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Alleviation of compaction on fine-textured Michigan soils

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ALLEVIATION OF COMPACTION ON FINE-TEXTURED MICHIGAN SOILS

By

Bradley Scott Johnson

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
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ABSTRACT

ALLEVIATION OF COMPACTION ON FINE-TEXTURED
MICHIGAN SOILS

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Bradley Scott Johnson

Normal fall and spring tillage practices create poor physical conditions for crop growth on Charity clay (fine, illitic (calcareous), mesic Aeric Haplaquept). This soil has an unstable surface and poor internal drainage due to its naturally dense subsoil. Tillage studies were conducted to evaluate the potential for increasing crop yields by reducing the physical limitations of Charity clay and a second lake-plain soil, Parkhill loam (fine-loamy, mixed, nonacidic, mesic Mollic Haplaquept). Both soils were subsoiled and subsequent traffic was controlled to avoid recompaction of the loosened soil. Experiments were established during 1983 to 1985 on Charity clay at the Saginaw Valley Bean and Beet Research Farm, Swan Creek, MI. An identical experiment was conducted in 1983 on Parkhill loam near Ithaca, MI. Both sites were artificially drained and nearly level.

Subsoiling improved the physical condition of Charity clay below the Ap Horizon. Physical changes created by subsoiling persisted through only one crop year. Compaction caused by preplant wheel traffic was evident in the surface of Charity clay and below the normal depth of plowing. Fall moldboard plowing plus conventional spring tillage produced the least favorable conditions for crop growth in terms of soil aeration.

Subsoiling tended to increase soybean and sugarbeet yields in 1983. Controlled traffic improved seedling emergence most of the time, increased dry bean rooting in 1983, and tended to increase crop yields.

Dry beans and sugarbeets were more sensitive to wheel induced compaction than other crops included in the study. Preplant wheel traffic decreased yields of these crops during two of three years. Soybeans were the least sensitive to soil compaction as preplant wheel traffic actually increased yields on Parkhill loam in 1983. Crop response depended on the climate each year. Tillage effects were most evident in 1983 when soil water excesses occured during the early part of the growing season followed by a dry June-to-August period.

Tillage effects on aeration of Charity clay were evaluated further using the CERES-Maize model. This simulation model proved to be useful because the soil water balance is calculated on daily basis and soil inputs can be altered to account for varying soil conditions created by tillage. Simulated water contents resembled the measured values for two diverse tillage treatments. Air porosities corresponding to the simulated water contents were used as the basis for calculation of cumulative stress day index (SDI). Deep tillage plus controlled traffic improved soil aeration each year based on the cumulative stress day indices. The SDI was greatest for 1983 when tillage effects on crop growth were most evident. Results of a long-term study using generated weather data suggest that poor aeration under conventional fall and spring tillage may limit yields on this soil during at least one of three years.

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INTRODUCTION

Soil compaction is a major problem in the United States. Restricted root growth and possible reductions in yield are the obvious consequences of soil compaction. Gill (1971) estimated that the value of crop losses resulting from soil compaction amounted to 1.18 billion dollars in the United States based on 1964 figures. In addition to yield losses, production costs associated with management of compacted soil are increased. More energy is required to till a compacted soil than a noncompacted one and wear on tillage tools increases with density of the soil (Voorhees and Hendrick, 1977). Since tilling compacted soil produces greater clodiness (Johnson et al., 1979), an increased number of tillage operations may be required to produce an adequate seedbed. Remedial actions are costly on compacted soils as a result.

Though some soils are naturally dense, most compaction is caused by wheels of agricultural vehicles. Changing cropping systems have contributed greatly to the incidence and degree of wheel induced compaction because of their influence on tillage intensity and the amount of residue returned to the soil. Crop rotations which include leguminous hay have been replaced by rotations in which an annual crop may be grown for several years in succession (Robertson, 1984). On prime farmlands in Michigan, the percentage of field crop hectarage in row crops increased from 45.8 to 71.7% during the period 1967 to 1982 at the expense of hectarage in small grains and sod crops (Whiteside and Lumbert, 1986). Thus, soils depleted in organic matter are being worked more intensively.

Problems associated with wheel induced compaction are worsened by the steadily increasing size of agricultural equipment. Most agricultural wheel traffic can be attributed to the rear tires of tractors which have increased in size as a necessary consequence of the more intensive use of land, the increase in size of farms, and the scarcity of farm labor (Gill, 1971). Tractors have increased in weight from an average of 2.7 Mg in the late 1940's (Voorhees, 1977) to current weights of large four wheel drive units which may exceed 22.4 Mg (Carpenter et al., 1985). Contact pressures under tractor tires have been held relatively constant as axle loads have increased by increasing tire diameter and width. However, high axle loads result in deeper compaction even though the weight may be distributed over a larger contact area.

Natural weathering forces such as freezing and thawing may not ameliorate wheel induced subsoil compaction even where frost penetration depth is substantial. Dense subsoils must be loosened mechanically as a result. Unfortunately, subsoil compaction is more difficult and costly to alleviate than compaction within the normal depth of plowing. Furthermore, disruption of a dense layer or horizon which inhibits root development may not always improve yields depending on the prevailing climate and management practices.

When deep tillage is deemed to be necessary to improve subsoil physical conditions, the most appropriate tillage operation should be selected and implemented at the proper time. For example, dense subsoils are shattered most effectively by subsoiling at low soil water contents. Post subsoiling traffic must be controlled or at least reduced to avoid recompaction of soil loosened by deep tillage. Thus, compaction prevention and occasional corrective procedures are essential components of a compaction management system. Even though techniques for reducing compaction under wheels are available, their adoption by farmers and manufacturers has been limited (Soane et al., 1982).

The objectives of this study were to: (1) evaluate the potential for reducing the physical limitations of Charity clay (Aeric Haplaquept) by subsoiling in the fall when it is dry; (2) determine the susceptibility of the loosened soil to recompaction during subsequent traffic and the persistence of changes brought about by subsoiling where traffic is controlled; (3) determine the influence of subsoiling and subsequent secondary tillage operations on growth of crops that are typical of the dry bean and sugarbeet production areas in Michigan; (4) further evaluate crop response to tillage using a crop simulation model and the stress day index approach; and (5) develop probabilities of crop response and benefit from subsoiling and controlled traffic using simulations over long periods of time and soil aeration as the criterion for response.

Chapter 1

LITERATURE REVIEW

Soil compaction is a major problem in Michigan. Robertson and Erickson (1980) reported the occurrence of symptoms of excessively compact soil in every county of the state. Visual symptoms in soil may include soil crusts, shrinkage cracks in vehicle wheel tracks, standing water and others. The authors also identified a variety of visual symptoms displayed by Michigan crops including distorted stems, variable plant emergence and/or size, wilting plants, discolored leaves, malformed roots and lodging.

Plants which exhibit the diversity of responses to compacted soil described in the preceding paragraph share one thing in common: all have soil environments which subject their roots to at least one, possibly several stresses simultaneously. Water and nutrient deficiencies are common environmental stresses accompanying soil compaction. Impeded aeration can result in oxygen deficiencies as well as the accumulation of carbon dioxide and other toxic substances in some compacted soils.

Soil properties influenced by compaction and their influence on plant root growth (and productivity) will be surveyed in the review which follows. Soil aeration and interactions with the prevailing climate will be emphasized. Approaches to amelioration of problem soils will be examined after considering causes of soil compaction in Michigan. Finally, the possibility of using simulation models to evaluate the influence of root zone modification (e.g., deep tillage) on crop responses will be discussed.

Soil Physical Properties Influenced by Compaction

Root growth and function are influenced by physical and chemical properties of soils but unfavorable physical conditions are most often associated with soil compaction. Physical properties characteristic of compacted soils have been reviewed (Barnes et al, 1971). Salient features of this review and subsequent studies were summarized in a review by Byrnes et al. (1982). The authors concluded that compaction increases soil bulk density and strength, decreases total porosity, but more importantly decreases the volume of large pores. Thus, resistance of the soil to penetration by roots and emerging seedlings is increased. Rates of water infiltration and internal drainage are reduced and water retention can be increased or decreased depending on the changes in porosity and pore size distribution. In addition, exchange of oxygen and carbon dioxide between the soil and atmosphere can be inhibited at times.

Measurement Of Soil Compaction

Soil compaction can be measured using a variety of techniques because there are so many soil properties that are indicators of compaction. Procedures used to measure soil compaction were reviewed by Freitag (1971) and Byrnes et al. (1982). Bulk density, the mass of dry soil per unit bulk volume, is the most frequently used measure of soil compaction. Soil bulk density (Db) can be determined using the core, coated clod, or radiation methods (Blake, 1965). Soil porosity is the simplest partial characterization of the soil pore system and can be calculated directly from Db if the density of the soil particles is known:

$$P = 1 - Db/Dp \qquad (1)$$

where P is the volume fraction of the total bulk not occupied by solids and Dp is the particle density (usually about 2.65 Mg m^{-3}).

Pore size distribution (PSD) is the volume of the various sizes of pores in a soil and is expressed as a fraction of the bulk volume. Since compaction affects the volume of larger pores more so than the volume of fine pores, PSD is an attractive measure of soil compaction.

No single dimension of a pore can unambiguously be defined as its size (Klute, 1982). Pore size must be defined by a method of measurement as a result. Vomocil (1965) described a procedure in which a capillary model is used to represent soil pore space. Water is extracted from an initially saturated soil sample of known volume by a series of suctions h. The volume of water extracted at each h is equal to the volume of pores having an effective radius greater than the corresponding value of r in the capillary rise equation:

$$r = \frac{2\, \gamma \cos \alpha}{g\, D_1\, h} \tag{2}$$

where γ is the surface tension (dyne cm^{-1}), α is the contact angle (usually assumed to be zero), g is the acceleration due to gravity (980.7 cm s^{-2}), and D_1 is the density of the liquid (g cm^{-3}). Since h is usually measured in cm of water, units given in paranthesis are appropriate for calculation of r in cm. When PSD is determined using this procedure, one is essentially measuring the volume fraction of air-filled pores (air porosity) at the same series of suctions h. Thus, results can also be reported as air porosities over the range of applied suctions.

Porosity and PSD influence the conductivity of soil to water, especially at high water potentials. Water flow through a cylindrical tube is proportional to the fourth power of the radius according to the Poiseuille equation. Thus, flow volume is decreased by a factor of 16 when the radius of the tube is reduced by a factor of two. Water flow through interconnecting soil macropores is affected just as dramatically by reductions in size based on the capillary model. Since most of the water is conducted through macropores at water contents near saturation, hydraulic conductivity of soil at high water potentials is a sensitive measure of soil compaction. Klute (1965) described the most prominent laboratory procedures used to measure saturated hydraulic conductivity (Ksat) of samples held in metal or plastic containers. Boersma (1965) described several field techniques which can be used to measure Ksat and Cassel (1975) demonstrated in situ measurement of unsaturated hydraulic conductivity at different depths in the soil profile.

Soil strength, its resistance to penetration and displacement, can be determined in the field using penetrometers and shear vanes. Numerous laboratory techniques also exist (e.g., unconfined compressive strength and modulus of rupture) but soil penetrometers have been used more extensively than any other device in mechanical impedance studies. Penetrometers of various sizes and shapes have been used. Penetrating elements were historically circular or rectangular flat plates or cone shaped. Techniques used to advance the penetrometer tips into the soil also lack standardization. For example, moving-tip penetrometers are forced into the soil at a constant rate. Penetrometers which measure pressure required to push the tip a specific distance are called static tip penetrometers. Moving-tip cone index types are presently considered to be standard penetrometers (Anonymous, 1985).

Penetrometer resistances (R), often reported as cone index, increase as soil bulk density increases or as soil water content decreases. The fact that R changes with water content is an important shortcoming of the penetrometer method. Changes in R (e.g., with tillage or compaction) may reflect variation in water content at sampling rather than changes in soil structure. The penetrometer method is also handicapped by the fact that changes in R with Db or soil water content are soil dependent.

No single measurement or procedure is appropriate for all situations since each have advantages and limitations. Vomocil and Flocker (1961) suggest that PSD is a more sensitive indicator of soil compaction than is Db because PSD suffers greater relative change with compaction than Db. Voorhees (1983) and Voorhees et al. (1986) agree that Db is a poor indicator of soil compaction because Db is sensitive mainly to pore volume. Bulk density is insensitive to pore structure and planes of weakness in the soil both of which relate directly to water flow characteristics and root extension. The authors concluded that hydraulic conductivity and penetrometer resistance are probably better indices of compaction as a result.

Hydraulic conductivity was also the measurement of choice in a study conducted by Allmaras et al. (1982) in the Pacific Northwest. Water transmission characteristics of a silt loam under various management systems were compared. Under the prevailing weather conditions, hydraulic conductivity was a pertinent measurement because internal drainage of these soils can influence water conservation through effects on runoff and evaporation. Obviously, the procedures or measurements should be selected to provide the most effective results.

Influence of Soil Conditions on Root Growth

Mechanical Impedance

In most situations, roots grow partly through existing pore space and partly by moving aside soil particles (Bowen, 1981). Because large pores are scarce in compacted soils, it becomes necessary for roots to expand pores by exerting a force greater than the mechanical strength of the soil (Cannell, 1977). Russell (1977) cited the work of several investigators who demonstrated that roots can exert longitudinal pressure of 0.9 to 1.3 MPa. However, relatively small external pressures (50 kPa) can drastically restrict root extension (Russell and Goss, 1974).

Root growth is mechanically impeded when strength of a soil or soil layer exceeds the maximum force the root is capable of exerting. Since soil strength decreases as soil water content increases, a soil layer that inhibits root growth when dry can become nonrestrictive to root growth when wet. This explains why, in some situations, perenials can penetrate dense soil layers that annuals cannot. Perenials are more likely to encounter the restrictive layer when the strength is reduced than are annuals. Vepraskas et al. (1986) demonstrated the influence of soil water content on soil strength and growth of tobacco (Nicotiana tabacum L.) roots in soils with dense tillage pans. The proportion of roots below the E-B horizon was dependent on cumulative rainfall in addition to bulk density and sand content.

Root responses to mechanical stress have been reviewed (Barley and Greacen, 1967; Taylor 1971,1974; Cannell, 1977). The usual effects of mechanical impedance are reduced availability of water and plant nutrient elements according to Bowen (1981) and may be attributed to one or more of the following factors identified by Taylor (1971): (a.) maximum depth of root development is restricted, (b.) root proliferation within the explored volume is diminished, (c.) an extra quantity of photosynthate is utilized by roots growing in high-strength media, or (d.) taproot diameter is sufficiently reduced retarding transport functions of the root.

The reader is cautioned that productivity of crops with mechanically impeded roots is not necessarily reduced (Russell, 1977). Productivity is influenced by additional factors such as climate and management practices. Where water is not limiting for example, plant growth is usually not increased by disruption of a dense soil layer that inhibits root development (Weatherly and Dane, 1979). Buxton and Zalewski (1983) demonstrated that with proper irrigation management, potato yields are not adversely affected by restricted rooting in compacted subsoils.

Soil Aeration

Root growth and survival require metabolic energy which is generated by respiration of sugars under aerobic conditions. Respiration occurs in the mitochondria and involves the transfer of electrons from sugars to a series of organic molecules and finally to oxygen, releasing energy along the way. Anaerobiosis will occur in soil whenever the demand for oxygen, determined by the respiratory requirements of roots and soil organisms, exceeds the rate at which it can enter the soil.

Air porosity of the soil is its physical characteristic which has the greatest influence on gas exchange with the atmosphere (Russell, 1977). Rates of gas exchange increase as the fractional volume of soil occupied by air increases. Since fractional air porosity and soil water content are inversely proportional, excess soil water is the cause of anaerobiosis. Taylor and Arkin (1981) suggests that oxygen stress is almost always caused by excessive soil water contents in noncompacted soils as in the presence of a shallow water table. However, Blake and Page (1948) recognized that aeration can be impeded in compacted soils at certain 'critical times'. Soil and weather conditions that promote soil water excesses will be described in subsequent sections.

Evaluation of Soil Aeration

Soil Air Composition

When gas exchange is restricted and anaerobic metabolism takes place, the composition of soil air changes towards lower concentrations of oxygen and higher concentrations of carbon dioxide. High concentrations of CO_2 can be toxic to plants but studies reviewed by Grable (1966) and Kramer (1969) indicate that CO_2 is a minor source of injury to plants compared to O_2 deficiencies. A wide variety of other toxic substances are produced during anaerobic metabolism and may affect roots which survive O_2 depletion itself. Major groups of toxic substances include organic acids, hydrocarbon gases (e.g., ethylene), and sulfides. Soil conditions such as pH and the presence of fresh organic debris as an energy source for microorganisms dictate the relative importance of these toxic substances.

Oxygen concentrations which inhibit root growth or respiration vary considerably and have been estimated at values ranging from 14 percent to less than one percent in reviews by Russell (1977) and Cannell and Jackson (1981). Russell (1977) attributes Such variation to differences in experimental conditions, especially temperature. Root growth may have been affected in some experiments by the production of toxic substances. In addition, the O_2 concentration of the soil air is not equivalent to the supply of O_2 actually available to the root. For example, rhizosphere organisms may deplete the partial pressure of O_2 at the surface of roots to an unknown extent. The aeration status of the soil may not be adequately assessed by measurement of O_2 concentration alone owing to these difficulties. Alternative methods can be used to measure soil aeration. Their usefulness will be evaluated following a discussion of mechanisms of gas exchange in the soil.

Gaseous Diffusion Rates

The most important mechanism of gas exchange between the soil and atmosphere is diffusion which obeys Fick's Law:

$$q_d = -D\ dc/dx \qquad (3)$$

where q_d is one dimensional flow of gas, D is the gas diffusion coefficient, and dc/dx is the concentration gradient. Typical units for q_d, D, and dc/dx used in the literature are g cm^{-2} min^{-1}, cm^2 min^{-1}, and g cm^{-3}/cm, respectively. The gas diffusion coefficient is a property of both the medium and the gas but it is also influenced by atmospheric pressure and temperature. Since O_2 diffuses 10^4 times more rapidly in air than in water, diffusion of O_2 occurs mainly in air filled pores.

The gas diffusion coefficient in soil (Ds) is smaller than the coefficient in free air (Do) because of the reduced cross sectional area available for movement and increased path length resulting from the tortuosity of the interconnected air filled channels. To compare rates of diffusion via the gaseous phase in various media Ds is usually expressed as a fraction of Do. Methods of measuring the relative diffusion coefficient (Ds/Do) have been reported by Taylor (1949) and Raney (1949).

Many functional relationships between Ds/Do and air porosity have been proposed (Hillel, 1980). Several equations are of the form:

$$Ds/Do = e\ Pa \qquad (4)$$

where Pa is the air porosity and e is a constant which represents tortuosity. Penman (1940) measured the diffusion of carbon bisulfide through packed soil cores in the range of $0.195 < Pa < 0.676$ and found values of e equal to 0.66. Other investigators have reported different values of e for different soils and ranges of air porosities. Blake and Page (1948) found that the ratio between Ds/Do and Pa varied between 0.62

and about 0.8. Their most significant finding was that Ds approached zero when air porosity fell below 10% ($0.1\ m^3\ m^{-3}$), an observation attributed to the discontinuity of air filled pores inside soil aggregates.

Wesseling (1962) proposed another linear model:

$$Ds/Do = 0.9Pa - 0.1 \tag{5}$$

which suggests that Ds becomes zero when air porosity falls below 11%. Grable (1971) endorsed these findings stating that the continuity of air filled pores to the soil surface is likely to be broken when air porosity is less than about 10%.

Several nonlinear models have been proposed, some of which account for the influence of soil characteristics other than just air porosity on diffusion. Millington and Quirk (1961) considered the geometry of flow paths and the probability of pore continuity in dry porous media and derived the equation:

$$Ds/Do = Pa^{10/3}/P^2 \tag{6}$$

where P is total soil porosity. Sallam et al. (1984) found best agreement between calculated and measured Ds at low air porosities (0.05, 0.10, and 0.15) using this model but with the Pa exponent reduced from 3.33 to 3.10.

It is clear that a strong relationship between Ds/Do and Pa exists but that it is not constant for all soils. In addition, Currie (1984) showed that no single relationship between the relative diffusion coefficient Ds/Do and Pa fitted the results for even one soil (a clay loam) that was packed to varying levels of bulk density.

Evaluation of the soil oxygen environment is further complicated by the existence of water films covering active root surfaces. The diffusion path for O_2 from the atmosphere to actively respiring cells of roots is completed via these water films. Lemon and Erickson (1952) introduced a method to measure oxygen diffusion rate (ODR) using platinum microelectrodes to simulate actively respiring roots. Their method is based on the principle that O_2 is reduced at the electrode surface producing a current proportional to the rate at which O_2 diffuses to the electrode from its surroundings. Stolzy and Letey (1964) reviewed studies of plant responses to measured ODR values. The authors concluded that roots of most plants do not grow in soils with ODR values less than 3.3×10^{-8} kg m^{-2} s^{-1} (20×10^{-8} g cm^{-2} min^{-1}) and that ODR must exceed 6.7×10^{-8} kg m^{-2} s^{-1} (40×10^{-8} g cm^{-2} min^{-1}) for optimum top growth.

A relationship exists between ODR and air porosity of the soil under most conditions. However, Lemon and Erickson (1952) used the platinum microelectrode method to show that O_2 supply to plant roots may at times be controlled by water film thickness rather than air porosity. Letey and Stolzy (1967) confirmed their results by calculating from theory the water film thickness corresponding to measured ODR values at various soil porosities. For a root which has a radius of 0.23 mm, an O_2 concentration of 20% in the gas phase, and a porosity of 0.5 m^3 m^{-3} for the soil surrounding the root, a water film thickness of 0.40 mm would limit the ODR to 3.3×10^{-8} kg m^{-2} s^{-1} even if the volume of air filled pores was substantial. Unfortunately, it is difficult to predict under what conditions water films restrict diffusion because there is poor agreement by researchers on what water film thicknesses occur in practice.

Air Porosity

Several aspects of soil aeration have been considered up to this point: oxygen concentration of soil air, diffusion rates in gas filled pores and in water films, and air porosity. Erickson (1982) categorized these indicators of soil aeration as intensity, rate, and capacity factors, respectively. Measurement of ODR in water films is the most reliable way to evaluate the O_2 environment of roots. The use of platinum microelectrodes simulate roots, eliminating the need to know the soil and water geometry surrounding them. Nevertheless, air porosity is the most commonly measured soil aeration parameter and may be attributed in part to the fact that growth limiting levels of air porosity exist. An air porosity of 10% is frequently cited as the level above which soil aeration should be adequate for plant growth (Wesseling and van Wyk, 1957; Vomocil and Flocker, 1961; Thomasson, 1978).

Factors Which Influence Air Porosity

Soil Compaction

The relative abundance of air filled pores depends on soil pore size distribution and the prevailing soil water regime. Compaction influences pore size distribution, especially in the larger pore size range (Klute, 1982). The soil water characteristic, or the relationship between soil water content and soil water matric potential, is altered accordingly as the result of soil compaction. The soil water regime following a heavy rain or irrigation is determined by the soil water characteristic.

Vomocil and Flocker (1961) suggest that the water potential at 'field capacity', the water content after free drainage is neglible, is -7.5 to -20 kPa. Webster and Becket (1972) demonstrated that the water potential at field capacity can be much higher in soils containing more than 30 to 40 percent clay and that only pores larger than 100 to 300 μm in diameter are air filled. More recently, Cannell and Jackson (1981) suggested that water drains freely under gravity only from pores larger than 30 to 60 μm in diameter to a water potential no less than about -5 to -10 kPa in most soils.

At any rate, only large pores are air filled at field capacity, the volume of which is diminished by compaction. Thus, in a given climate compacted soils exhibit a greater tendancy to become anaerobic than noncompacted ones and remain so for longer periods of time based on their altered drainage and water retention properties. Several investigators have demonstrated the influence of compaction on drainage and duration of anaerobiosis. Blake et al. (1976) calculated the time required for soil profiles in packed and nonpacked plots to drain to matric potentials corresponding to an air porosity of 10%. In the absence of evaporation and plant water uptake, air porosity at the 0.30 to 0.40 m depth would reach 10% after 10 days of free drainage in the nonpacked plots compared to more than 30 days in the packed plots. Agnew and Carrow (1985) found that ODR measured with platinum microelectrodes remained below critical levels for a longer period of time following irrigation in compacted pots compared to noncompacted pots.

Climate

Occurrence of aeration stress is dependent on weather conditions during the growing season just as water stress of plants with mechanically impeded roots may not occur depending on the distribution of rainfall and irrigation. Therefore, before aeration stress can be diagnosed as the primary physical limitation of a problem soil, likelihood of its occurrence must be considered. This prompted Greenwood (1968) to suggest that the aeration status of a soil must be defined in terms of the probability of occurrence of a particular set of weather conditions that are necessary to induce O_2 deficiencies in soils having given drainage characteristics.

When soil conditions and climate are such that excess soil water may exist at times, the extent of plant injury due to impeded aeration is influenced by plant species or cultivar, growth stage, and duration of stress. For example, some species of grain legumes are regarded as waterlogging tolerant (e.g., Vicia Fabia L.) while others are very sensitive to short periods of waterlogging (Cannell and Jackson, 1981). Injury caused by excess moisture varies with growth stage. This may be attributed in part to seasonal differences in O_2 consumption but plant sensitivity may also change during their life cycle. Erickson and Van Doren (1960) demonstrated that pea (Pisum sativum L.) yields were reduced greatest when O_2 deficiency occurred just prior to blossoming. Soil water excesses seem most harmful to corn (Zea mays) during early growth stages (Hiler and Clark, 1971; Singh and Ghildyal, 1980). Thus, it may not be sufficient to examine the probability of occurrence of O_2 stress without considering the crop and stage of growth during which stress is likely to develop.

The importance of duration of anaerobiosis may be attributed to the fact that soil air contains only a limited supply of O_2 at any one time. For example, Cannell and Jackson (1981) compared the volumes of O_2 contained in a sand and clay soil after draining freely. The volumes were 0.03 and 0.005 m^3 m^{-3} in the sand and clay, respectively. Even short term interruption of gas exchange between the soil and atmosphere can be harmful when the quantity of O_2 required for soil respiration is large. Hillel (1980) calculated that a soil with an effective root zone depth of 0.6 m and 15% air porosity contained 0.09 m^3 of air under each m^2 of soil surface. With an initial O_2 concentration in the gas phase of 20% (i.e., 0.03 m^3 m^{-3} O_2) and an O_2 requirement of 10 g m^{-2} d^{-1} the oxygen reserve would last only 2.5 days but stress symptoms would probably begin earlier. Erickson and Van Doren (1960) showed dramatic effects of only one day of oxygen deficiency. Yields of peas subjected to one day of O_2 deficiency just prior to blossoming were reduced 30 percent.

Causes of Soil Compaction in Michigan

Naturally Occurring Compaction

Many Michigan soils are characterized by naturally dense layers or horizons. Some of these horizons may be attributed to chemical cementation of soil particles as in fragipans and orsteins. However, dense soil layers formed under physical phenomenon as in till and lacustrine deposits are more common. For example, the parent materials of the soils in Huron County were deposited directly by glaciers (basal till) or by melt water from glaciers (ablational till). This till is calcareous and its texture is sandy loam, loam, or clay loam. Approximately 60 percent of the Huron County soils have naturally dense C horizons with bulk densities ranging from 1.70 to 2.13 Mg m^{-3} (g cm^{-3}) and 62 percent of these C horizons occur within 1 m of the soil surface (Linsemier, 1980). Daddow and Warrington (1983) established a relationship between growth-limiting bulk density and soil texture based on their influence on mechanical resistance to root penetration. Growth-limiting bulk densities corresponding to textural classes found in the Huron County subsoils range from 1.50 to 1.70 Mg m^{-3}, well below the prevailing bulk densities.

Some Michigan soils are considered to be naturally compacted not because they have high bulk densities, but because they are fine textured, exhibit poor internal drainage, and therefore lack adequate aeration for root growth at certain times during the growing season. Charity clay (Aeric Haplaquept) is an example of such a soil. It is a lake plain soil of lacustrine origin which has poor structure and is so dense that little rooting occurs below the plow zone except in shrinkage cracks that occur late in the growing season (Erickson, 1982). Charity clay is part of the expansive Erie-Huron Lake Plain which covers more than 1.7 million hectares (4.22 million acres) in Michigan's southern lower peninsula.

Wheel Induced Compaction

Compacted soil conditions induced by man are more extensive than those that occur naturally. Agricultural vehicles are the primary source of compactive forces (Cohron, 1971). Wheels of agricultural vehicles produce pressures at the soil surface and within the soil body. Vertical pressures are equivalent to normal stresses such as stresses exerted by a static load. Shearing stresses also arise under rolling tires, especially when wheel slippage occurs. When the combined stresses are sufficient to cause soil compaction, the major actions in the soil are rearragement of soil particles and reduction in pore space, especially of large pores (Harris, 1971). Tractors contribute most to total vehicle traffic but tillage implements, harvesting equipment, and hauling units may also lead to considerable amounts of vehicle traffic.

The extent of vehicle traffic and vehicle weight are two of the most important factors influencing the degree of wheel-induced compaction. Excessive traffic is a problem wherever modern agricultural practices are employed. There are several ways of reporting the extent of vehicle traffic. Gohlich (1984) examined farming practices in Europe and concluded that tractors travel 30 to 60 km ha^{-1} on the average in one season. Another approach is to determine the size of the wheel tracks in relation to the soil surface. By multiplying this value by the total number of field operations, the wheel track surface caused by vehicle wheels can be determined. Voorhees (1977) calculated the amount of wheel traffic associated with a six-row operation covering a width of 4.6 m, and using 0.46 m wide rear tractor tires. Assuming a total of six operations per growing season, half of them with dual wheels, the tractor tires make enough wheel tracks to cover every square meter of the field twice. In Sweden, the total wheel track surface is commonly between four and five times as great as the surface where small grains are the main crop but even higher with other crops such as sugarbeets and potatos (Eriksson et al., 1974).

When every point on the soil surface is exposed to wheel traffic two times on the average, it is obvious that some points may be driven across several times while others not at all. However, the probability that a particular point on the field will be affected by at least one pass of a tractor tire is high because most wheel traffic is randomly distributed over the field under normal farming operations (Voorhees et al., 1979). Exceptions are well defined areas of concentrated wheel traffic from planting, cultivation and harvest of row crops. The adverse effects of random wheel traffic on freshly tilled soil become obvious when one considers the well documented phenomenon that most soil compaction occurs after one pass of a tire. For example, Taylor et al. (1982) showed that three fourths of the total change in bulk density and 90% of the sinkage on a silt loam occurred after the first of four passes.

The second factor that influences the depth and degree of soil compaction is vehicle weight and weight distribution. Carpenter et al. (1985) reported the results of a University of Nebraska survey of U.S. tractor weights during the last 17 years. The average tractor weight has increased from 4.6 Mg in 1968 to an average of 6.8 Mg in 1985, with large four-wheel drive units exceeding 22.4 Mg. Transport vehicles such as commercial fertilizer spreaders and trucks used to haul agricultural products have also increased in size. Capacities of trucks used to haul sugarbeets from fields to processing plants have increased from 5.5 to 9.0 Mg over the last 40 years according to Anderson and Peterson (1985).

Prior to the classic work by Soehne (1958), it was commonly believed that increasing tire width or diameter as the load increases will not result in an increase in compaction because tire inflation pressure and soil contact pressure can be held constant. Soehne (1958) disproved this notion by examining the theoretical distribution of vertical pressures under a load applied normal to the soil surface. Important findings were: (1) pressure in the upper soil layer is determined by the specific pressure at the soil surface which depends on tire inflation pressure and soil deformation, and (2) pressure in the deeper soil layers is determined by the magnitude of the load. Taylor et al. (1980) and Blackwell and Soane (1981) verified the second finding by measuring vertical pressure (normal stress) within the soil body under various loads.

Subsoil compaction is an issue of great concern to agriculturalists because it is more difficult and costly to correct than is compaction within the normal depth of plowing. Eriksson et al. (1974) measured actual changes in soil physical properties as larger and larger loads were applied to the soil surface. Measurable differences in pore volume and permeability appeared in the upper part of the subsoil at axle loads of 6.0 Mg. The authors speculated that the continuing trend towards heavier machinery may cause a gradual shift in equilibrium soil conditions towards an increasing degree of subsoil compaction. Saini (1978) and Voorhees et al. (1978) have since cited the ever increasing machinery sizes as the primary reason for persistence of subsoil compaction. This claim may be especially valid in northern climates where the natural forces of freezing and thawing might otherwise decrease bulk density of the compacted subsoil.

