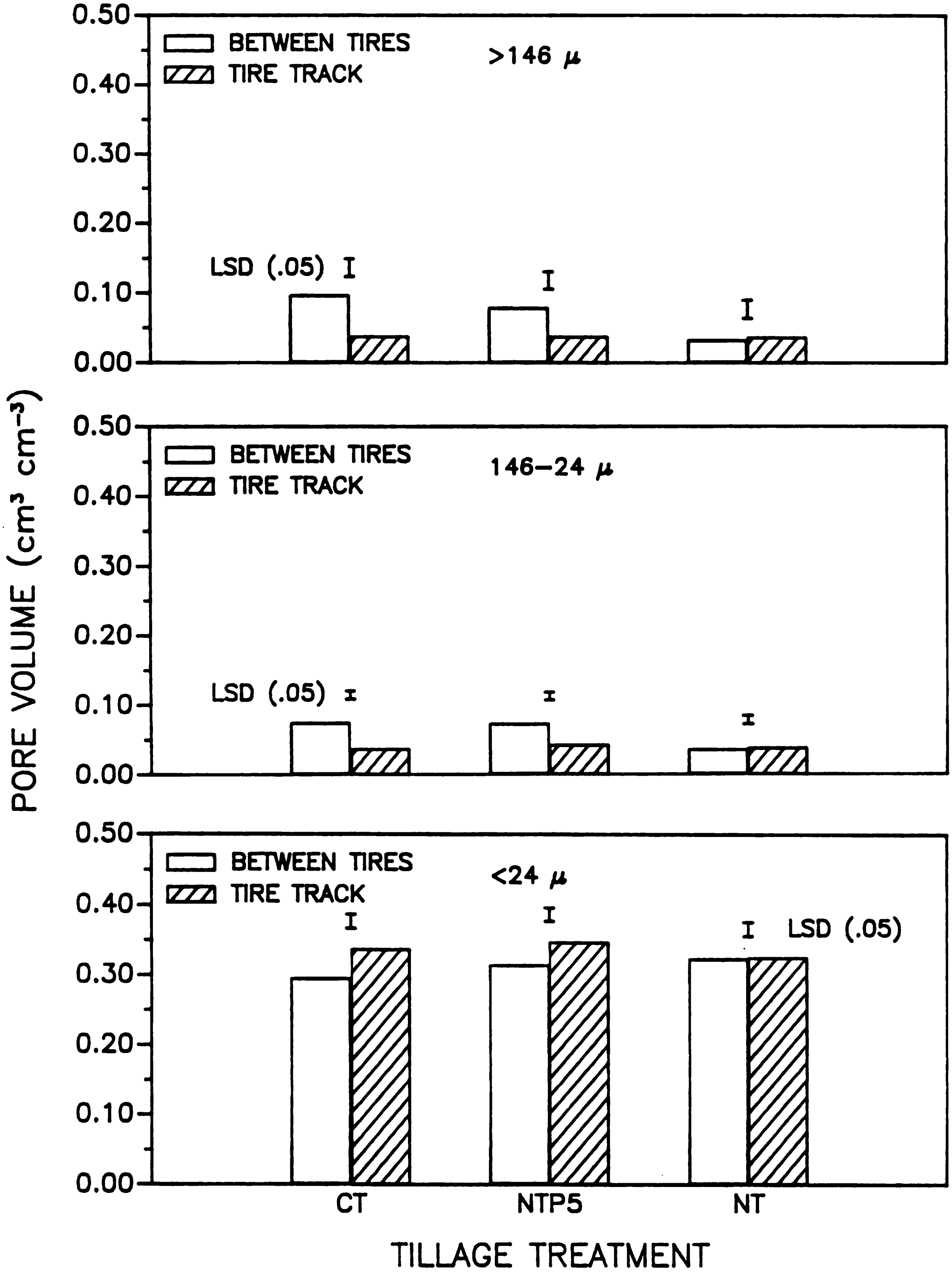

Figure 17. Tire traffic effects on the pore size distribution at the 7.5 to 15 cm depth from 9/16/86.

pores with radii less than 24 um in the plowed treatments. However, the NT treatment was not significantly affected by wheel traffic.

Wheel traffic significantly reduced the total pore volume of the CT and the NTP5 treatments, but had no effect on the NT treatment (Tables 4 and 5). This was true for both sampling dates and both sampling depths. The reduction ranged from .03 cm^3 cm^{-3} to .05 cm^3 cm^{-3}.

Ksat was significantly affected by wheel traffic in the CT and NTP5 treatments, but not in the NT treatment (Tables 4 and 5). At the 0 to 7.5 cm depth, Ksat was significantly reduced by wheel traffic for the CT and NTP5 treatments. At the 7.5 to 15 cm depth, wheel traffic significantly reduced the Ksat values of the CT treatment from the 9/16/86 sampling only. Wheel traffic compaction decreased the Ksat values of the plowed treatments at the soil surface. This could cause reduced infiltration and increased surface runoff.

Chemical Properties

In 1986, no significant differences were found in nitrogen mineralization between tillage treatments (see Appendix Figure 1). However in 1987, tillage did significantly affect nitrogen mineralization in the spring as illustrated in Figure 18. At the 0 to 5 cm sampling depth, NTP5 consistantly had the lowest inorganic N content. This was in contrast to the N mineralization pattern observed in 1986 (see Appendix Figure 1). Plowing significantly increased the inorganic N content of the NTP6 treatment over that of the NT on the last four sampling dates. The difference between NTP6 and NT ranged from 6.6 ug g^{-1} on 4/17 to 13.2 ug g^{-1} on 4/30. At the 5 to 10 cm depth, the NTP6 treatment had the highest inorganic N content on all six sampling dates. NTP6 was significantly higher than NT on 4/17 and

Table 4. Total porosity and saturated hydraulic conductivity (Ksat) from 6/21/86 compared between tire tracks and non-tire tracks.

Tillage	Depth (cm)	Between tires	Tire track
	0-7.5	Total porosity	
		---------- cm^3 cm^{-3}	----------
CT		.48 a	.45 b
NTP5		.49 a	.45 b
NT		.46 a	.45 a
	[1]LSD (.05)	.019	
	7.5-15		
		---------- cm^3 cm^{-3}	----------
CT		.47 a	.43 b
NTP5		.50 a	.45 b
NT		.42 a	.41 a
	[1]LSD (.05)	.029	
	0-7.5	Ksat	
		----------- cm hr^{-1}	----------
CT		3.93 a	1.28 b
NTP5		5.88 a	.95 b
NT		3.98 a	2.88 a
	[1]LSD (.05)	2.63	
	7.5-15		
		----------- cm hr^{-1}	----------
CT		4.08 a	3.38 a
NTP5		8.26 a	2.70 a
NT		8.70 a	5.03 a
	[1]LSD (.05)	8.32	

Means in each row which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test. [1]LSD for comparing two location means at the same level of tillage.

Table 5. Total porosity and saturated hydraulic conductivity (Ksat) from 9/16/86 compared between tire tracks and non-tire tracks.

Tillage	Depth (cm)	Between tires	Tire track
	0-7.5	Total porosity	
		---------- $cm^3\ cm^{-3}$	----------
CT		.48 a	.45 b
NTP5		.49 a	.44 b
NT		.44 a	.43 a
	[1]LSD (.05) .015		
	7.5-15		
		---------- $cm^3\ cm^{-3}$	----------
CT		.46 a	.41 b
NTP5		.46 a	.43 b
NT		.39 a	.40 a
	[1]LSD (.05) .014		
	0-7.5	Ksat	
		----------- $cm\ hr^{-1}$	----------
CT		20.85 a	5.40 b
NTP5		46.50 a	5.55 b
NT		9.00 a	5.70 a
	[1]LSD (.05) 15.29		
	7.5-15		
		----------- $cm\ hr^{-1}$	----------
CT		16.35 a	4.80 b
NTP5		9.60 a	4.35 a
NT		1.95 a	1.95 a
	[1]LSD (.05) 8.32		

Means in each row which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test. [1]LSD for comparing two location means at the same level of tillage.

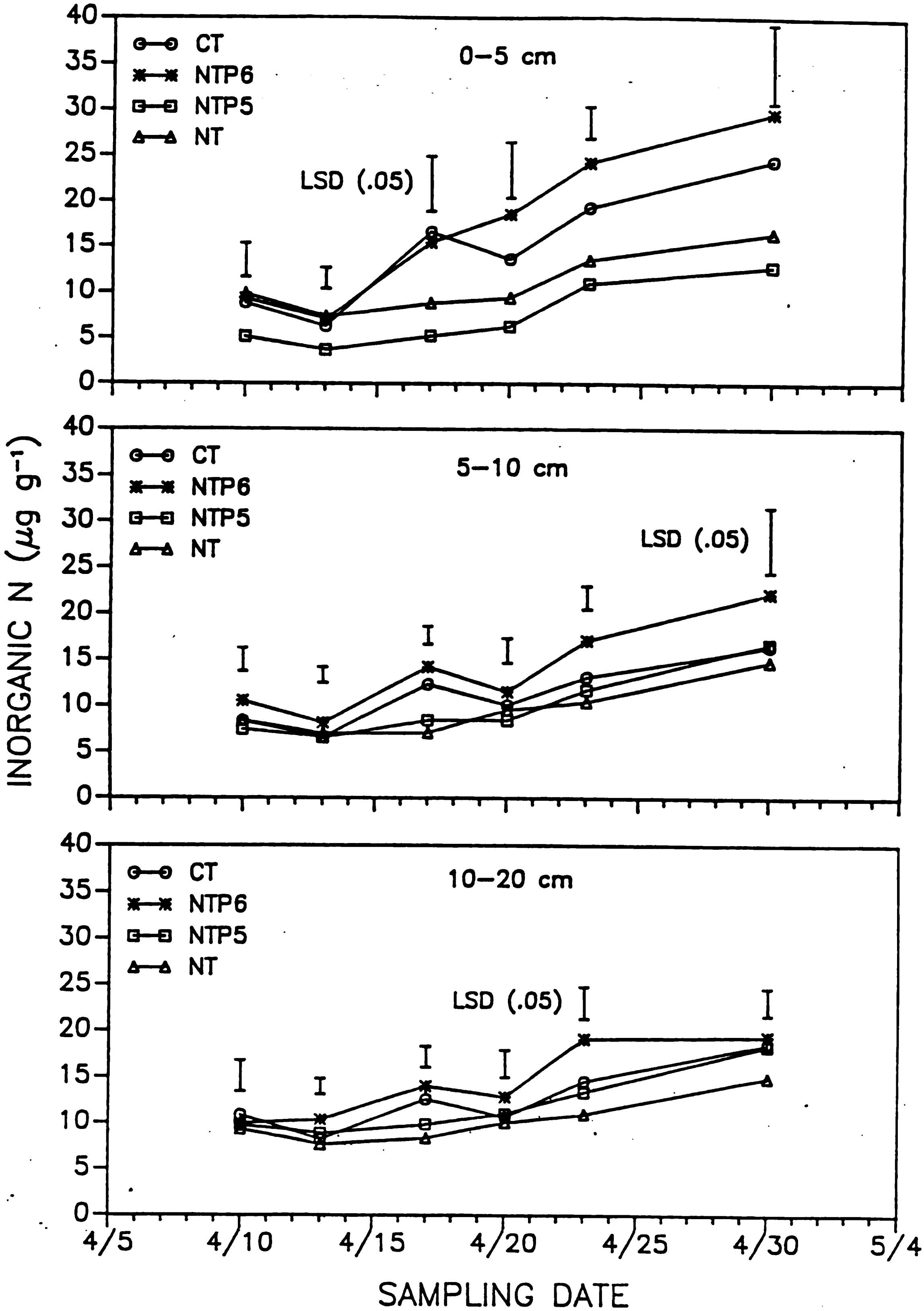

Figure 18. Inorganic nitrogen content at three depths as affected by tillage from 1987.

4/23. The minimum difference was 6.5 ug g^{-1}. At the 10 to 20 cm depth, the inorganic N content was the highest for the NTP6 treatment on the last five sampling dates. NTP6 was significantly higher than NT on 4/13, 4/17, 4/23, and 4/30. The difference between NTP6 and NT ranged from 2.7 ug g^{-1} on 4/13 to 8.15 ug g^{-1} on 4/23.

No-tillage can reduce N mineralization by decreasing the availability of organic N (Phillips and Phillips, 1984). Plowing increases the soil-residue contact which increases the availability of organic N. Plowing increases the soil aeration which leads to an increase in the population of the aerobic nitrifiers. The bare surface of the plowed soil allows the temperature to increase more rapidly than on a no-till soil. This can cause higher N mineralization rates particularly in temperate climates.

Therefore more N is mineralized from the soil reserves when no-till is plowed. This could potentially reduce the application rate of N fertilizer after plowing of a no-till field.

The organic carbon contents of the tillage treatments were determined in the spring of 1987 and are presented in Figure 19. At the 0 to 5 cm sampling depth, NT had significantly more organic carbon than the other treatments. NT was 3 g kg^{-1} higher than NTP6 and 5 g kg^{-1} higher than CT. This agrees with other reports of organic carbon accumulations at the surface of no-till soils (Blevins et al., 1977; Juo and Lal, 1979; and Dick, 1983). Dick (1983) stated that the reduced soil-residue contact, reduced soil erosion, and reduced biological oxidation found in no-tillage soils led to this accumulation of organic carbon on the surface. At the 5 to 10 cm depth, no significant differences occurred. However, the NTP6 and NTP5 treatments had the highest organic carbon

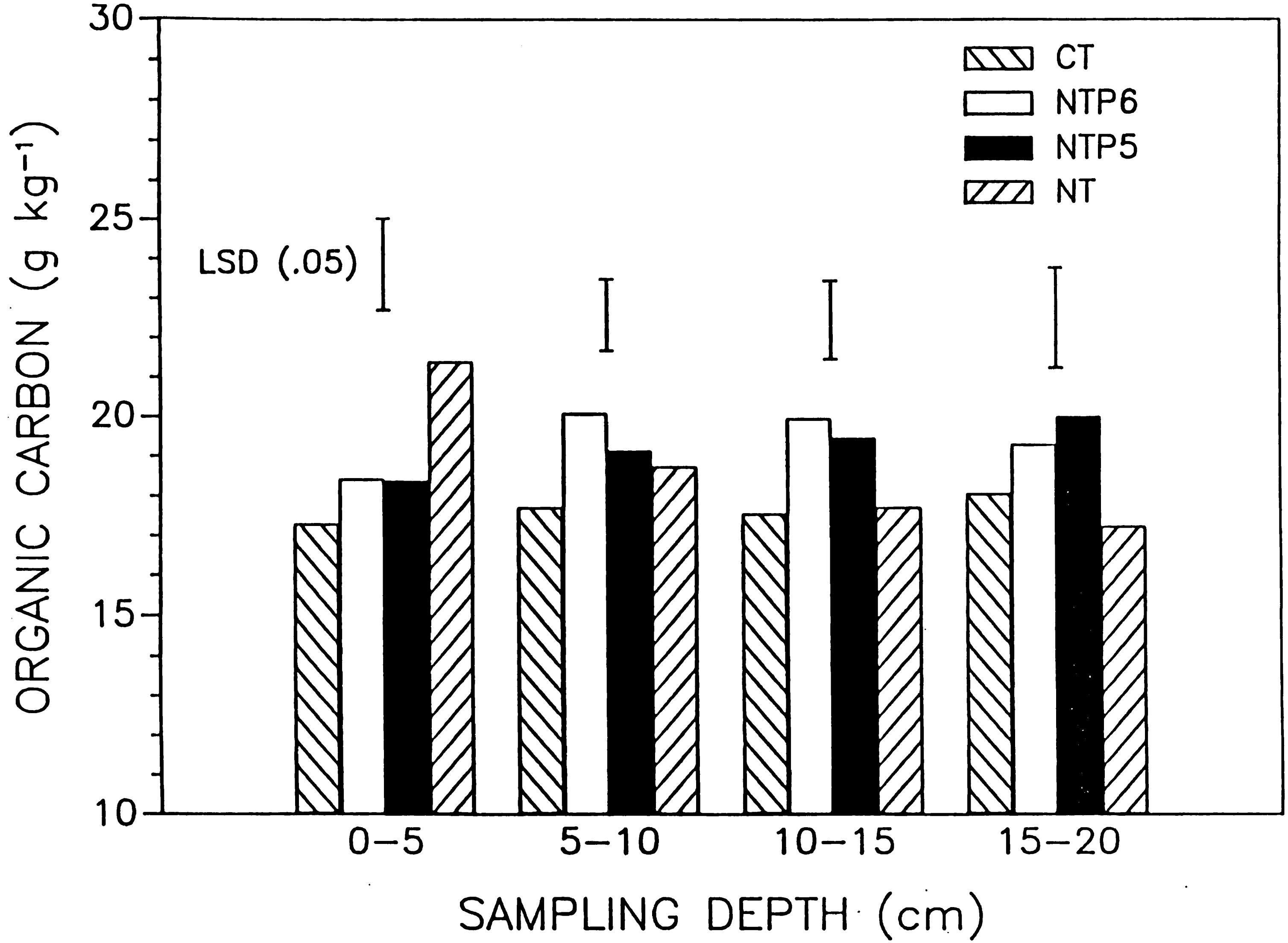

Figure 19. Organic carbon contents at four depths as affected by tillage from 4/10/87.

contents. At the 10 to 15 cm depth, NTP6 contained significantly higher amounts of organic carbon than CT. Both the NTP6 and NTP5 treatments contained more organic carbon than NT. At the 15 to 20 cm depth, NTP6 and NTP5 contained the most organic carbon. However, the difference was not significant at the five percent probability level.