Changing Cropping Systems

Soil compaction is usually more prevelant under continuous or intensive cropping systems than under rotations, especially those including meadows or legumes. Several factors associated with crop rotations or cropping systems influence the degree of compaction. Tillage intensity, the kind and amount of residue returned to the soil are the primary factors but their effects on soil conditions are difficult to separate (Larson and Allmaras, 1971). Results of some studies imply tillage intensity or the amount of wheel traffic is the dominant factor. Compaction was associated with continuous corn culture in a 13 year rotation experiment on Brookston clay (Bolton et al., 1979). The authors concluded that a four year rotation which included two years of alfalfa was superior to continuous corn because overall tillage intensity was reduced. Saini (1980) reported the results of bulk density (Db) measurement under traffic rows in continuous potatos. Soil bulk density was directly related to the number of years under continuous cropping and not organic matter levels indicating that the amount of vehicle traffic was the primary factor influencing the degree of compaction.

Many rotation experiments have been conducted which show that the degree of compaction is related to soil organic matter levels. Crop rotations retard the decline of soil nitrogen and organic C compared to continuous cropping systems (Hageman and Shrader, 1979; Odell et al., 1984; Skidmoore et al., 1986). Products of biological decompostion of organic materials are required to stabilize soil structure. Larson and Allmaras (1971) summarized the results of numerous long term rotation experiments designed to evaluate the influence of cropping systems on soil structure. Addition of crop residues or cropping systems that included legumes promoted low Db and the decreases in Db were roughly proportional to increases in organic matter content. Further, changes in stability of soil structure (e.g., water stability of aggregates) associated with various cropping systems were even more evident than changes in organic matter content.

Recent studies have been conducted in which the influence of organic matter on susceptibility to compaction is clearly demonstrated because the effects of machinery travel were nonexistent or accounted for. Howard et al. (1981) evaluated the susceptibility of 14 California forest and range soils to compaction by measuring Proctor maximum bulk densities. The four most susceptible soils were range soils, each of which was characterized by low organic C content. Pikul and Allmaras (1986) imposed several residue management treatments on a winter wheat-fallow system in the Pacific Northwest. Soil bulk density and soil water desorption curves indicated that compaction was greatest where organic C addition was lowest.

The trend towards intense crop rotations is recognized as a key factor contributing to Michigan's growing compaction problem (Robertson, 1984). Such rotations do not include leguminous hay, an important source of organic matter required to stabilize soil structure. Whiteside and Lumbert (1986) summarized the extent of this trend in their comparison of land use changes from 1967 to 1982. In the southern lower peninsula, where most of Michigan's farmland is located, there was a shift to an increased percentage of field crop hectarage in row crops from (45.8 to 71.7) and decreased percentages in small grains (from 24.4 to 16.3) and sod crops (from 29.8 to 12.0). These shifts in land uses have been most pronounced on the prime farmlands which were thought to have the least limitations to use in terms of physical and chemical properties.

Untimely Field Operations

Soil texture and water content influence the susceptibility of a soil to compaction given a particular compactive effort. Larson et al. (1980) and Denton et al. (1986) showed that coarse textured soils, especially those with a wide range of particle size, can be compacted to high Db. Larson et al. (1980) classified finer textured soils into three groups whose compressibilities were dominated by the type of clay rather than particle size distribution.

Producers are unable to control soil texture but timely field operations, if possible, can reduce the risk of soil compaction. Robertson and Erickson (1980) attributed deterioration of physical conditions of Michigan soils to inadequate drainage and field operations on wet soil in addition to causes of compaction already cited. Inadequate drainage is a problem because it increases the likelihood that certain field operations will be conducted when the soil is wet and most susceptible to compaction.

The relationship between soil water content and Db resulting from a given compactive effort has been described by Soehne (1958), Gill and Vanden Berg (1967), Harris (1971), and Saini et al. (1984). For every compactive effort, there is a soil water content called the 'optimum moisture content' at which the maximum Db is obtained. Dry soils resist compaction due to particle-to-particle bonding and frictional resistance. As water content increases, moisture films develop on particle surfaces which weaken interparticle bonds and reduce internal friction by lubricating the particles (Hillel, 1980; Hamdani, 1983). At water contents above the optimum moisture content, the fractional volume of expellable air is reduced and soil density can no longer be increased to the same degree as before. As compactive effort increases, the maximum attainable Db increases and the optimum moisture content is shifted to lower values because less moisture is required to lubricate the soil particles.

A laboratory test for the determination of the optimum moisture content and corresponding maximum attainable Db was developed by Proctor (1933). This test is routinely used by engineers who view soil as construction material and strive to manipulate it so that strength of a soil layer can be increased and permeability can be decreased. These objectives are contrary to those of agriculturalists. Saini et al. (1984) proposed that the term 'optimum moisture content' which corresponds to the maximum attainable Db, should be replaced by 'critical moisture content' to account for this contradiction. Field operations should be conducted when the soil water content is less than the critical water content. Unfortunately, rainfall probabilities increase during the period August to October in Michigan's major production areas. Some crops are unavoidably harvested during unfavorable soil conditions as a result. This problem is particularly acute in production of sugarbeets because the required harvest machinery and hauling equipment are so massive.

Alleviation of Compaction

Natural Forces

Raney and Edminster (1961) suggested that there is an equilibrium density or degree of compaction that is characteristic of each kind of soil. Water content and temperature changes and biotic activity in soil bring about bulk density changes following loosening or compaction of soil and these changes will usually be toward this equilibrium Db (Larson and Allmaras, 1971). Two implications can be drawn from this statement: (1) natural forces can alleviate soil compaction under some conditions, and (2) the ameliorative effects of tillage are probably transient. The influence of swelling and shrinking, freezing and thawing, and plant root activity on soil structure will be considered in this section.

Swelling and Shrinking associated with wetting and drying cycles tend to decrease the Db of compacted soil and increase that of a loose aggregated soil. Blackwell et al. (1985) demonstrated beneficial effects of alternate periods of wetting and drying on a swelling clay soil which was previously wheeled uniformly by a combine harvester and a tractor. Bulk density decreased and porosity increased within the surface 0.15 m of soil where wetting and drying was most prevalent. In addition to Db changes, vertical cracks may develop along planes of structural weakness as the soil volume changes during wetting and drying. Bullock et al. (1985) attributed regeneration of structure to the development of planar voids as the result of wetting and drying. These shrinkage cracks may not always reflect measurable Db changes but they provide a recurring path for root penetration (Greacen et al., 1968; Taylor, 1974; Jones, 1983). Detrimental effects of wetting and drying on soil loosened by tillage will be discussed in a subsequent section.

Freezing and Thawing has long been recognized for its beneficial effects on soil tilth when fine textured soils are plowed in the fall (Baver, 1972). The mellowing effect of freezing on free-lying clods can produce a favorable seed bed without further soil manipulation under some conditions. The effect of freezing and thawing on clods can be attributed to disruption by freezing and some reaggregation during thawing and drying. The structure formed (i.e., degree of aggregation) depends on soil type, conditions of freezing and thawing (e.g., rate of cooling), and the water content at the time of freezing.

Apart from its effects on aggregation of surface soil, freezing and thawing is expected to decrease Db in soil more packed than the natural density and to increase the density of soil which is looser than its natural state. Thus, the physical conditions of a naturally dense subsoil are not expected to change with freezing and thawing. Freezing promotes a loosening effect on soil as pores become enlarged to accomodate the 9% volume increase associated with the water-to-ice transition. Migration of water to sites of ice formation can produce sites of dehydration. Thus, loosening effects of freezing and thawing are often difficult to distinguish from wetting and drying.

Ameliorative potential of freezing and thawing is often overestimated in the literature. Krumbach and White (1964) compared Db of frozen soil to Db of soil in the same depth prior to freezing. The authors concluded that freezing can decrease Db of Michigan soils as the densities in all frozen depths (to a depth of 0.37 m) were lower than the average before freezing. However, subsequent studies have shown that substantial reconsolidation of soils can occur upon thawing. For example, Kay et al. (1985) demonstrated that Db of two Ontario soils decreased 40% in the surface 0.15 m during freezing but quickly returned to near prefreezing Db's prior to spring planting.

Gill (1971) assessed the magnitude of the compaction problem in the United States in terms of the area affected. Frost penetration depth was used as the criterion to determine the distribution of 'perpetuating' compaction. The soil profile may not receive adequate natural amelioration where frost penetration is less than 0.25 m. The author added that, soil compaction can occur in areas where frost penetration exceeds 0.25 m, but annual penetration of frost may diminish its persistance.

In the same monograph, Larson and Allmaras (1971) stated that there was no evidence of structural amelioration below a depth of 0.20 m due to freezing and thawing. Numerous investigators have substantiated this statement. In Sweden, where frost depth ranges from 0.60 to 0.80 m, Eriksson et al. (1974) were unable to detect structural changes in subsoil compacted two to three years earlier. In Minnesota, subsoil compaction persisted for a nine-year period in the presence of freezing and thawing despite attempts to enhance frost heaving with the application irrigation water prior to freezing (Blake et al., 1976).

Voorhees et al. (1978) and Voorhees (1983) demonstrated that wheel induced subsoil compaction was not alleviated by natural weathering forces in Minnesota. In a more recent study conducted in the same area, Voorhees et al. (1986) imposed subsoil compaction on a clay loam by applying high axle loads typical of modern harvest and transport equipment. Bulk density, penetrometer resistance, and hydraulic conductivity measurements showed that subsoil compaction persisted up to four years despite annual freezing to a depth of 0.90 m. Thus, farmers cannot afford to depend on the natural weathering forces of freezing and thawing to alleviate compaction below the normal depth of plowing.

Plant Roots impart structural changes that may be attributed largely to their influence on aggregate formation. Baver (1972) suggests that products of microbial metabolism are intimately involved in the cementation and stabilization of soil aggregates. Exudates from living plant roots and dead tissues from pre-existing roots are the primary energy sources for these microbial transformations (Russell, 1978).

Larson and Allmaras (1971) and Baver (1972) described additional mechanisms of aggregate formation involving plant roots. Particles adjacent to roots may be reoriented and pressed together into aggregates as the result of pressures exerted by roots. Extraction of water from the soil is another factor as greater shrinkage can occur near the root surface than at some distance from the roots. Extensive aggregate initiation can occur within about five times the radius of the root as the result of this mechanism. The influence of alfalfa roots on subsoil aggregation was demonstrated by Radcliffe et al. (1986) on a highly weathered soil of the southeast. Subsoil mechanical impedance was reduced as aggregates larger than 4.0 mm in diameter were created at the expense of aggregates smaller than 0.5 mm in diameter.

Roots can bring about structural changes by mechanisms other than their influence on aggregation. Decayed root channels can increase the transmission of water through slowly permeable soils. Since roots can more easily widen an existing channel than create its own, root channels provide a preferred path for root growth through high strength soils (Greacen et al., 1968). Bowen (1981) cited results of a study in which Pensacola bahiagrass roots were shown to penetrate soil layers that impeded cotton roots. Root length densities of subsequent cotton crops were increased because the volume of pores greater than 1.0 mm in diameter was increased by the rooting activity of the bahiagrass.

Subsoiling

Deep tillage is defined as a primary tillage operation which manipulates soil to a greater depth than normal plowing (Soil Science Society of America, 1984). Deep tillage can be accomplished with a variety of implements including a large heavy-duty moldboard or disk plow which inverts the soil, or with a heavy-duty chisel plow which shatters the soil. Thus, subsoiling consists of deep tillage without inversion and a minimal mixing of the soil.

Deep tillage is a beneficial management practice only where a specific soil factor is limiting plant growth (Burnett and Hauser, 1968). Russel

(1956) demonstrated the importance of this requirement by surveying the results of nearly 100 deep tillage experiments conducted in England. Deep tillage was beneficial on 50% of the fields but yields were unaffected or sometimes reduced by deep tillage in the remaining experiments.

Recent studies have shown that even when soil strength is thought to be the soil factor limiting plant growth, deep tillage may not always be beneficial. Since critical strength can be identified for a particular plant grown on a given soil, Gerard et al. (1982) suggested that periodic evaluation of mechanical impedance would be an excellent way to determine the need for deep tillage. Vepraskas et al. (1986) evaluated diagnostic soil properties and values that could be used to identify soils where subsoiling would improve root growth. The authors showed that the success of subsoiling was dependent on Db and sand content of the subsoil in addition to soil strength (cone index).

Excessive strength of soil layers such as fragipans, hardpans, clay pans, high-clay horizons, or plowpans is an example of a soil factor which can limit plant growth. The objective of deep tillage conducted on soils with such layers is almost always allevation of water stress by increasing the effective depth of root growth or root proliferation within the explored volume. Root-impeding layers are commonly disrupted by subsoiling.

When subsoiling is carried out on dry soil, the maximum degree of shattering can be achieved (Cooper, 1971; Cannel, 1977; Byrnes et al., 1982). Cooper (1971) and Bowen (1981) decribed patterns of soil disturbed by subsoilers. These patterns of disturbance are influenced by soil water content during subsoiling and subsoiler working depth. Subsoiling has been shown to reduce Db (Douglas et al., 1980; Ross, 1986) and reduce penetrometer resistance (Buxton and Zalewski, 1983; Vepraskas and Miner, 1986) within the volume of soil disturbed.

Since root-impeding layers are usually disrupted to alleviate water stress, subsoiling may or may not increase crop yields depending upon subsequent rainfall. As the amount of growing season rainfall increases, it is expected that the beneficial effect of subsoiling would be reduced (Weatherly and Dane, 1979). Subsoiling had no effect on yields during wet years in southeastern parts of the United States (Campbell et al., 1974; Box and Langdale, 1984). In the Pacific Northwest, physical properties of a tillage pan were improved dramatically by subsoiling but potato yields were increased only at low irrigation rates (Ross, 1986).

Few studies have been conducted in which the primary objective of deep tillage was improved soil aeration. Woodruff and Smith (1946) evaluated the potential for improvement of a claypan soil using subsoil shattering alone and with lime fertilizer mixed with the subsoil. Increased corn yields were attributed to improved aeration in the subsoil. Unger and Stewart (1983) reported results of a profile modification study on a Houston Black clay. Deep profile mixing caused greater and more uniform aeration throughout the profile, increased root proliferation, and increased cotton and grain sorghum yields.

Cannell and Jackson (1981) stated that artificial drainage (i.e., subsurface system of pipes) is the principal method that can be used to alleviate poor aeration. However, the authors add that artificial drainage will only be useful if continuous transmission pores exist in the topsoil and subsoil and these pores may have to be created by machinery in some situations. Greenland (1977) defined transmission pores as those which are greater than 100 μm in diameter and are important to achieve rapid movement of water. Since it is the volume of these large pores which is affected by tillage (Cassel and Nelson, 1985), tillage of a dense soil with poor aeration characteristics can correct temporarily the aeration problem (Burnett and Hauser, 1968; Erickson, 1982). Salient points in this section were summarized in a statement by Cannell (1977) who suggested that subsoiling is justified only in soils with a definite hard pan or horizon impeding root growth or water movement.

Controlled Traffic

Subsoil compaction can be corrected, if only temporarily, using subsoiling or some other form of deep tillage. Subsoiling is expensive and frequently treats only the symtoms, not the basic problem. Except where subsoil compaction is naturally occurring, the probelm is wheel induced compaction. Wheel traffic can be random, excessive, untimely, or any combination of the three. Soane et al. (1982) considered these possibilities and suggested three ways in which the overall compaction (surface and subsoil) of field soils by agricultural vehicles can be minimized: (1) reduction of vehicle mass and contact pressure of wheels; (2) reduction of the number of passes of conventional machinery; and (3) confinement of traffic to permanent or temporary wheel tracks (i.e., controlled traffic). Options two and three will be discussed at greater length in the remainder of this section.

Advantages of reduced or minimim tillage systems became apparent as soils depleted in organic matter have been worked more intensively and with increasingly massive machinery. Recognizing these trends, Cook et al. (1953) compared minimum tillage with conventional tillage during seedbed preparation on a Brookston loam in Michigan. Highest sugarbeet and dry bean yields were obtained when the least tillage was performed. The authors concluded that farmers were working their soil more than was necessary. Similarly, Glenn and Dotzenko (1978) demonstrated that on a fine montmorillinitic soil in Colorado, conventional and minimum tillage (field operations were reduced 40%) produced sugarbeet crops of comparable tonnage and quality.

The controlled traffic concept was initiated 30 years ago as a method for increasing crop yields by reducing wheel induced compaction (Taylor, 1983). The controlled traffic concept is based on the fact that soil conditions required by plants are exactly opposite those needed for efficient operation of pneumatic tires. Plants require uncompacted, moist soil while firm, dry surfaces are needed for optimum traction. Williford (1980) described a controlled traffic system in which zones planted to cotton and zones restricted to wheel traffic were referred to as production zones and traffic zones, respectively.

Controlled traffic has gained greatest popularity where subsoiling is routinely used to disrupt traffic pans. Cooper (1971) stated that soil which has been broken up is easily recompacted and can become more dense than it was before tillage. Trouse (1983) demonstrated the susceptibility of a clay loam to compaction during post-subsoiling traffic. The author found that the edge of a tractor tire must be at least 0.30 m from the subsoiled channel to prevent recompaction.

Wheel traffic associated with field operations that follow subsoiling can be controlled to avoid recompaction of the loosened soil and reduce the need for annual subsoiling. Williford (1980) compared penetrometer profiles from areas where post-subsoiling traffic was controlled with profiles under conventional tillage consisting of random wheel traffic. Recompaction levels were more severe and cotton yields were diminished with conventional tillage. In California, Carter (1985) showed that the surface 0.30 m of a fine sandy loam was recompacted to an average Db of

1.69 Mg m^{-3} in wheel trafficked interrows compared to 1.61 Mg m^{-3} under no traffic. Dumas et al. (1973) demonstrated that controlled traffic following deeper-than-normal tillage significantly affected soil compaction and cotton yields. Subsoiling was not beneficial under normal tractor traffic on a silty clay soil in Florida (Colwick et al., 1981).

Soane et al. (1982) and Cooper et al. (1983) suggest that adoption of controlled traffic for commercial production has been inhibited by the lack of standardization of wheel widths on production machinery. This obstacle must be overcome because the success of controlled traffic depends on the ability of farmers to maintain traffic-free zones.

<u>Persistence of Tillage-Induced Changes</u>

Wheel traffic is one of several factors which can influence the persistence of changes brought about by deep tillage. As indicated in an earlier section, there is a tendency for the density of soil loosened by tillage to change towards an equilibrium value under the influence of natural forces. Cassel and Nelson (1985) measured numerous soil physical properties at three depths during the first two months after tillage and planting. All properties exhibited significant temporal variability and were attributed to alternate wetting and drying. Changes were greatest in the 0 to 0.14 m depth of nontrafficked interrows where the difference between the post-tillage Db and the 'equilibrium Db' was greatest. Mapa et al. (1986) demonstrated that the first wetting and drying cycle resulted in most of the temporal variability of four soil hydraulic properties following tillage which consisted of subsoiling at one site, moldboard plowing at another.

Burnett and Hauser (1968) suggested that physical changes in the soil profile created by deep tillage are long lasting if: (1) the soils are fine textured throughout the profile; (2) the tillage operation is drastic, such as tillage with large plows; and (3) the dense or fine textured zones are essentially genetic. The authors commented further on the third requirment indicating that physical changes in the soil brought about by deep tillage are transient if the compacted layers are induced by machinery. This statement may have been based on the inability or unwillingness of farmers to implement controlled traffic systems.

Direct evidence showing the influence of soil texture on the persistence of changes brought about by deep tillage is lacking in the literature. However, the second condition cited by Burnett and Hauser (1968) as a requirement for lasting deep tillage changes can be substantiated. Hauser and Taylor (1964) showed that Db differences were apparent four years after deep disk plowing. The effects of hand digging on subsoil physical conditions were detected up to four years after the soil was loosened (Gooderham, 1977). By contrast, hardpans loosened by paraplowing did not always remain loose during the first growing season (Wilkins et al., 1986). The paraplow is the trade name for a slant-legged tillage tool which is similar to subsoilers in that it loosens the soil by lifting without inversion.

Drastic deep tillage operations may in general produce results that are more persistent than those from subsoiling. However, these tillage operations require larger equipment, consume more fuel, and can bring soil layers with unfavorable chemical properties closer to the soil surface.

The Role of Simulation Models

Simulation models, a collection of quantitative relationships used to describe a system, can be used to evaluate the impact of root zone modifications. Taylor and Arkin (1981) described difficulties associated with more conventional approaches. First, root observations are costly, time consuming, and destructive. Second, crop responses to root zone modification are frequently masked by other environmental and management factors. Computer simulations derived from models may be used to distinguish crop response to root zone modifications from other confounding responses. In addition, simulations for long periods of time (e.g., using generated weather data) can be used to develop probabilities of crop response and benefit (Arkin and Taylor, 1981).

Relationships between water use and production of various crops are abundant in the literature. Feddes (1981) reviewed numerous models based on these relationships. The author suggested that one can consider the effects of soil manipulation on production through water use but few attempts have been made to do so. This may be explained in part by our inability to predict physical changes brought about by tillage. Recent advances by Linden (1979), Blackwell and Soane (1981), and Gupta and Larson (1982) have increased our ability to predict tillage effects on soil conditions.

Models based on water use describe only one part of the more complex production system. The influence of tillage on soil physical conditions is another part of the system. Until recently, few models were available which described other components of the system such as those discussed in previous sections.

Soil aeration is an important component of production systems in Michigan because so many of the prevailing soils are poorly drained or prone to compaction. Whisler et al. (1982) described a cotton growth simulation model (GOSSYM) which was modified to account for the effects of cultivation and wheel traffic on (1) hydraulic properties, (2) mechanical impedance, and (3) changes in root growth due to low O_2 stress. The soil O_2 status is evaluated by calculating O_2 concentrations due to one dimensional diffusion into the soil profile. Apparently, the influence of O_2 deficiency on cotton growth in their model is due only to reduced root elongation rates during anaerobiosis.

Erickson (1982) suggested that a cumulative product representing some combination of deficiency duration and intensity (e.g., O_2 concentration) could be used as a measure of stress and that a further improvement would be to consider the type of crop and its growth stage. Hiler and Clark (1971) proposed the use of a stress day index (SDI) to account for the influence of soil water deficits and excesses on corn yields. The SDI for each period during the growing season can be calculated by multiplying a stress day factor (SD) times a crop susceptibility factor (CS). The SD factor is a measure of the degree of water or O_2 deficit. The CS factor quantifies the plant susceptibility to a given stress. Its magnitude depends on the crop species and stage of development.

The SDI concept was employed by Hardjoamidjojo et al. (1982) to quantify the effect of excessive and deficient soil water conditions on corn yields. The SD factor originally defined by Sieben (Wesseling, 1974) was used to calculate the SDI for excessively wet conditions. Crop susceptibility factors varied from 0.51 during the first 42 days after planting to 0.02 during the period 81 to 120 days after planting. The relationship obtained was subsequently incorporated into the water management model DRAINMOD to quantify the effect of soil water stresses (deficiencies and excesses) on corn during simulation of drainage system designs (Hardjoamidjojo and Skaggs, 1982).

Sumary

Poor physical conditions of Charity clay limit yields at the Saginaw Valley Bean and Beet Research Farm. This soil is considered to be compacted because its pores are so small that root penetration and internal drainage are impeded. Soils with poor internal drainage lack adequate aeration for root growth at certain times during the growing season when rainfall is excessive.

Normal fall and spring tillage practices perpetuate the physical problems associated with Charity clay. Results of this survey suggest that the following procedures may promote more favorable conditions for crop growth on this fine-textured soil: (1) deep tillage can be used to alleviate temporarily the aeration problem; (2) subsoiling is a practical deep tillage practice even though more drastic tillage procedures may create more persistent physical changes; and (3) subsequent traffic must be controlled or at least reduced to obtain the maximum benefit from subsoiling.

Traditional soil and plant measurements can be used to evaluate the effectiveness of these approaches. Recent evidence in the literature demonstrate that crop simulation models can be used to distinguish crop response to tillage from other confounding responses and to evaluate the probability of crop response and benefit.

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Chapter 2

Physical Conditions of Charity Clay as Affected by Deep Tillage and Controlled Traffic

INTRODUCTION

Many Michigan soils are characterized by naturally dense layers or horizons formed under physical phenomenon as in till and lacustrine deposits. Lake plain soils of lacustrine origin are prevalent in the Saginaw Valley, an important dry bean and sugarbeet production area. These fine textured soils are considered to be compact not because they have high bulk densities, but because their pores are so small that root penetration and internal drainage is impeded. Soils with poor internal drainage lack adequate aeration for root growth at certain times during the growing season when the fractional volume of air-filled pores is diminished by the presence of excess water.

Physical problems caused by farming practices are more common than those that occur naturally (Robertson and Erickson, 1980). Field operations on wet soil, such as harvest of sugarbeets, are often a necessary consequence of rainfall patterns in Michigan. Changing cropping systems have also contributed to the incidence and degree of wheel induced compaction because of their influence on tillage intensity and amounts of plant residue returned to the soil (Larson and Allmaras, 1971). Levels of organic matter needed to stabilize soil structure are difficult to maintain in crop production systems that include dry beans and sugarbeets because only small quantities of residue are produced

(Lucas and Vitosh, 1978). Thus, soils depleted in organic matter are being worked more intensively.

Subsoiling is a beneficial tillage operation on soils where root penetration is mechanically impeded by a high strength layer or horizon. The objective of subsoiling under these conditions is almost always alleviation of water stress by increasing the effective depth of root growth or root proliferation within the explored volume. Subsoiling has been shown to reduce bulk density (Douglas et al., 1980; Ross, 1986) and reduce penetrometer resistance (Buxton and Zalewski, 1983; Vepraskas and Miner, 1986). However, Williford (1980), Trouse (1983), and Carter (1985) demonstrated that post subsoiling traffic must be controlled to avoid recompaction of the loosened soil.

Few studies have been conducted in which the primary objective of subsoiling, or deep tillage in general, was improved soil aeration. Subsoiling improved aeration and increased corn yields on a claypan soil (Woodruff and Smith, 1946). Unger and Stewart (1983) reported results of a profile modification study on Houston black clay. Deep profile mixing caused greater and more uniform aeration throughout the profile, increased root proliferation, and increased cotton and grain sorghum yields.

Cannell and Jackson (1981) stated that artificial drainage is the principle method that can be used to alleviate poor aeration. The authors stressed that artificial drainage is useful only when continuous transmission pores exist in the topsoil and subsoil and that these pores may have to be created by machinery. Since it is the volume of these large pores which is effected by tillage (Cassel and Nelson, 1985), tillage of a dense soil with poor aeration characteristics can correct temporarily the aeration problem (Burnett and Hauser, 1968; Erickson, 1982).

The objectives of this portion of the study were to: (1) evaluate the potential for reducing the physical limitations of a lake plain soil, characterized by a naturally dense subsoil and an unstable surface, by subsoiling in the fall when it is dry; (2) determine the susceptibility of the loosened topsoil and subsoil to recompaction during subsequent traffic; and (3) determine the persistence of changes brought about by subsoiling where traffic is controlled.

MATERIALS AND METHODS

Field experiments were conducted from the fall of 1982 through 1985 on Charity clay (Aeric Haplaquept) at the Saginaw Valley Bean and Beet Research Farm, Swan Creek, MI. Charity clay has an unstable surface and poor internal drainage when wet but cracks moderately when dry. The site is level and artifically drained with tiles spaced at 10.1 m. The experimental design was a split-plot with fall primary tillage as main plots and spring secondary tillage as subplots, arranged in randomized complete blocks and replicated four times. The influence of primary and secondary tillage on the growth of several crops was tested and will be reported in a subsequent chapter.

Main plot treatments, half of which included deep tillage, were applied each fall from 1982 through 1984 to areas previously cropped to alfalfa (Medicago sativa L.). The alfalfa crop was mowed periodically during the summer and sprayed with glyphosate a week or two before treatments were implemented. Main plot treatments were: (1) deep tillage-moldboard plow (DTMP); (2) deep tillage-chisel plow, (DTCH); (3) no deep tillage-moldboard plow (NDTMP); and (4) no deep tillage-chisel plow (NDTCH). During the fall of 1982, only the DTMP and NDTMP treatments were applied. Deep tillage was accomplished by subsoiling to a depth of about 0.35 to 0.45 m at right angles using a triple shanked susoiler with shanks spaced at 0.71 m. Moldboard plowing to a depth of 0.20 to 0.28 m and chiseling to a depth of 0.15 to 0.20 m was applied each fall after the surface of subsoiled areas was subjected to one or two wetting and drying cycles.

Main plots were split to include secondary tillage variables consisting of conventional spring tillage and no spring tillage. Conventional spring tillage (CST) involved the normal amount of preplant wheel traffic and was implemented by applying wheel-to-wheel track compaction with a tractor weighing 4.2 Mg. A seedbed was prepared using a spring and spike tooth harrow after the entire plot surface was covered by one pass of a rear tractor tire. Under no spring tillage (NST) wheel traffic was restricted to interrows bordering the four-row plots and was accomplished by combining planting and herbicide application into a single operation. All plots were planted using a four-row minimum tillage planter except those planted to small grains. Tractor and planter tire spacings were 2.03 m. Plot dimensions were 2.03 m wide by 20 m in length during 1983 but reduced to 10 m in length during 1984 and 1985. Plots were wide enough to accomodate four 0.51-m rows. Thus, interrows adjacent to the center two rows of each plot were unaffected by wheel traffic during planting. When field operations were required after planting, wheel traffic was restricted to the interrows bordering the plots under both CST and NST.

Sufficient numbers of plots were established each year so that each crop from a corn-dry bean-sugarbeet rotation appeared in all eight combinations (four in 1983) of primary and secondary tillage. One crop from a soybean-wheat and one crop from an oats-soybean rotation also appeared. In addition, plots established during 1983 and 1984 were maintained through 1985 but with the following restrictions: (1) deep tillage was applied only once so that possible residual effects of changes brought about by deep tillage could be determined. Thus, one half of the plots established for 1983 were subsoiled the previous fall but primary tillage operations in the fall of 1983 (shallow chiseling) and 1984 (moldboard plowing) were applied uniformly to all plots and did not include deep tillage; (2) the two secondary tillage treatments were applied without rerandomization each spring so that cumulative effects, if any, of preplant wheel traffic could be evaluated; and (3) crops were rotated according to the crop sequences cited above.

Soil physical properties were measured to determine the extent of changes brought about by subsoiling and recompaction caused by preplant wheel traffic. Sampling was restricted to plots planted to sugarbeets in the corn-dry bean-sugarbeet rotation and plots planted to small grains in the soybean-wheat and oat-soybean rotation. With one exception, sampling was further restricted to plots in which the DTMP-CST, DTMP-NST, NDTMP-CST, and NDTMP-NST treatments appeared. Physical conditions of soil in the plow layer were measured during the first and second crop year after subsoiling. Subsoil physical conditions were measured during the first, second, and third crop year after subsoiling. Undisturbed soil cores 76-mm diam and 76-mm length were obtained with a double-cylinder, hammer-driven sampler (Blake, 1965) and weighed in the field using a portable balance (Ainsworth, Denver, CO, Model SC-2000 Electronic Balance) to determine volumetric water content. Five soil cores were obtained from each rep of each treatment and at each of two depths (0.03 to 0.10 and 0.13 to 0.20 m) within the plow layer and one depth (0.27 to 0.34 m) below the normal depth of plowing.

All soil cores obtained from the plow layer were taken during 1985 in plots planted to sugarbeets. One half of these plots represented the first crop year after subsoiling (site 1). The other half represented the second crop year after subsoiling as these plots were established in 1984 when they were planted to dry beans (site 2). Sampling efforts at each depth and site were completed in one day to circumvent variable sampling conditions in terms of soil water content. Sampling dates were: 23 June for the 2.5 to 10.1 cm depth at site 2; 24 June for the same depth at site 1; 25 June for the 12.7 to 20.3 cm depth at site 1; and 21 August for the same depth at site 2.

The number of soil cores obtained from the last measurement depth were doubled, wherever possible, by sampling during successive field seasons. Soil cores obtained from this depth, in plots representing the first crop year after subsoiling, were obtained during 1983 and 1984 where primary tillage variables were applied during the fall of 1982 and 1983, respectively. Soil cores taken in 1983 were from plots planted to sugarbeets and those taken in 1984 were from plots planted to oats. Soil had to be excavated to a depth of about 0.24 m before undisturbed soil cores could be obtained at the 0.27 to 0.34 m depth. This process was destructive and diminished the area available for yield measurement. All remaining samples at this depth were obtained from plots planted to small grains so that cores could be taken after harvest of oats or wheat. Soil cores taken in plots representing the second crop year after subsoiling were obtained during 1984 and 1985. Soil cores taken in plots representing the third crop year were obtained only during 1985.

Each undisturbed soil core was used to determine bulk density, porosity, water retention in the -1 to -100 kPa matric potential range, pore size distribution, and saturated hydraulic conductivity (Ksat). Soil cores were saturated by wetting from the bottom for at least 48 h. Soil water retention at matric potentials of -1, -2, -3, -4 and -6 kPa was determined using a tension table apparatus (Leamer and Shaw, 1941). Drainage steps corresponding to matric potentials of -10, -33.3, and -100 kPa were achieved using a pressure plate apparatus (Richards, 1965). Cores obtained during the 1985 field season were not subjected to the final drainage step.

Water loss between saturation and oven drying was taken to represent total soil porosity. Sample shrinkage over the -1 to -100 kPa matric potential range was negligible. Therefore, air porosity at each matric potential could be determined by subtracting the measured volumetric water content from the total porosity. Air porosity at the soil water matric potential of -6 kPa was taken to represent macroporosity. Pore size distribution was determined using capillary concepts as effective pore sizes corresponding to various matric potentials were estimated using the capillary rise formula (Vomicil, 1965).

Soil cores obtained during in 1985 were resaturated after removal from the last drainage step. Saturated hydraulic conductivity of these samples was determined using the constant head method (Klute, 1965).

Tillage effects on soil physical properties were evaluated using analysis of variance. Analyses were combined over years where undisturbed soil cores were obtained during successive field seasons. Treatments were compared using least significant differences (LSD) appropriate for a split-plot arranged in randomized complete blocks (Steel and Torrie, 1960). Our sampling scheme precluded statistical tests of depth and rotation effects on soil physical properties.

RESULTS AND DISCUSSION

Subsoil Physical Conditions

Soil bulk density (Db) and porosity (P), below the normal depth of plowing, and during the first crop year after subsoiling are shown in Table 1. Deep tillage followed by moldboard plowing (DTMP) reduced bulk density and increased porosity from levels under moldboard plowing alone (NDTMP). Though significant, these differences were not large as Db under DTMP averaged 0.05 Mg m^{-3} (4 percent) less than Db under NDTMP. Differences reported in Table 1 compare favorably with those reported by researchers on lake plain soils in neighboring areas of Canada. Douglas et al. (1980) showed that subsoiling St. Rosalie clay decreased the average Db of the 0 to 0.30 m depth 5 percent below values measured before application of compaction treatments. The magnitude of changes brought about by subsoiling may have been biased in their experiment by the Db measurements obtained closest to the soil surface where tillage effects were likely greatest. Plowing below conventional depths did not alleviate compaction on Brookston clay based on Db and P measurements (Bolton et al., 1981).

The influence of wheel traffic associated with conventional spring tillage on Db and P is also demonstrated in Table 1. Normal preplant wheel traffic associated with conventional spring tillage (CST) increased Db about 0.06 Mg m^{-3} and decreased P accordingly from levels where traffic was restricted to interrows bordering plots (NST). Both subsoiled and nonsubsoiled areas appeared to be equally susceptible to compaction at the 0.27 to 0.34 m depth. The magnitude of the Db increase caused by wheel traffic was about the same as the Db decrease produced by deep tillage. The combined effects of deep tillage and controlled

Table 1. Influence of primary and secondary tillage on bulk density and porosity of Charity clay at the 0.27 to 0.34 m depth during the first crop year.

Primary Tillage	Secondary Tillage CST	NST
bulk density (Db)		
	--------- $Mg\ m^{-3}$	---------
DTMP	1.33 Ba[1]	1.26 Aa
NDTMP	1.38 Bb	1.32 Ab
	[2] LSDp(.05)=0.05	
	[3] LSDs(.05)=0.06	
porosity (P)		
	--------- $m^3\ m^{-3}$	---------
DTMP	0.50 Ab	0.54 Bb
NDTMP	0.48 Aa	0.51 Ba
	LSDp(.05)=0.02	
	LSDs(.05)=0.03	

1/ Means in each row followed by the same upper-case letter are not different at the indicated probability level using LSD as the criterion for significance. Means in the same column followed by the same lower-case letter are not different.

2/ LSD for comparison of two primary tillage means at the same or different levels of secondary tillage.

3/ LSD for comparison of two secondary tillage means at the same level of primary tillage.

traffic were evident as the Db under DTMP-NST was 0.12 Mg m^{-3} less than the Db under the NDTMP-CST treatment.

Bulk density is not the most sensitive indicator of soil compaction because it reflects only changes in total soil porosity (Voorhees, 1983). Since soil aeration can be impeded at certain times on Charity clay, the soil environment for root growth is better characterized by its soil water retention properties. Figure 1 compare soil water retention and air porosities over the -0.1 to -100 kPa matric potential range (i.e., matric suction ranging from 0.1 to 100 kPa). Water content (and air porosity) at the matric potential of -0.1 kPa correspond to saturated values. Water contents at saturation reflect differences in soil porosity (Table 1) but water retention for matric potentials ranging from -1.0 to -100 kPa was not influenced significantly by the four treatments shown in Figure 1b.

By contrast, air porosities under DTMP-NST were consistently greater than values under NDTMP-CST for the same range of matric potentials (Figure 1a). Results illustrated in Figure 1a are important because water drains freely under gravity only from pores larger than 30 to 60 μm in diameter to a water potential no less than about -5 to -10 kPa in most soils (Cannell and Jackson, 1981). In addition, the air porosity of 0.10 m^3 m^{-3} is frequently cited as the level below which soil aeration is inadequate for plant growth (Wesseling and van Wyk, 1957; Vomocil and Flocker, 1961). Only subsoiling followed by controlled preplant wheel traffic, produced air porosities greater than 0.10 m^3 m^{-3} at matric potentials greater than -10 kPa (Figure 1a).

The primary and secondary tillage variables affected pore size distribution (PSD) which in turn produced the differences illustrated in Figure 1a. Figure 2 compare the PSD under the various combinations of

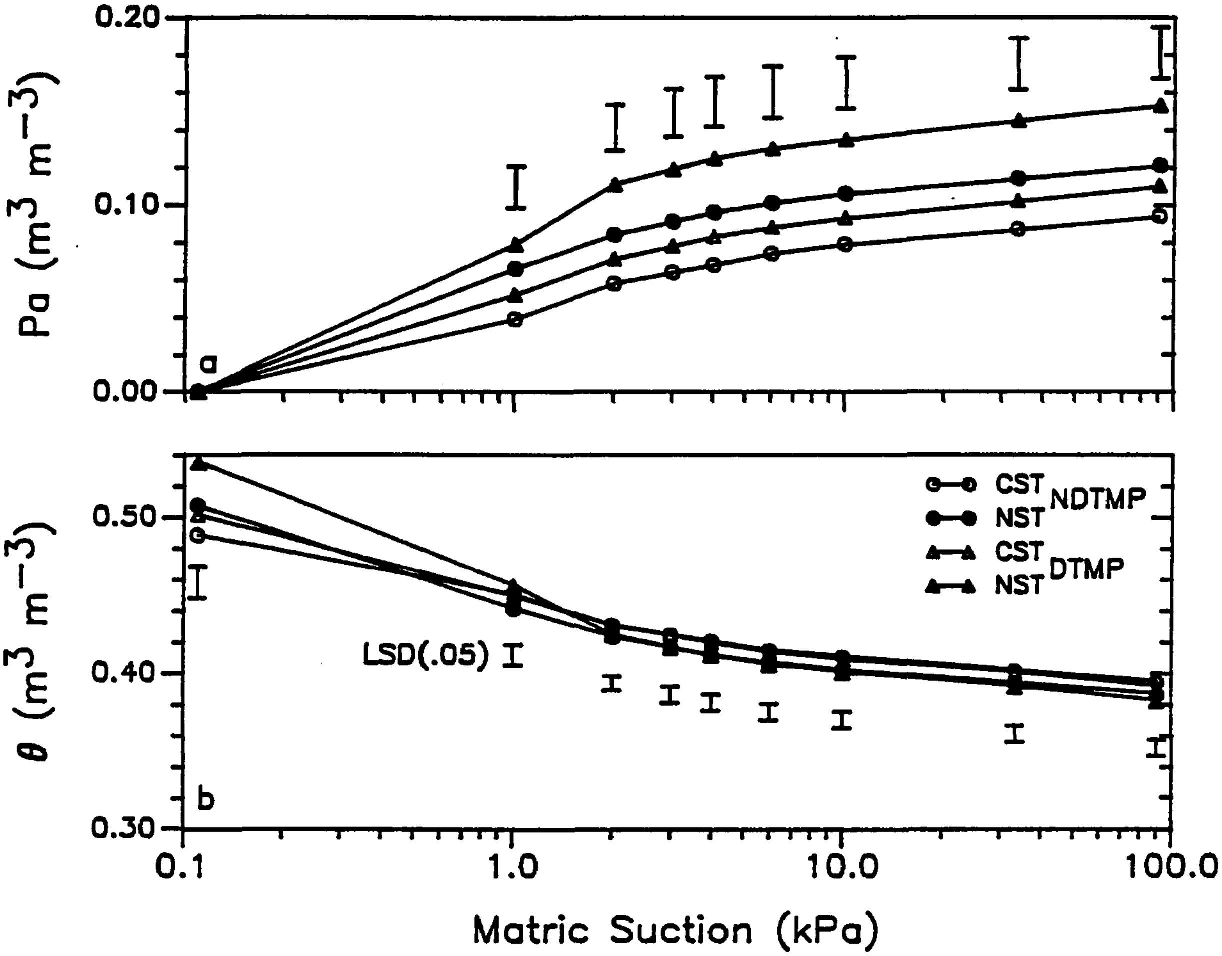

Figure 1. Air porosities (a) and soil water retention (b) at the 0.27 to 0.34 m depth during the first crop year as affected by primary and secondary tillage.

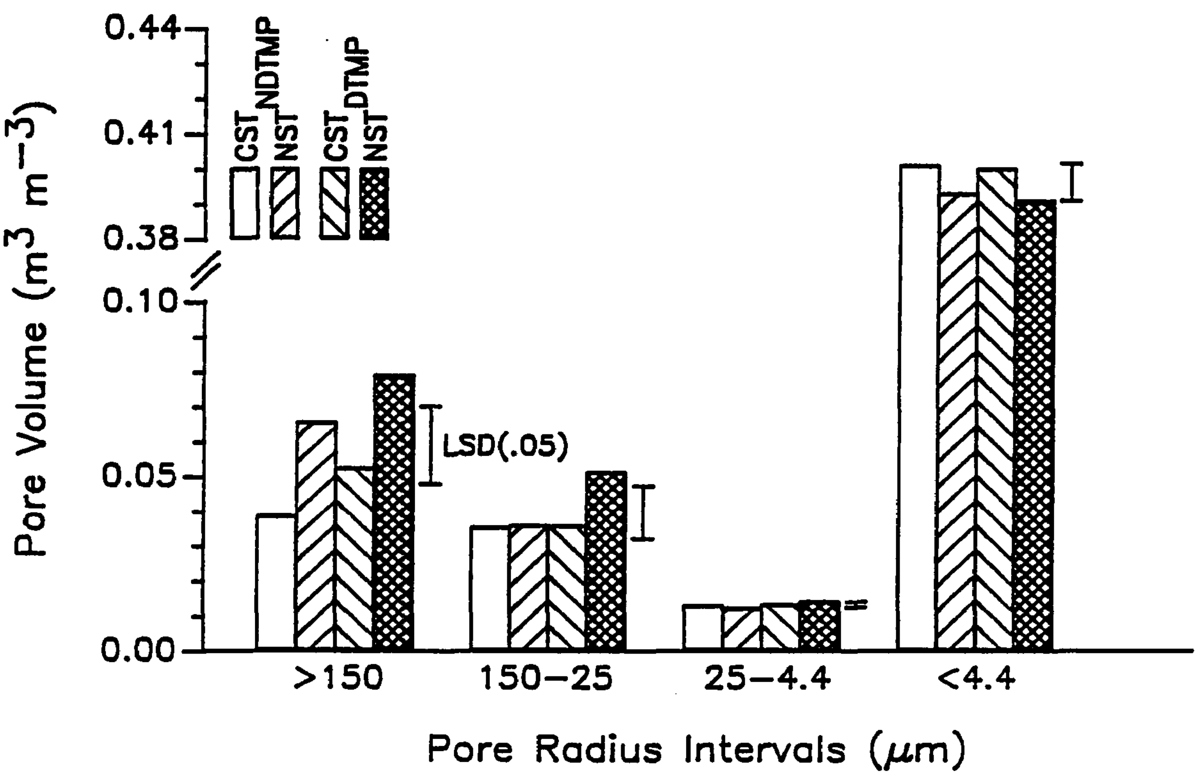

Figure 2. Pore size distribution of Charity clay at the 0.27 to 0.34 m depth during the first crop year as affected by primary and secondary tillage.

primary and secondary tillage. Pore radii of 150, 25, and 4.4 μm correspond to matric potentials of -1, -6, and -33.3 kPa, respectively. Based on the capillary model, pores with radii less than 4.4 μm retain water at the -33.3 kPa matric potential and pores with radii greater than 150 μm are air filled at the -10 kPa matric potential. Figure 2 shows that the volume of pores with radii greater than 150 μm was doubled by controlling wheel traffic after subsoiling (DTMP-NST) compared to the normal tillage and traffic patterns (NDTMP-CST). The volume of pores in the remaining size classes were unaffected but it is the large pores that facilitate soil aeration by draining readily under gravity.

Data reported in Table 1 and in Figures 1 and 2 represent the combined result of measurements obtained during successive field seasons (1983 and 1984) from plots representing the first crop year after subsoiling. In 1984 only, subsoil physical conditions were measured in plots that where subsoiled and chiseled (DTCH) in addition to plots subjected to the four treatments discussed up to this point. Results shown in Table 2 indicate that subsoiling followed by shallow chiseling produced the most desirable physical conditions as Db was lowest, P and macroporosity (air porosity at the -6 kPa matric potential) were highest under DTCH. Furthermore, soil at the 0.27 to 0.34 m depth appeared to be less susceptible to recompaction under DTCH compared to DTMP. Conventional spring tillage seemed to increase Db, reduce P and M only in plots which were moldboard plowed after subsoiling (DTMP).

Changes brought about by subsoiling were not evident during the second and third crop year despite the fact that post-subsoiling traffic was controlled on one half of the plots. Soil physical properties during a second and third crop year are reported in Table 3. Soil bulk density,

Table 2. Influence of primary and secondary tillage on bulk density, porosity, and macroporosity of Charity clay at the 0.27 to 0.34 m depth during the first crop year[1].

Primary Tillage	Secondary Tillage CST	Secondary Tillage NST
bulk density (Db)		
	--------- Mg m^{-3}	---------
DTMP	1.37 Bab[2]	1.29 Aa
DTCH	1.32 Aa	1.31 Aab
NDTMP	1.42 Ab	1.38 Ab
	[3]LSDp(.05)=0.07	
	[4]LSDs(.05)=0.08	
porosity (P)		
	--------- m^3 m^{-3}	---------
DTMP	0.48 Aab	0.52 Bb
DTCH	0.50 Ab	0.51 Ab
NDTMP	0.47 Aa	0.48 Aa
	LSDp(.05)=0.03	
	LSDs(.05)=0.03	
macroporosity (M)		
	--------- m^3 m^{-3}	---------
DTMP	0.06 Aa	0.11 Bab
DTCH	0.11 Ab	0.12 Ab
NDTMP	0.06 Aa	0.08 Aa
	LSDp(.05)=0.04	
	LSDs(.05)=0.05	

1/ Measured only during the 1984 field season.

2/ Means in each row followed by the same upper-case letter are not different at the indicated probability level using LSD as the criterion for significance. Means in the same column followed by the same lower-case letter are not different.

3/ LSD for comparison of two primary tillage means at the same or different levels of secondary tillage.

4/ LSD for comparison of two secondary tillage means at the same level of primary tillage.

Table 3. Influence of primary and secondary tillage on bulk density, porosity, and saturated hydraulic conductivity (Ksat) of Charity clay at the 0.27 to 0.34 m depth during the second and third crop year.

	Primary Tillage	Crop Year 2 CST	Crop Year 2 NST	Crop Year 3 CST	Crop Year 3 NST
bulk density (Db)			$Mg\ m^{-3}$		
	DTMP	1.38 Aa[1]	1.33 Aa	1.35 Ba	1.29 Aa
	NDTMP	1.39 Aa	1.35 Aa	1.36 Ba	1.31 Aa
		[2]LSDp(.05)=0.06		LSDp(.05)=0.05	
		[3]LSDs(.05)=0.06		LSDs(.05)=0.05	
porosity (P)			$m^3\ m^{-3}$		
	DTMP	0.49 Aa	0.51 Ba	0.49 Aa	0.51 Ba
	NDTMP	0.49 Aa	0.50 Aa	0.50 Aa	0.50 Aa
		LSDp(.05)=0.02		LSDp(.05)=0.02	
		LSDs(.05)=0.02		LSDs(.05)=0.02	
Ksat			$10^6\ m\ s^{-1}$		
	DTMP	4.7 Aa	18 Aa	2.9 Aa	6.7 Ba
	NDTMP	4.2 Aa	17 Aa	6.2 Aa	8.4 Ba
		LSDp(.05)=21		LSDp(.05)=6.4	
		LSDs(.05)=19		LSDs(.01)=1.3	

1/ Means in each row followed by the same upper-case letter are not different at the indicated probability level using LSD as the criterion for significance. Means in the same column followed by the same lower-case letter are not different.

2/ LSD for comparison of two primary tillage means at the same or different levels of secondary tillage.

3/ LSD for comparison of two secondary tillage means at the same level of primary tillage.

porosity, and saturated hydraulic conductivity (Ksat) were similar under DTMP and NDTMP.

Burnett and Hauser (1968) suggest that physical changes created by deep tillage are long lasting where the soil is fine textured throughout the profile, as is Charity clay, and where the tillage operation is drastic. The authors add that changes may be transient if the deep tillage implement used is a subsoiler or chisel. Data reported in Table 3 seem to substantiate this claim and are important for two reasons. First, changes produced by subsoiling should ideally persist through more than one crop year because farm managers are unable to subsoil each hectare of their farms each fall. For example, soil water content can be too high during the fall of some years to achieve optimum shattering. Second, deep tillage operations that are more drastic than subsoiling are impractical to apply on a soil resembling Charity clay. Since the texture of this soil is uniform throughout the profile, profile mixing is not beneficial except for the additional soil loosening which may accompany mixing. In additon, larger and more powerful equipment is required as the desired amount of soil manipulation increases. Chiseling below the normal depth of plowing seems to be the most practical deep tillage operation on Charity clay even though changes produced may be transient.

The effects of preplant wheel traffic were evident during each crop year unlike the effects of subsoiling which were detected through only the first crop year. Data reported in Table 3 demonstrate the effects of preplant wheel traffic on Db, P, and Ksat. Physical properties for crop year 2 were influenced by only one application of preplant wheel traffic as they were measured in wheat plots that were planted after soybean harvest, during the fall of the first crop year, but without applying the secondary tillage treatments. Though differences were generally not significant, data in Table 3 suggest that Db was lowest under NST. Saturated hydraulic conductivities seemed much higher under NST averaging 17.5×10^{-6} m s^{-1} (6.3 cm h^{-1}) compared to 4.4×10^{-6} m s^{-1} (1.6 cm h^{-1}) under CST. Statistical comparison of Db, P, and Ksat means for the second crop year was hampered by the fact that these soil parameters were measured in only three of four reps.

Soil physical properties measured in the third crop year represent the cumulative effects of preplant wheel traffic applied during each of three consecutive field seasons. Normal amounts of preplant wheel traffic decreased bulk density by about 0.05 Mg m^{-3} from levels where traffic was controlled (Table 3). These differences are about the same as differences reported in Table 1 where preplant wheel traffic was applied only once. Thus, recompaction caused by three consecutive years of normal preplant wheel traffic was no greater than recompaction caused by only one application of wheel traffic.

Comparisons shown in Figures 3 and 4 illustrate further the physical changes caused by preplant wheel traffic during the second and third crop year. Water retention of soil at the 0.27 to 0.34 m depth was unaffected by primary or secondary tillage. The corresponding air porosities were averaged over DTMP and NDTMP because they were not influenced by the primary tillage variables (Figure 3). Air porosities for matric potentials ranging from -1 to -33.3 kPa were influenced positively and significantly during the second and third crop year by controlling preplant wheel traffic (NST).

Since large pores are affected most by tillage and compaction, the volume of pores with radii greater than 150 μm are compared in Figure 4. In aggreement with data in Table 3, deep tillage effects were not evident

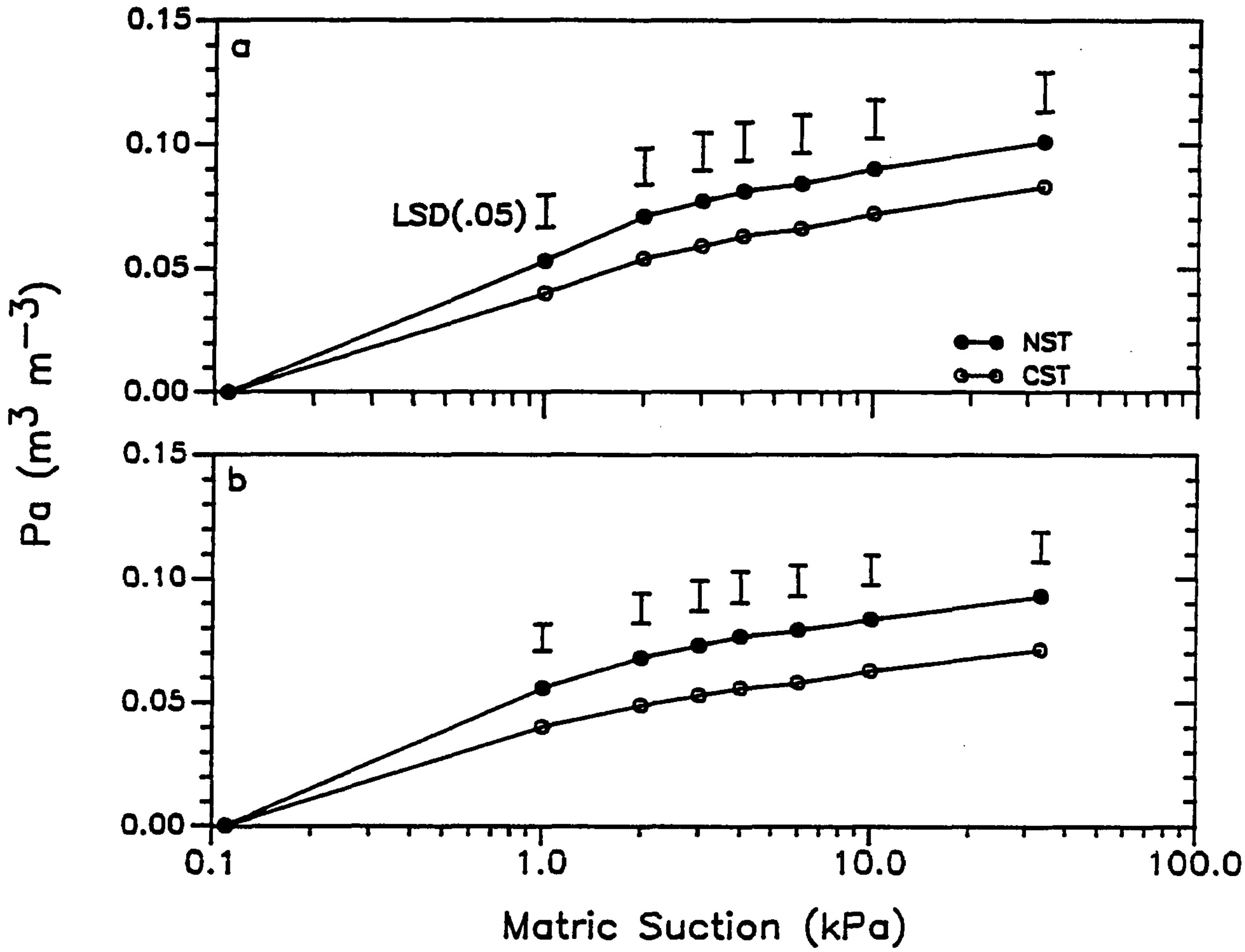

Figure 3. Air porosities of Charity clay at the 0.27 to 0.34 m depth during the second (a) and third (b) crop year as affected by secondary tillage.

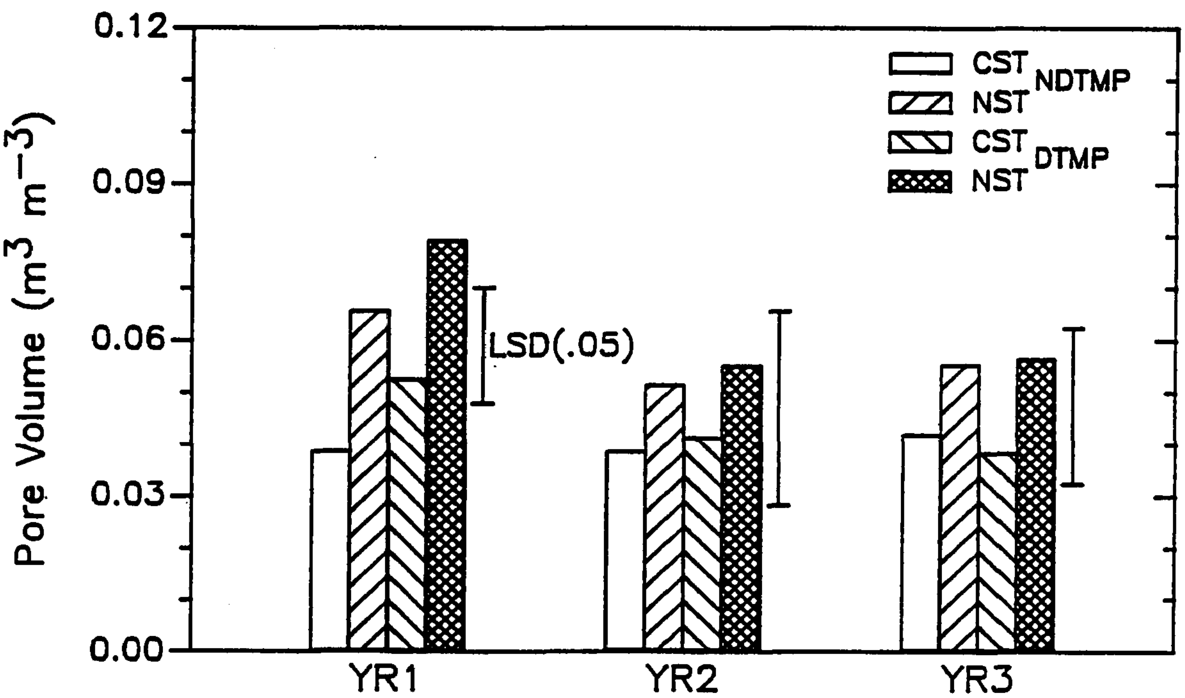

Figure 4. Influence of primary and secondary tillage on the volume of large pores (i.e., > 150 x 10^{-6} m in diameter) at the 0.27 to 0.34 m depth during the first (YR1), second (YR2), and third (YR3) crop year.

after the first crop year (YR1). Wheel induced compaction decreased the volume of pores in this size class most extensively during the first crop year but differences can also be seen in YR2 and YR3.

The effects of wheel traffic on subsoil physical conditions shown in Tables 1 and 3 and in Figures 3 and 4 are not surprising as wheel traffic associated with normal farming operations can compact soil to a depth of 0.45 m (Voorhees et al., 1978). However, normal farming operations may include the use of combines or transport vehicles that are considerably larger than the 4.2 Mg tractor used to apply wheel traffic in this study. In Sweden, Ericksson et al. (1974) were unable to detect measurable changes in porosity and permeability in the upper part of the subsoil at axle loads less than 6.0 Mg. Charity clay appears to be sensitive to wheel induced compaction below the normal depth of plowing even when soil at this depth was not previously loosened by deep tillage.

Topsoil Physical Conditions

Soil physical properties at two depths within Ap horizon (i.e., plow layer) are reported in Tables 4 and 5. Primary tillage variables, applied prior to plot establishment, had no effect on Db, Ksat, or water content at either depth. Soil porosity at the 0.03 to 0.10 m depth was enhanced by deep tillage based one treatment comparison shown in Table 4.

Data in Tables 4 and 5 demonstrate that preplant wheel traffic caused significant compaction at both depths and during each year that compaction was assessed. Wheel traffic associated with the CST treatment increased Db of the 0.03 to 0.10 m depth by 15 and 18 percent during the first and second year, respectively (Table 4). The same treatment decreased P accordingly. Saturated hydraulic conductivities were an order of magnitude lower under CST than under NST. As an example, normal preplant wheel traffic decreased Ksat to 1.5×10^{-5} m s^{-1} (5.4 cm h^{-1}) from

Table 4. Influence of primary and secondary tillage on bulk density, porosity, saturated hydraulic conductivity (Ksat), and volumetric water content of Charity clay at the 0.3 to 0.10 m depth during the first and second crop year.

	Primary Tillage	Crop Year 1 CST	Crop Year 1 NST	Crop Year 2 CST	Crop Year 2 NST
bulk density (Db)		----------- $Mg\ m^{-3}$	-----------	-----------	-----------
	DTMP	1.29 Ba[1]	1.11 Aa	1.32 Ba	1.14 Aa
	NDTMP	1.31 Ba	1.15 Aa	1.37 Ba	1.14 Aa
		[2]LSDp(.05)=0.06		LSDp(.05)=0.05	
		[3]LSDs(.01)=0.07		LSDs(.01)=0.05	
porosity (P)		----------- $m^3\ m^{-3}$	-----------	-----------	-----------
	DTMP	0.53 Aa	0.58 Bb	0.50 Aa	0.57 Ba
	NDTMP	0.52 Aa	0.56 Ba	0.49 Aa	0.57 Ba
		LSDp(.05)=0.02		LSDp(.05)=0.02	
		LSDs(.01)=0.02		LSDs(.01)=0.02	
Ksat		----------- $10^5\ m\ s^{-1}$	-----------	-----------	-----------
	DTMP	2.2 Aa	19 Ba	2.1 Aa	20 Ba
	NDTMP	0.8 Aa	15 Ba	1.8 Aa	24 Ba
		LSDp(.05)=8.9		LSDp(.05)=6.7	
		LSDs(.01)=11		LSDs(.01)=12	
water content		----------- $m^3\ m^{-3}$	-----------	-----------	-----------
	DTMP	0.37 Ba	0.32 Aa	0.38 Ba	0.33 Aa
	NDTMP	0.38 Ba	0.34 Aa	0.37 Ba	0.31 Aa
		LSDp(.05)=0.02		LSDp(.05)=0.02	
		LSDs(.01)=0.03		LSDs(.01)=0.03	

1/ Means in each row followed by the same upper-case letter are not different at the indicated probability level using LSD as the criterion for significance. Means in the same column followed by the same lower-case letter are not different.

2/ LSD for comparison of two primary tillage means at the same or different levels of secondary tillage.

3/ LSD for comparison of two secondary tillage means at the same level of primary tillage.

Table 5. Influence of primary and secondary tillage on bulk density, porosity, saturated hydraulic conductivity (Ksat), and volumetric water content of Charity clay at the 0.13 to 0.20 m depth during the first and second crop year.

	Primary Tillage	Crop Year 1 CST	Crop Year 1 NST	Crop Year 2 CST	Crop Year 2 NST
bulk density (Db)			Mg m^{-3}		
	DTMP	1.27 Ba[1]	1.11 Aa	1.42 Ba	1.26 Aa
	NDTMP	1.28 Ba	1.14 Aa	1.45 Ba	1.25 Aa
		[2]LSDp(.05)=0.05		LSDp(.05)=0.09	
		[3]LSDs(.01)=0.07		LSDs(.01)=0.12	
porosity (P)			m^3 m^{-3}		
	DTMP	0.53 Aa	0.58 Ba	0.51 Aa	0.56 Ba
	NDTMP	0.53 Aa	0.57 Ba	0.50 Aa	0.57 Ba
		LSDp(.05)=0.02		LSDp(.05)=0.04	
		LSDs(.01)=0.02		LSDs(.01)=0.04	
Ksat			10^5 m s^{-1}		
	DTMP	2.1 Aa	22 Ba	1.5 Aa	5.8 Aa
	NDTMP	3.6 Aa	20 Ba	2.1 Aa	6.4 Aa
		LSDp(.05)=9.7		LSDp(.05)=5.3	
		LSDs(.01)=12		LSDs(.05)=4.7	
water content			m^3 m^{-3}		
	DTMP	0.43 Ba	0.38 Aa	0.31 Ba	0.29 Aa
	NDTMP	0.43 Ba	0.38 Aa	0.30 Ba	0.27 Aa
		LSDp(.05)=0.04		LSDp(.05)=0.03	
		LSDs(.05)=0.05		LSDs(.05)=0.02	

1/ Means in each row followed by the same upper-case letter are not different at the indicated probability level using LSD as the criterion for significance. Means in the same column followed by the same lower-case letter are not different.