Plowing tended to mix the organic carbon-rich surface layer found in the NT treatment throughout the plow layer. This process is demonstrated by the data in Figure 19. Organic carbon is important in maintaining good soil structure. The primary cementing agents which hold aggregates together are microbial gums (Foth, 1978). These are produced by microbes feeding on the organic carbon. Periodic plowing of no-tillage could lead to improved soil structure by distributing the carbon throughout the plow layer.

The effect of tillage on soil pH determined on samples obtained on 4/10/87 is illustrated by data given in Table 6. In the surface 5 cm, NT was found to have the lowest pH. This difference was significant at the five percent level. This agrees with the reports of Shear and Moschler (1969), Blevins et al.(1977), and Dick (1983), who reported that no-till soils had lower pH values at the surface than conventionally tilled soils. This process is attributed to the broadcast application of acidifying nitrogen fertilizer on the surface of no-tilled soils (Blevins, et al., 1977; and Letaw, et al., 1984) These acidic conditions can be harmful to crop growth. Low pH conditions can cause aluminum toxicity (Tisdale and Nelson, 1985), poor weed control by deactivating herbicides, and inhibiting nitrification (Tisdale and Nelson, 1985). No significant differences occurred between treatments at the lower three depth increments.

Table 6. Soil pH, phosphorus content, and potassium content from 4/10/87.

Tillage	Depth (cm) 0-5	5-10	10-15	15-20
		Soil pH		
CT	6.2 a	6.2 a	6.1 a	6.2 a
NTP6	6.1 a	5.8 a	5.8 a	6.1 a
NTP5	6.0 a	6.2 a	6.2 a	6.1 a
NT	5.5 b	6.0 a	6.4 a	6.4 a
LSD (.05)	.5	.5	.5	.6
		Phosphorus		
	----------	mg kg^{-1}	----------	
CT	113 a	112 a	117 a	107 a
NTP6	103 a	134 a	120 a	115 a
NTP5	91 a	116 a	109 a	131 a
NT	118 a	103 a	88 a	89 a
LSD (.05)	54	54	32	35
		Potassium		
	----------	mg kg^{-1}	----------	
CT	101 c	110 b	135 ab	135 a
NTP6	124 bc	159 a	164 a	158 a
NTP5	131 b	110 b	122 b	135 a
NT	177 a	133 ab	112 b	92 b
LSD (.05)	26	27	33	29

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Plowing buried and mixed the acidic surface layer of the NT treatment, thus eliminating any potential adverse plant responses.

The exchangeable potassium (K) contents of the four tillage treatments are presented in Table 6. In the surface 5 cm, NT contained significantly greater exchangeable K concentrations than the other three tillage treatments. In the 5 to 10 cm depth, the NTP6 treatment contained significantly more exchangeable K than either the NTP5 treatment or the CT treatment. At the 10 to 15 cm depth, the NTP6 treatment contained more K than the other treatments. The differences between the NTP6 and the NT and NTP5 treatments were significant at the five percent probability level. At the 15 to 20 cm depth, the exchangeable K contents for the CT, NTP6, and NTP5 treatments were similar and significantly higher than the NT treatment.

Potassium has been shown to accumulate at the surface of no-till soils (Shear and Moschler, 1969; Triplett and Van Doren, 1969; Fink and Wesley, 1974; Juo and Lal, 1979; and Hargrove, 1985). This accumulation is attributed to the fact that K is a relatively immobile nutrient and remains at the soil surface when K fertilizers are broadcast applied to no-till soils. The NT treatment had the greatest amount of exchangeable K at the surface and the least amount at the 15 to 20 cm depth. Plowing tended to decrease the K content of the surface and distribute it throughout the plow layer. Research has shown that in terms of plant uptake, the nutrient layering which occurs when K fertilizer is broadcast on no-till fields does not present a problem where soil test levels are adequate. This was because plant roots tended to proliferate in the nutrient-rich surface layer.

The phosphorus (P) concentration of the four tillage treatments presented in Table 6 are all at high soil test levels. No significant differences were found between the four tillage treatments. This could be attributed to the fact that P fertilizer was banded near the row and the sampling was performed between the rows in the NT plots.

Plant Response and Yields

Corn seedling emergence data are given in Table 7. Tillage did not significantly affect the emergence of corn seedlings in 1986. However, seedling emergence was significantly affected by tillage in 1987 (Table 8). At 15 days after planting, the NT treatment had less than half the number of seedlings as either the CT treatment or the NTP6 treatment. At 22 days after planting, the NT treatment had approximatly 15,000 fewer plants than either CT or NTP6. The NTP5 treatment had significantly fewer seedlings at 15 days after planting than both CT and NTP6. By 19 days after planting, the plant population of the NTP5 treatment was similar to that of the CT and NTP6 treatments.

Soils under no-tillage management have been shown to warm up slower in the spring than conventional tillage (Kladivko, et al., 1986). This is caused by the surface crop residues intercepting radient energy and providing thermal insulation. Reduced soil temperatures can cause a delay in seedling emergence in no-till. Periodic plowing buries the residues which leads to increased soil temperatures favoring germination and seedling growth.

The 1986 plant tissue nitrogen concentrations are presented in Table 9. Tillage did not significantly affect the tissue nitrogen concentrations of the ear leaf, stover, or grain. This indicates that the nitrogen fertilizer application of 181 kg ha^{-1} was sufficient.

Table 7. Emergence data from 1986.

Tillage	Days after planting 12	14	17	26
	------------- plants ha^{-1}			--------------
CT	49,674 a	52,722 a	53,619 a	53,619 a
NTP6	46,984 a	56,619 a	54,516 a	54,695 a
NTP5	49,315 a	50,212 a	51,109 a	51,109 a
NT	45,908 a	50,212 a	51,288 a	51,647 a
LSD (.05)	6,758	5,895	5,453	5,595

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Table 8. Emergence data from 1987.

Tillage	Days after planting 15	17	19	22
	------------- plants ha^{-1}			--------------
CT	54,604 a	56,486 a	56,755 a	56,755 a
NTP6	57,831 a	58,907 a	58,907 a	58,907 a
NTP5	36,313 b	46,265 b	50,031 a	51,914 a
NT	24,477 c	36,313 b	40,078 b	41,692 b
LSD (.05)	11,315	10,109	9,453	8,387

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Table 9. Total nitrogen contents in ear leaf, stover, and grain from 1986.

Tillage	Plant material		
	Ear leaf	Stover	Grain
	----------------	g kg^{-1}	----------------
CT	26.55 a	7.35 a	13.10 a
NTP6	27.63 a	7.00 a	12.58 a
NTP5	24.68 a	7.60 a	13.28 a
NT	24.70 a	7.20 a	12.33 a
LSD (.05)	3.31	.99	1.06

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by duncan's Multiple Range Test.

No-till has been shown to have increased immobilization and denitrification rates and decreased rates of N mineralization when compared to conventional tillage. These processes can be important factors in determining N availability especially at low application rates. Since we applied a surplus of fertilizer N, the effects of these factors on N uptake were minimized.

Yield data for the 1986 and 1987 field seasons are presented in Table 10. The moisture content of the grain, plant populations, grain yield, and stover yield were measured and compared over tillage treatments. In 1986, tillage did not significantly affect grain moisture, plant population, or stover yield. However, grain yield was significantly different between tillage treatments. The highest yield (8.31 Mg ha^{-1}) and the lowest yield (7.46 Mg ha^{-1}) occurred in treatments NTP6 and NT respectively. Both of these treatments were in their sixth year of continuous no-till. There are no apparent explanations for this observation.

In 1987, grain moisture was significantly affected by tillage. The NTP5 and NT moisture contents were 15.8 percent and 15.6 percent respectively. These were significantly higher than either of the plowed treatments, indicating delayed maturity. This probably resulted from the reduced early growth of the seedlings in the these treatments.

The NT treatment had approximately 10,000 fewer plants ha^{-1} than the other treatments at harvest. This affected the grain yield with NT having approximately 1 Mg ha^{-1} less grain than all other treatments. The NTP5 treatment produced the highest grain and stover yields, 7.37 and 4.34 Mg ha^{-1} respectively despite having approximately 2,000 fewer plants ha^{-1} than CT or NTP6.

Table 10. Yield data from 1986 and 1987.

Tillage	Grain moisture (%)	Plant population (plants ha^{-1})	Grain yield (Mg ha^{-1})	Stover yield (Mg ha^{-1})
		1986		
CT	36.6 a	51,109 a	8.07 a	4.89 a
NTP6	37.5 a	54,875 a	8.31 a	4.95 a
NTP5	37.5 a	54,337 a	7.83 ab	5.37 a
NT	37.8 a	51,288 a	7.46 b	4.91 a
LSD (.05)	1.1	3,312	.47	1.13
		1987		
CT	14.9 b	55,233 a	6.57 ab	3.04 b
NTP6	15.0 b	56,309 a	6.75 a	3.45 b
NTP5	15.8 a	52,543 a	7.37 a	4.34 a
NT	15.6 a	43,756 b	5.74 b	3.22 b
LSD (.05)	.5	4,559	.93	.75

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

CONCLUSIONS

When a no-tilled Conover loam soil was plowed, the soil's physical properties became similar to those of a continuously plowed soil. The bulk density was significantly decreased and the pore size distribution of the soil was altered by plowing. The volume of soil occupied by pores with radii greater than 24 um was increased, while the pore volume with radii less than 24 um was decreased after plowing. The total porosity of the soil was increased significantly by plowing. The change in total porosity and pore size distribution improved the soil's ability to conduct water when saturated.

Nitrogen mineralization was increased throughout the plow layer by plowing. This was probably brought about by increasing soil-residue interaction, increasing nitrifier populations, increasing soil temperature, and increasing the air-filled volume of the soil. Plowing redistributed P and K stratification throughout the plow layer. The acidic surface layer found in the NT plots was buried and mixed throughout the plow layer.

Plowing distributed the high organic matter surface layer found in NT throughout the plow layer. This material is converted to microbial gums which cement aggregates together (Foth, 1978). Thus, plowing this high carbon layer down and returning to no-tillage for five or more years could eventually lead to improved soil structure.

Wheel traffic compaction significantly affected the plowed soil, but not the NT soil. Soil bulk density was increased by wheel traffic. Pore size distribution was significantly affected. There was a decrease in the volume of pores greater than 24 um and an increase in the volume of pores with radii less than 24 um. Total porosity was also significantly reduced in the wheel track. These reductions in total porosity and the volume of large pores could potentially cause aeration problems. The saturated hydraulic conductivity of the wheel track was significantly reduced, thus possibly causing a reduction in infiltration and an increase in surface runoff and soil erosion.

The 1986 emergence data showed no significant differences to exist between tillage treatments. However in 1987, the emergence of the two no-till treatments was delayed by as much as a week. This was probably due to lower soil temperatures.

Total nitrogen uptake was not significantly affected by tillage. This was probably due to the high application rates of nitrogen fertilizer.

Grain yields were the highest and the lowest in the NT treatments in 1986. In 1987, the plant populations were approximately 10,000 plants per hectare less than the other treatments. This resulted in a yield decrease for the NT treatment. Grain moisture was significantly higher in the two no-tillage treatments. This is probably due to the delayed emergence experienced by the plants in these treatments.

For whatever reason no-till fields are plowed, periodic plowing mixes soil nutrients, improves soil physical properties, and increases nitrogen mineralization throughout the plow layer.

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Chapter 3

Immediate and Residual Effects of Zone Tillage on Soil Physical Properties and Corn Yields

INTRODUCTION

Subsoiling is a practice used to improve soil physical conditions below the normal depth of plowing with the purpose of increasing yields. Busscher et al. (1986) found that soil strength was significantly reduced immediately following subsoiling, but after one year no residual effects were observed. Chaudhary et al. (1985) showed that subsoiling increased rooting depth and rooting density in coarse textured soils in India. Mukhtar et al. (1985) reported that subsoiling increased infiltration rates when compared to conventional tillage and no-tillage. Trouse (1983) found that subsoiling increased the availability of water to plants by two mechanisms: deeper root growth and increased soil water recharge. Grain yields have been increased by subsoiling in areas where root restricting layers exist and rainfall is limiting (Trouse, 1983; and Box et al., 1984).

Zone tillage refers to a tillage system where the rigid tines of the subsoiling tool are set at the same spacing as the crop rows. This allows the crop row to be planted directly above the loosened zone. This practice has been widely used on the coastal plain soils of the southeastern United States. These soils have a dense A2 horizon which restricts root growth and water movement (Campbell, 1974). These properties cause yields to be reduced when rainfall is limited.

Normally, to achieve maximum shattering, subsoiling should be performed when the soil is dry (Spoor and Godwin, 1978). This condition rarely occurs in the spring in Michigan.

The objectives of this research were to: 1) determine if satisfactory soil loosening can be achieved by spring subsoiling operations; 2) determine if the loosened zone created by subsoiling will persist for one or two years after the initial tillage operation was performed; and 3) determine the effects of zone tillage on corn production and yield.

MATERIALS AND METHODS

The experiment was conducted from 1985 to 1988 on the research plots of Michigan State University. The soil at the experimental site was a Riddles (Fine-Loamy, Mixed, Mesic, Typic Hapludalf) and is naturally well drained. The experiment covered four adjacent ranges: A-3, A-4, B-3, and B-4.

Zone tillage (subsoiling in the row) was evaluated against chisel plowing (CP) and no-tillage (NT) in each of three years. Zone tillage was accomplished with a Bushhog Ro-Till and a Howard Paraplow in 1985 and 1986. The Ro-Till (RT) and Paraplow (PP) are rigid tined subsoilers which operated at depths of 30 to 45 cm. In 1987, the Paraplow was replaced with the Tye Paratill which had the same tine design as the Paraplow. The Ro-Till was set at the 76 cm tine spacing for all years of the experiment.

In the spring of 1985, the four treatments implemented in range A-4 were CP, NT, RT, and the Paraplow at the 51 cm tine spacing (PP51).

In the spring of 1986, five tillage treatments were implemented in ranges A-3 and B-3: CP, NT, RT, the Paraplow at the 51 cm tine spacing (PP51), and the Paraplow at the 76 cm tine spacing (PP76).

In 1986, only the CP treatment from range A-4 was tilled. The two subsoiled treatments were planted as no-tillage. Wheel traffic was controlled in all plots so that the vehicle tires remained in the previous year's tracks.

Four tillage treatments were implemented on range B-4 in the spring of 1987. These were: CP, NT, RT, and PT76 (the Paratill at the 76 cm tine spacing). In 1987, both the subsoiling treatments from 1985 and 1986 were planted as no-tillage. Vehicle traffic was restricted to the previous years' tire tracks.

Corn was planted on range A-4 for all three years of the experiment. Ranges A-3 and B-3 were planted to corn in the 1986 and 1987 field seasons. Corn was planted on range B-4 only in 1987. A Buffalo no-till planter set to deliver 65,000 seeds ha^{-1} was used in all three years of the experiment. The row spacing was 76 cm and every effort was made to plant the row directly over the loosened zone in all subsoiled treatments having 76 cm tine spacings. Pioneer 3744 seed corn was planted in 1986 on May 12. In 1987, Pioneer 3737 was planted on April 28.

Chemical weed control was employed in all years and involved the following herbicides and application rates: 5.8 liter alachlor ha^{-1}, 2.3 liter atrazine ha^{-1}, and 3.5 liter cyanazine ha^{-1}. Paraquat was applied at 2.3 liter ha^{-1} to the no-till plots. These chemicals and rates were applied in all years of the experiment. The same fertilizers and application rates were applied to all the plots. During planting, 13 kg N ha^{-1} and 19 kg P ha^{-1} as ammonium polyphosphate were banded near the row. Ammonium nitrate was surface broadcast at the rate of 168 kg N ha^{-1} prior to seedling emergence.

The number of plants emerged in two 20-foot rows were recorded in 1986 for ranges A-3 and B-3, and in 1987 for range B-4. In 1986, emergence counts were made 16, 18, and 21 days after planting. In 1987, seedling emergence was monitored 15, 17, 19, and 21 days after planting. In 1986, corn earleaf samples were taken when 50 percent of the plants were silking. Fifteen leaves, sampled opposite and below the ear, comprised a composite sample from each plot. Grain and stover were hand-harvested from two 30-foot rows in the center of each plot. In 1986, the earleaf, grain, and stover from the 1985 and 1986 tillage plots were analyzed for total nitrogen.