2/ LSD for comparison of two primary tillage means at the same or different levels of secondary tillage.

3/ LSD for comparison of two secondary tillage means at the same level of primary tillage.

$17x10^{-5}$ m s^{-1} (61 cm h^{-1}) where wheel traffic was controlled. Differences reported in Table 4 were significant at the 0.01 probability level and were approximately the same each year.

All indicators of soil compaction at the 0.13 to 0.20 m depth were also significantly influenced by the secondary tillage variables (Table 5). Bulk density was 13 and 14 percent higher, P was 8 and 11 percent lower under CST than NST, repsectively. Preplant wheel traffic reduced Ksat, but less dramatically at this depth than at the 0.03 to 0.10 m depth. During the first crop year, Ksat averaged $21x10^{-5}$ m s^{-1} (76 cm h^{-1}) with NST compared to $2.8x10^{-5}$ m s^{-1} (10 cm h^{-1}) with CST . Saturated hydraulic conductivities measured in the second crop year were not influenced by secondary tillage based on the least significant differences (LSDs) reported in Table 5. However, the average Ksat of $6.1x10^{-5}$ m s^{-1} under NST was greater than the average of $1.8x10^{-5}$ m s^{-1} for CST at the 0.05 level of significance.

Field water contents of soil samples obtained for physical measurements are included in Tables 4 and 5 to illustrate the influence that wheel induced compaction can have on profile soil water content. Volumetric water content was consistently and significantly higher under CST than under NST. These results are in agreement with those reported by Raghaven and McKyes (1978) where machinery traffic altered the soil environment such that higher moisture contents occurred in heavily compacted plots. Differences illustrated in Tables 4 and 5 were not created by the sampling procedure used or by differential plant water extraction in wheel tracked and non-wheeled plots. Thus, water contents measured at sampling reflect true effects of the secondary tillage variables on soil physical conditions.

Water content differences in Tables 4 and 5 can be attributed in part to varying rates of evaporation under CST and NST. Evaporation can be extensive in the surface 0.15 m of soil but is reduced where soil is compacted by wheel traffic (Voorhees, 1985). Except for undisturbed soil cores obtained from the 0.13 to 0.20 m depth in the second crop year, soil cores were obtained immediately following a 13 day period in which rainfall totaled 47 mm. Differential evaporation under CST and NST was diminished as a result and differences caused by wheel traffic can be attributed primarily to altered drainage and soil water retention under CST.

Air porosities and soil water retention at the 0.03 to 0.10 m depth, during the first and second crop year, are shown in Figures 5 and 6, respectively. Since the relationships shown in Figures 5 and 6 were not influenced by the primary tillage variables, water contents and air porosities were averaged for DTMP and NDTMP. Conventional spring tillage increased water retention for the -1 to -33.3 kPa matric potential range in both years. At each matric potential, CST decreased air porosity (Figures 5a and 6a) but to a greater extent than the water content increase due to total porosity differences between CST and NST (Table 4).

Bullock et al. (1985) showed that wheel induced compaction can decrease macroporosity by over half. Changes caused by wheel traffic in this study were comparable. One application of wheel traffic reduced macroporosity, air porosity at the -6 kPa matric potential, from 0.18 m^3 m^{-3} under NST to a level of 0.08 m^3 m^{-3} (Figure 5a). Macroporosity was 0.20 m^3 m^{-3} under NST but only 0.07 m^3 m^{-3} under CST during the second crop year (Figure 6a). Macroporosity is an indicator of the soil aeration status following a heavy rain because it approximates the volume of air-filled pore space near field capacity. Controlling preplant wheel

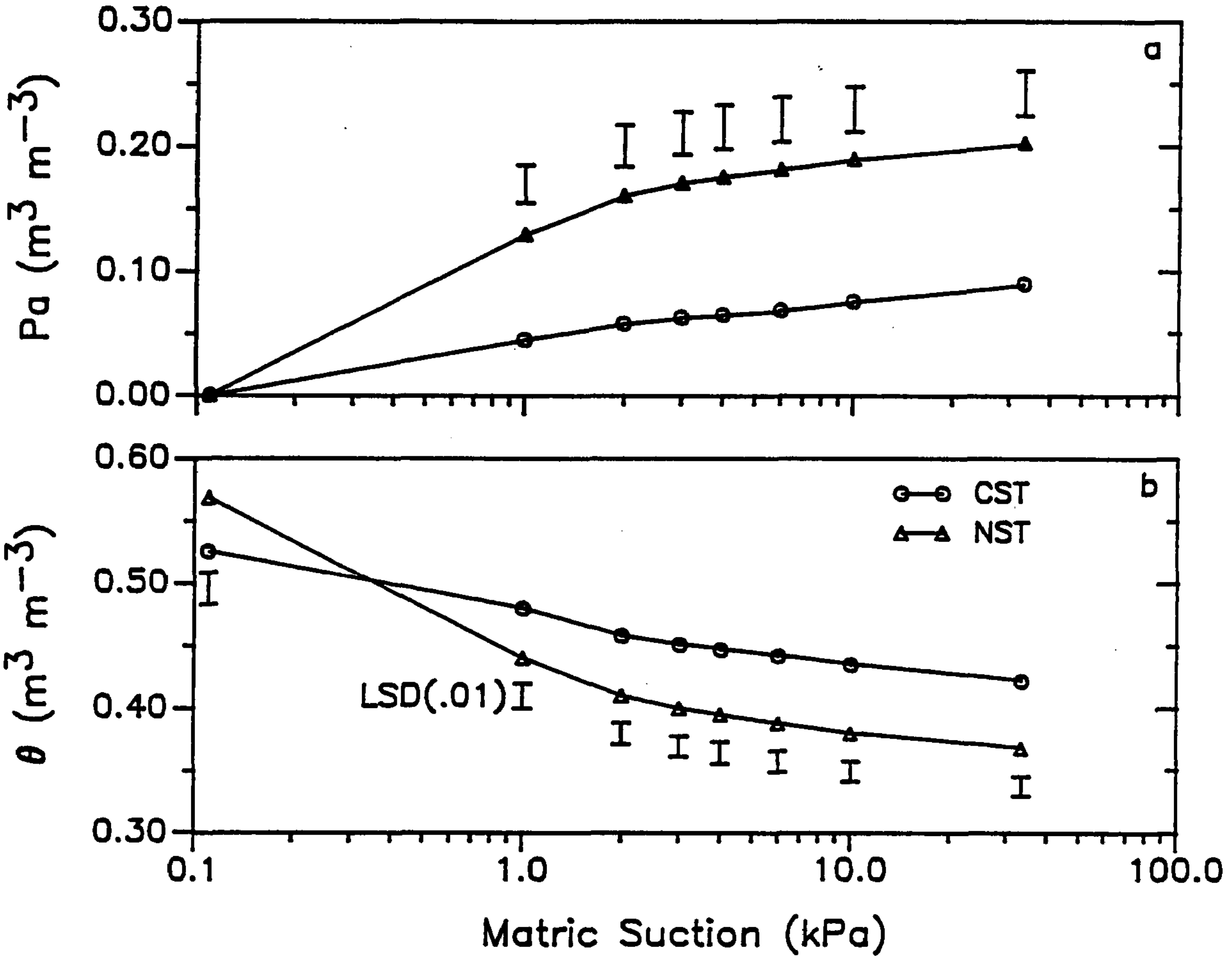

Figure 5. Influence of secondary tillage on air porosity (a) and soil water retention (b) of Charity clay at the 0.03 to 0.10 m depth during the first crop year.

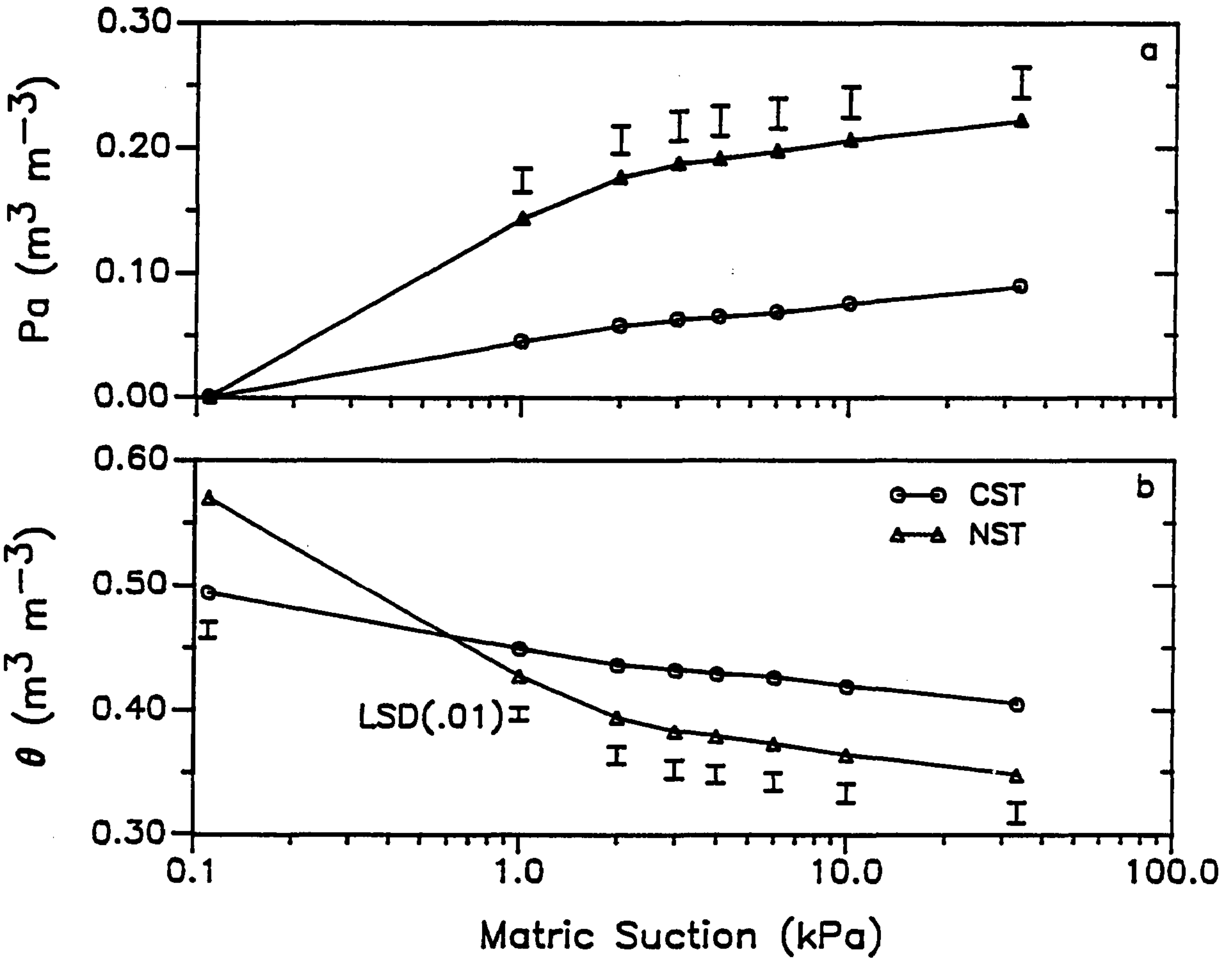

Figure 6. Influence of secondary tillage on air porosity (a) and soil water retention (b) of Charity clay at the 0.03 to 0.10 m depth during the second crop year.

traffic improved soil aeration as critically low air porosities are less likely to occur under NST than under CST.

Pore size distributions corresponding to relationships shown in Figures 5 and 6 are illustrated in Figure 7. Wheel traffic associated with CST increased water retention and decreased air porosity because the volume of small pores was increased at the expense of the volume of large pores. The volume of pores in the intermediate size classes was relatively unaffected by one or two years of preplant wheel traffic.

The influence of secondary tillage on air porosities and water retention at the 0.13 to 0.20 m depth, during the first and second year, are demonstrated in Figures 8 an 9, respectively. Though highly significant, differences shown were smaller than those reported for the shallower measurement depth. Air porosities for the -1 to -33.3 kPa matric potential range were reduced by a factor of 2 during each crop year. The corresponding pore size distributions in Figure 10 show that CST created small pores at the expense of pores with radii greater than 150 μm.

CONCLUSIONS

Normal fall and spring tillage operations on charity clay create unfavorable physical conditions for crop growth as internal drainage is poor and soil aeration may be impeded at certain critical times. Physical conditions of Charity clay were improved below the normal depth of plowing by subsoiling in the fall when the soil was relatively dry. Results of this investigation indicate that changes brought about by subsoiling may persist through only one crop year even when post-subsoiling traffic is controlled. Results also indicate that shallow chiseling after subsoiling may be more beneficial than moldboard plowing.

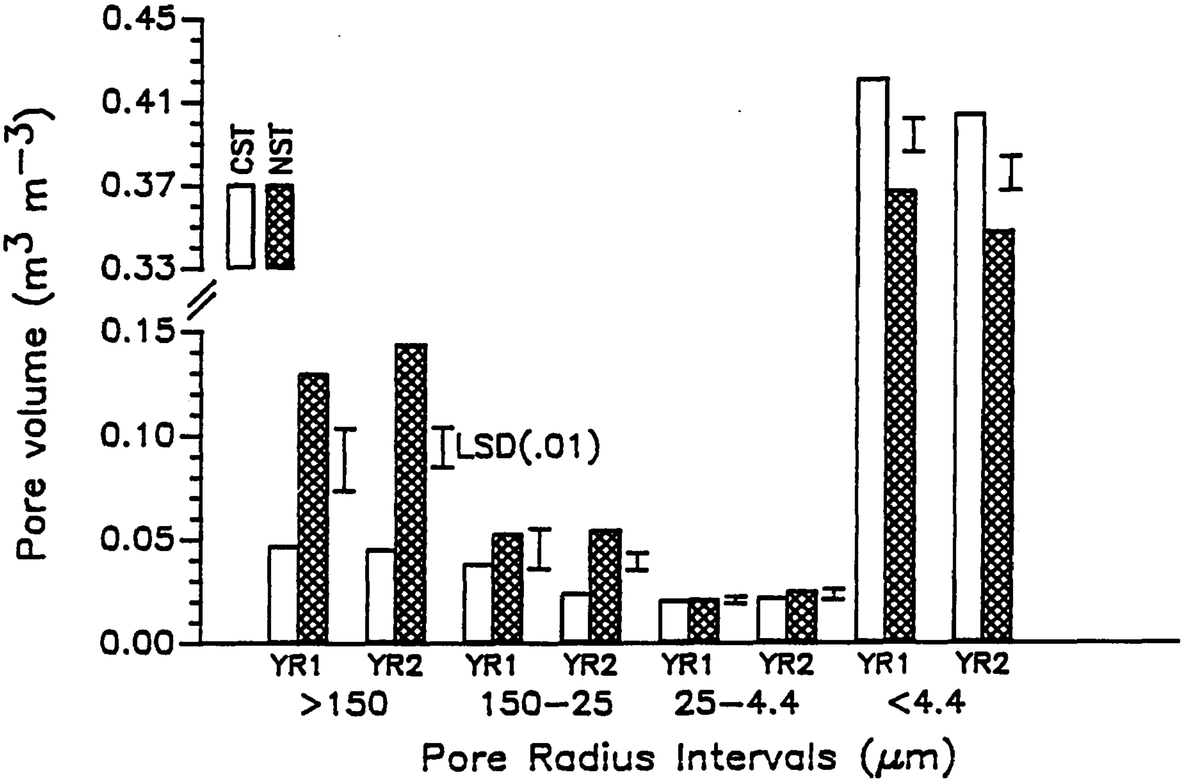

Figure 7. Pore size distribution of Charity clay at the 0.03 to 0.10 m depth as affected by secondary tillage during the first (YR1) and second (YR2) crop year.

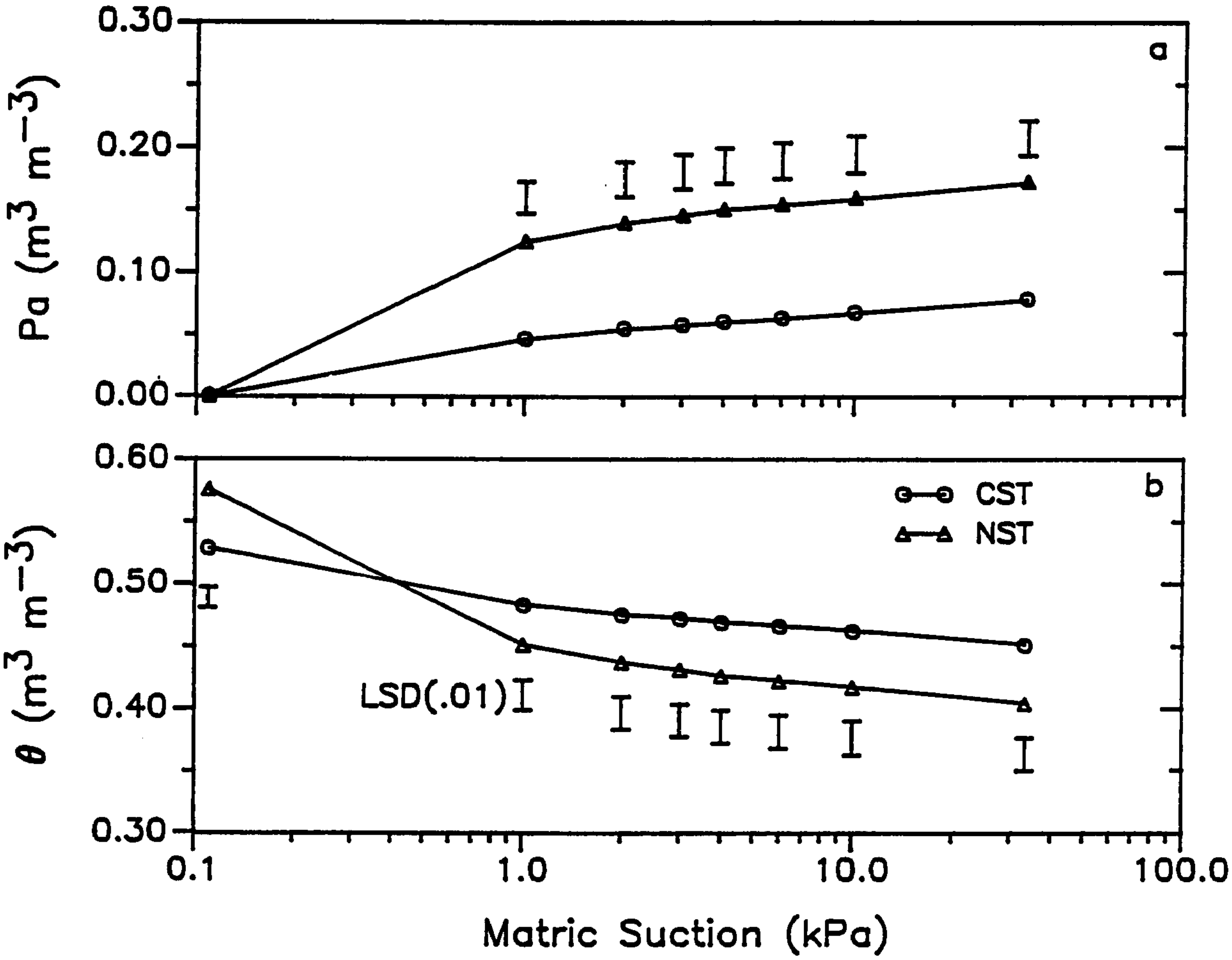

Figure 8. Influence of secondary tillage on air porosity (a) and soil water retention (b) of Charity clay at the 0.13 to 0.20 m depth during the first crop year.

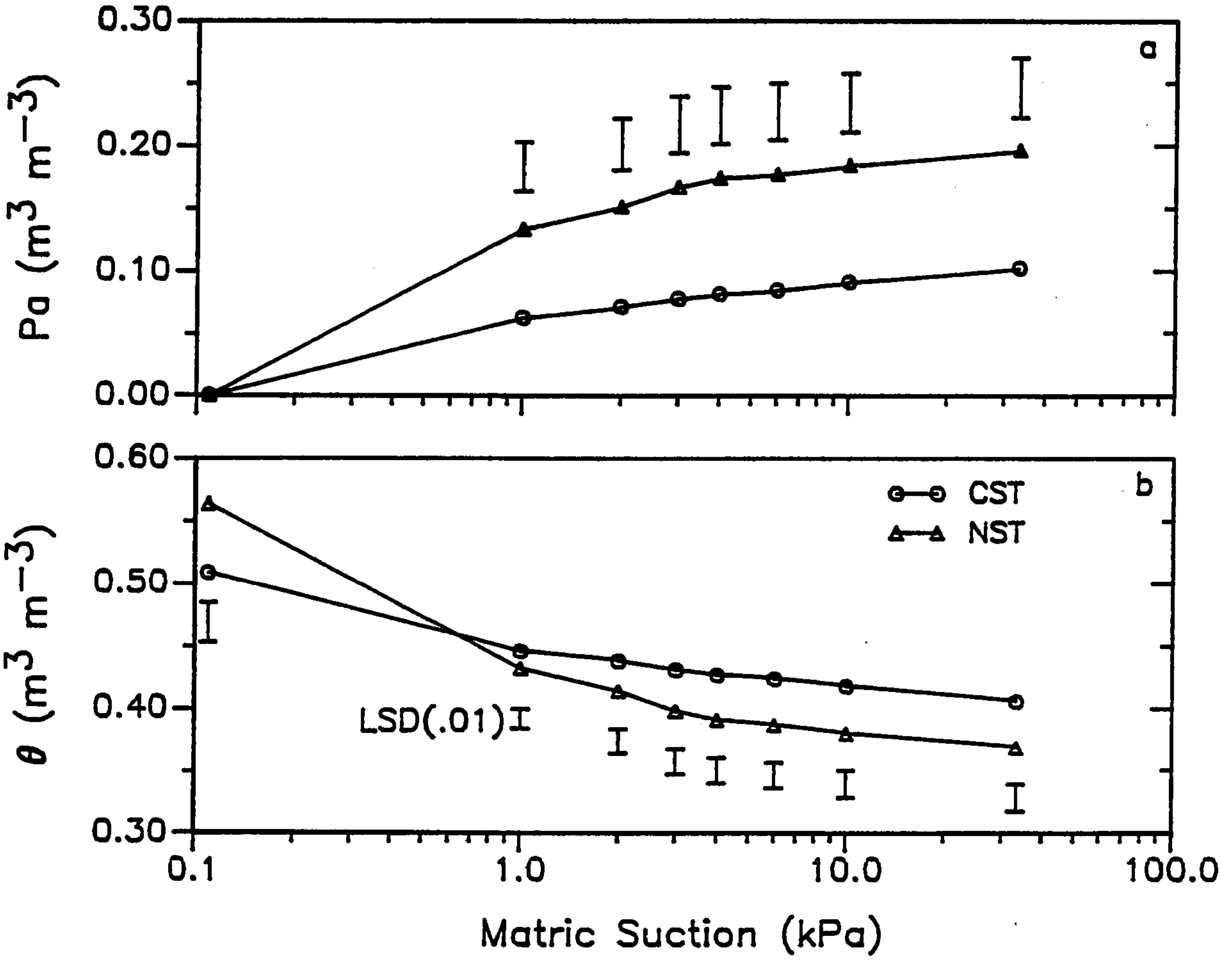

Figure 9. Influence of secondary tillage on air porosity (a) and soil water retention (b) of Charity clay at the 0.13 to 0.20 m depth during the second crop year.

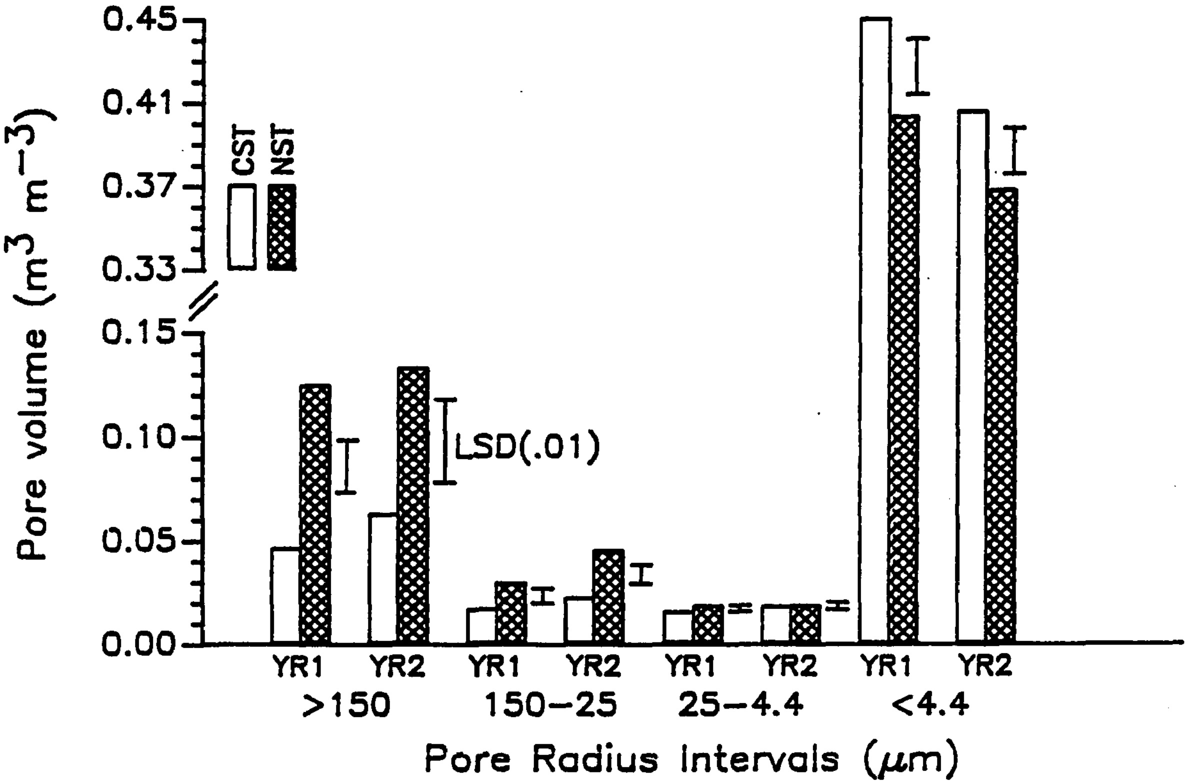

Figure 10. Pore size distribution of Charity clay at the 0.13 to 0.20 m depth as affected by secondary tillage during the first (YR1) and second (YR2) crop year.

Wheel traffic associated with conventional spring tillage recompacted soil loosened by deep tillage and increased the density of subsoil where normal fall tillage was applied. Effects of wheel traffic on physical properties below the normal depth of plowing were evident each year but were not cumulative when applied three years in succession. The unstable surface of Charity clay proved to be extremely susceptible to wheel-induced compaction. Saturated hydraulic conductivity and pore size distribution were the most sensitive indicators of compaction in the Ap horizon. Subsoiling followed by controlled preplant wheel traffic produced the most favorable environment for root growth based on improved internal drainage and soil aeration.

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Chapter 3

Influence of Deep Tillage and Controlled Traffic on Profile Water Content of Two Lake-Plain Soils

INTRODUCTION

Normal tillage operations associated with row crop production in the Saginaw Valley create unfavorable soil conditions for root growth. Data reported in the previous chapter demonstrate that fall moldboard plowing and normal amounts of preplant wheel traffic (NDTMP-CST) produced the highest bulk densities (Db) in three depth increments of Charity clay. During the first year of plot establishment, the NDTMP-CST treatment produced Db of 1.31 (Table 4), 1.28 (Table 5), and 1.38 Mg m^{-3} (Table 1) at depths of 0.03 to 0.10, 0.13 to 0.20, and 0.27 to 0.34 m, respectively. Deep tillage and controlled traffic (DTMP-NST) produced the most favorable soil conditions as Db was 1.14, 1.11, and 1.26 Mg m^{-3} for the same depths.

Daddow and Warrington (1983) and Jones (1983) developed relationships between soil texture and Db that limit root growth. Comparison of these limiting bulk densities with values reported in Chapter 2 suggest that root growth may be mechanically impeded on a soil consisting of 70 percent clay (e.g., Charity clay), especially under normal tillage operations. However, the growth limiting Db is higher on a soil with high shrink-swell potential because roots can proliferate along planes of weakness that develop upon drying. Since Charity clay cracks moderately upon drying, mechanical impedance may not be the most important limitation to root growth on this soil.

Soil aeration is probably the single most important physical limitation of Charity clay. The effects of tillage and wheel traffic on pore size distribution (PSD), a sensitive indicator of soil compaction, were demonstrated in Chapter 2. Deep tillage and controlled traffic altered PSD such that internal drainage was improved (i.e., Ksat was increased), water retention was decreased, and air porosity was increased over the -1.0 to -100 KPa matric potential range. Soil aeration was improved as critically low air porosities are less likely to occur and may persist for a shorter period of time under DTMP-NST than NDTMP-CST.

Susceptibility of a soil to the development of poor aeration is determined by its physical conditions but the occurrence of aeration stress is dictated by the prevailing weather conditions. When mechanical impedance is influencing root growth, root growth has been shown to depend on cumulative rainfall which in turn influences soil water contents and strength (Vepraskas et al., 1986). Seasonal rainfall influences the occurrence and duration of aeration stress in a similar manner because the abundance of air-filled pores depends on soil water content.

The objectives of this portion of the study were: (1) given the prevailing weather conditions, evaluate further the effects of tillage and wheel traffic on the environment of Charity clay for root growth by monitoring soil water content during the 1983 to 1985 growing seasons; and (2) evaluate the effects of the same treatments on water content of a second lake plane soil during 1983.

MATERIALS AND METHODS

A second field experiment, in addition to the experiment on Charity clay (fine, illitic (calcareous), mesic Aeric Haplaquept), was initiated during the fall of 1982 on Parkhill loam (fine-loamy, mixed, nonacidic, mesic Mollic Haplaquept), located five miles east of Ithaca, MI. Experiments were conducted at two sites in 1983 to compare the effectiveness of the ameliorative procedures on a problem soil (Charity clay) with a soil characterized by fewer physical limitations (Parkhill loam). The experiment at the second site (site 2) was carried out through the fall of 1983. The experimental design, treatments, and methods used to apply the treatments were identical to those described in Chapter 2 for the experiment on Charity clay near Swan Creek, MI (site 1). Thus, treatments existing during 1983 on Parkhill loam were: (1) deep tillage-moldboard plow and conventional spring tillage (DTMP-CST); (2) deep tillage-moldboard plow and no spring tillage (DTMP-NST); (3) no deep tillage-moldboard plow and conventional spring tillage (NDTMP-CST); and (4) the same as treatment 3 except no spring tillage was applied (NDTMP-NST).

Daily rainfall was monitored at the Saginaw Valley Bean and Beet Research Farm using standard U.S. Weather Bureau equipment. Daily precipitation amounts for the second study site, on Parkhill loam, were obtained from a recording station at Alma, MI.

A neutron probe (Campbell Pacific Nuclear Corporation; Pacheco, CA; Model 503 Hydroprobe), calibrated in situ, was used to monitor soil water content during 1983 on Parkhill loam and during the 1983 to 1985 growing seasons on Charity clay. Measurements were obtained from depths of 0.15, 0.30, 0.46, 0.61, and 0.76 m in plots planted to corn on Parkhill loam.

One access tube was installed in each plot, in one of the two center-rows of the four row plots, and equidistant from adjacent plants which were spaced at 0.30 m within the row.

Neutron probe measurements were obtained from only the 0.15, 0.30, and 0.46 m depths on Charity clay where the depth of rooting is limited by a naturally dense subsoil. Soil water content was measured in plots where corn and sugarbeets appeared except for 1985 when it was monitored only in plots planted to corn. Access tubes were installed only in plots representing the first crop year after subsoiling. Access tubes were also restricted to plots where the DTMP-CST, DTMP-NST, NDTMP-CST, and NDTMP-NST treatments appeared even though the number of treatments was increased from four to eight after 1983.

Neutron probe calibration was conducted during the 1982 and 1984 field seasons on Charity clay. The relationship between soil water content and neutron probe readings at the 0.15 m depth is shown in Figure 11. Each datum represents the mean of eight volumetric water contents plotted against the mean of four ratios. Values obtained in 1982 and 1984 were included to maximize the range of water contents over which the relationship was determined. Undisturbed soil cores 76-mm diam and 76-mm in length were used to determine the volumetric water contents. Ratios consisted of one-minute neutron counts divided by a standard count. The equation shown in Figure 11 was used to calculate water content of Charity clay and Parkhill loam at the 0.15 m depth. Neutron probe readings were probably influenced by nearness to the soil surface only at this depth (Grant, 1975).