In May and June of 1987, intact soil cores were sampled from all ranges. The sampling depths were 0 to 7.5 cm, 7.5 to 15 cm, and 22.5 to 30 cm. Thirteen cores were sampled from each plot: six cores from the surface, four cores at the 7.5 to 15 cm depth, and three cores at the 22.5 to 30 cm depth. In the subsoiled treatments, care was taken to ensure that the cores were sampled from the loosened zones. In the CP and NT treatments, the cores were sampled from the non-wheel-tracked areas of the plots. Initially, only the NT and CP treatments from the 1987 tillage treatments were sampled. However, in December of 1987, the NT and CP treatments from the 1985 and 1986 tillage plots were sampled. Only the 7.5 to 15 cm and 22.5 to 30 cm depths were sampled due to a 5 cm deep layer of frozen soil.

The cores were saturated from the bottom for 48 hours before the saturated hydraulic conductivities were determined by the constant head method (Klute, 1965). The cores were resaturated and weighed. Moisture retention was determined at matric potentials of -1, -2, -4, -6, and -33.3 kPa for the cores sampled from the 1985 and 1986 tillage plots. The cores from the 1987 plots were subjected to matric potentials of -1, -2, -3, -4, -6, -10, -33.3, and -100 kPa. Moisture retentions for the cores sampled in December were determined only at the -1 and -6 kPa matric potentials. Matric potentials from -1 to -6 kPa were applied using the blotter paper method (Leamer and Shaw, 1941). Moisture retention at matric potentials from -10 to -100 kPa were determined using pressure plates (Richards, 1965). The pore size distribution of the soil was determined by applying the capillary rise equation to the moisture retention curve (Vomocil, 1965). Bulk density was determined on a dry mass per volume basis.

A recording cone penetrometer was used to measure mechanical resistance (cone index). In the subsoiled treatments, the penetrometer readings were taken in the loosened zone. Moisture samples were taken at depths of 0 to 10 cm, 10 to 20 cm, and 20 to 30 cm from each plot (see Appendix Table 2). These samples were oven dried at 105 degrees centigrade for 48 hours and gravimetric moisture contents were determined. These values were converted to volumetric water contents by multiplying by the soil bulk density.

The experimental design was a randomized complete block in all years and the treatments were replicated four times. Analysis of variance was used to detect significant differences between tillage treatments. Duncan's Multiple Range Test was employed to separate and rank the treatment means. A split plot design was used to compare the effects of time on the physical properties of the zone tillage treatments. Time made up the main plots and tillage made up the subplots. There was no interaction between time and tillage, so the reported means in this section were averaged across replication and tillage.

RESULTS AND DISCUSSION

The immediate effects of zone tillage on soil bulk density are presented in Figure 20. At the 0 to 7.5 cm depth, the NT treatment had the highest bulk density. This was at least .12 g cm^{-3} higher than the other treatments. At the 7.5 to 15 cm depth, the soil bulk densities of the CP and NT treatments were similar. However, the bulk density of the NT treatment was significantly higher than the two zone tillage treatments. At the 22.5 to 30 cm depth, the soil bulk densities of the CP and the NT treatments were 1.56 g cm^{-3}. This was .2 g cm^{-3} higher than the bulk densities of the zone tillage treatments. The bulk densities of the RT and the PT76 treatments were not significantly different at all depths. Zone tillage significantly reduced the bulk density of the soil to a depth of 30 cm.

Zone tillage significantly affected the soil's pore size distribution (Figure 21). At the 0 to 7.5 cm depth, the CP, RT, and PT76 treatments significantly increased the volume of soil occupied by pores with radii greater than 146 um over that of the NT treatment. The volume of soil occupied by pores with radii between 146 and 24 um was significantly increased by the CP, RT, and PT76 treatments. However, the CP, RT, and PT76 significantly reduced the volume of soil occupied by pores whose radii were less than 24 um.

At the 7.5 to 15 cm depth, the volume of pores with radii greater than 146 um was increased by a factor of 1.6 by zone tillage. The zone tillage treatments increased the volume of pores with radii between 146 and 24 um by a factor of 1.5 over that of the NT treatment. The RT treatment reduced the volume of pores with radii less than 24 um by a factor of 1.5 compared to the NT treatment.

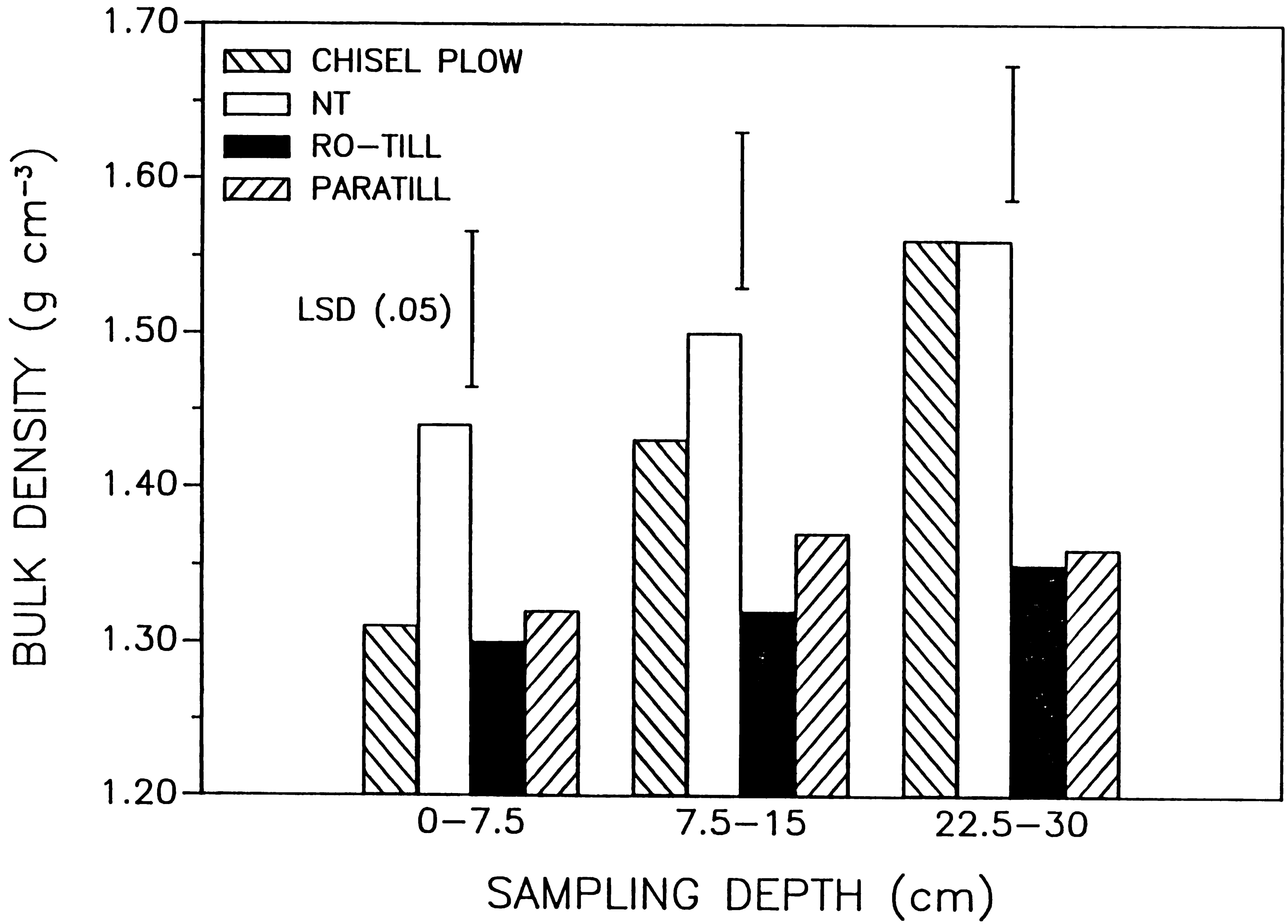

Figure 20. Immediate effects of tillage on soil bulk density.

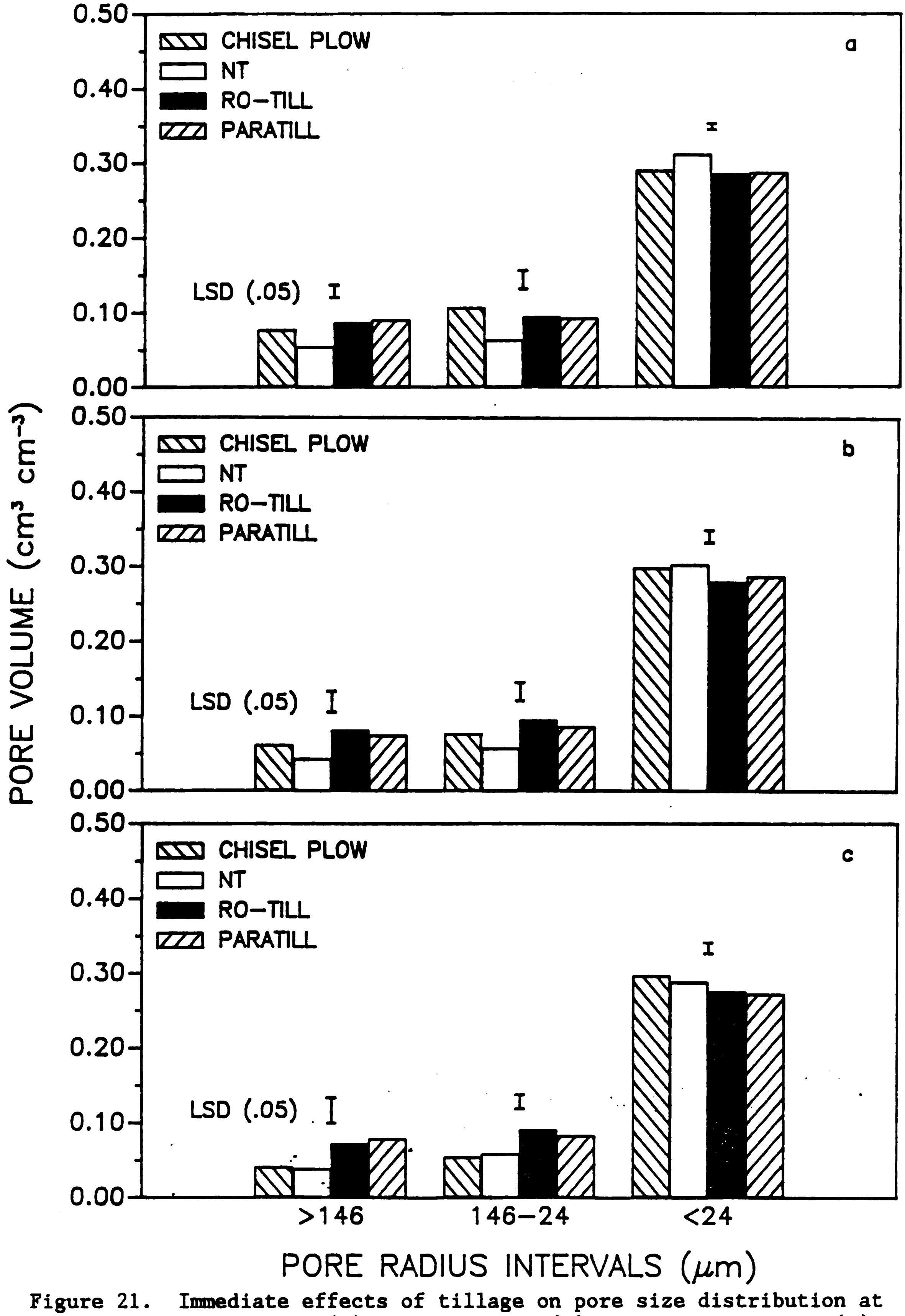

Figure 21. Immediate effects of tillage on pore size distribution at 0 to 7.5 cm (a), 7.5 to 15 cm (b), and 22.5 to 30 cm (c).

Zone tillage significantly affected the soil's pore size distribution at the 22.5 to 30 cm depth. The volume of pores with radii greater than 146 um for the PP76 treatment was double that of the NT treatment. Both the RT and the PP76 treatments increased the volume of pores with radii between 146 and 24 um over that of the NT treatment. The volume of pores with radii less than 24 um was not significantly different between the treatments.

Zone tillage increased the volume of pores greater than 24 um at all depths. These are the pores which will drain at the soil's field capacity (Cannel and Jackson, 1981). This property, in turn, affects the volume of soil which will be filled with air at field capacity.

Water retention data for the 0 to 7.5 cm depth are presented in Figure 22. The volumetric water contents at the 0 to 7.5 cm depth were lower for the CP, RT, and PT76 treatments than the NT treatment at matric potentials less than -6 kPa. At 7.5 to 15 cm (Figure 23), the RT and the PT76 treatments tended to have higher volumetric water contents at high matric potentials and lower volumetric water contents at low matric potentials than the CP and NT treatments. At the 22.5 to 30 cm depth (Figure 24), these same trends were exhibited.

The importance of these properties is two-fold: the water holding capacity of the soil is reduced and the air-filled volume of the soil was increased by zone tillage.

Tillage significantly affected the air-filled porosity of the soil. Air-filled porosity data for the 0 to 7.5 cm, 7.5 to 15 cm, and 22.5 to 30 cm depths are presented in Figures 22, 23, and 24 respectively. Foth (1978) stated that the field capacity of medium to coarse textured soils occurs at a matric potential of -6 kPa. Therefore, particular

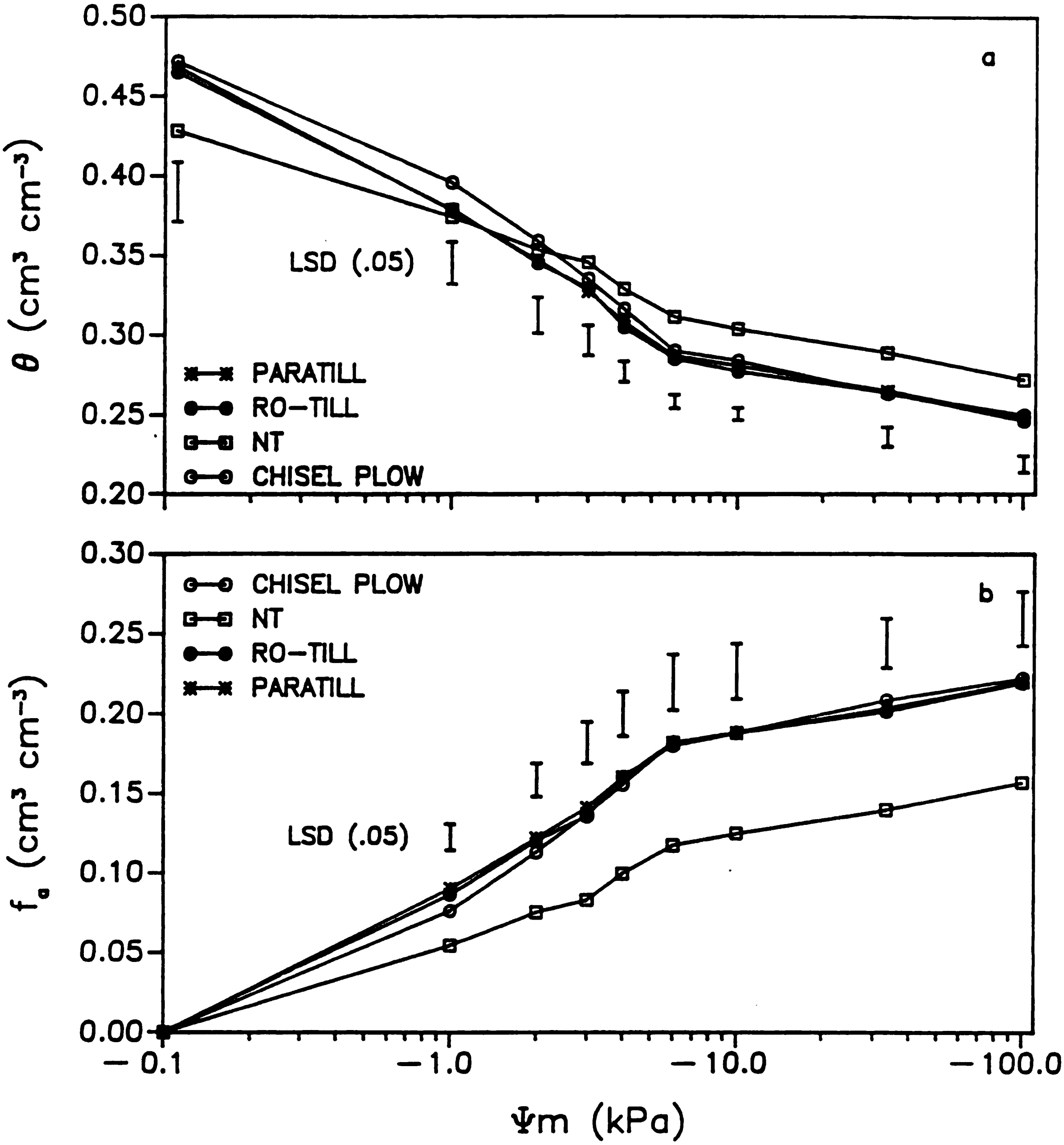

Figure 22. Immediate tillage effects on moisture retention (a) and air-filled porosity (b) at the 0 to 7.5 cm depth.

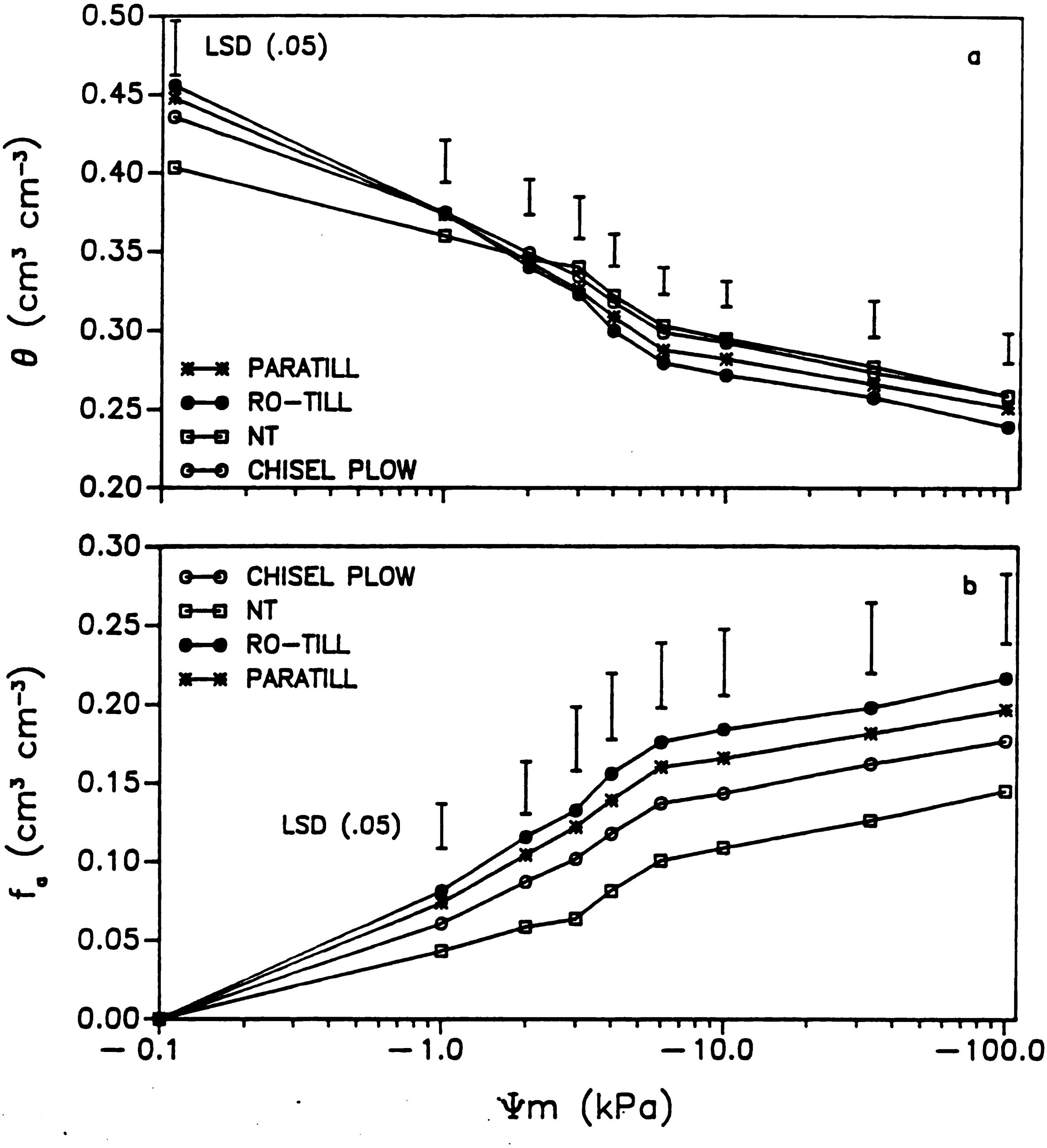

Figure 23. Immediate tillage effects on soil moisture retention (a) and air-filled porosity (b) at the 7.5 to 15 cm depth.

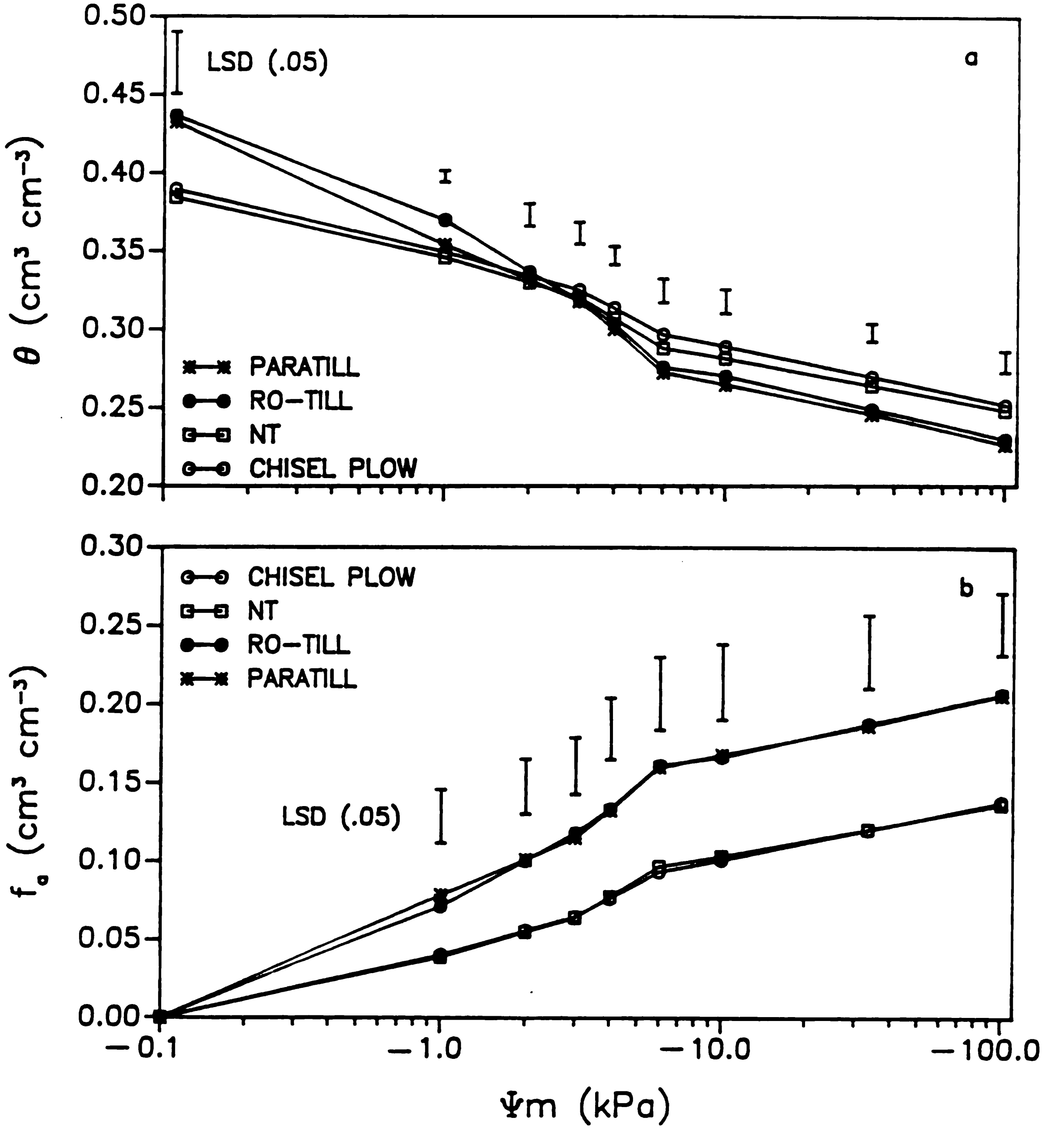

Figure 24. Immediate tillage effects on soil moisture retention (a) and air-filled porosity (b) at the 22.5 to 30 cm depth.

attention will be given to the air-filled porosity which occurred at this matric potential. At the 0 to 7.5 cm depth, the CP, RT, and PT76 treatments contained significantly higher air-filled porosities than the NT treatment at all matric potentials. The air-filled porosity at the -6 kPa matric potential was 1.5 times higher for the CP, RT, and PT76 treatments than for the NT treatment. At the 7.5 to 15 cm depth, the volume of air-filled pores was significantly higher for the RT and the PT76 treatments when compared to the NT treatment at all matric potentials. The volume of air-filled pores in the CP treatment was intermediate between those of the zone tillage and NT treatments. The volumes of air-filled pores at a matric potential of -6 kPa for the RT and PT76 treatments were increased by a factor of 1.5 over the NT treatment. At the 22.5 to 30 cm depth, zone tillage significantly increased the volume of air-filled pores over both the NT and the CP treatments at matric potentials from -2 to -100 kPa. The volume of air-filled pores at a matric potential of -6 kPa was below 10 percent for the CP and NT treatments. These values were increased by a factor of 1.7 in the RT and PT76 treatments. The volume of air-filled pores in the PT76 and RT treatments were never significantly different. Zone tillage significantly increased the volume of air-filled pores at -6 kPa over that of the NT treatment to a depth of 30 cm. The volume of air-filled pores fell below 10 percent in the NT and CP treatments at the 22.5 to 30 cm depth. Vomocil and Flocker (1961) stated that no gas exchange occurs between the atmosphere and the soil when the volume of air-filled pores was around 10 percent. The lack of gaseous exchange can cause aeration stress to occur in plants when precipitation is significant.

Total porosity was significantly affected by tillage (Table 11). Total porosity was higher in the CP and PT76 treatments than in the NT treatment at the 0 to 7.5 cm depth. The total porosities ranged from .47 to .43 cm^3 cm^{-3} for the PT76 and NT treatments respectively. At the 7.5 to 15 cm depth, the RT and PT76 treatments had significantly higher total pore volume than the NT treatment. The total porosity of the CP treatment was intermediate between the zone tillage and the NT treatments. Total porosity was significantly higher for the RT and PT76 treatments than for the CP and NT treatments at the 22.5 to 30 cm depth.

The saturated hydraulic conductivity (Ksat) was significantly affected by tillage (Table 11). At the 0 to 7.5 cm depth, the CP, RT, and PT76 treatments significantly increased the Ksat values over that of the NT treatment. The Ksat values ranged from 28.2 cm hr^{-1} to 7.0 cm hr^{-1} for the CP and NT treatments respectively. At the 7.5 to 15 cm depth, the RT and the PT treatments significantly increased the Ksat over that of the NT treatment. The CP treatment's Ksat was intermediate between the zone tillage and NT treatments. At the 22.5 to 30 cm depth, no significant differences occurred between the tillage treatments. The soils in the zone tillage treatments were very loose when intact cores were sampled. Some disturbance may have occurred when these treatments were sampled affecting Ksat by altering pore continuity and tortuosity.

Zone tillage significantly increased the Ksat of the soil to a depth of 15 cm. The CP treatment significantly increased Ksat values to a depth of 7.5 cm. The CP treatment also demonstrated a trend to increase Ksat to a depth of 15 cm. However, Ksat at this depth for the

Table 11. Immediate effects of tillage on total porosity and saturated hydraulic conductivity (Ksat) from 1987.

Tillage	Depth (cm)	Total porosity (cm^3 cm^{-3})	Ksat (cm h^{-1})
	0-7.5		
Chisel Plow		.47 a	28.2 a
NT		.43 b	7.0 b
Ro-Till		.46 ab	25.7 a
Paratill		.47 a	23.6 a
LSD (.05)		.04	12.2
	7.5-15		
Chisel Plow		.44 ab	15.8 ab
NT		.40 b	6.9 b
Ro-Till		.46 a	24.2 a
Paratill		.45 a	19.8 a
LSD (.05)		.04	11.1
	22.5-30		
Chisel Plow		.39 b	6.3 a
NT		.38 b	5.3 a
Ro-Till		.44 a	6.1 a
Paratill		.43 a	4.6 a
LSD (.05)		.04	5.1

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

CP treatment was not significantly different from the NT treatment at the five percent probability level.

The strength of the soil was significantly reduced by tillage (Figure 25). The soil moisture contents at the time of sampling are shown in Appendix Table 2. The CP, RT, and PT76 treatments significantly reduced the cone index to a depth of 10 cm. From 10 to 30 cm, the cone index values of the RT and the PT76 treatments were significantly lower than those of the CP and the NT treatments. The cone index values at 30 cm ranged from 28.6 kPa to 2.6 kPa for the NT and PT76 treatments respectively. No significant differences were found between the cone index values of the RT and the PT76 treatments.

When the cone index of the soil is high enough, root growth can be mechanically impeded (Taylor and Burnett 1964). Russell and Goss (1974) found that barley root elongation was reduced by 50 percent at pressures of 20 kPa. The cone index values at the 30 cm depth were 28.6 kPa, 3.2 kPa, and 2.6 kPa for the NT, RT and PT76 treatments respectively. Reduced root elongation could occur in the NT treatment.

Residual Effects of Zone Tillage

After one year, the bulk density of the RT treatment at the 7.5 to 15 cm depth was significantly lower than the NT treatment (Table 12). The bulk density values ranged from 1.41 g cm^{-3} to 1.53 g cm^{-3} for the RT and NT treatments respectively. The bulk density of the PP treatment was intermediate between the RT and the NT treatments. At the 22.5 to 30 cm depth, no significant differences occurred between the tillage treatments. However, there was a trend for the zone tillage treatments to have slightly lower bulk densities than the NT treatment.

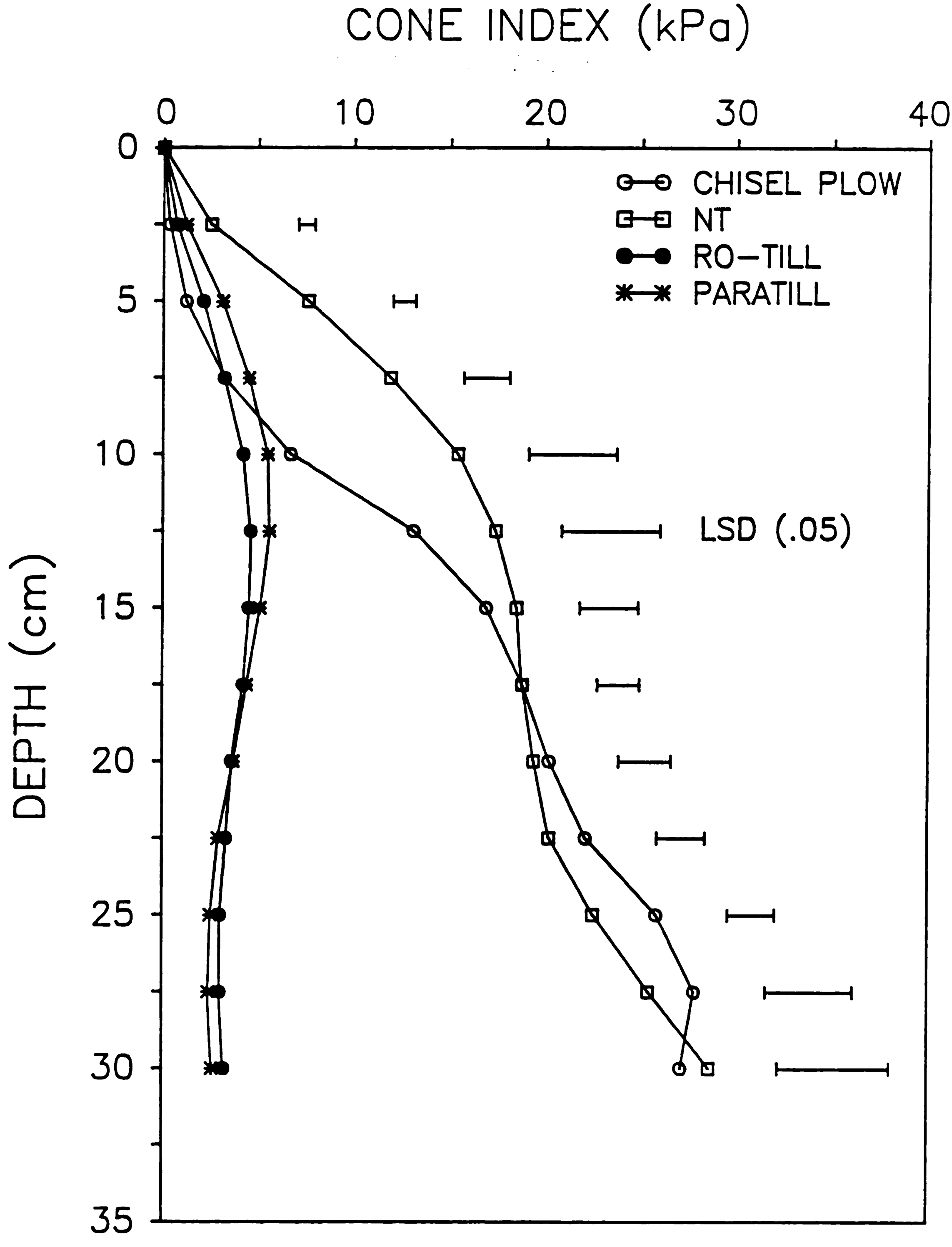

Figure 25. Immediate tillage effects on cone index.