The relationship between volumetric water content and neutron probe ratio at the 0.30 m depth is shown in Figure 12. Only values obtained

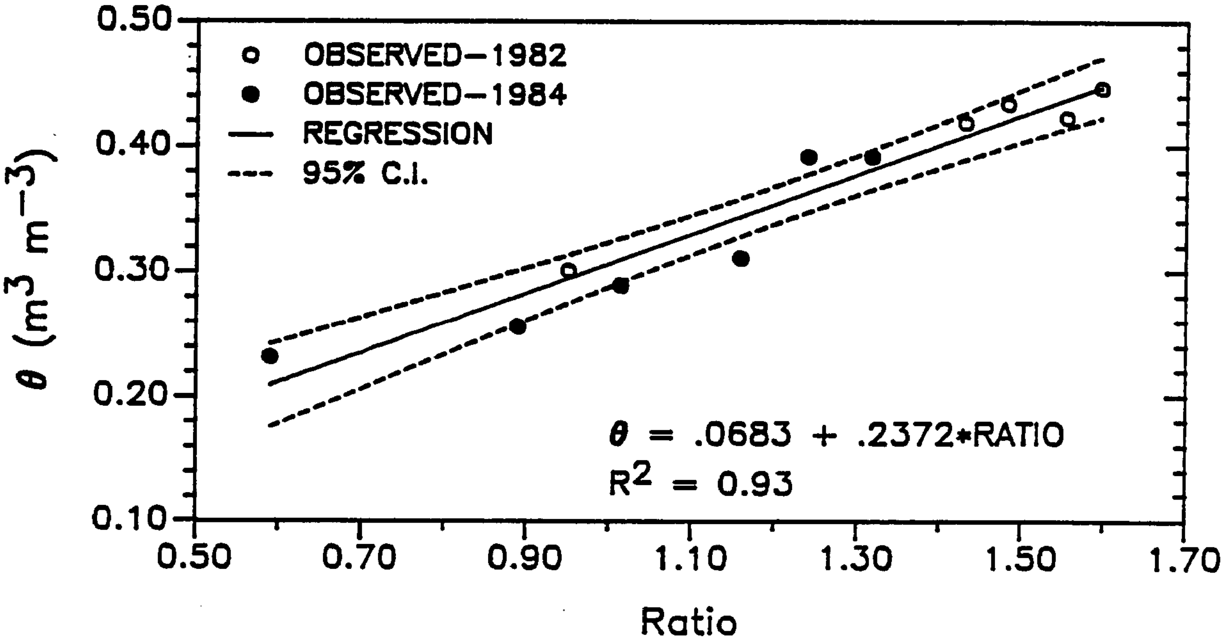

Figure 11. Linear regression of soil water content on neutron-probe ratio at the 0.15 m depth.

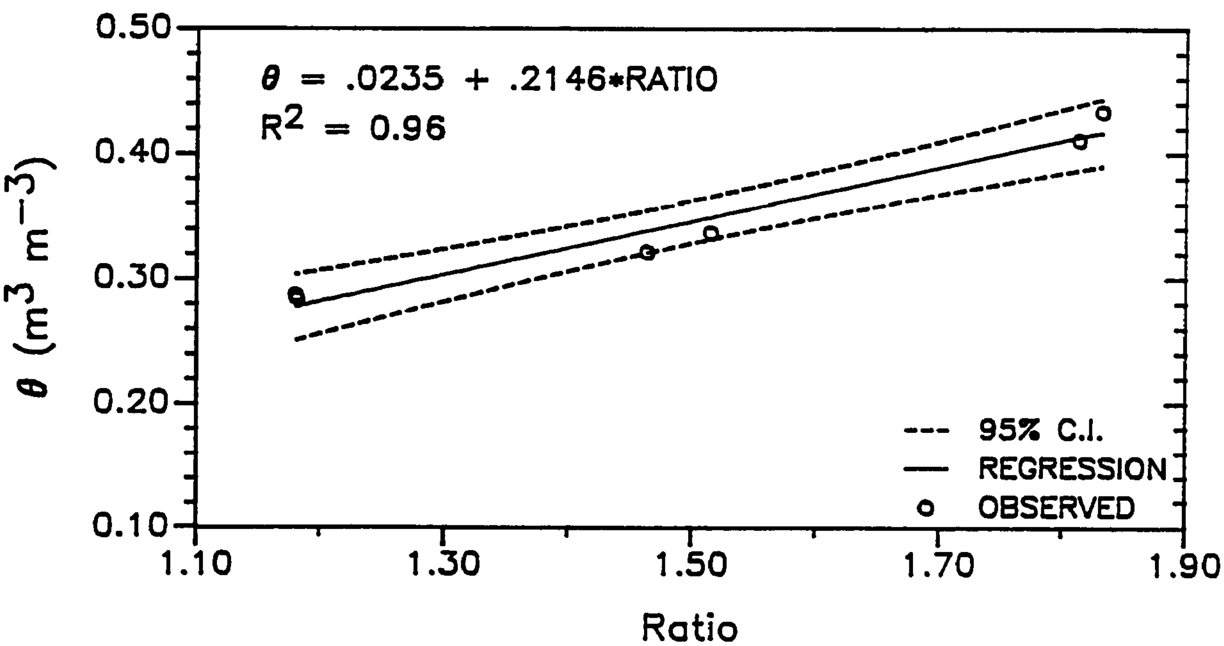

Figure 12. Linear regression of soil water content on neutron-probe ratio at the 0.30 m depth.

during 1984 were used to determine the equation given in Figure 12. This calibration equation was used to calculate water content of both soils at all depths greater than 0.15 m.

Treatment effects on soil water content were evaluated separately for each depth, on each measurement date, using analysis of variance. Treatments were compared using least significant differences (LSD) appropriate for a split-plot design arranged in randomized complete blocks (Steel and Torrie, 1960). The least significant differences are reported where significance was established at the 0.05 probability level.

RESULTS AND DISCUSSION

Site 1

Rainfall patterns during 1983 to 1985 at the Saginaw Valley Research Farm are illustrated in Figures 13 and 14. Cumulative rainfall during the April to September period in 1983 and 1985 were approximately equal averaging 600 mm (Figure 13a). Cumulative rainfall during the same period in 1984 was 514 mm. Precipitation for the six month period exceeded the long term average (1940-1985) of 456 mm each year.

The distribution of growing season precipitation differed each year from 1983 to 1985. Monthly precipitation departures shown in Figure 13b demonstrate that rainfall was approximately equal to the long term average during each month in 1984. By contrast, 1983 was characterized by an excessively wet period early in the growing season. Rainfall was 125 mm above normal for April and May combined, accounting for 84 percent of the 149-mm departure for the April to September period. The situation was much different during the 1985 growing season as precipitation was below normal from April to July but exceeded the long term average by 174 mm during the August to September period. Rainfall patterns illustrated in Figures 13 and 14 suggest that conditions for crop growth varied greatly during the three year study.

Water content of Charity clay at the 0.15, 0.30, and 0.45 m depths during 1983 to 1985 are shown in Figures 15 to 19. Temporal variation of water content reflect daily rainfall occurrences that are included in each Figure and seasonal rainfall reported in Figures 13 and 14. Water contents under both corn and sugarbeets were excessive during the early part of the measurement period in 1983 (Figures 15 and 16). Since precipitation was above normal during April and May, water contents on the first measurement date were lower than expected. These initial

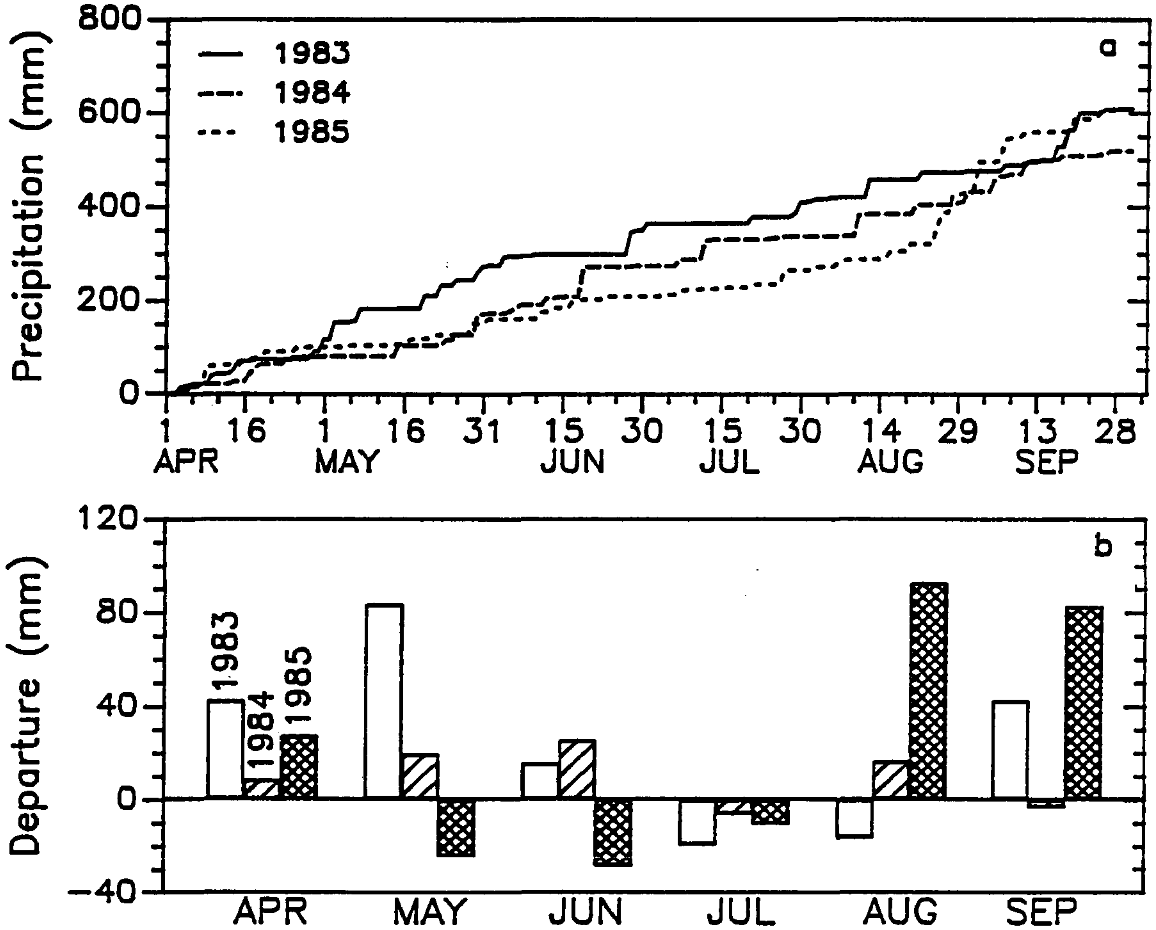

Figure 13. Cumulative growing season precipitation (a) and monthly precipitation departures (b) during 1983 to 1985 at the Saginaw Valley Bean and Beet Research Farm.

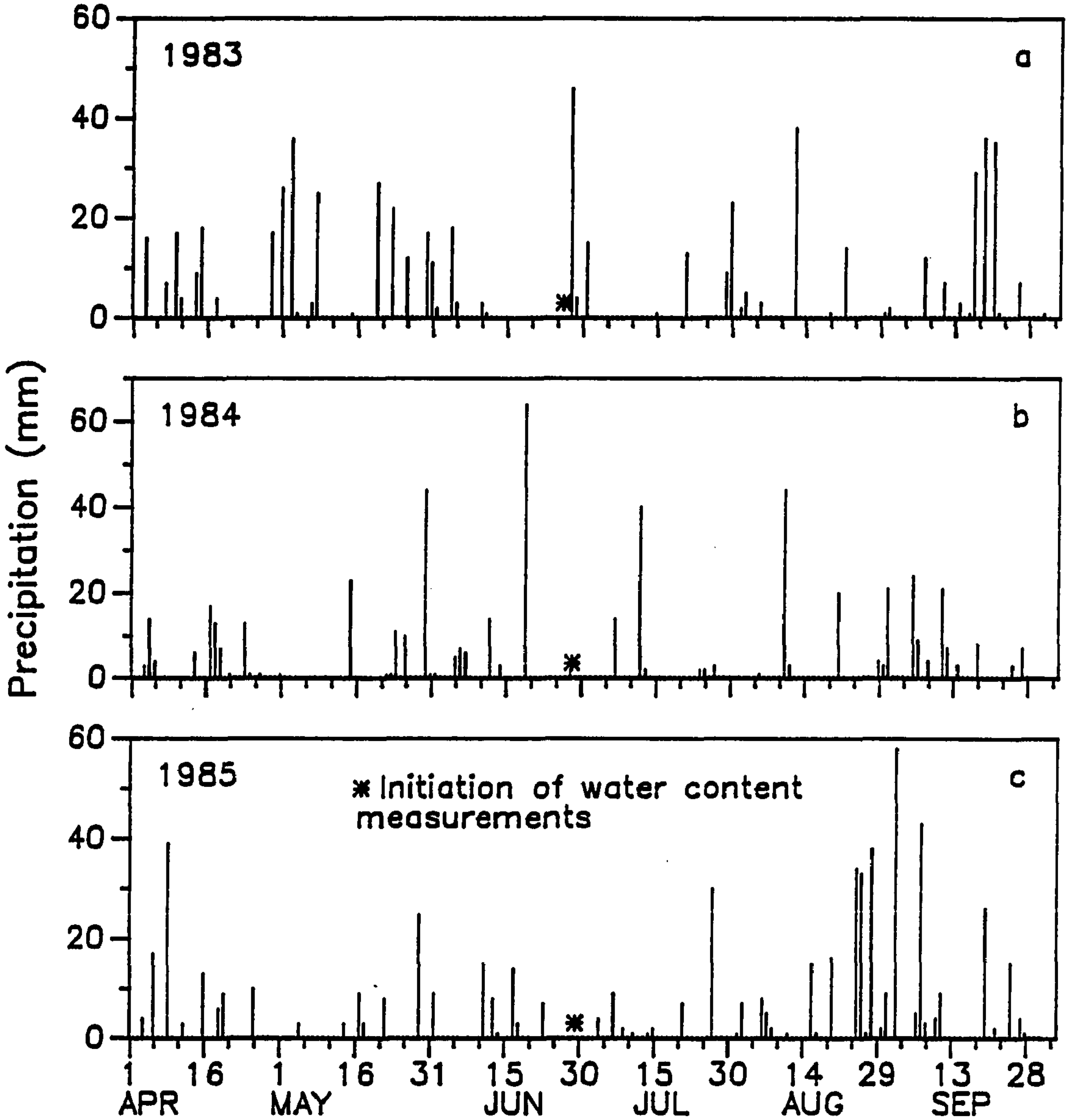

Figure 14. Daily growing season precipitation during 1983 (a), 1984 (b), and 1985 (c) at the Saginaw Valley Bean and Beet Research Farm.

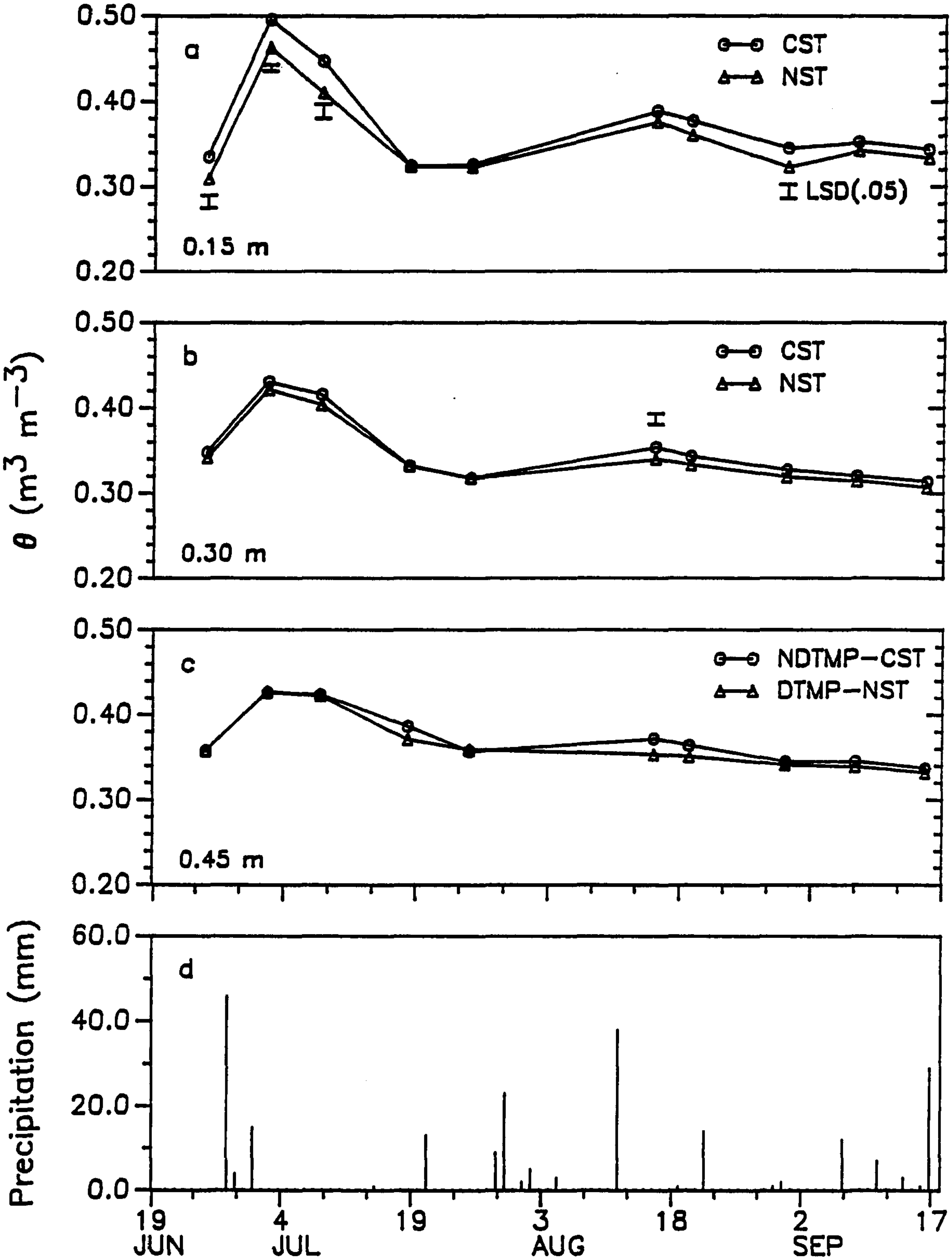

Figure 15. Water content of Charity clay at three depths in plots planted to corn (a-c) and daily precipitation (d) during 1983.

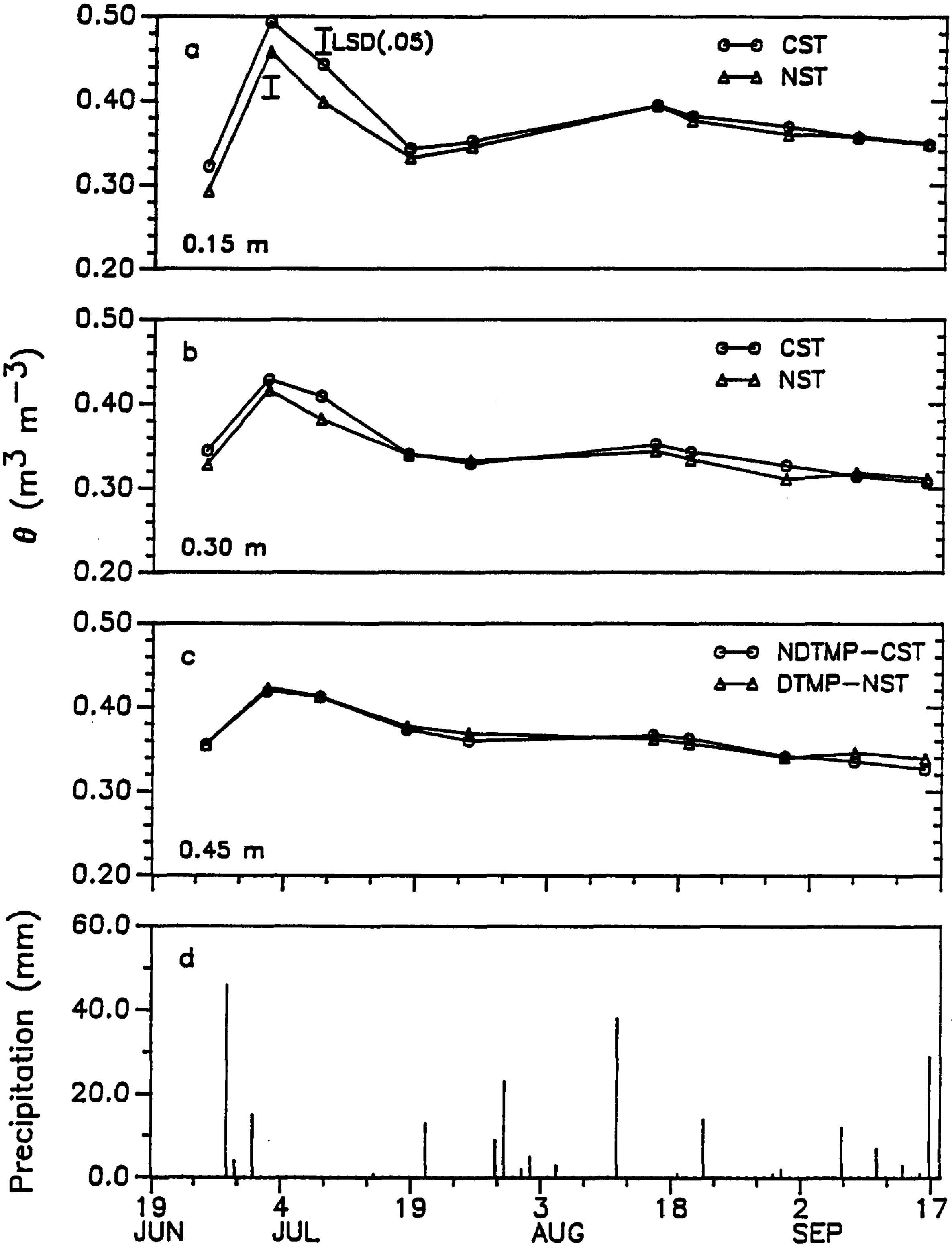

Figure 16. Water content of Charity clay at three depths in plots planted to sugarbeets (a-c) and daily precipitation (d) during 1983.

measurements suggest that subtantial loss of water from the surface 0.45 m of soil must have occurred during the 5 June to 24 June period when rainfall was only 4 mm (Figure 14a). Soil water content was relatively constant at each depth during the last 45 days of measurement in 1983 (3 August to 17 September).

A much different situation existed in 1984 as water content of Charity clay at the 0.15 m depth was consistently low during the 24 June to 8 August period (Figures 17 and 18). Water contents decreased gradually at the 0.30 and 0.45 m depths during the same 45 day period. Water contents corresponding to the first measurement date in 1984 were lower than expected because neutron probe measurements were initiated only four days after the occurrence of a 64 mm rainfall (Figure 14b). The water content at each depth increased gradually under corn and sugarbeets during the 8 August to 22 September period (Figures 17 and 18) as the daily amount of plant water extraction decreased.

The water content of Charity clay during 1985 is illustrated in Figure 19. Above normal August and September precipitation (Figure 13b) produced excessive water contents on the last two measurement dates. Soil water excesses were also evident during the first few days of July (Figure 19) as was the case in 1983 (Figures 15 and 16). Given the diverse seasonal rainfall patterns in 1983 and 1985, these apparent similarities between water contents in 1983 and 1985 were produced in part by the timing of water content measurements. For example, rainfall was far greater than average during April and May in 1983 but measurements were initiated that year after a 20 day period with negligible rainfall. Rainfall was 48 mm for the 20 day period preceding the initial water content measurements in 1985 (Figure 14c) even though rainfall for the April to July period was below normal.

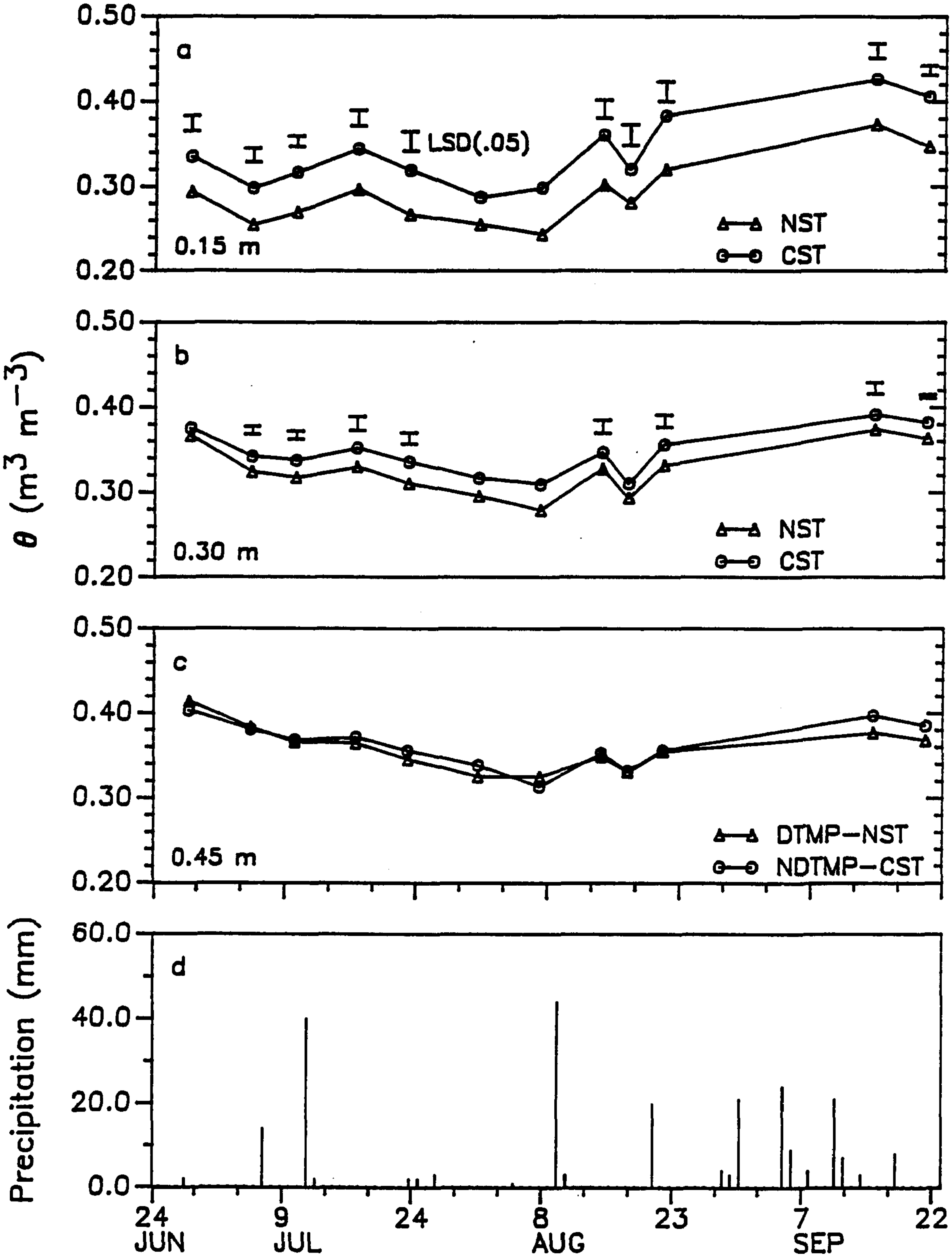

Figure 17. Water content of Charity clay at three depths in plots planted to corn (a-c) and daily precipitation (d) during 1984.

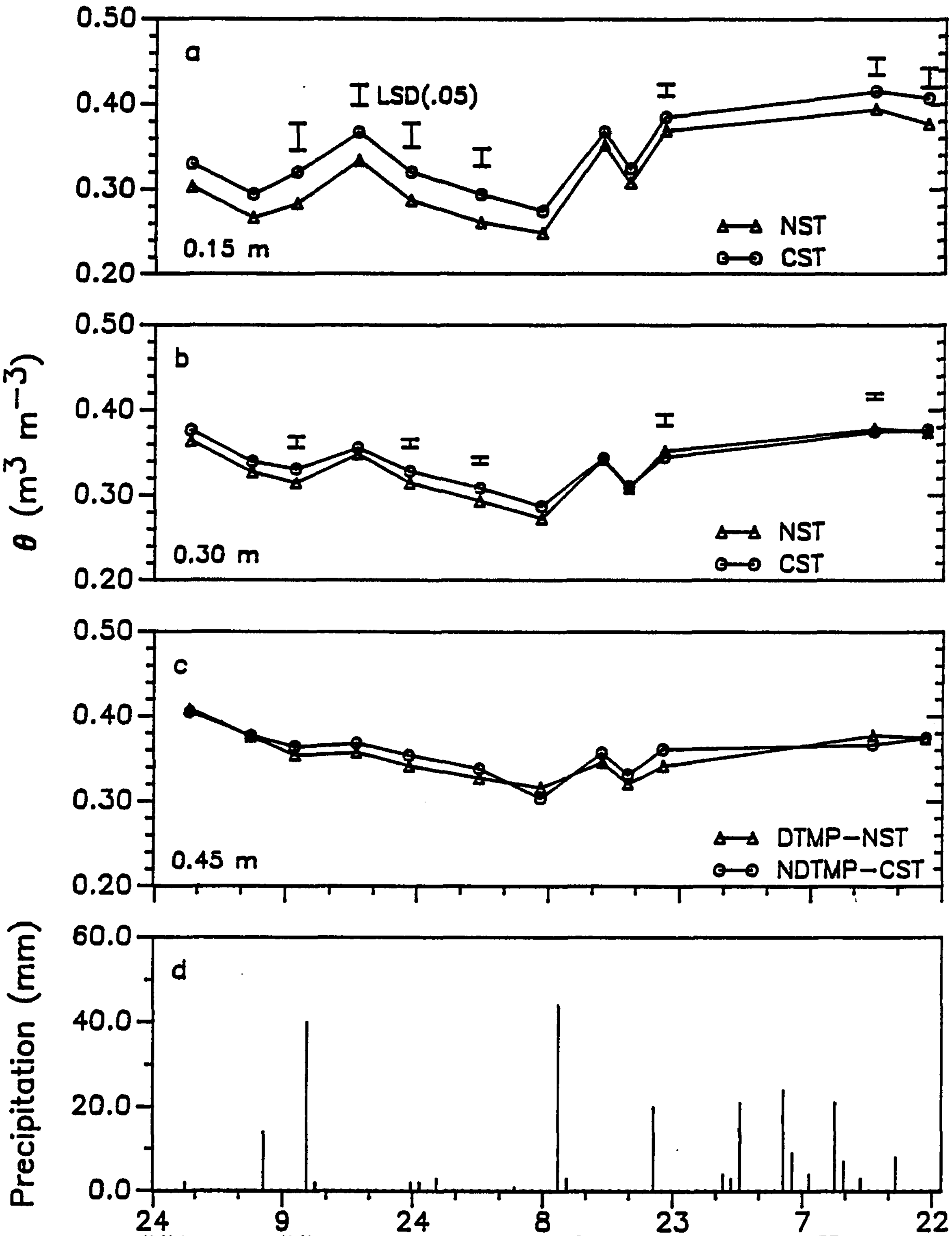

Figure 18. Water content of Charity clay at three depths in plots planted to sugarbeets (a-c) and daily precipitation (d) during 1984.