Table 12. Residual effects of zone tillage on bulk density after one year.

Tillage	Depth (cm) 7.5-15	22.5-30
	Bulk density	
	---------- $g\ cm^{-3}$ ----------	
NT	1.53 a	1.54 a
Ro-Till	1.41 b	1.52 a
Paraplow	1.47 ab	1.49 a
LSD (.05)	.08	.06

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

After two years, the soil bulk density values were not significantly different between the tillage treatments at the 7.5 to 15 cm depth (Table 13). However, there was a trend for the zone tillage treatments to have lower bulk densities than the NT treatment. At the 22.5 to 30 cm depth, the bulk density values for the RT and PP treatments were significantly lower than the NT treatment after two years. The bulk density values ranged from 1.38 g cm^{-3} for the RT treatment to 1.57 g cm^{-3} for the NT treatment.

At the 7.5 to 15 cm depth, the soil bulk density in the RT treatment was significantly lower than that of the NT treatment after one year, but after two years it was not. At the 22.5 to 30 cm depth, the soil bulk density of the tillage treatments were not significantly different after one year, however after two years the zone tillage treatments were significantly lower than the NT treatment. There are no apparent explanations for these observations.

The soil's pore size distribution after one year (Figure 26) was significantly affected by tillage. At the 7.5 to 15 cm depth, no significant differences occurred between the tillage treatments for pores whose radii were greater than 24 um. However, the pore volume with radii less than 24 um was significantly increased in the zone tillage treatments. This would indicate that soil aggregates were fractured by zone tillage which led to a reduction in aggregate size, creating a reduction in pore size. At the 22.5 to 30 cm depth after one year, no significant differences occurred between tillage treatments for pore volumes with radii greater than 146 um. The pore volume with radii from 146 to 24 um was the highest for the NT treatment and lowest for the RT treatment. The PP treatment was

Table 13. Residual effects of zone tillage on bulk density after two years.

Tillage	Depth (cm) 7.5-15	22.5-30
	Bulk density	
	---------- $g\ cm^{-3}$ ----------	
NT	1.57 a	1.57 a
Ro-Till	1.51 a	1.38 b
Paraplow	1.51 a	1.40 b
LSD (.05)	.10	.10

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

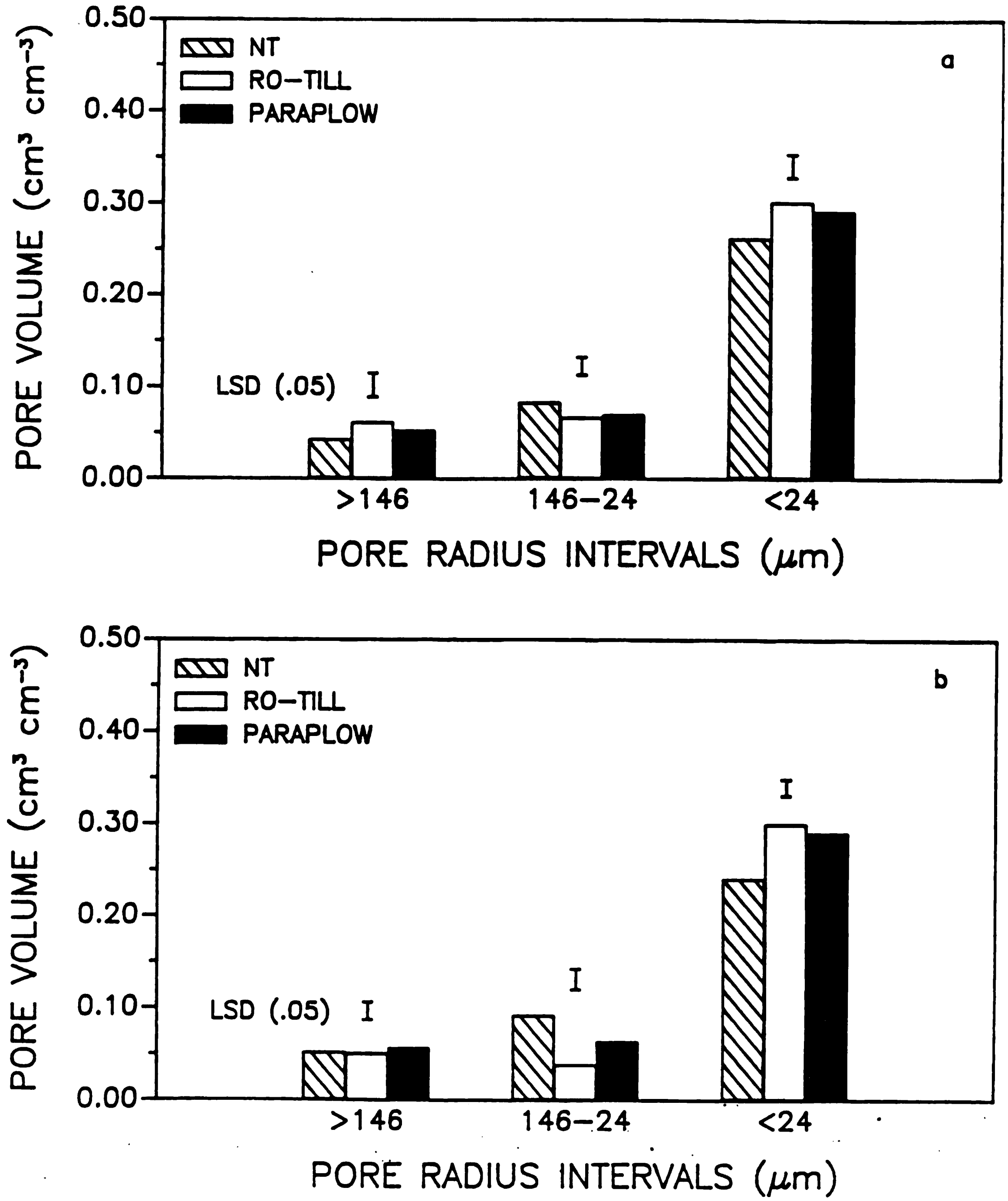

Figure 26. Residual effects of zone tillage after one year on soil pore size distribution at the 7.5 to 15 cm (a) and 22.5 to 30 cm (b) depths.

intermediate between the RT and the NT treatments. All the treatments were significantly different from each other at the five percent probability level. This would indicate that the PP treatment was less destructive to the soils structural units than the RT treatment. The pore volume with radii less than 24 um was significantly increased in the zone tillage treatments.

Pore size distributions after two years are shown in Figure 27. No significant differences occurred between tillage treatments in the volume of pores with radii greater than 24 um. This was true at both depths. At the 7.5 to 15 cm depth, pore volumes with radii less than 24 um were significantly higher in the zone tillage treatments. At the 22.5 to 30 cm depth, the pore volume with radii less than 24 um was the highest in the RT treatment and the lowest in the NT treatment. These two treatments were significantly different at the five percent probability level. The reduction in pore size in the zone tillage treatments indicates increased consolidation with time due to fracture of soil aggregates.

The water retention data for one year after subsoiling are presented in Figures 28 and 29. At the 7.5 to 15 cm depth, the RT had significantly higher volumetric water contents than the NT treatment at matric potentials from -.11 to -6 kPa. The PP treatment had significantly higher volumetric water contents than the NT treatment at matric potentials from -1 to -6 kPa. At 22.5 to 30 cm, the volumetric water content of the zone tillage treatments were significantly higher than the NT treatment at a matric potential of -6 kPa.

The water retention data for two years after subsoiling are presented in Figures 30 and 31. At the 7.5 to 15 cm depth, the RT and the PP

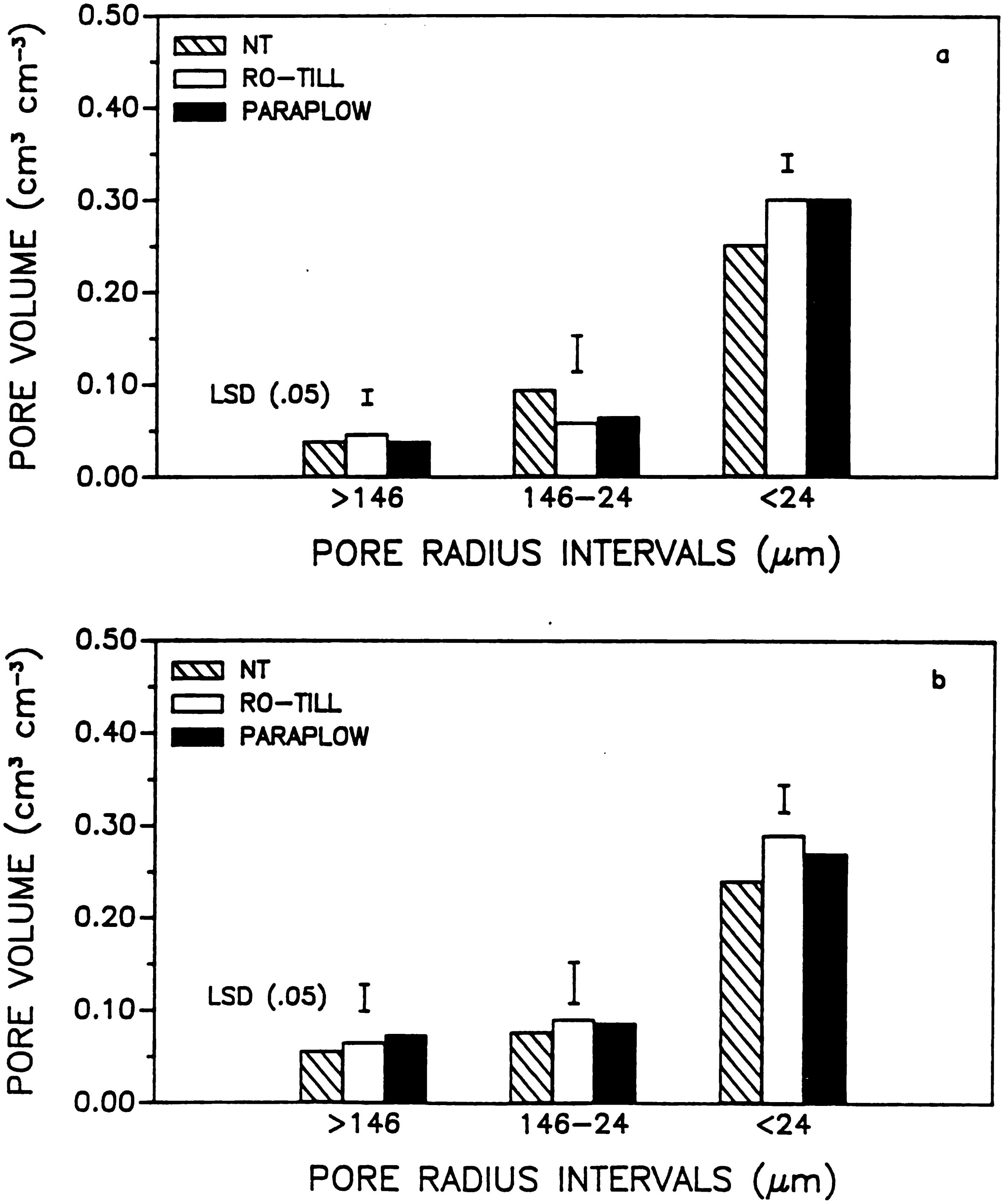

Figure 27. Residual effects of zone tillage after two years on soil pore size distribution at the 7.5 to 15 cm (a) and 22.5 to 30 cm (b) depths.

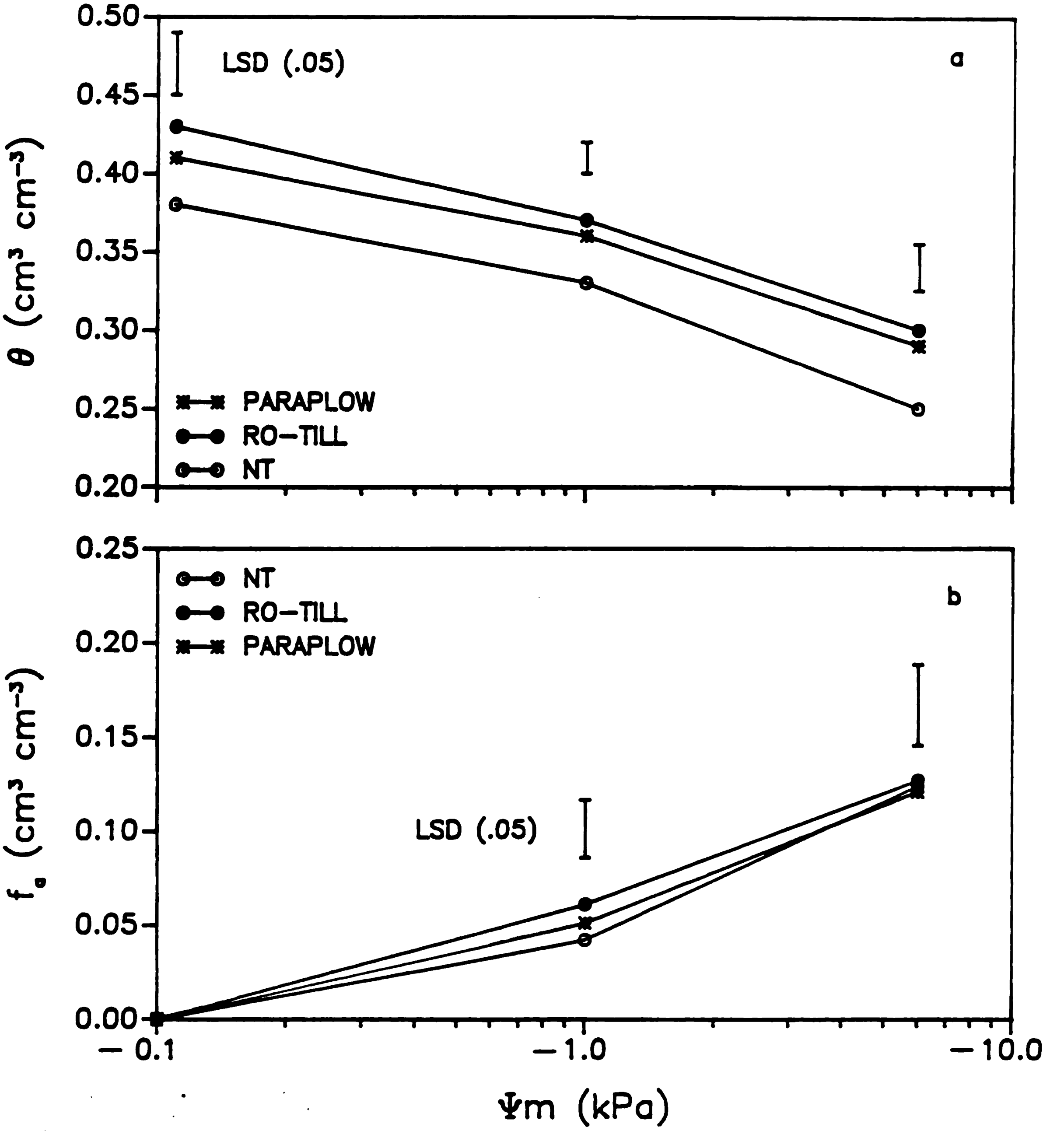

Figure 28. Residual effects of zone tillage after one year on soil moisture retention (a) and air-filled porosity (b) at the 7.5 to 15 cm depth.

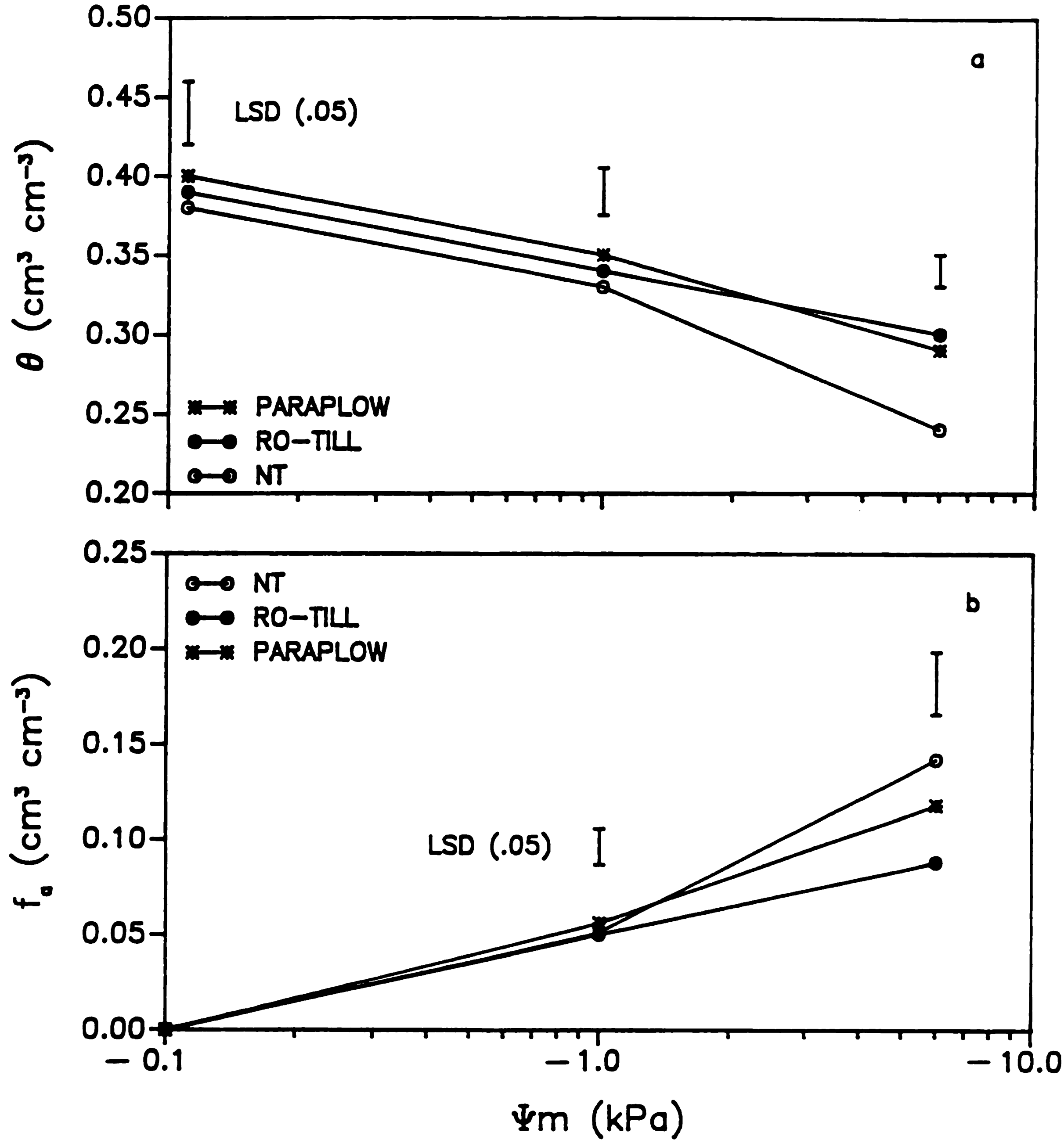

Figure 29. Residual effects of zone tillage after one year on soil moisture retention (a) and air-filled porosity (b) at the 22.5 to 30 cm depth.

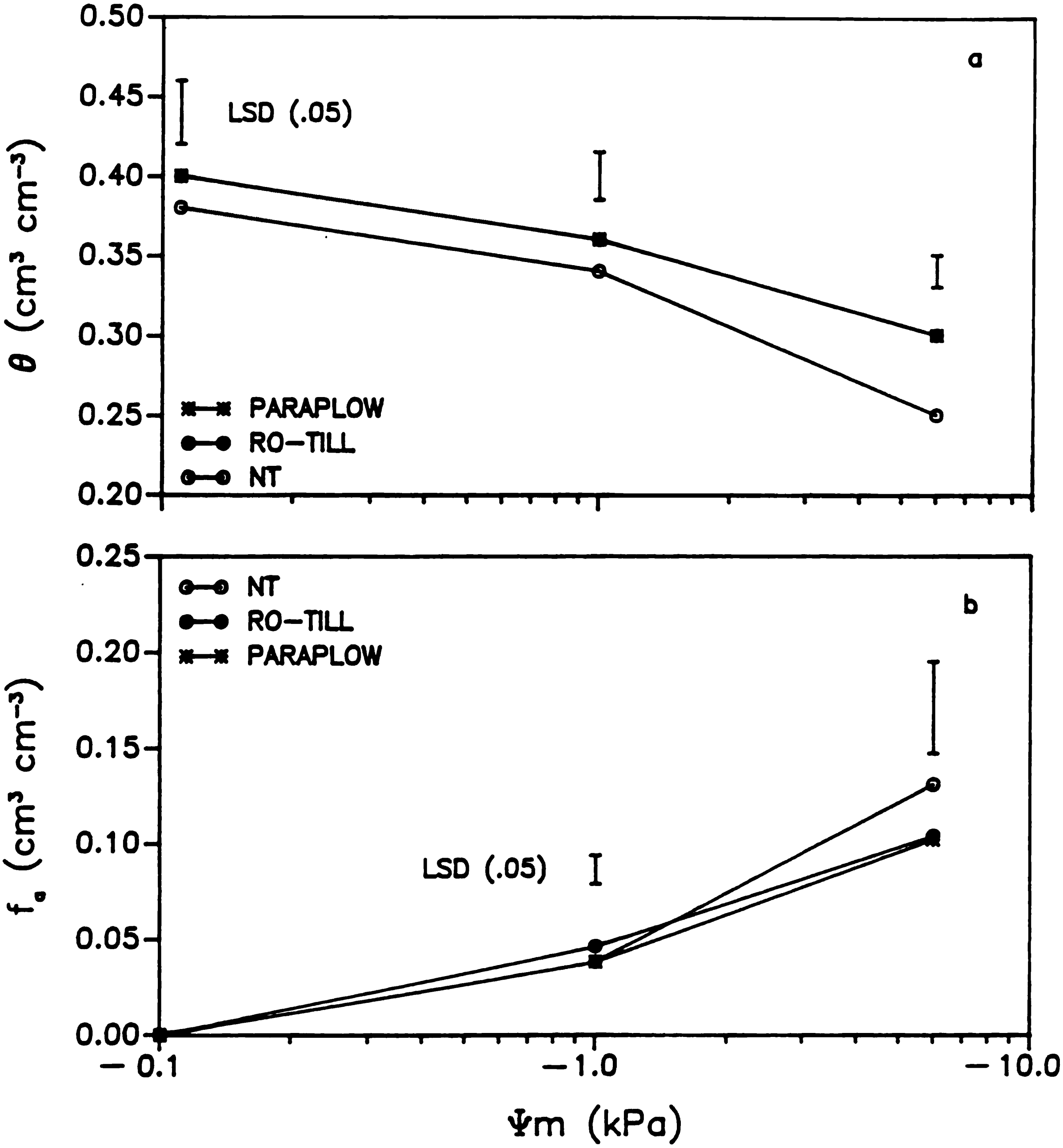

Figure 30. Residual effects of zone tillage after two years on soil moisture retention (a) and air-filled porosity (b) at the 7.5 to 15 cm depth.

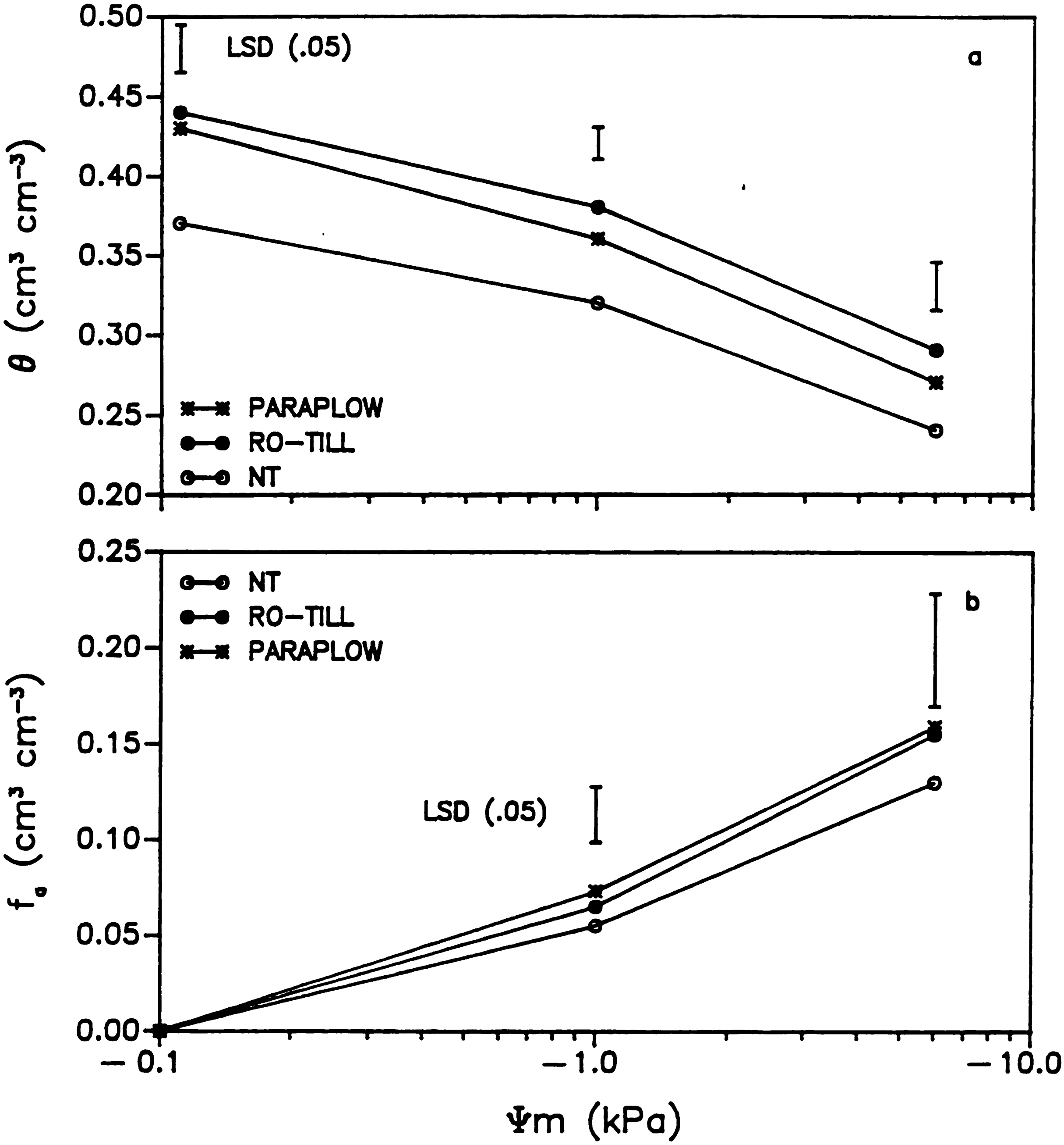

Figure 31. Residual effects of zone tillage after two years on soil moisture retention (a) and air-filled porosity (b) at the 22.5 to 30 cm depth.

treatments had significantly higher volumetric water contents than the NT treatment at a matric potential of -6 kPa. At the 22.5 to 30 cm depth, the RT treatment had significantly higher volumetric water contents than the NT treatment at matric potentials from -.11 to -6 kPa. The PP treatment had higher volumetric water contents than the NT treatment at matric potentials from -.11 to -1 kPa.

The air-filled porosity data are presented in Figures 28, 29, 30, and 31. At a matric potential of -6 kPa, the only significant differences in the volume of air-filled pores occurred at the 22.5 to 30 cm depth one year after subsoiling. The NT treatment had the largest volume of air-filled pores at this depth. The volume of air-filled pores was below 10 percent one year after subsoiling for the RT treatment at the 22.5 to 30 cm depth. Air-filled porosity was around 10 percent for both zone tillage treatments at the 7.5 to 15 cm depth after two years. Air-filled porosity is a function of the total porosity and the pore size distribution of the soil.

The zone tillage treatments tended to have a larger volume of small pores which retain water at field capacity. This property caused the zone tillage treatments to have a smaller volume of air-filled pores at field capacity than the NT treatment.

Total porosity after one year (Table 14) was significantly affected by tillage. At the 7.5 to 15 cm depth, the RT treatment had the largest total porosity and the NT had the lowest total porosity: .43 and .38 cm^3 cm^{-3} respectively. At the 22.5 and 30 cm depth, no significant differences in total porosity were found between the tillage treatments.

Table 14. Residual effects of zone tillage on total porosity and saturated hydraulic conductivity (Ksat) after one year.

Tillage	Depth (cm) 7.5-15	22.5-30
	Total porosity	
	-------- cm^3 cm^{-3} --------	
NT	.38 b	.38 a
Ro-Till	.43 a	.39 a
Paraplow	.41 ab	.40 a
LSD (.05)	.04	.04
	Ksat	
	-------- cm h^{-1} --------	
NT	8.63 a	7.70 a
Ro-Till	19.31 a	5.18 a
Paraplow	16.27 a	10.98 a
LSD (.05)	16.84	6.13

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Two years after subsoiling, the total porosity of the soil was significantly affected by tillage (Table 15). At the 7.5 to 15 cm depth, no significant differences were found. However, there was a trend for the zone tillage treatments to have larger total porosities than the NT treatment. At the 22.5 to 30 cm depth, the zone tillage treatments had significantly larger total pore volumes than the NT treatment. The total porosities at the 22.5 to 30 cm depth were .44 $cm^3\ cm^{-3}$, .43 $cm^3\ cm^{-3}$, and .37 $cm^3\ cm^{-3}$ for the RT, PP, and NT treatments respectively.

Saturated hydraulic conductivity was not significantly affected by tillage after one year (Table 14). However, at the 7.5 to 15 cm depth, the Ksat values for the zone tillage treatments were double that of the NT treatment. The saturated hydraulic conductivity was not significantly affected by tillage after two years (Table 15). Although at both depths, the Ksat values of the zone tillage treatments were double that of the NT treatment.

<u>Zone Tillage Effects on Soil Properties Compared over Time</u>

There was no interaction between time and tillage. Therefore, in all of the following results, the means were averaged across replication and tillage.

The soil bulk densities of the zone tillage treatments were significantly affected by time (Table 16). At the 0 to 7.5 cm depth, the bulk density of the first year treatment was .11 $g\ cm^{-3}$ lower than the bulk densities after one and two years. At the 7.5 to 15 cm depth, soil bulk density during the first year was .10 $g\ cm^{-3}$ and .17 $g\ cm^{-3}$ lower than the bulk densities after one and two years respectively. However, at the 22.5 to 30 cm depth, the bulk densities in the first

Table 15. Residual effects of zone tillage on total porosity and saturated hydraulic conductivity (Ksat) after two years.

Tillage	Depth (cm) 7.5-15	22.5-30
	Total porosity	
	--------- $cm^3\ cm^{-3}$ ---------	
NT	.38 a	.37 b
Ro-Till	.40 a	.44 a
Paraplow	.40 a	.43 a
LSD (.05)	.04	.03
	Ksat	
	---------- $cm\ h^{-1}$ ----------	
NT	5.49 a	7.97 a
Ro-Till	11.73 a	20.19 a
Paraplow	11.65 a	28.39 a
LSD (.05)	11.82	23.23

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Table 16. Residual effects of zone tillage on bulk density compared over time.

Time	Depth (cm) 0-7.5	7.5-15	22.5-30
		Bulk density	
		g cm^{-3}	
First year	1.31 b	1.34 b	1.36 b
Second Year	1.42 a	1.44 a	1.50 a
Third year	1.42 a	1.51 a	1.39 b
LSD (.05)	.05	.08	.06

The means are averaged across replication and tillage. Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

year and the third year were not significantly different. The bulk density one year after subsoiling was significantly higher than the first year or the third year.

Water retention for the zone tillage treatments compared over time are presented in Figures 32, 33, and 34 for the 0 to 7.5 cm, 7.5 to 15 cm, and 22.5 to 30 cm depths respectively. Time did not significantly affect the volumetric water contents of the soil at matric potentials from -1 to -33.3 kPa. This was true at all sampling depths.

The volume of air-filled pores in the zone tillage treatments was significantly affected by time. At the 0 to 7.5 cm depth (Figure 32), the volume of air-filled pores was significantly higher in the first year than in the second or third year at a matric potential of -6 kPa. The volume of air-filled pores was 1.6 times higher in the first year than for the second or third year. At the 7.5 to 15 cm depth (Figure 33), the volume of air-filled pores at -6 kPa was significantly higher for the first year than for the third year. The air-filled porosities at -6 kPa were .17 cm^3 cm^{-3} and .10 cm^3 cm^{-3} for the first and third years respectively. The volume of air-filled pores at the 22.5 to 30 cm depth (Figure 34) was similar for the first year and the third year at -6 kPa. The volume of air-filled pores in the second year was significantly lower than the first and third years. The air-filled porosity of the second year at -6 kPa was reduced by a factor of 1.4 in comparison with the other two years.