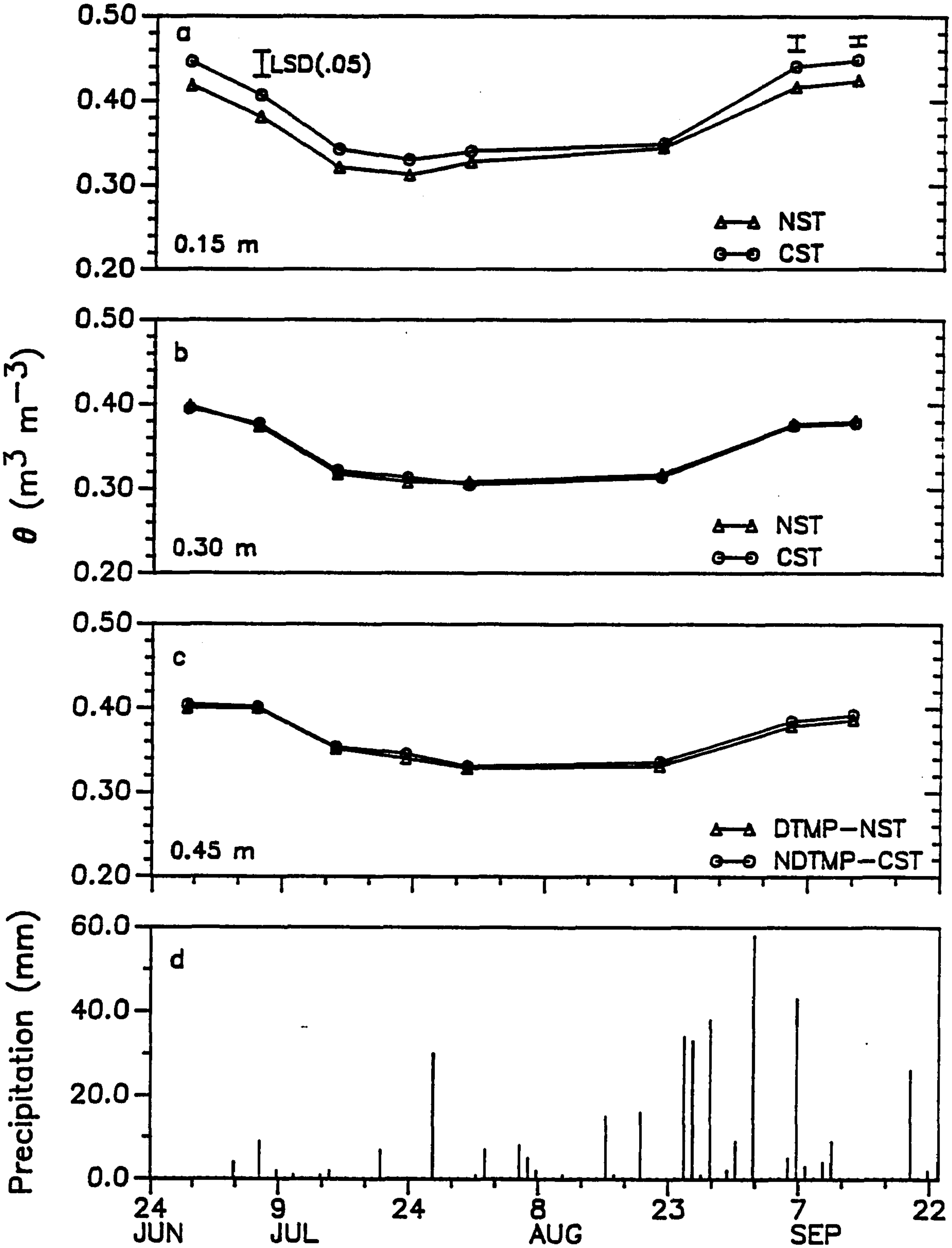

Figure 19. Water content of Charity clay at three depths in plots planted to corn (a-c) and daily precipitation (d) during 1985.

Seasonal variation of soil water content could have been assessed more effectively by obtaining measurements more frequently. However, water content was monitored primarily to evaluate treatment effects on this soil parameter at discrete points in time. Cassel and Nelson (1981) suggest that measurement of volumetric water content may be inappropriate for comparison of tillage effects on soil conditions due to variation of water content within any one experimental treatment. Our results fail to substantiate the authors claim as water contents for the 0.15 and 0.30 m depths were measurably different under the secondary tillage variables that were applied in this study.

Water content data for the 0.15 and 0.30 m depths (Figures 15a,b to 19a,b) were averaged for DTMP and NDTMP because water content at these depths was unaffected by the primary tillage variables. Thus, each datum at the 0.15 and 0.30 m depths represent the mean of eight observations (i.e., 2 levels of primary tillage x 4 reps). Wheel traffic applied prior to corn and sugarbeet planting increased the water content of Charity clay at the 0.15 m depth, during the earliest portion of the measurement period in 1983 (Figures 15 and 16). Differences were occasionally detected on later measurement dates in plots planted to corn.

Water content of the 0.15 and 0.30 m depths were consistently and significantly greater under CST than NST in 1984 (Figures 17 and 18). Differences were as large as 0.07 $m^3\ m^{-3}$ at the 0.15 m depth in plots planted to corn causing an even larger air porosity difference between CST and NST because the total soil porosity was diminished under CST (Chapter 2, Tables 4 and 5). Though significant, differences appeared smaller at both depths in plots where sugarbeets appeared. Significant differences between water content under CST and NST were occasionally detected at the 0.15 m depth in 1985 (Figure 19).

The effects of preplant wheel traffic on soil moisture levels, suggested by periodic water content measurement, produced results similar to those reported in Chapter 2. The water content of undisturbed soil cores obtained for physical measurements was higher in plots compacted by preplant wheel traffic than in nontrafficked plots (Tables 4 and 5). The undisturbed soil cores from the plow layer were obtained during 1985 when CST increased water content of the 0.15 m depth on only three measurement dates (Figure 19). Differences between CST and NST seemed larger and were detected more frequently during 1984 based on water contents reported in Figures 17 and 18. This suggests that preplant wheel traffic may have altered the physical conditions of the plow layer to a greater extent in 1984 than in 1985.

Varying soil water content under CST and NST can be attributed primarily to the direct influence of the secondary tillage variables on soil conditions. Plant water extraction from a particular soil layer has been shown to be proportional to root density (Garay and Wilhelm, 1983; Lascano and van Bavel, 1984). Since tillage can affect root density, it is logical to assume that differences in Figures 15 to 19 may be due in part to differential extraction of water by plants under CST and NST. However, differences seemed most prevelant after periods of frequent or excessive rainfall. Such conditions tend to diminish differences, if any, caused by differential water extraction under CST and NST. In agreement with results of Chapter 2, differences can be attributed primarily to physical changes (e.g., water retention, internal drainage) associated with wheel induced compaction.

Water content of Charity clay at the 0.45 m depth was unaffected by the primary and secondary tillage variables on virtually every measurement date based on statistical comparison of treatments. Water content at this depth is reported for the DTMP-NST and NDTMP-CST treatments which produced the most dissimilar soil conditions at the 0.27 to 0.34 m depth (Chapter 2). Figures 15c to 19c verify that water contents at the 0.45 m depth were the same under these diverse treatments during the three year study.

Site 2

Figure 20 illustrates cumulative rainfall and the distribution of growing season precipitation in 1983 near the second study site. April and May rainfall was above normal (Figure 20b) as was rainfall during the same period at site 1 (Figure 13b). However, the rainfall departure for the June to August period was -92 mm at the second site compared to -19 mm at site 1. Precipitation for the April to September period at site 1 (on Charity clay) exceeded the precipitation at site 2 (on Parkhill loam) by 100 mm. Thus, growing season precipitation differed substantially at the two sites during 1983.

The water content of Parkhill loam at the 0.15 and 0.30 m depths are illustrated in Figure 21. Soil moisture levels appeared to be unaffected by two relatively large rainfalls near the middle of the measurement period (Figure 20c) as the water content at these depths were stable after mid July. Again, the length of the measurement intervals masked temporal fluctuation of this soil parameter.

Wheel induced compaction increased the water content of Parkhill loam at the 0.15 m depth (Figure 21a). The physical properties of Parkhill loam were not characterized to the same extent as those for Charity clay (Chapter 2). However, it seems reasonable to assume that physical

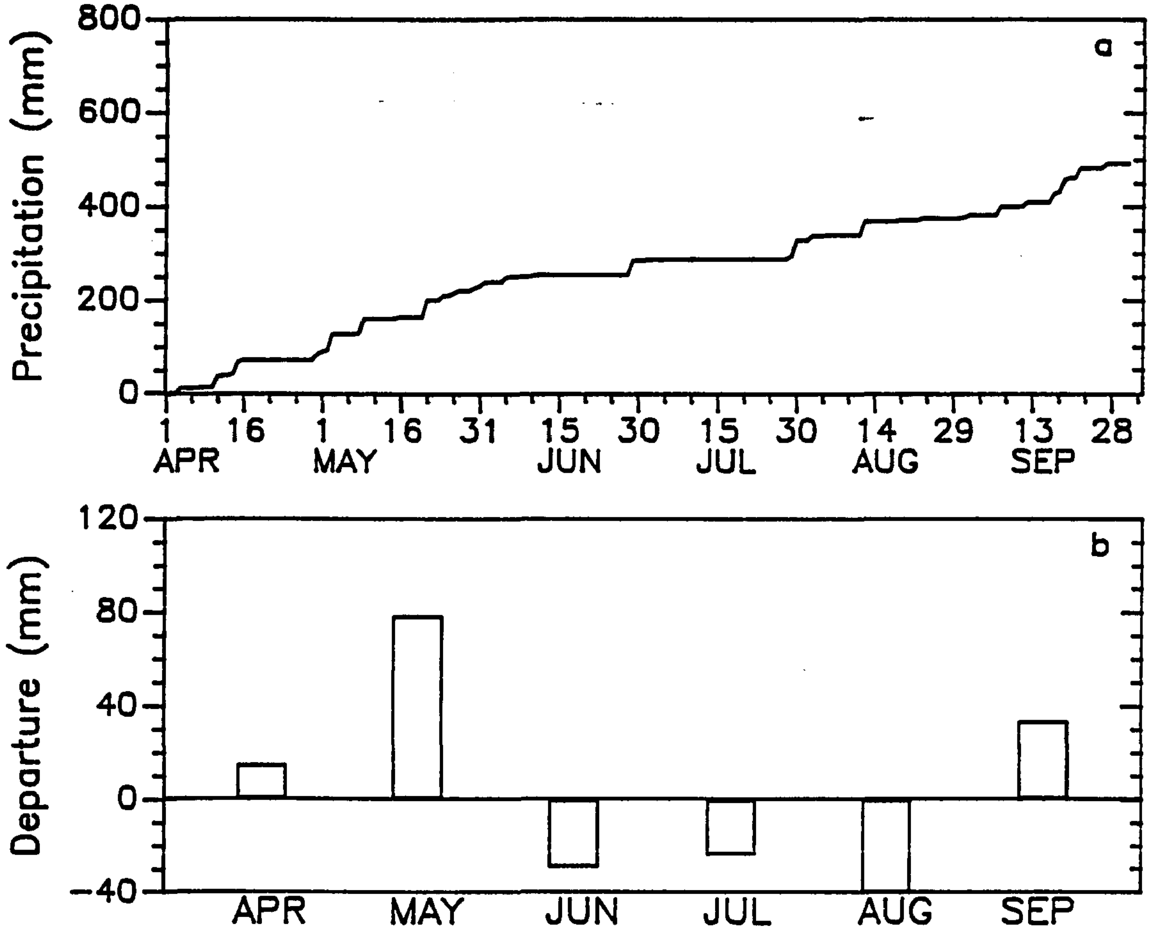

Figure 20. Cumulative growing season precipitation (a) and monthly precipitation departures (b) during 1983 at Alma, MI.

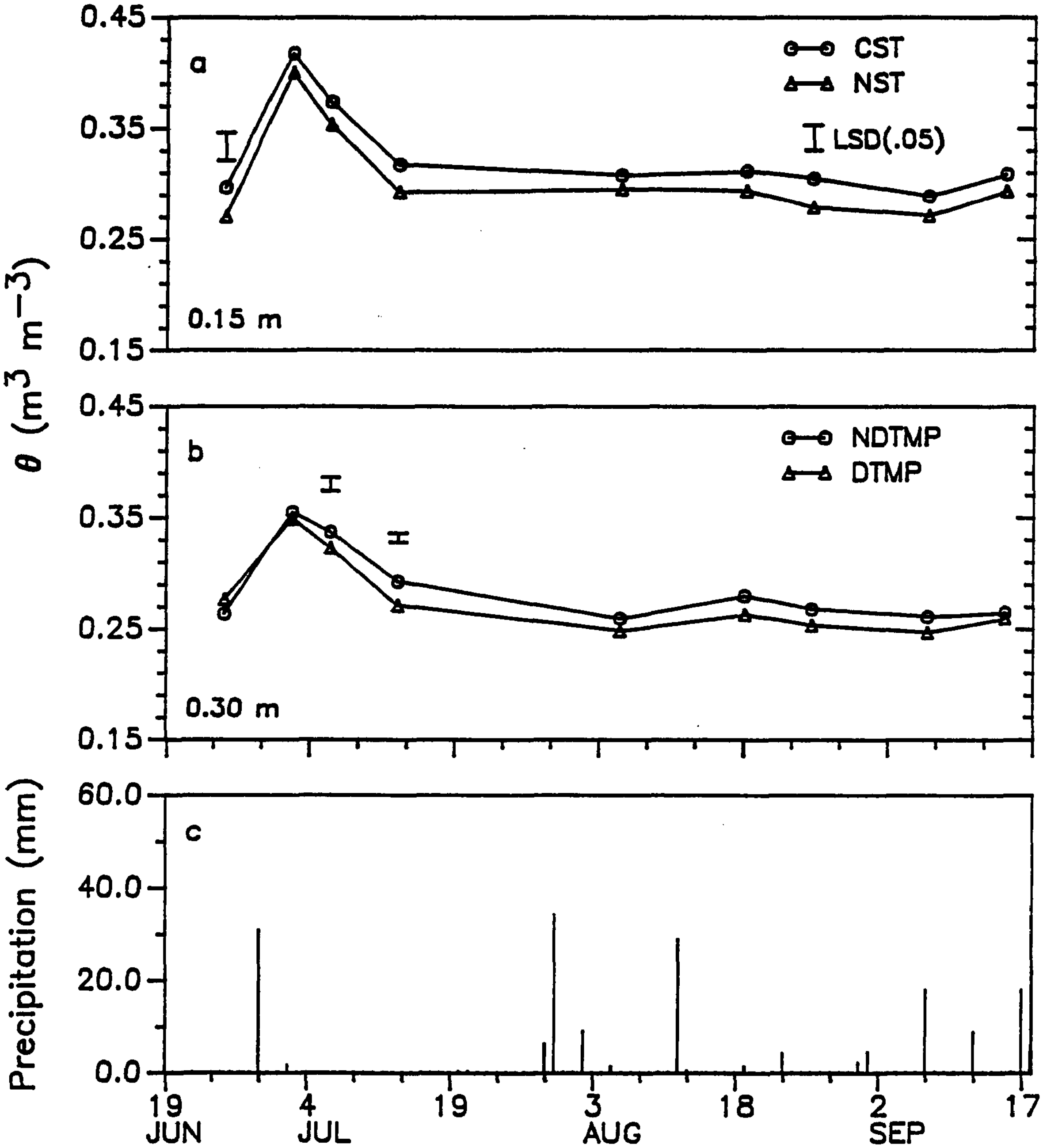

Figure 21. Water content of Parkhill loam at two depths in plots planted to corn (a-b) and daily precipitation (c) during 1983.

changes caused by preplant wheel traffic were similar on the two soils, at least for the 0.15 m depth. The secondary tillage variables had no effect on water content of the 0.30 m depth. Values averaged for CST and NST levels of secondary tillage in Figure 21b show that water content was slightly higher in nonsubsoiled plots (NDTMP) than in subsoiled plots (DTMP).

The primary and secondary tillage variables had no effect on water content of Parkhill loam at the 0.46, 0.61, and 0.76 m depths. Water contents for only the diverse treatments, NDTMP-CST and DTMP-NST, are reported for these depths in Figure 22. Soil at the 0.61 and 0.76 m depths was probably unaffected by tillage or by pressure from preplant wheeling. If treatment differences were evident at these depths, they could have been attributed to altered depth of root penetration or root densities under the various treatments. Figures 22b and 22c demonstrate that plant water extraction was extensive at each depth but similar under the two treatments which should have produced diverse physical conditions at shallower depths. Data in Figure 22 suggest that corn rooting was not altered substantially by the treatments applied on Parkhill loam based on periodic water content measurements in 1983.

CONCLUSIONS

The distribution of growing season precipitation varied greatly during the three year study at the Saginaw Valley Research Farm. Rainfall patterns during April and May were similar at the two study sites in 1983, the only year in which experiments were conducted at two sites. During the critical June to August period of 1983, precipitation was 92 mm below normal at site 2 (on Parkhill loam) compared to only 19 mm below normal at site 1 (on Charity clay).

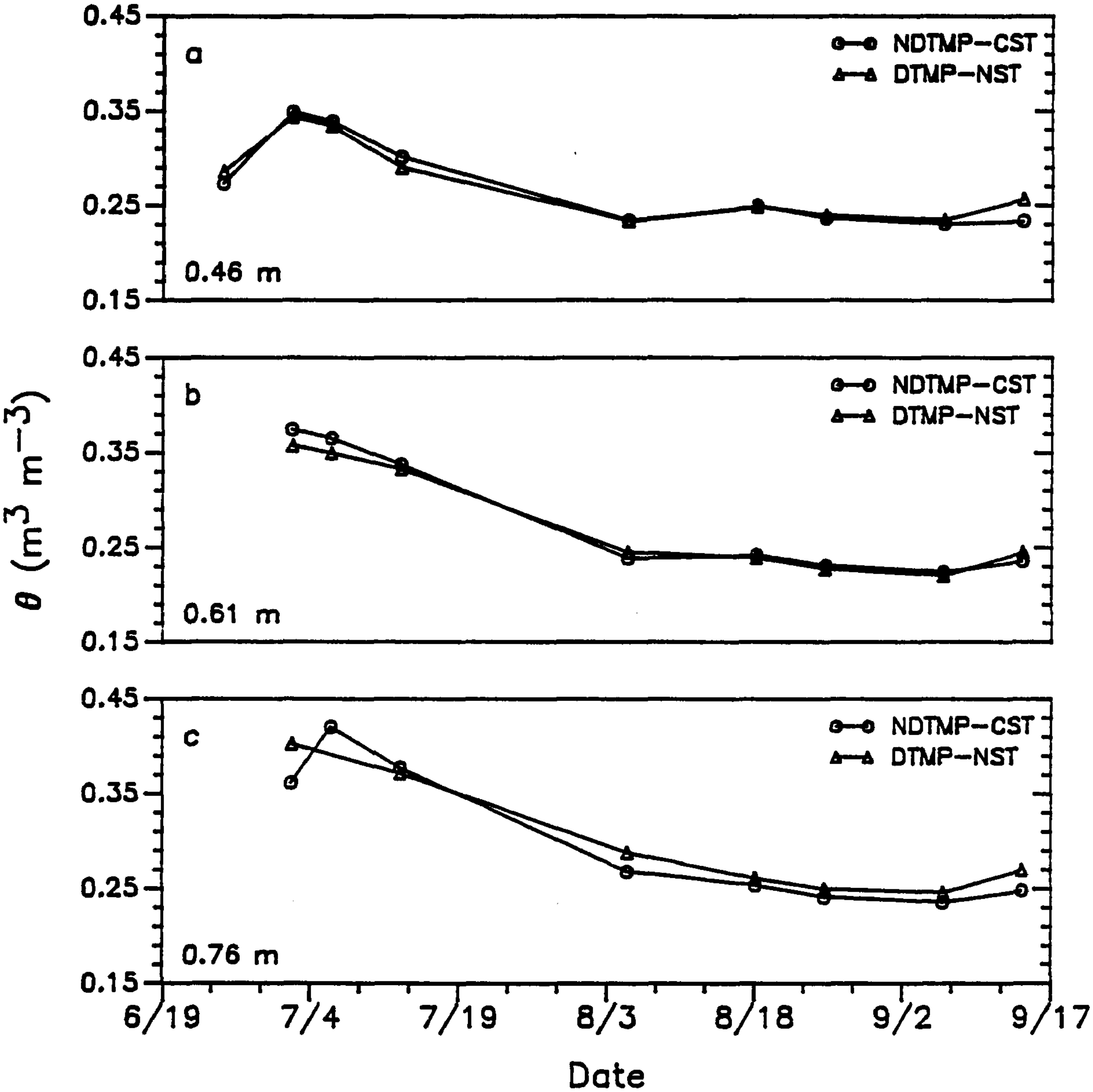

Figure 22. Water content of Parkhill loam at the 0.46 (a), 0.61 (b), and 0.76 m (c) depths during 1983 in plots planted to corn.

Water content of Charity clay and Parkhill loam, determined by neutron scattering, were related to the prevailing rainfall patterns for the most part. The seasonal variation of soil water content could have been assessed more effectively each year by obtaining measurements more frequently. However, water content measured at weekly intervals verified that preplant wheel traffic altered thephysical conditions of the plow layer such that water content was consistently greater under CST than under NST. Preplant wheel traffic associated with the CST treatment decreased air porosity accordingly indicating that controlled traffic (NST) improved soil aeration when soil water excesses occurred. The primary tillage variables had no effect on the water content of Charity clay at the 0.15 to 0.30 m depths or water content of Parkhill loam at the 0.46 to 0.76 m depths.

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Chapter 4

Seedling Emergence, Rooting, and Crop Yields as Affected by Deep Tillage and Controlled Traffic

INTRODUCTION

Soil loosening produced by subsoiling and compaction caused by wheel traffic affect plant growth through their effects on soil physical conditions. Rosenberg (1964) suggested that the prevailing weather conditions must be considered before the physically measured properties can be correlated with plant growth.

Numerous investigators have since demonstrated that plant response to actions that alter the soil physical environment vary dramatically with climate. Where water stress is the primary limitation to crop production, root impeding layers can be disrupted to alleviate water stress by increasing the rooting depth or proliferation within the explored volume. Subsoiling has been shown to increase crop yields during dry years in this way (Campbell et al., 1974; Parker et al., 1975; Kamprath et al., 1979). When water stress is not limiting, as in wet years or when adequately irrigated, crop yields may not be improved by subsoiling (Weatherly and Dane, 1979; Buxton and Zalewski, 1983; Box and Langdale, 1984; Ross, 1986; Miller, 1987).

The deleterious effects of wheel induced compaction on corn (Phillips and Kirkham, 1962; Raghaven et al., 1978; Negi et al., 1980), sugarbeet (Blake et al., 1960; Hebblethwaite et al., 1980), soybean (Nelson et al., 1975), and oat yields (Blackwell et al., 1985) have been demonstrated.

However, plant response to compaction varies with weather conditions (Rosenberg, 1964) just as subsoiling to alleviate water stress produces results that depend on weather. During wet years, Gaultney et al. (1982) and Lindeman et al. (1982) showed that compaction tends to reduce yields of corn and soybeans, respectively. By contrast, crop yields were actually favored by moderate wheel induced compaction in dry years (Raghaven et al., 1979; Anazodo et al., 1983; Voorhees et al., 1985) as compaction presumably increased soil water availability.

Poor physical conditions of Charity clay limit yields at the Saginaw Valley Bean-Beet Research Farm during some years. This soil has an unstable surface and poor internal drainage due to its naturally dense subsoil that impedes water movement. Charity clay, and other imperfectly drained soils in the area, may lack adequate aeration for root growth at certain times during the season as a result. Plants with root growth impeded by these physical limitations may experience water stress when rainfall is deficient.

Tillage of a soil with poor aeration characteristics can correct temporarily the aeration problem (Burnett and Hauser, 1968; Erickson, 1982). Field studies were conducted to evaluate the potential for reducing the physical limitations of Charity clay and a second lake plain soil. Both soils were subsoiled and subsequent traffic was controlled to avoid recompaction of the loosened soil. Physical changes produced by various primary and secondary tillage variables were reported in Chapter 2. Environmental conditions were characterized each year by measuring daily rainfall amounts and monitoring profile soil water content on a weekly basis (Chapter 3).

The objectives of this portion of the study were: (1) to evaluate the influence of physical changes brought about by tillage on crop growth; and (2) determine whether or not plant responses each year were related to seasonal rainfall and therefore environmental stresses.

MATERIALS AND METHODS

Field experiments were conducted in 1983 on Parkhill loam (fine-loamy, mixed, nonacidic, mesic Mollic Haplaquept) and from 1983 to 1985 on Charity clay (fine, illitic (calcareous), mesic Aeric Haplaquept). The experimental design at each location was a split-split-plot, arranged in randomized complete blocks, and replicated four times. Main plots consisted of the following primary tillage variables in 1983: (1) deep tillage-moldboard plow (DTMP); and (2) no deep tillage-moldboard plow (NDTMP). Secondary tillage variables, applied as subplot treatments were: (1) conventional spring tillage (CST); and (2) no spring tillage (NST). Equipment and procedures used to apply the tillage treatments were described in Chapter 2. A sufficient number of main plots were established at each location so that tillage effects on growth and production of several crops could be tested.

Subplots were split to include two cultivars of each crop. All plots were planted using a four-row (0.51 m spacing) minimum tillage planter except those planted to small grains. Plot dimensions were 2.1 m wide x 20.1 m in length for the experiment on Charity clay and 2.1 m x 15.2 m at the second location on Parkhill loam. Crops and cultivars used for the 1983 experiments are shown in Appendix Table 1. Planting dates, seeding rates, and fertilizer application rates are also given in Appendix Table 1. Herbicide programs used for each crop are shown in Appendix Table 2.

The same experimental design was used during 1984 and 1985 on Charity clay but the number of main plot treatments applied during the fall of 1983 and 1984 was increased from two to four. This was accomplished by moldboard plowing one half of the subsoiled and nonsubsoiled areas and shallow chiseling the other half. Primary tillage variables applied to the main plots were: (1) deep tillage-moldboard plow (DTMP); (2) deep tillage chisel plow (DTCH); and (3) no deep tillage-moldboard plow (NDTMP); and (4) no deep tillage-chisel plow (NDTCH). Individual plots were reduced from 20.1 to 10.0 m in length where four main plot treatments were applied.

As indicated in Chapter 2, plots established for 1983 and 1984 on Charity clay were maintained through 1985. Crops were rotated according to the crop sequences described in Chapter 2. Primary tillage variables were applied to main plots only once so that the possible residual effects of deep tillage on crop growth could be determined. Plots established during the first, second, or third year after application of the primary tillage variables are referred to as 'first year', 'second year', or 'third year' plots, respectively. Crops grown in the first-year plots represent the 'first crop year' and so forth for crops grown on second and third-year plots. The cumulative effects of preplant wheel traffic on crop growth was evaluated by applying the secondary tillage variables prior to planting each spring but without re-randomization. Management practices used for crops grown during 1984 and 1985 are illustrated in Appendix Tables 3 to 6.

The influence of the DTMP-CST, DTMP-NST, NDTMP-CST, and NDTMP-NST treatment combinations on emergence of row crop seedlings was determined by measuring plant density periodically after planting each year. Seedling emergence was evaluated only in the first-year plots (ie., all plots in 1983). Plant density at harvest was measured in each plot, at both locations, planted to row crops in 1983. The density of corn and sugarbeet plants at harvest was measured in 1984 and 1985.

Root length density (RLD) of the Pioneer 3901 corn, C20 dry bean, and Hodgson 78 soybean cultivars on Charity clay was determined each year except for RLD of corn which was determined only in 1983. Root length density was measured during the latter part of August each year where the DTMP and NDTMP treatments appeared but only where these primary tillage variables were applied the previous fall. Root samples, two per plot in 1983 and one in each plot in 1984 and 1985, were taken to the 0.46 m depth using the method described by Srivastava et al. (1982). Samples were taken between the center two rows of the four row plots with the sampling device positioned next to one of the center crop rows.

Samples were fractionated into 18 76x76x76 mm subsamples, three at each of six depths. Roots were separated from the soil in each subsample using the method developed by Smucker et al. (1982) after soaking for 16 hours in sodium hexametaphosphate. Root length was determined using the equation developed by Tennant (1975) for application of the line intersect method (Newman, 1966) on a regular grid. Root dry weight was determined but only for the last three 76-mm measurement depths as it was difficult to remove plant residue from subsamples corresponding to depths within the plow layer.

Yields of all row crops were taken from the center two rows of the four-row plots. Sugarbeet roots were harvested manually from a 6.2-m^2 area in 1983 and 1984. Second and third-year plots were harvested mechanically in 1985 using a two-row sugarbeet lifter after removing the tops by flailing. Harvest areas were 9.8 and 20.4 m^2 for the second and third-year plots, respectively. Excessive rainfall during the fall of 1985 prevented completion of sugarbeet harvest using this procedure. The first-year plots were harvested manually from 6.2-m^2 areas as a result. Excess soil was removed from the roots before yield samples were weighed.

Ten roots from each yield sample were obtained for quality analysis. Raw juice was extracted from the brei produced by sawing the roots lengthwise. The juice obtained was frozen immediately and analyzed at the Michigan Sugar company analytical laboratory. Sucrose content, clear juice purity (CJP), recoverable sucrose content, and alph-amino-N content was determined using procedures described by Dexter et al. (1967).

Corn was harvested manually from 7.7-m^2 areas. A shelling percentage of 82 percent was used to adjust ear-sample weights to equivalent weights of corn grain. Yields are reported on a 155 g kg^{-1} moisture content basis.

Dry bean plants were pulled manually from harvest areas of 6.2 m^2 and threshed after drying for a few hours. Soybean plants were pulled manually from harvest areas of 6.2 m^2 in 1983. Harvest areas were increased to 7.7 m^2 in 1984 and 1985 when soybeans were harvested using a plot combine. Yields of dry bean and soybean seed were corrected to seed moisture contents of 180 and 130 g kg^{-1}, respectively.

Oat plants were taken manually from a 2.4-m section of the center six rows of each plot in 1983. Plants from these 2.6-m^2 areas were threshed using a plot thresher. A plot combine was used to harvest the center eight rows of the oat and wheat plots in 1984 and 1985. Harvest areas were dictated by plot dimensions, and ranged from 13.0 m^2 where plots were 10.0 m in length to 27.3 m where plots were 20.1 m in length. Yields of oat and wheat grain for 1985 are reported on a 140 and 120 g kg^{-1} moisture content basis, respectively. Yields for 1983 and 1984 were uncorrected for grain moisture as only test weights of oat and wheat grain were available.

Tillage effects on plant parameters were evaluated by analysis of variance. Treatments were compared using least significant differences (Little and Hills, 1978). Analysis of variance of crop yields were combined over locations for 1983, the only year in which the experiments were conducted at two sites. Analyses were combined over years for the experiment on Charity clay. All combined analyses were applied to single crop cultivars and procedures described by McIntosh (1983) were used to test the various effects.

RESULTS AND DISCUSSION

Corn Response

Emergence of corn seedlings at the two study sites in 1983 and one site in 1984 and 1985 is shown in Figure 23. Plant densities were averaged over the two primary tillage variables (DTMP and NDTMP) because they had no effect on the measured values. Emergence was also unaffected by secondary tillage except for 1983 when plant densities on Charity clay were favored by controlled traffic on the first measurement date (Figure 23b).

Grain moisture at harvest in 1983 was higher under CST than under NST (Appendix Table 7) indicating that the crop matured more rapidly under the latter. Raghaven et al. (1978) and Gaultney (1980) also demonstrated that compaction retards maturation and therefore increases the moisture content of the grain at harvest. The effects of compaction on seedling emergence and crop maturity during the wet year of 1983 was due in part to impeded soil aeration under CST.

Root distribution of the Pioneer 3901 corn cultivar was measured during only 1983 on Charity clay. Mean squares from analysis of variance of root length density (RLD) at six depths and root weight density (RWD) at three depths are shown in Appendix Table 9. Corn root density was influenced significantly by soil depth but was unaffected by the tillage variables.

Root length densities at six depths, averaged for the DTMP and NDTMP primary tillage variables, are illustrated in Figure 24. Maximum RLD was 2.1×10^4 m m^{-3} (2.1 cm cm^{-3}) at the 0.11 m depth. Root length density decreased monotonically to 1.0×10^4 m m^{-3} at the 0.42 m depth. Root weight density for the three depths below the Ap horizon are reported in Appendix Table 10.