The total porosity of the soil was significantly affected by time (Table 17). At the first two sampling depths, the total pore volume of the first year was significantly higher than that of the third year. At the 7.5 to 15 cm depth, the total pore volume of the second year was

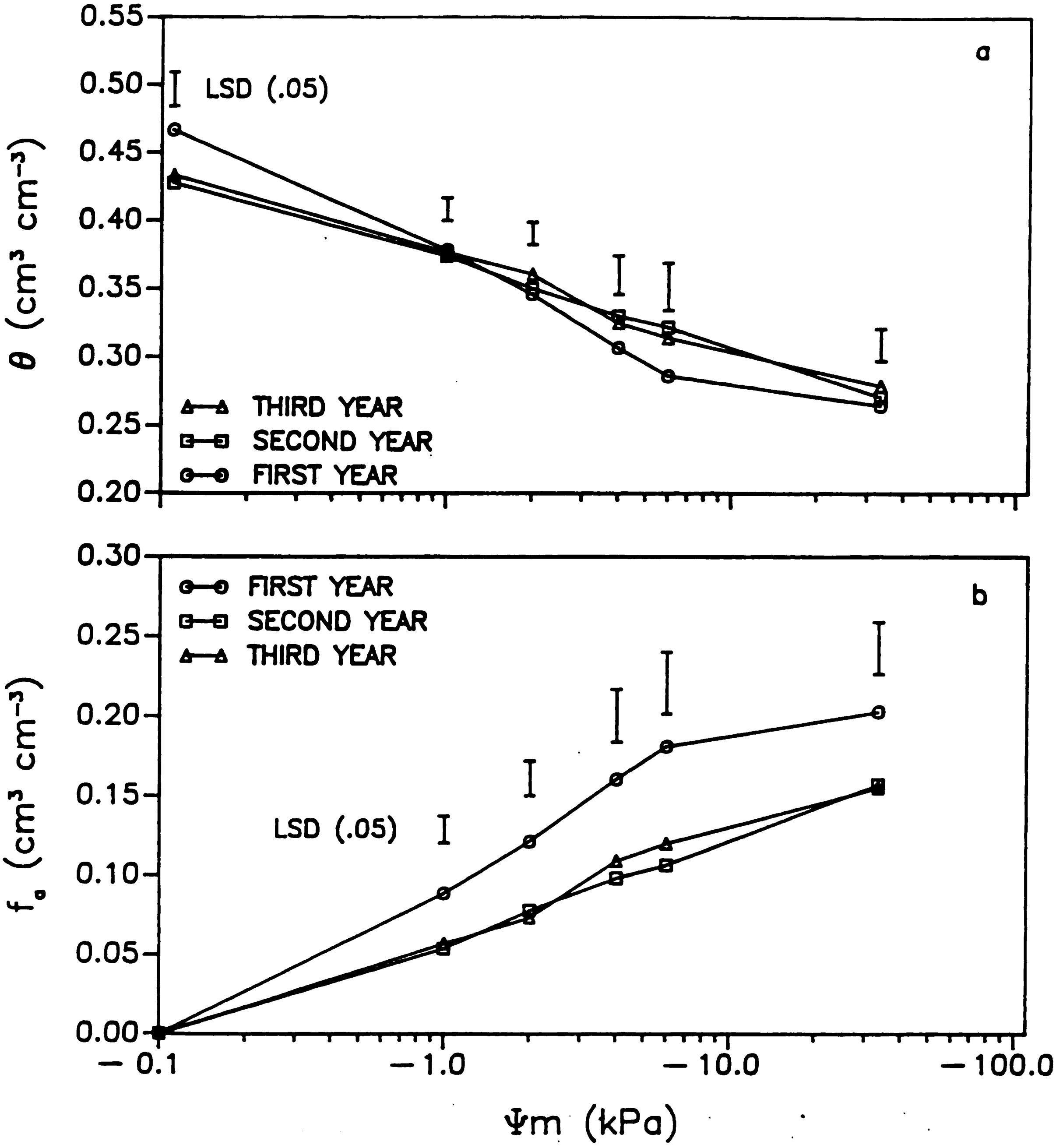

Figure 32. Zone tillage effects on soil moisture retention (a) and air-filled porosity (b) compared over time at the 0 to 7.5 cm depth.

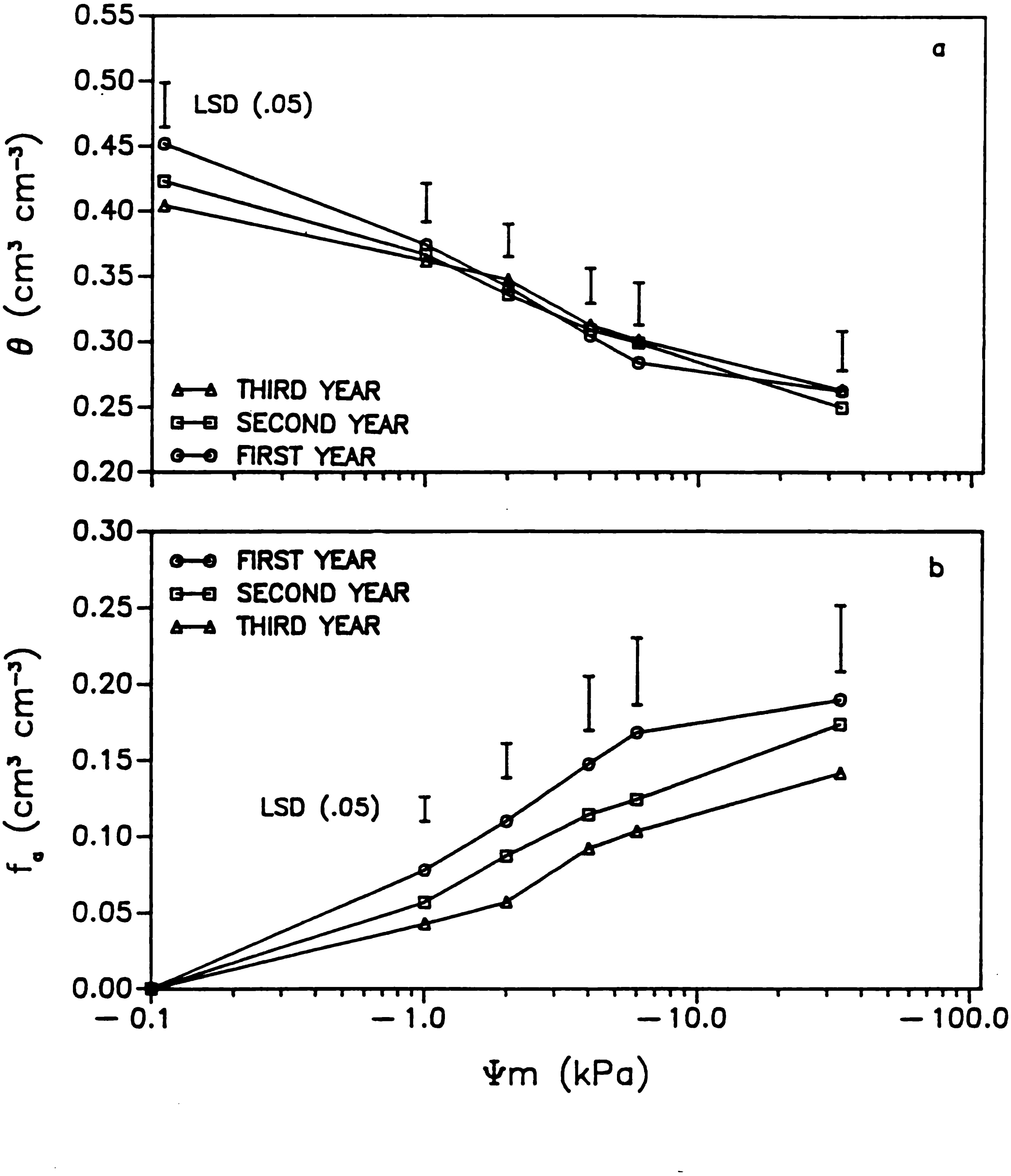

Figure 33. Zone tillage effects on soil moisture retention (a) and air-filled porosity (b) compared over time at the 7.5 to 15 cm depth.

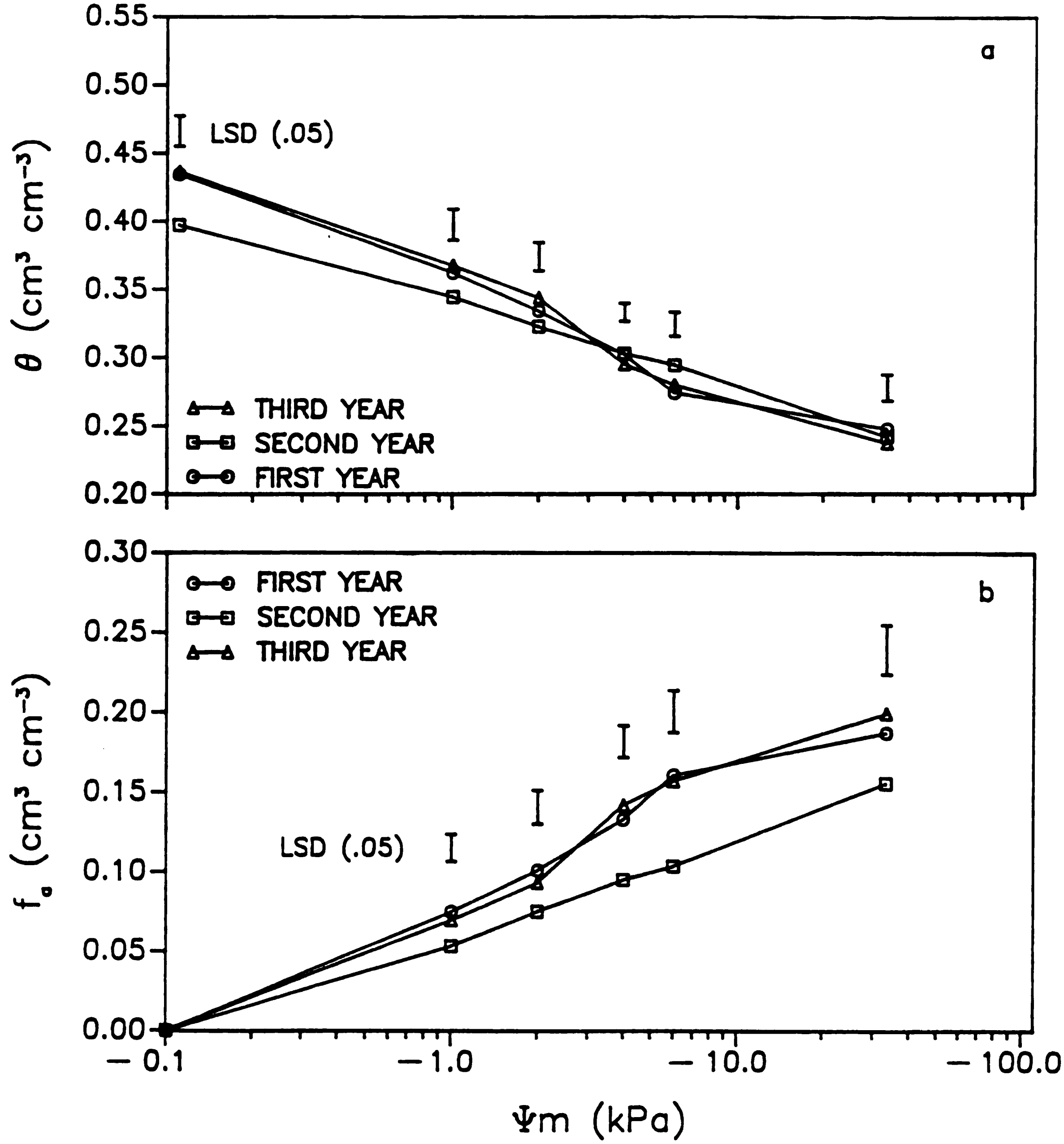

Figure 34. Zone tillage effects on soil moisture retention (a) and air-filled porosity (b) compared over time at the 22.5 to 30 cm depth.

Table 17. Residual effects of zone tillage on total porosity and saturated hydraulic conductivity compared over time.

Time	Depth (cm) 0-7.5	7.5-15	22.5-30
		Total porosity	
		$cm^3\ cm^{-3}$	
First Year	.47 a	.45 a	.43 a
Second Year	.43 b	.42 ab	.40 b
Third Year	.43 b	.40 b	.44 a
LSD (.05)	.03	.04	.02
		Ksat	
		$cm\ h^{-1}$	
First Year	24.54 a	21.99 a	5.34 b
Second Year	12.90 b	17.79 a	8.29 b
Third Year	12.13 b	11.69 a	24.29 a
LSD (.05)	8.69	10.62	9.08

The means are averaged across replication and tillage. Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

not significantly different than the first or the third year. The total porosity at the 22.5 to 30 cm depth was not significantly different between the first year and the third year. However, the total porosity of the second year was .03 $cm^3\ cm^{-3}$ lower than the first year. This difference was significant at the five percent probability level.

The saturated hydraulic conductivity at the 0 to 7.5 cm depth was significantly affected by time (Table 17). The Ksat mean of the first year was double that of the second or third year. The Ksat means at the second depth were not significantly different. However, the first year had the highest Ksat and the third year had the lowest Ksat. At the 22.5 to 30 cm depth, the Ksat of the third year was about three times higher than the first or second year. The low Ksat values of the first year can probably be attributed to disturbance during sampling. The soil was very loose and some rearrangement may have occurred which affected the Ksat by altering pore continuity and tortuosity.

Soil strength, as indicated by cone index, increased with time (Figure 35). The first year of subsoiling had significantly lower cone index values than one and two years after subsoiling. However, the cone index after one and two years was still less than 10 kPa. Soil strengths in this range should not significantly inhibit root elongation (Russell and Goss, 1984).

Plant Responses and Yields

Seedling emergence was not affected by tillage in 1986 (Table 18). However, in 1987, tillage did significantly affect seedling emergence (Table 19). At 15 days after planting, the NT treatment had at least 12,000 fewer emerged seedlings per hectare than the CP and the RT

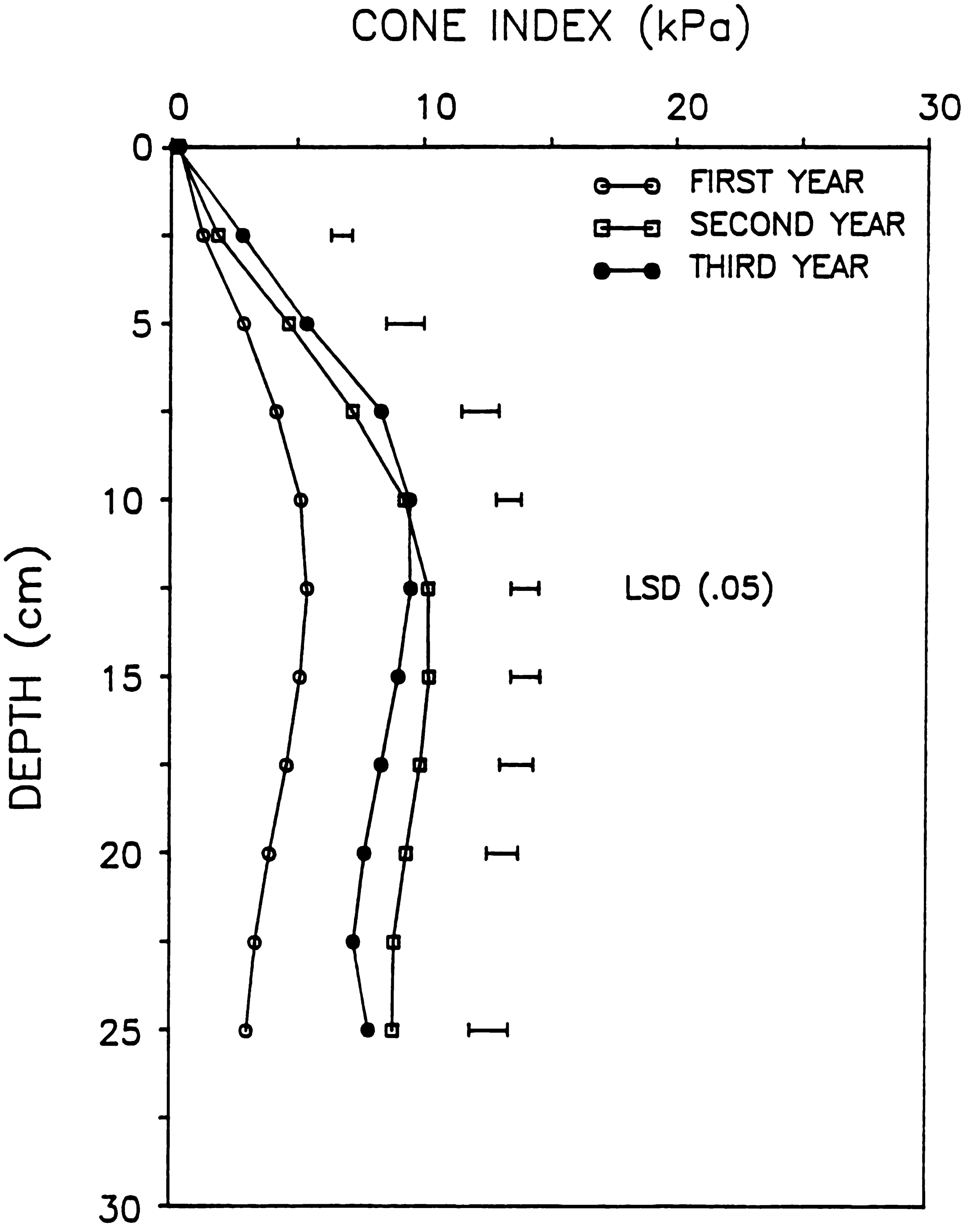

Figure 35. Residual tillage effects on cone index.