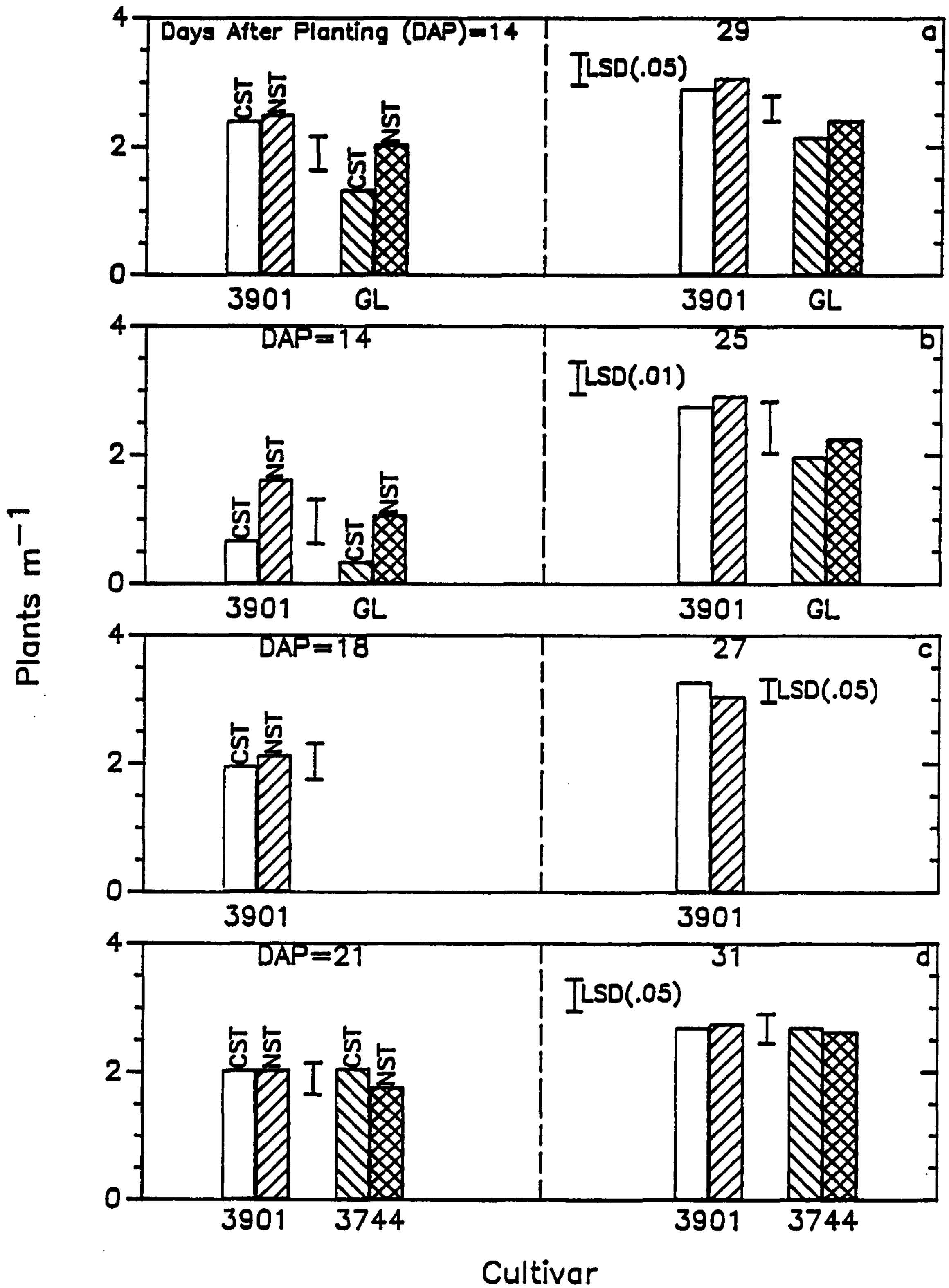

Figure 23. Emergence of corn seedlings on Parkhill loam in 1983 (a) and on Charity clay during 1983 to 1985 (b-d) as affected by secondary tillage. Cultivars used were Great Lakes-422 (GL), Pioneer-3901 (3901), and Pioneer-3744 (3744).

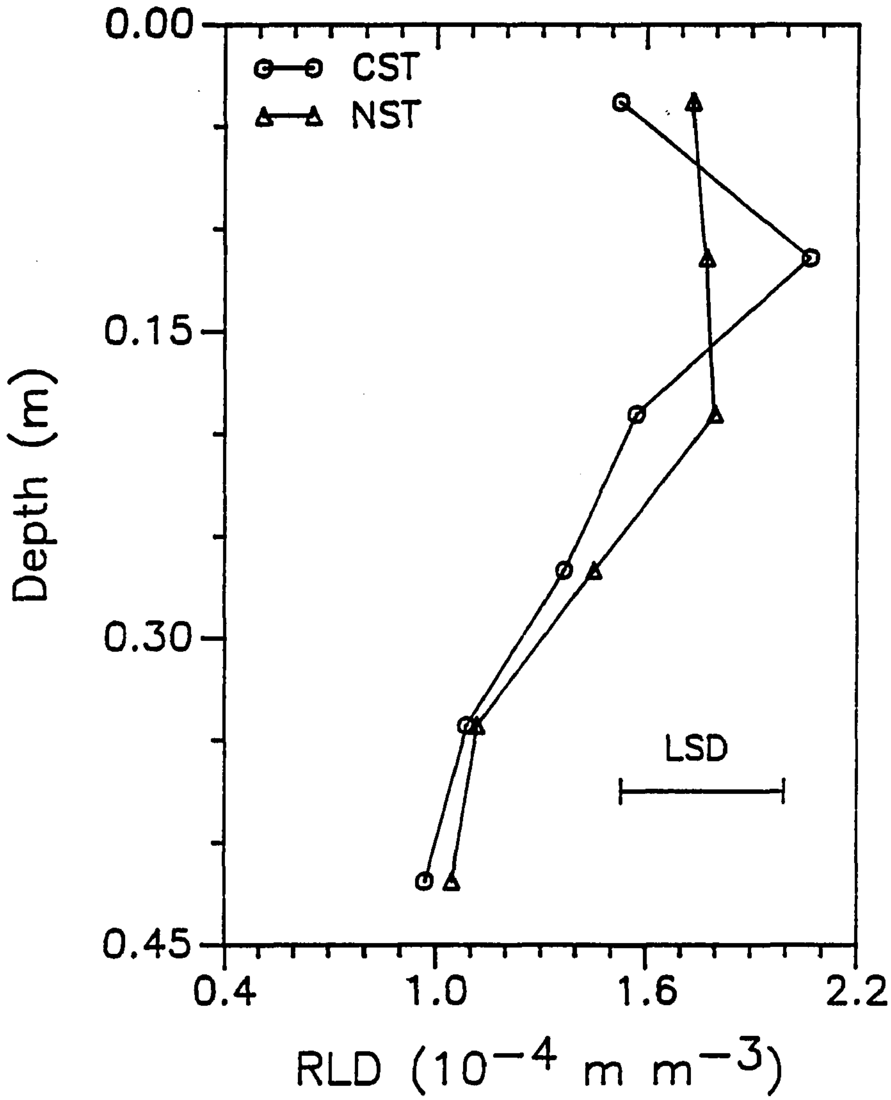

Figure 24. Corn root length density on Charity clay in 1983 as affected by secondary tillage.

Grain moisture, population, and grain yield were unaffected by primary or secondary tillage on Parkhill loam in 1983 (Table 6). Yields were similar for both cultivars despite lower populations in plots planted to the Great Lakes 422 cultivar than the Pioneer 3901 cultivar. All plant populations reported in Table 6 were lower than the desired population of 64 500 plants ha^{-1}.

Table 7 compares corn grain yield on Charity clay under the various combinations of primary and secondary tillage. Yields of both cultivars were increased by controlling wheel traffic (NST) in 1983, the same year when seedling emergence was slowed and grain moisture was increased by wheel track compaction (CST). These results are in agreement with those of Van Doren (1959) where damage to corn from soil compaction occurred at planting time and was attributed to poor seedling emergence. Erbach et al. (1986) suggested that tillage systems with the best early growth tend to have the greatest grain yields. Thus, seedling emergence, maturity, and yields are expected to be diminished by excessive preplant wheel traffic on Charity clay when early season rainfall is above normal as in 1983.

Yields of the Pioneer 3744 cultivar, grown in the second-year plots (CY2) in 1984, were affected by secondary tillage but the effects were different where deep tillage and normal fall tillage were applied. Grain yields in 1984 exceeded yields reported for 1983 and 1985 regardless of the cropping history (CY1 and CY2). This discrepancy can be explained only by the observation that plant populations were similarly greater in 1984 than in the preceding and following year (Appendix Table 8).

Sugarbeet Response

The effects of secondary tillage on seedbed conditions for emergence and early growth of sugarbeets are illustrated in Figure 25. Final

Table 6. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on corn grain moisture, plant population, and grain yield during 1983 on Parkhill loam.

Cultivar	P/S	Moisture		Population		Yield	
		CST	NST	CST	NST	CST	NST
		- percent -		10^{-3} plants ha^{-1}		- Mg ha^{-1} -	
Pioneer	DTMP	32.6	32.2	58.8	57.8	8.44	7.80
-3901	NDTMP	32.6	33.3	52.3	56.5	8.18	7.50
Great Lakes	DTMP	26.5	25.3	44.2	46.5	8.16	7.34
-422	NDTMP	27.5	27.3	39.4	46.8	7.19	7.71

Statistics[1]

	Moisture	Population	Yield
P	NS	NS	NS
S	NS	NS	NS
P x S	NS	NS	NS
C	**	**	NS
P x C	NS	NS	NS
S x C	NS	NS	NS
P x S x C	NS	NS	NS
LSDp(.05)	4.8	11.9	1.88
LSDs(.05)	4.1	10.7	1.21

1 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 7. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on corn grain yield from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C[2]	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		Mg ha^{-1}											
P-3901	DTMP	9.24Aa[3]	10.2Aa	12.0	11.7	11.3Aa	11.9Aa	8.55	9.13	missing		8.30	9.06
	DTCH			12.4	12.2			8.14	8.59	"			
	NDTMP	8.52Aa	9.88Ba	12.6	11.2	11.0Aa	11.7Aa	8.17	8.75	"		8.35	7.82
	NDTCH			12.0	11.5			7.08	8.30	"			
P-3744	DTMP	8.35Aa	9.45Ba	12.2	12.5	12.5Ab	11.8Aa	8.63	9.02	"		8.72	7.83
	DTCH			12.5	12.2			8.60	8.84	"			
	NDTMP	8.19Aa	8.59Aa	12.4	11.3	11.3Aa	12.8Bb	8.46	8.83	"		7.42	7.36
	NDTCH			12.0	11.9			8.63	7.91	"			

Statistics:[4]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	NS	NS	NS		NS
S	**	NS	**	NS		NS
P x S	NS	NS	**	NS		NS
C	**	NS	**	NS		NS
P x C	NS	NS	NS	NS		NS
S x C	NS	NS	NS	NS		NS
P x S x C	NS	NS	*	NS		NS
LSDp(.05)	1.41	1.1	1.0	1.31		1.57
LSDs(.05)	1.05	1.2	0.7	1.34		1.30

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 P-3901 = Pioneer hybrid 3901; P-3744 = Pioneer 3744 except for 1983 when C No. 2 was Great Lakes 422.

3 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

4 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

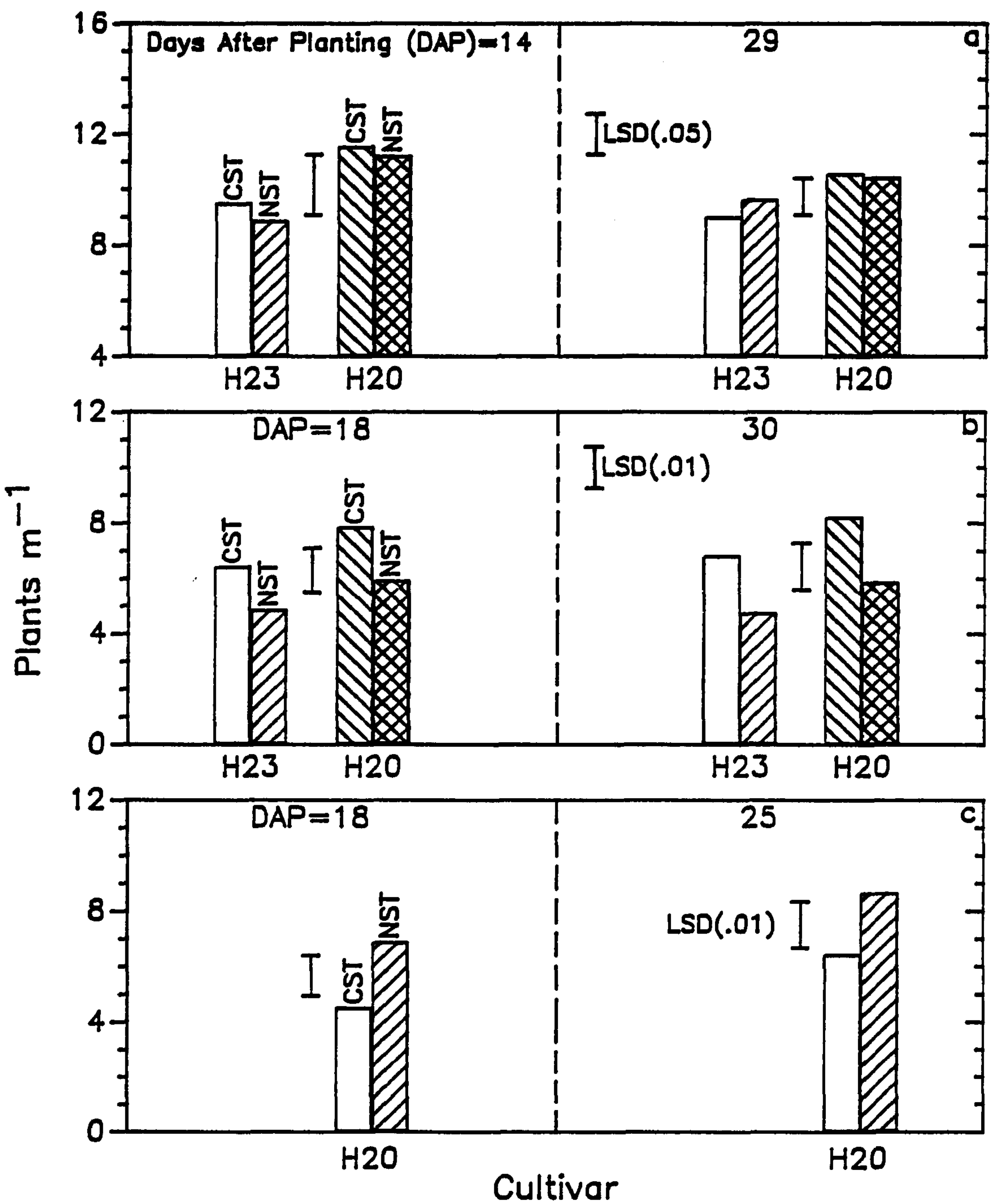

Figure 25. Emergence of US-H23 (H23) and US-H20 (H20) sugarbeet seedlings during 1983 on Parkhill loam (a) and during 1983 to 1984 on Charity clay (b-c) as affected by secondary tillage.

stands were somewhat lower than the plant densities reported in Figure 25 because plants were thinned each June to the desired spacing of approximately 5 plants m^{-1}. Emergence of sugarbeet seedlings on Charity clay was influenced by secondary tillage in 1983 (Figure 25B) and in 1984 (Figure 25c) but the effects were opposite each year.

Trends shown in Figure 25b were probably produced by varying depth of seed placement rather than the direct effects of differing soil environments under CST and NST. The natural weathering forces of freezing-thawing and wetting-drying, between fall tillage and spring planting each year, have a mellowing effect on the surface of Charity clay. Though depth bands on the seed opening disks were adjusted to 25 mm for each planting, sugarbeet seed was forced to a greater depth under NST where the soil was not altered by preplant wheel traffic. This effect was most prominent during the spring of 1983 when rainfall was above normal and the most favorable conditions for seedling growth and development should have existed under NST.

Sugarbeet productivity on Parkhill loam during 1983 is given in Table 8. The density of sugarbeet plants in each harvest area differed under the various combinations of primary and secondary tillage as indicated by the significant P x S interaction. Though significance of the primary tillage main effect was not established at the 0.05 probability level, deep tillage (DTMP) seemed to produce consistently higher root yields than normal fall tillage (NDTMP). The significant P x C interaction suggests that the two cultivars were affected differently by deep tillage.

Sugarbeet yield is commonly reported in terms of root yield but recoverable sucrose is the marketable product (Adams et al., 1983). Recoverable sucrose yield seemed consistently higher where the DTMP

Table 8. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on sugarbeet plant density, root yield, and recoverable sugar yield (RSY) during 1983 on Parkhill loam.

Cultivar	P/S	Population		Root Yield		RSY	
		CST	NST	CST	NST	CST	NST
		- plants m^{-1} -		- - - - - - Mg ha^{-1} - - - - - -			
US-H20	DTMP	4.62Aa[1]	4.23Aa	75.5	72.8	11.6	11.4
	NDTMP	4.23Aa	4.53Aa	64.4	62.4	9.67	9.58
US-H23	DTMP	4.49Aa	4.35Aa	68.3	70.4	10.6	11.0
	NDTMP	4.25Aa	4.43Aa	64.5	63.8	9.68	9.67

	Statistics[2]		
	Population	Root Yield	RSY
P	NS	NS	NS
S	NS	NS	NS
P x S	*	NS	NS
C	NS	NS	NS
P x C	NS	*	NS
S x C	NS	NS	NS
P x S x C	NS	NS	NS
LSDp(.05)	0.48	13.2	1.96
LSDs(.05)	0.42	4.79	0.95

1 Means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

2 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

treatment was applied compared to NDTMP (Table 8). Sugarbeet quality in terms of sugar content, clear juice purity, recoverable sugar content, and alpha-amino-N content, were unaffected by the tillage methods used on Parkhill loam (Appendix Table 11).

Root yields on Charity clay (Table 9) were favored by controlled traffic in 1983 even though plant stands at harvest (Appendix Table 12) were diminished by the same practice. Yields averaged across cultivars and primary tillage treatments were greater under NST (71.3 Mg ha^{-1}) than under CST (62.9 Mg ha^{-1}). During 1985, NST increased root yields where the secondary tillage variables were applied once (CY1) and where they were applied for three consecutive years (CY3).

The primary tillage variables affected root yields in 1984 and 1985 but only where they were applied the previous fall (Table 9). The two deep tillage treatments (DTMP and DTCH) increased root yields 7.8 Mg ha^{-1} from the combined average for NDTMP and NDTCH in 1984. Treatments that included moldboard plowing produced the highest yields in 1985.

Responses illustrated in Table 9 are consistent with evidence in the literature which demonstrate that compaction reduces root yields (Blake et al., 1960; Hebblethwaite and McGowan, 1980) and that soil air porosity is an important factor in sugarbeet production (Farnsworth and Baver, 1940; Smith and Cook, 1946). Soil aeration can be impeded when water content is excessive and air porosity is reduced to critically low levels. Compaction was most severe and impeded aeration was most prevelant under NDTMP-CST (Chapter 2). This treatment combination reduced internal drainage and increased soil water retention compared to the other tillage combinations. The NDTMP-CST treatment produced the lowest root yields in 1983 when above normal April and May rainfall

Table 9. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on sugarbeet root yields from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		Mg ha^{-1}											
US-H20	DTMP	69.2Aa[2]	74.8Aa	83.2Ab	80.7Ab	69.2	76.4	79.7Aab	87.0Aa	57.6	71.2	63.7Aa	74.2Aa
	DTCH			82.0Ab	75.6Aab			79.1Aab	80.8Aa	71.5	72.9		
	NDTMP	58.4Aa	70.5Aa	74.4Aab	75.9Aab	77.6	71.6	88.4Ab	86.8Aa	65.7	72.9	62.3Aa	77.3Ba
	NDTCH			72.3Aa	69.5Aa			77.4Aa	79.1Aa	74.3	72.5		
US-H23	DTMP	61.4Aa	72.6Aa	81.0Ab	78.4Aab	65.8	73.5	86.1Ab	88.2Aab	70.1	76.4	61.8Aa	77.1Ba
	DTCH			83.1Ab	80.6Ab			73.7Aa	86.8Bab	72.0	69.7		
	NDTMP	62.7Aa	67.2Aa	75.2Aab	73.4Aab	67.5	72.6	84.2Ab	93.3Bb	72.7	72.7	56.6Aa	73.3Ba
	NDTCH			70.9Aa	70.8Aa			73.2Aa	80.8Aa	68.9	74.6		

Statistics:[3]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	**	NS	*	NS	NS
S	*	NS	NS	**	NS	**
P x S	NS	NS	NS	NS	NS	NS
C	NS	NS	*	NS	NS	NS
P x C	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	13.8	9.4	10.5	9.8	11.0	14.8
LSDs(.05)	13.7	10.3	8.8	8.4	11.2	13.3

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

(Chapter 3) produced frequent occurrances of soil water excess during the early part of the growing season.

Negative associations between beet quality and root yield have been demonstrated in recent studies. As N fertilization increased, root yield increased curvilinearly but sucrose content and clear juice purity decreased linearly (Halvorson and Hartman, 1980). Campbell and Cole (1986) found a negative relationship between sucrose content and root yield for data collected from 17 environments (years x locations) in the Red River Valley. Similar relationships were not evident in this study. Sucrose content (Appendix Table 13), clear juice purity (Appendix Table 14), and therefore recoverable sugar content (Appendix Table 15) were unaffected by secondary tillage where root yields were increased by NST (CY1 in 1983; CY1 and CY3 in 1985). Primary tillage influenced root yields in 1984 and 1985 (CY1 only) but had no effect on sugarbeet quality for the same combinations of Year x Crop-Year.

Recoverable sucrose yields (Table 10) and root yields were influenced similarly by tillage because quality was maintained where deep tillage and/or controlled traffic increased root yields. Controlled traffic increased recoverable sucrose yields in 1983 averaging 11.3 and 9.9 Mg ha^{-1} under NST and CST, respectively. Where the two deep tillage treatments increased root yields by 7.8 Mg ha^{-1} in 1984 (CY1), recoverable sucrose yields were increased 1.1 Mg ha^{-1}. The secondary tillage effects on economic yield were significant at the 0.01 probability level in 1985 (CY1 and CY3) as NST increased recoverable sucrose yields, especially for the US-H23 cultivar.

The NST treatment used in this study was designed to avoid recompaction of soil loosened by deep tillage and to exploit the ideal seedbed conditions produced by natural weathering forces each winter. Tillage

Table 10. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on recoverable sucrose yield of sugarbeets from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		$Mg\ ha^{-1}$											
US-H20	DTMP	11.1Aa[2]	12.0Aa	12.9Aa	12.5Aa	11.1	12.3	12.0Aa	13.1Aa	8.2Aa	10.3Ba	9.3Aa	9.4Aa
	DTCH			12.8Aa	11.8Aa			11.9Aa	12.3Aa	10.5Ab	11.0Aa		
	NDTMP	9.2Aa	11.2Aa	11.8Aa	11.8Aa	11.7	11.4	13.0Aa	12.9Aa	9.8Aab	11.2Aa	8.9Aa	8.7Aa
	NDTCH			11.2Aa	11.0Aa			11.6Aa	11.9Aa	10.9Ab	10.7Aa		
US-H23	DTMP	9.7Aa	11.5Aa	11.9Aab	11.8Aa	10.1	11.5	12.8Ab	13.3Aab	10.0Aa	11.2Aa	9.4Aa	12.1Ba
	DTCH			12.8Ab	12.4Aa			11.0Aa	13.0Bab	10.4Aa	10.6Aa		
	NDTMP	9.7Aa	10.5Aa	11.5Aab	11.1Aa	10.6	11.5	12.4Aab	13.5Ab	10.6Aa	10.9Aa	8.7Aa	11.4Ba
	NDTCH			11.0Aa	11.1Aa			11.2Aa	11.9Aa	10.0Aa	11.1Aa		

Statistics:[3]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	*	NS	*	NS	NS
S	*	NS	NS	**	*	**
P x S	NS	NS	NS	NS	NS	NS
C	NS	NS	*	NS	NS	NS
P x C	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	2.3	1.8	1.8	1.5	1.7	2.1
LSDs(.05)	2.3	1.8	1.7	1.3	1.6	1.8

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

methods similar to the NST treatment have been developed in western parts of the United States to control erosion. In North Dakota, root yield and recoverable sucrose content of beets were equal under a conventional tillage system that included secondary tillage and three other systems that did not include secondary tillage (Sojka et al., 1980). Root and recoverable sucrose yields were maintained at comparable levels under reduced and conventional tillage in Colorado (Glenn and Dotzenko, 1978) and in Montana (Halvorson and Hartman, 1984). Reduced tillage is considered to be a successful management practice in these areas when yields can be maintained while the number of tillage operations, and therefore production costs are minimized. Our results are significant because yields were actually increased as the number of tillage operations was reduced.

Sugarbeet quality in terms of sucrose content (Appendix Table 13) differed only between cultivars. By contrast, levels of the impurity amino-N (Appendix Table 16) were affected by primary and/or secondary tillage for several combinations of Year x Crop-Year. Tillage variables that increase yields seemed to increase the amino-N content of beets. In 1984 (CY1), the amino-N content was greatest under deep tillage (DTMP and DTCH) averaging 98 mmol kg^{-1} for DTMP and DTCH compared to 80 mmol kg^{-1} for the treatments that did not include deep tillage (NDTMP and NDTCH). Controlled traffic increased yields and the amino-N content of the US-H23 cultivar in 1985 but only for the first crop year. Our results suggest that N fertility x tillage interactions should be considered when tillage methods for sugarbeet production on the prevailing soils are altered.

Soybean and Dry Bean Plant Responses

Emergence of soybean seedlings was enhanced by controlled traffic on both soils in 1983 (Figure 26). Differences between NST and CST

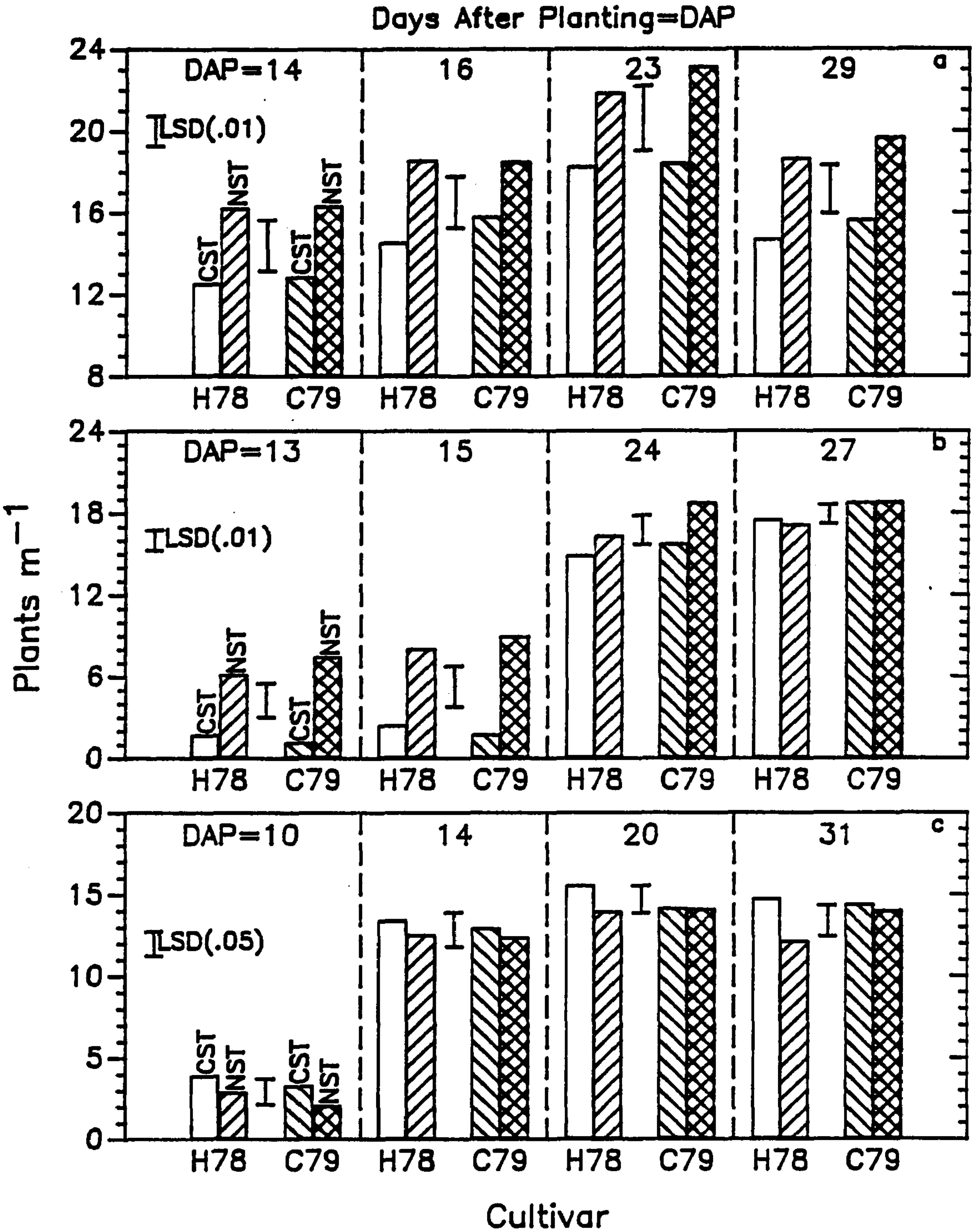

Figure 26. Emergence of Hodgson-78 (H78) and Corsoy-79 (C79) soybean seedlings on Parkhill loam in 1983 (a) and on Charity clay in 1983 (b) and 1985 (c) as affected by secondary tillage.

persisted throughout the measurement period illustrated in Figure 26a on Parkhill loam. On Charity clay (Figure 26b), plant densities were greater under NST than under CST until the final measurement date, 27 days after planting.

Controlled traffic improved emergence of dry bean seedlings on Charity clay in 1983 and in 1985 (Figure 27). Plant density differences between NST and CST were greatest during the wet year of 1983 when wheel track compaction impeded seedling emergence for at least 18 days after planting. Seedling emergence occurred uniformily under NST and CST during 1983 on Parkhill loam (data not shown).

Final stands were evaluated during only 1983 (Table 11). Results were consistent with plant densities shown for the final measurement dates in Figures 26 and 27. On Charity clay, the main effect of secondary tillage on final soybean stand was nonsignificant. Differences produced by varying seedling emergence under NST and CST on Parkhill loam were evident at harvest as the density of both soybean cultivars was greatest for NST. The adverse effects of wheel traffic on soybean stand contrast the results of Gray and Pope (1986) where compaction had no effect on population of a soybean cultivar that was resistant to Phytophthora root rot.

Controlled traffic increased the final stand of dry bean plants on Charity clay (Table 11). Emergence of dry bean seedlings was unaffected by secondary tillage on Parkhill loam but final plant stands were greatest under NST.

Soybean and dry been rooting was unaffected each year by the DTMP and NDTMP primary tillage variables (Appendix Table 9). The P x S interactions were likewise nonsignificant indicating that root length

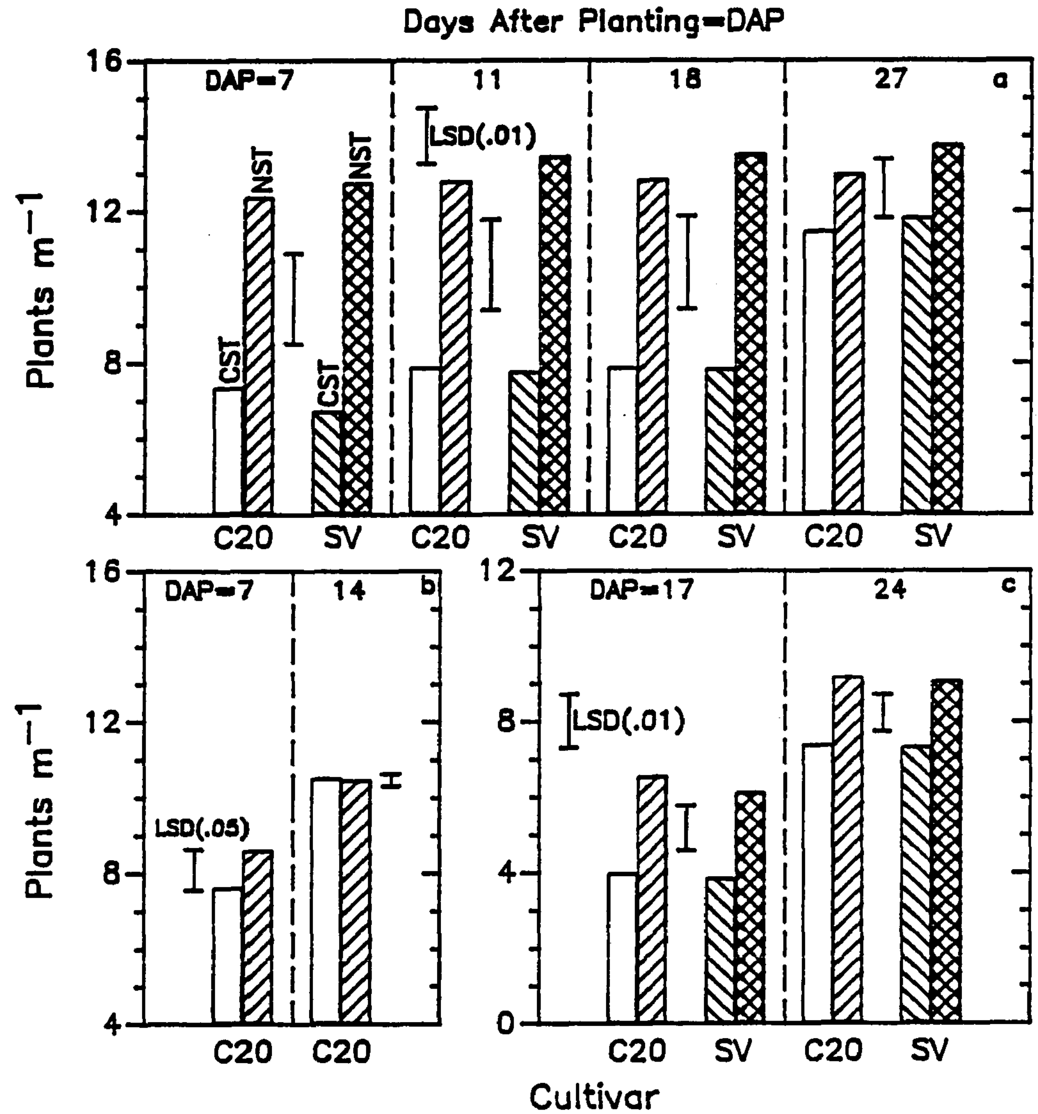

Figure 27. Emergence of C20 and Swan Valley (SV) dry bean seedlings on Charity clay as affected by secondary tillage in 1983 (a), 1984 (b), and 1985 (c).