Table 18. Immediate tillage effects on seedling emergence from 1986.

Tillage	Days after planting 16	18	21
		Seedling emergence	
	-----------	Plants ha^{-1}	-----------
Chisel Plow	58,100 a	58,369 a	58,369 a
NT	59,983 a	60,790 a	60,790 a
Paraplow51	58.907 a	59,445 a	59,445 a
Ro-Till	51,645 a	52,183 a	52,183 a
Paraplow76	55,948 a	56,217 a	56,217 a
LSD (.05)	5,986	5,839	5,839

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Table 19. Immediate tillage effects on seedling emergence in 1987.

Tillage	Days After Planting 15	17	19	21
		Seedling emergence		
	-------------	Plants ha^{-1}		-------------
Chisel Plow	44,113 a	53,797 a	55,410 a	56,755 a
NT	25,284 c	41,961 b	49,762 b	52,990 a
Ro-Till	37,927 ab	53,527 a	56,486 a	56,755 a
Paratill	28,512 bc	44,382 b	50,569 b	53,797 a
LSD (.05)	9,660	6,310	4,198	3,872

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

treatments. Seedling emergence in the PT76 treatment was significantly lower than the CP treatment. At 17 days after planting, the NT and PT76 treatments had at least 9,000 fewer emerged plants per hectare than the CP and RT treatments. Seedling emergence at 19 days after planting continued to be significantly reduced in the NT and PT76 treatments. However, at 21 days after planting, no significant differences occurred between tillage treatments.

The 1986 plant tissue nitrogen contents are presented in Table 20. Tillage significantly affected the tissue nitrogen contents of the ear leaf, stover, and grain. The NT treatment had the highest nitrogen content in the ear leaf tissue and the PP76 treatment had the lowest level. The nitrogen content of the grain was significantly higher in the RT treatment than for the PP76 treatment. The nitrogen contents of the grain were 11.2 g kg^{-1} and 9.8 g kg^{-1} for the RT and PP76 respectively. The NT and RT treatments had significantly higher stover nitrogen contents than the PP76 treatment. The stover nitrogen contents were 6.5 g kg^{-1}, 6.9 g kg^{-1}, and 5.3 g kg^{-1} for the NT, RT, and PP76 treatments respectively.

The 1986 yield data are shown in Table 21. Grain moisture, plant populations, grain yield, and stover yield were not significantly affected by tillage in 1986. This was true for plots that were subsoiled in 1986 and those that were subsoiled in 1985.

The 1987 yield data are shown in Table 22. In the first year of subsoiling, the PT76 treatment had a significantly lower plant population than the NT and RT treatments. However, no significant differences occurred between tillage treatments for grain moisture, grain yield, and stover yield. One year after subsoiling, grain

Table 20. Plant tissue nitrogen contents from 1986.

Tillage	Earleaf N content ($g\ kg^{-1}$)	Grain N content ($g\ kg^{-1}$)	Stover N content ($g\ kg^{-1}$)
	First year of subsoiling		
Chisel Plow	25.1 ab	10.4 ab	6.4 ab
NT	25.7 a	10.5 ab	6.5 a
Paraplow51	24.6 ab	11.0 ab	6.1 ab
Ro-Till	25.3 ab	11.2 a	6.9 a
Paraplow76	23.3 b	9.8 b	5.3 b
LSD (.05)	1.8	1.1	5.3
	One year after subsoiling		
Chisel Plow	24.4 a	11.5 a	7.0 a
NT	25.9 a	11.5 a	6.6 a
Ro-Till	25.4 a	11.3 a	7.1 a
Paraplow	25.5 a	11.4 a	7.0 a
LSD (.05)	2.6	.7	.9

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Table 21. Yield data from 1986.

Tillage	Grain moisture (%)	Plant population (plants ha^{-1})	Grain yield (Mg ha^{-1})	Stover yield (Mg ha^{-1})
		First year of subsoiling		
Chisel Plow	25.9 a	56,847 a	9.0 a	4.5 a
NT	26.4 a	56,309 a	9.2 a	4.9 a
Paraplow51	26.9 a	52.543 a	9.1 a	4.0 a
Ro-Till	26.6 a	56,847 a	9.0 a	4.5 a
Paraplow76	26.2 a	57,565 a	9.1 a	4.6 a
LSD (.05)	1.1	5,715	1.3	.6
		One year after subsoiling		
Chisel Plow	27.7 a	53,799 a	9.1 a	3.7 a
NT	27.3 a	56,130 a	8.9 a	4.8 a
Ro-Till	28.0 a	53,619 a	9.0 a	4.8 a
Paraplow	28.1 a	55,950 a	9.3 a	4.3 a
LSD (.05)	1.4	5,202	.8	1.3

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

Table 22. Yield data from 1987.

Tillage	Grain moisture (%)	Plant population (plants ha^{-1})	Grain yield (Mg ha^{-1})	Stover yield (Mg ha^{-1})
		First year of subsoiling		
Chisel Plow	17.0 a	55,413 ab	8.2 a	4.6 a
NT	17.7 a	58,999 a	9.1 a	4.5 a
Ro-Till	16.9 a	57,744 a	9.0 a	4.5 a
Paratill	17.3 a	50,929 b	8.4 a	4.8 a
LSD (.05)	1.1	5,001	1.2	1.0
		One year after subsoiling		
Chisel Plow	16.6 a	56,309 a	8.0 a	4.0 a
NT	16.5 a	55,592 a	8.1 a	4.5 a
Paraplow51	16.9 a	52,723 a	8.5 a	4.4 a
Ro-Till	17.1 a	50,929 a	8.6 a	4.3 a
Paraplow76	17.3 a	50,929 a	7.2 a	4.3 a
LSD (.05)	1.2	5,785	1.5	.7
		Two years after subsoiling		
Chisel Plow	17.7 b	56,847 a	8.3 a	4.4 a
NT	19.3 a	54,876 a	8.5 a	4.4 a
Ro-Till	18.7 ab	54,516 a	7.9 a	4.1 a
Paraplow	19.1 ab	53,799 a	8.1 a	4.0 a
LSD (.05)	1.2	5,125	.7	1.1

Means in each column which are followed by the same letter are not significantly different at the indicated alpha level by Duncan's Multiple Range Test.

moisture, grain yield, plant population, and stover yield were not significantly affected by tillage. Two years after subsoiling, grain moisture was similar for the NT, RT and PT76 treatments. However, the CP treatment had significantly lower grain moisture than the NT treatment. Plant populations, grain yield, and stover yield were not affected by tillage two years after subsoiling.

CONCLUSIONS

Zone tillage performed in the spring significantly improved the physical condition of the Riddles sandy loam soil. The volume of pores which were air-filled at the soil's field capacity was increased by zone tillage. This could decrease the frequency and duration of aeration stress under high precipitation. The saturated hydraulic conductivities at the 0 to 7.5 cm depth were improved by zone tillage. When the soil is saturated, infiltration rates are dependent on the Ksat of the soil. Ksat was increased under the zone tillage treatments, suggesting that infiltration would also be increased. The soil strength, as indicated by cone index, for the NT treatment was at a level where root growth has been shown to be impeded (Russell and Goss, 1974). Zone tillage significantly reduced the soil strength.

Some residual effects of the zone tillage treatments persisted for one or two years after the original subsoiling operations were performed. The soil bulk density was decreased in the two zone tillage treatments at the 22.5 to 30 cm depth. After one year, the total porosity at the 7.5 to 15 cm depth for the RT treatment was still significantly higher than the NT treatment. After two years, the total porosities at the 22.5 to 30 cm depth for the zone tillage treatments were higher than for the NT treatment. Cone index values increased with time. However, the values after two years were below 10 kPa and should not significantly impede root growth.

Tillage did not significantly affect seedling emergence in 1986. However, in 1987, tillage did significantly affect seedling emergence. In the NT and PT76 treatments, seedling emergence was significantly delayed by as much as a week. 1986 plant tissue nitrogen contents in the first year of subsoiling were the lowest for the PP76 treatment. One year after subsoiling, there was no effect of tillage on the plant tissue nitrogen contents. Grain and stover yields were not significantly affected by tillage in 1986 or 1987.

Zone tillage performed in the spring improved the physical condition of the Riddles soil. Some of the beneficial effects of zone tillage persisted for two years. However, corn yields were not affected by zone tillage.

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SUMMARY AND CONCLUSIONS

No-tillage cropping systems cause a unique soil environment to form. Some of these altered soil properties create unfavorable conditions for crop growth. Periodic plowing of the Conover loam soil improved these soil physical and chemical conditions.

Plowing the no-tilled Conover loam soil created soil physical properties similar to a continuously plowed soil. Plowing lowered soil bulk density and altered the soil's pore size distribution. The volume of soil occupied by large pores was increased and the volume of soil occupied by small pores was decreased by plowing. Plowing also increased the total porosity and the saturated hydraulic conductivity of the no-till soil.

Soil chemical properties were improved by plowing. Nitrogen mineralization was increased after plowing. No-till soil surface layers, having low pH values and high organic carbon, P, and K contents were mixed throughout the plow layer.

In 1987, seedling emergence was delayed by as much as a week in the no-tillage treatments. This may have caused the higher grain moisture contents of the no-tilled treatments at harvest.

Soil compaction occurring below the normal depth of plowing can be alleviated by subsoiling. Subsoiling only under the crop row (zone tillage) ensures that the crop roots will explore the loosened soil.

Zone tillage performed in the spring improved the physical condition of the Riddles loam soil. Soil bulk density was decreased, total porosity was increased, and saturated hydraulic conductivities were increased by zone tillage. Zone tillage significantly lowered the strength of the Riddles soil, alleviating mechanical impedance to root growth. Water availability to plants could be increased by zone tillage due to two mechanisms: the increased saturated hydraulic conductivity would indicate that the soil water recharge could be increased and the lowered soil strength would allow for increased root growth.

Some residual effects of the zone tillage treatments persisted for two years after the original subsoiling operations were performed. The total porosity and soil bulk density effects of zone tillage were still present after two years. Also, the soil strength remained at a level where mechanical impedance to root growth would be minimal.

Zone tillage did not affect corn yields. This would indicate that adequate moisture was available to the plants in all treatments. In 1987, corn seedling emergence was significantly delayed in the no-till and the Paratill treatments.

Recommendations

If it is suspected that soil physical or chemical properties in no-till are inhibiting crop growth, periodic plowing could be performed. Periodic plowing alleviated soil physical and chemical limitations to crop growth.

When soil compaction occurs below the normal depth of plowing, the soil should be subsoiled. Soil physical properties were significantly improved by subsoiling. Subsoiling in the row combined with controlled traffic will increase the probability that the loosened zone will persist for more than one growing season. The benefits of zone tillage will most likely be realized during a dry year in soils that have an impermeable layer.

APPENDIX FIGURES

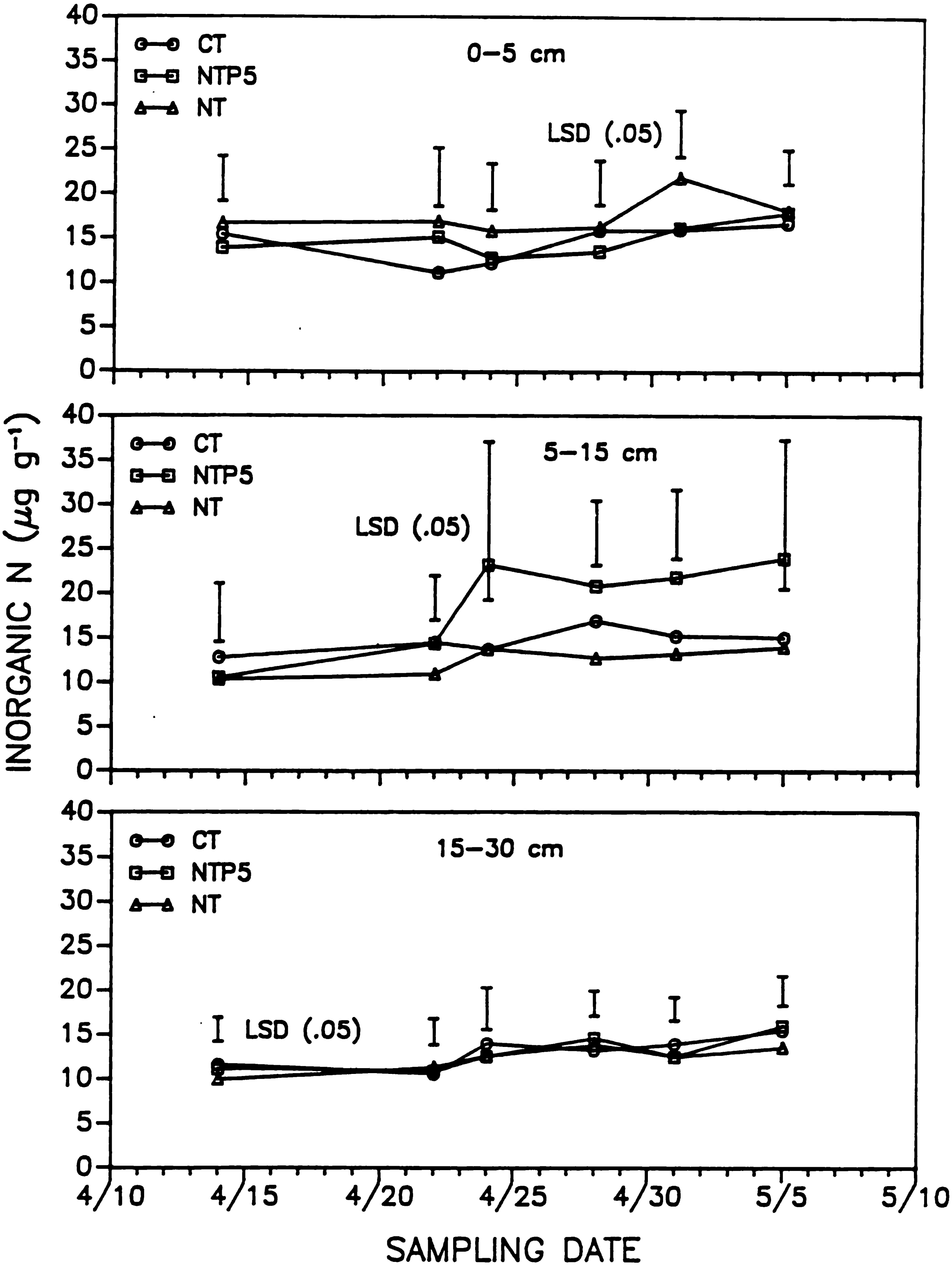

Figure 1. Inorganic nitrogen contents at three depths as affected by tillage from 1986.

APPENDIX TABLES

Table 1. Soil volumetric moisture contents at the time of subsoiling from 1986 and 1987.

Year	Depth (cm)	
	0-15	15-30
	--------- cm^3 cm^{-3} ----------	
1986	.15	.18
1987	.17	.17

Table 2. Soil volumetric moisture contents at the time of penetrometer sampling of tillage treatments implemented in 1985, 1986, and 1987.

Tillage	Depth (cm)		
	0-10	10-20	20-30
		1985	
	------------	$cm^3\ cm^{-3}$	------------
Ro-Till	.20	.21	.19
Paraplow	.19	.20	.19
		1986	
	------------	$cm^3\ cm^{-3}$	------------
Ro-Till	.19	.19	.22
Paraplow	.20	.20	.20
		1987	
	------------	$cm^3\ cm^{-3}$	------------
Chisel Plow	.18	.20	.21
NT	.22	.22	.23
Ro-Till	.19	.20	.21
Paratill	.19	.20	.20