Table 11. Final soybean and dry bean stands on two soils (Parkhill loam and Charity clay) as affected by primary tillage (p), secondary tillage (S), and cultivar (C) during 1983.

		Soybean						Dry Bean			
		Parkhill		Charity				Parkhill		Charity	
C[1]	P/S	CST	NST	CST	NST	C	P/S	CST	NST	CST	NST
		------ plants m^{-1} ------						------ plants m^{-1} ------			
H78	DTMP	16.4Ab[2]	18.7Ba	18.1Aa	18.9Aa	C20	DTMP	12.3Aa	13.2Aa	11.2Aa	12.8Ba
	NDTMP	12.8Aa	18.5Ba	16.7Ba	15.2Aa		NDTMP	11.7Aa	13.5Ba	11.7Aa	13.1Aa
C79	DTMP	17.9Ab	20.1Ba	19.2Aa	20.1Aa	SV	DTMP	12.4Aa	12.6Aa	9.4Aa	12.8Ba
	NDTMP	13.3Aa	19.1Ba	18.2Aa	17.4Aa		NDTMP	11.3Aa	12.8Ba	9.4Aa	11.4Ba

Statistics[3]

	Soybean		Dry Bean	
	Parkhill	Charity	Parkhill	Charity
P	NS	NS	NS	NS
S	**	NS	**	**
P x S	*	*	*	NS
C	*	**	NS	**
P x C	NS	NS	NS	NS
S x C	NS	NS	NS	NS
P x S x C	NS	NS	NS	NS
LSDp(.05)	2.3	3.8	1.4	1.9
LSDs(.05)	1.2	1.4	1.0	1.6

1 SV = Swan Valley; H78 = Hodgson 78; C79 = Corsoy 79.

2 Means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

density (RLD) at each depth could be averaged over the DTMP and NDTMP treatments.

Soybean and dry bean rooting are illustrated in Figures 28 and 29, respectively. Least significant differences in Figures 28a to 28c exceed differences between the NST and CST means at each depth. Thus, soybean rooting was unaffected by preplant wheel traffic each year. Wheel track compaction produced by the CST treatment decreased dry bean rooting at two depths near the bottom of the Ap horizon in 1983 (Figure 29). Root length densities seemed to be greater at the 0.27 to 0.42 m depths under NST than under CST in 1985. These differences were nonsignificant at the 0.05 probability level based on the LSD included in Figure 29c.

The lack of tillage effects on soybean rooting each year and on dry bean rooting in two of three years may be due in part to the shrink-swell properties of Charity clay. Plant roots can grow along planes of structural weakness that usually develop in this soil late in the season (Erickson, 1982). Mayfield et al. (1978) suggest that clay soils that fracture upon drying are usually not improved by subsoiling. Crop rooting did not benefit from controlled traffic at depths greater than 0.30 m on a shrink-swell soil in Texas (Gerik et al., 1987).

Shrinkage cracks may not develop, they may appear too late, or dissappear too soon after development to benefit crops grown on Charity clay during a wet year. Under these conditions, soil aeration influences crop rooting to a greater extent than soil water deficits or increased resistence to penetration that accompanies soil drying. This may explain why NST enhanced rooting of at least one crop in 1983 when early season rainfall was above normal and aeration was inadequate at times under CST.

Soybean root distributions varied between years as RLD decreased gradually with depth during only 1983 and 1984 (Figure 28). In 1985, RLD

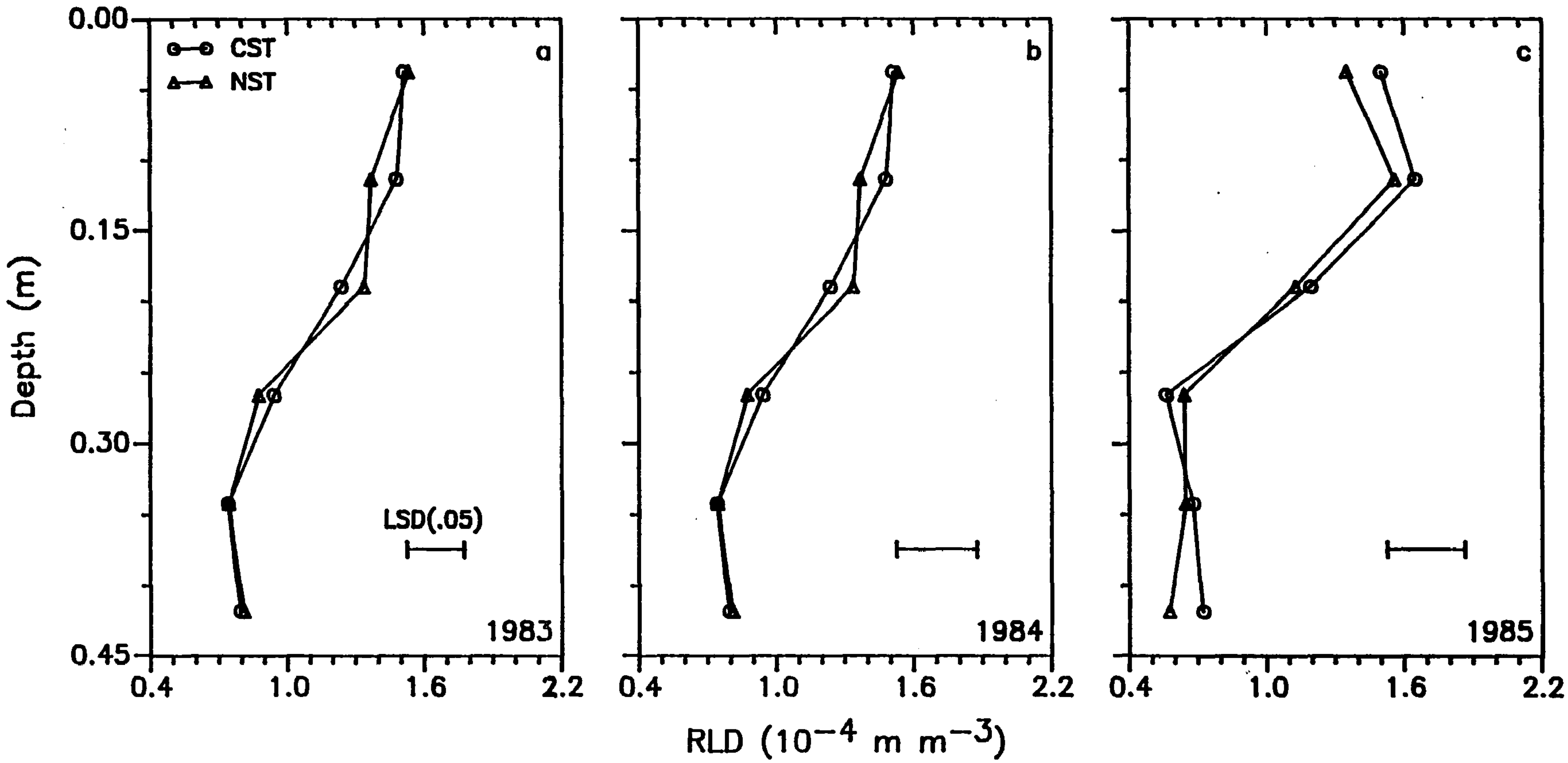

Figure 28. Soybean root length density on Charity clay during 1983 to 1985 (a-c) as affected by secondary tillage.

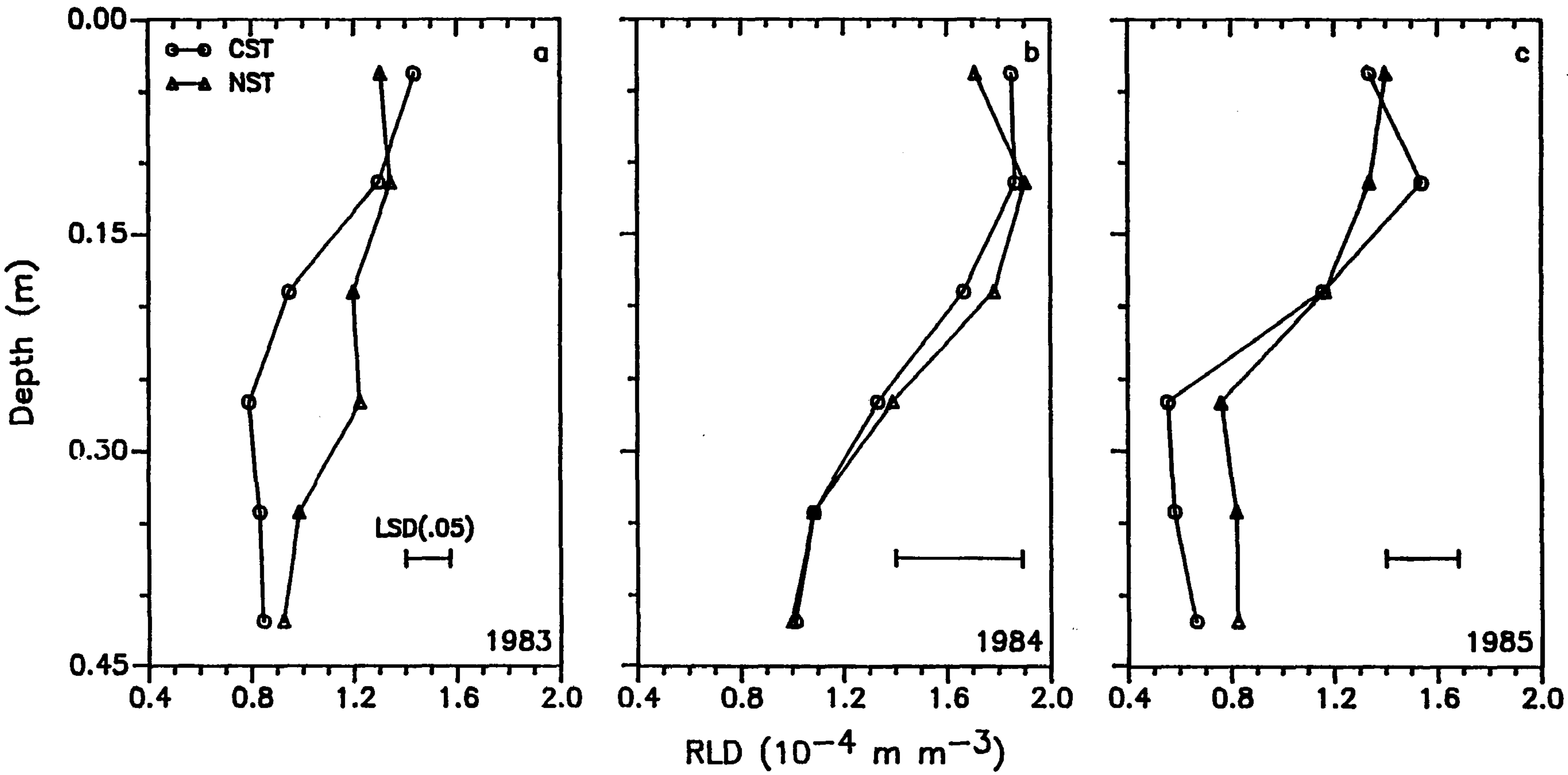

Figure 29. Dry bean root length density on Charity clay during 1983 to 1985 (a-c) as affected by secondary tillage.

decreased abruptly from 1.6×10^4 m m^{-3} (1.6 cm cm^{-3}) at the 0.11 m depth to approximately 0.6×10^4 m m^{-3} at the 0.27 m depth, just below the normal depth of moldboard plowing. Dry bean root distributions exhibited similar yearly variation (Figure 29). Root length density decreased gradually with depth in 1983, especially where wheel traffic was controlled (NST). Root length density decreased linearly from 1.9×10^4 m m^{-3} at the 0.11 m depth to 1.1×10^4 m m^{-3} at the 0.34 m depth in 1984. In 1985, RLD decreased 0.8×10^4 m m^{-3} in the same depth increment (0.11 to 0.27 m) that produced a rapid decrease in soybean RLD.

Yields on Parkhill Loam

Soil compaction created by preplant wheel traffic increased soybean yields on Parkhill loam (Table 12) despite lower stands under CST than under NST (Table 11). This apparent contradiction is explained by the results of several investigations which demonstrate that soybeans perform well over a wide range of plant densities (Wilcox, 1974; Lueschen and Hicks, 1977; Beaver and Johnson, 1981). Yields varied between the Hodgson-78 and Corsoy-79 cultivars but secondary tillage had the same effect on each cultivar averaging 0.26 Mg ha^{-1} higher for CST than for NST.

The beneficial effects of soil compaction on soybean yields in 1983 were probably due to increased soil water availability under CST during the unseasonably dry June to August period (Chapter 3) when rainfall was 92 mm below normal. Compaction studies on fine-textured soils in Minnesota have produced similar results. Preplant wheel traffic increased yields of spring wheat during a dry year because compaction reduced soil water evaporation and increased water use efficiency (Voorhees et al., 1985). Lindeman et al. (1982) also suggest that compaction tended to increase soybean yields during dry years.

Table 12. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on soybean seed moisture and yield during 1983 on Parkhill loam.

Cultivar	P/S	Moisture CST	Moisture NST	Yield CST	Yield NST
		- percent -		- - Mg ha^{-1} - -	
Hodgson-78	DTMP	14.1	14.2	3.97Ba	3.65Aa
	NDTMP	13.8	14.2	3.49Aa	3.28Aa
Corsoy-79	DTMP	13.0	13.1	4.31Ba	3.94Aa
	NDTMP	13.0	13.2	3.51Aa	3.38Aa

Statistics[2]

	Moisture	Yield
P	NS	NS
S	NS	**
P x S	NS	NS
C	**	**
P x C	NS	NS
S x C	NS	NS
P x S x C	NS	NS
LSDp(.05)	0.51	0.91
LSDs(.05)	0.52	0.27

1 Means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

2 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Dry bean yields on Parkhill loam varied between cultivars as yields were greatest for the Swan Valley dry beans (Table 13). The significant P x C interaction indicates that primary tillage had different effects on yields of each cultivar. Deep tillage tended to improve yields of the C20 cultivar. Both cultivars appeared to have matured more rapidly in plots that were deep tilled as seed moisture was lower for DTMP than for NDTMP.

Yields on Charity Clay

Yields of Corsoy-79 exceeded yields of the Hodgson-78 soybean cultivar for most combinations of Year x Crop-Year (Table 14). Deep tillage increased yields of the Hodgson-78 cultivar by 0.22 Mg ha^{-1} in 1983. Main effects of primary and secondary tillage on soybean yields were nonsignificant in 1984 and 1985 but the interacting effects of primary or secondary tillage with cultivar (P x C or S x C) were evident. For example, the Hodgson-78 and Corsoy-79 cultivars seemed to respond differently to compaction caused by the CST treatment in the first-year plots (CY1) during 1985. These results demonstrate the varying effects tillage can have on cultivars that mature at different rates and therefore experience environmental stresses at different growth stages.

Dry bean yield responses on Charity clay (Table 15) differed from responses reported for soybeans as dry beans proved to be sensitive to wheel induced compaction on this soil. Yields of the C20 and Swan Valley dry beans were similar for all but one of the Year x Crop-Year combinations because growth habits and maturity ratings of each cultivar are similar. Deep tillage had no effect on seed yield, but controlled traffic increased yields for three of the six Year x Crop-Year combinations. Controlled traffic increased yields of the two cultivars by 18 percent in 1983 when yields averaged 3.12 and 3.67 Mg ha^{-1} under

Table 13. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on dry bean seed moisture and yield during 1983 on Parkhill loam.

Cultivar	P/S	Moisture		Yield	
		CST	NST	CST	NST
		- percent -		- - Mg ha^{-1} - -	
C20	DTMP	20.2Aa[1]	20.7Aa	2.96Aa	2.94Aa
	NDTMP	20.9Aa	22.0Bb	2.58Aa	2.60Aa
Swan Valley	DTMP	19.9Aa	20.0Aa	3.04Aa	3.13Aa
	NDTMP	21.3Ab	21.4Ab	2.90Aa	3.18Ba

Statistics[2]

	Moisture	Yield
P	**	NS
S	NS	NS
P x S	NS	NS
C	NS	**
P x C	NS	*
S x C	NS	NS
P x S x C	NS	NS
LSDp(.05)	1.1	0.41
LSDs(.05)	1.0	0.24

1 Means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

2 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 14. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on soybean seed yields from 1983 to 1985 on Charity clay.

C	P/S	1983 CY1[1] CST	1983 CY1 NST	1984 CY1 CST	1984 CY1 NST	1984 CY2 CST	1984 CY2 NST	1985 CY1 CST	1985 CY1 NST	1985 CY2 CST	1985 CY2 NST	1985 CY3 CST	1985 CY3 NST
		Mg ha^{-1}											
Hodgson	DTMP	3.98Aa[2]	3.98Ab	3.65Aa	3.68Aa	3.67	3.73	3.42Ba	3.02Aa	3.29Aa	3.11Aa	3.18Aa	3.01Aa
-78	DTCH			3.76Aa	3.75Aa			3.54Aa	3.33Aab	3.16Aa	3.15Aa		
	NDTMP	3.76Aa	3.75Aa	3.70Aa	3.97Aa	3.38	3.70	3.55Aa	3.41Ab	3.19Aa	3.18Aa	3.10Aa	3.02Aa
	NDTCH			3.62Aa	3.78Aa			3.76Aa	3.50Ab	3.20Aa	3.10Aa		
Corsoy	DTMP	3.76Aa	3.80Aa	4.13Aa	4.01Aab	3.75	3.84	3.75Aa	4.00Aa	3.47Aa	3.62Aa	3.49Aa	3.28Aa
-79	DTCH			4.14Aa	3.91Aab			3.73Aa	3.87Aa	3.36Aa	3.35Aa		
	NDTMP	3.78Aa	3.82Aa	3.96Aa	4.21Ab	3.69	4.05	3.53Aa	3.74Aa	3.55Aa	3.67Aa	3.48Aa	3.44Aa
	NDTCH			3.88Aa	3.84Aa			3.67Aa	3.65Aa	3.24Aa	3.58Aa		

Statistics:[3]	1983 CY1	1984 CY1	1984 CY2	1985 CY1	1985 CY2	1985 CY3
P	*	NS	NS	NS	NS	NS
S	NS	NS	NS	NS	NS	NS
P x S	NS	NS	NS	NS	NS	NS
C	NS	**	NS	**	**	**
P x C	NS	NS	NS	**	NS	*
S x C	NS	*	NS	**	*	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	0.23	0.34	0.44	0.38	0.41	0.32
LSDs(.05)	0.23	0.31	0.51	0.30	0.35	0.29

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 15. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on dry bean seed yields from 1983 to 1985 on Charity clay.

		1983 CY1[1]		1984 CY1		1984 CY2		1985 CY1		1985 CY2		1985 CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		$Mg\ ha^{-1}$											
C20	DTMP	3.28Aa[2]	3.62Aa	3.30	3.36	3.18Aa	3.00Aa	2.85	2.95	2.85Aa	3.10Aa	2.84Aa	2.90Aa
	DTCH			3.34	3.53			2.95	2.84	2.47Aa	3.30Ba		
	NDTMP	3.14Aa	3.72Ba	3.28	3.15	3.19Aa	3.07Aa	3.19	3.14	2.60Aa	3.06Ba	2.74Aa	2.95Aa
	NDTCH			3.18	3.10			3.21	3.22	2.91Aa	3.13Aa		
Swan-Valley	DTMP	2.92Aa	3.66Ba	3.28	3.59	2.93Aa	3.28Aa	2.41	3.02	2.02Aa	2.77Ba	2.66Aa	2.91Aa
	DTCH			2.86	3.43			2.95	2.88	2.10Aa	2.71Ba		
	NDTMP	3.15Aa	3.67Ba	3.23	3.48	3.02Aa	3.22Aa	3.05	2.97	2.12Aa	3.03Ba	2.60Aa	2.81Aa
	NDTCH			3.31	3.28			3.07	3.14	1.99Aa	2.98Ba		

Statistics:[3]	1983 CY1	1984 CY1	1984 CY2	1985 CY1	1985 CY2	1985 CY3
P	NS	NS	NS	NS	NS	NS
S	**	NS	NS	NS	**	*
P x S	NS	NS	NS	NS	NS	NS
C	NS	NS	NS	NS	**	NS
P x C	NS	NS	NS	NS	NS	NS
S x C	NS	NS	**	NS	**	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	0.44	0.58	0.47	0.45	0.45	0.47
LSDs(.05)	0.38	0.59	0.39	0.36	0.43	0.33

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

CST and NST, respectively. Response to controlled traffic in 1983 can be attributed to impeded seedling emergence (Figure 27) and reduced stands (Table 11) under the CST treatment.

Differences between CST and NST were greatest in 1985 when controlled traffic increased yields of the C20 and Swan Valley cultivars grown in the second-year plots (CY2) by 16 and 39 percent, respectively (Table 15). Yields of dry beans grown in the third-year plots during 1985 were also favored by controlled traffic averaging 2.89 Mg ha^{-1} for NST compared to 2.71 Mg ha^{-1} for CST. Soil compaction retarded dry bean maturity in addition to reducing yields as grain moisture at harvest was usually higher for the CST than the NST treatment (Appendix Table 18).

Oat and Wheat Response

Wheat and oats are important crops in the Saginaw Valley, a prominent dry bean and sugarbeet production area in Michigan (Michigan Department of Agriculture, 1986). Tillage effects on the growth of these small grains were not of primary concern in this study. However, yields of oat and wheat grain were determined whenever they appeared in one of the rotations described in Chapter 2.

Controlled traffic increased oat yields during the wet year of 1983, especially for the Mariner cultivar (Table 16). Yields of Marinar oats were 0.58 Mg ha^{-1} (20 percent) greater under NST than under CST in 1983. Yields of both cultivars were favored by conventional spring tillage on 1984 when the seasonal distribution of rainfall was near normal.

Primary tillage influenced the yield of oats grown in the first-year plots in 1985 (Table 16). Yields were lowest where fall tillage consisted of only shallow chiseling (NDTCH). The NDTCH treatment reduced yields because stands were poor and weeds were controlled ineffectively where this treatment was applied.

Table 16. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on oat yields from 1983 to 1985 on Charity clay.

		1983 CY1[1]		1984 CY1		1985 CY1		1985 CY3	
Cultivar	P/S	CST	NST	CST	NST	CST	NST	CST	NST
		Mg ha^{-1}							
Heritage	DTMP	3.96Aa[2]	3.83Aa	6.19Aa	5.90Aa	3.55Ab	4.12Ab	3.91	3.80
	DTCH			5.98Aa	5.28Aa	3.03Aab	3.24Aab		
	NDTMP	3.60Aa	4.04Ba	5.44Aa	5.34Aa	3.33Aab	3.36Aab	3.81	3.95
	NDTCH			5.74Aa	5.47Aa	2.42Aa	2.49Aa		
Mariner	DTMP	2.82Aa	3.56Ba	5.33Aa	4.67Aa	3.30Ab	3.33Ab	3.47	3.74
	DTCH			5.13Ba	4.22Aa	2.81Aab	2.56Aab		
	NDTMP	3.10Aa	3.52Ba	4.91Aa	4.54Aa	2.56Aab	2.69Aab	3.33	3.68
	NDTCH			4.87Aa	4.72Aa	2.06Aa	1.83Aa		

Statistics:[3]	1983 CY1	1984 CY1	1985 CY1	1985 CY3
P	NS	NS	*	NS
S	**	*	NS	NS
P x S	NS	NS	NS	NS
C	**	**	*	NS
P x C	NS	NS	NS	NS
S x C	*	NS	NS	NS
P x S x C	*	NS	NS	NS
LSDp(.05)	0.38	0.93	1.07	0.88
LSDs(.05)	0.38	0.91	0.96	0.72

1 CY1 = crop year 1; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Wheat yields were favored by controlled traffic in 1985 averaging 0.15 Mg ha^{-1} higher under NST than under CST (Table 17). Response to the secondary tillage variables is surprising because they were applied only once, prior to establishment of the preceding crop (soybeans). All plots planted to wheat were chiseled uniformly to a depth of 0.15 to 0.20 m after soybean harvest. Shallow chiseling should have diminished physical differences produced by the CST and NST treatments in the surface of Charity clay. The small but significant response to secondary tillage in 1985 can be attributed to the influence of preplant wheel traffic on soil physical conditions below the depth of shallow chiseling (Chapter 2).

Location effects on yield responses in 1983

Identical tillage experiments were conducted at two locations in 1983. The soil at one location was Parkhill loam and Charity clay at the other. Analysis of variance of yields that year were combined over locations to compare tillage effects on crop growth for the two soils.

Yields of both corn cultivars and one dry bean cultivar varied between locations (Table 18) as yields were greater on Charity clay than on Parkhill loam. The significant primary tillage (P) main effect indicates that yields of the US-H20 sugarbeet cultivar were increased by deep tillage on the average.

Significant location x tillage interactions (L x P or L x S) suggest that the tillage variables affected crop growth in Parkhill loam and Charity clay differently. The L x P and L x S interactions were significant for the Corsoy-79 soybean cultivar. Both deep tillage and conventional spring tillage tended to increase yields of this cultivar on Parkhill loam (Table 12) but not on Charity clay (Table 14).

The collective response of each dry bean cultivar to secondary tillage was pronounced as indicated by the significant secondary tillage (S) main

Table 17. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on wheat yields from 1984 to 1985 on Charity clay.

		1984 CY2[1]		1985 CY2	
Cultivar	P/S	CST	NST	CST	NST
		Mg ha^{-1}			
Frankenmuth	DTMP	5.42	5.34	5.19Aa[2]	5.47Ab
	DTCH			5.23Aa	5.41Ab
	NDTMP	5.66	5.45	4.96Aa	5.16Aab
	NDTCH			4.93Aa	4.95Aa
Arther	DTMP			4.27Aa	4.34Aa
	DTCH			4.01Aa	4.10Aa
	NDTMP			4.07Aa	4.17Aa
	NDTCH			3.92Aa	4.15Aa

Statisitics[3]

	1984 CY2		1985 CY2
P	NS	P	NS
S	NS	S	*
P x S	NS	P x S	NS
LSDp(.05)	0.35	C	**
LSDs(.05)	0.33	P x C	NS
		S x C	NS
		P x S x C	NS
		LSDp(.05)	0.37
		LSDs(.05)	0.30

1 CY2 = crop year 2.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 18. Mean squares from combined analysis of variance over locations[1] for sugarbeet root yield (SRY), sugarbeet recoverable sugar yield (RSY), corn grain yield (CGY), soybean and dry bean seed yields in 1983.

		RY		RSY		CGY[2]		Soybean		Dry bean	
	df	US-H20	US-H23	US-H20	US-H23	P3901	GL422	H-78	C-79	C20	SV
L[3]	1	2.41	4.52	0.647	0.078	17.404**	8.748*	588 314	255	3 603 069*	720 720
B/L	6	69.83	32.35	1.318	0.853	1.061	0.684	180 835	174 021	307 940	192 545
P	1	673.81*	106.18	20.979*	5.281	1.268	1.308	840 942	873 644	279 098	3 894
L x P	1	20.29	19.36	0.641	0.775	0.117	0.087	78 755	992 288*	222 795	77 520
Error a	6	65.38	48.05	1.635	1.060	0.919	0.619	184 278	149 884	60 799	50 711
S	1	84.44	144.88	3.400	4.485	0.497	0.719	141 419	85 037	434 615**	1 223 830**
L x S	1	250.99*	101.35	5.273	2.785	6.642*	1.609	136 673	166 869*	431 497**	465 420*
P x S	1	25.99	44.35	0.928	0.959	0.068	0.218	5 716	28 096	40 449	3 399
L x P x S	1	16.70	7.97	0.586	0.252	0.096	2.091	10 357	31 063	18 755	64 100
Error b	12	36.95	53.43	1.129	1.214	0.579	0.799	31 286	28 789	21 991	67 493

1 Location 1 = The experiment on Charity clay, Swan Creek, MI; location 2 = the experiment on Parkhill loam, Ithaca, MI.

2 P3901 = Pioneer hybrid 3901; GL422 = Great Lakes 422; H-78 = Hodgson 78; C-79 = Corsoy 79; SV = Swan Valley.

3 L = location; B = blocks; P = primary tillage; S = secondary tillage; *,** significant at the 0.05 and 0.01 levels, respectively.

effect (Table 18). Controlled traffic increased dry bean yields on both soils but responses were much greater on Charity clay (Table 15) than on Parkhill loam (Table 13). Varying response of dry bean yields to secondary tillage on the two soils produced the significant LxS interactions illustrated in Table 18.

Yearly Variation of Yield Response on Charity clay

The significant Year (Y) effects suggest that yields of crops grown in the first-year plots differed from one year to the next (Table 19). This variation is an expected consequence of the diverse seasonal rainfall distributions that occurred during 1983 to 1985 (Chapter 3). Responses to primary tillage were not evident in analyses combined for the three-year study period.

Significant year x tillage interactions (Y x P or Y x S) are evident in Table 19. These interactions occur in tillage studies because: (1) soil physical changes created by tillage vary from year to year depending on soil conditions that exist when tillage is applied, especially water content; and (2) crop response to varying soil conditions depend on the prevailing weather each year. Yields of one corn, soybean, and dry bean cultivar exhibited significant Y x S interactions (Table 19). Controlled traffic tended to increase corn yields in 1983 and 1985 but decrease yields in 1984 (Table 7) when rainfall was near normal. The L x S interaction was significant for the Hodgson-78 soybean cultivar because conventional spring tillage enhanced yields during only 1985 (Table 14).

Controlled traffic increased yields of both drybean cultivars during the wet year of 1983 (Table 15). The L x S interaction was nonsignificant for the Swan Valley cultivar (Table 19) because yields were improved by controlled traffic during each year. Yields of the C20

Table 19. Mean squares from combined analysis of variance over years[1] for sugarbeet root yield (SRY), sugarbeet recoverable sugar yield (RSY), corn grain yield (CGY), soybean and dry bean seed yields on Charity clay at the Saginaw Valley Research Farm, Swan Creek, MI.

		RY		RSY		CGY	Soybean		Dry bean	
	df	US-H20	US-H23	US-H20	US-H23	P3901[2]	H-78	C-79	C20	SV
Y[3]	2	1208.21**	1925.57**	15.655**	28.390**	45.285**	1 166 285**	501 383*	678 093	1 380 386**
B/Y	9	66.18	72.35	0.919	1.043	0.497	49 381	76 331	280 049	142 796
P	1	135.51	46.32	4.302	1.829	1.013	53 273	54 197	22 690	151 875
Y x P	2	175.62	49.17	3.213	0.267	0.321	264 113	91 423	151 275	145 201
Error a	9	53.41	27.39	1.279	1.407	0.445	51 570	136 397	85 649	83 150
S	1	167.37	168.86	4.113	4.644	1.114	19 509	148 219*	272 918**	1 838 484**
Y x S	2	89.42	110.60	2.791	2.702	4.174**	183 817*	42 423	300 474**	174 361
P x S	1	0.81	0.30	0.021	0.226	0.180	80 910	33 904	2 649	316 160
Y x P x S	2	68.84	47.12	1.576	0.611	0.631	25 116	50 417	54 751	104 660
Error b	18	68.29	80.77	2.022	1.846	0.579	45 626	27 000	26 955	73 639

1 Year 1 = 1983; year 2 = 1984; year 3 = 1985; the analyses included only yields from plots where the DTMP and NDTMP primary tillage variables appeared and where these tillage variables were applied the previous fall.

2 P3901 = Pioneer hybrid 3901; H-78 = Hodgson 78; C-79 = Corsoy 79; SV = Swan Valley.

3 Y = Year; B = blocks; P = primary tillage; S = secondary tillage; *,** significant at the 0.05 and 0.01 levels, respectively.

dry bean cultivar were increased by controlled traffic during only 1983 resulting in the significant Y x S interaction.

CONCLUSIONS

Plant responses to tillage substantiate the results of Chapter 2 where deep tillage and controlled traffic improved soil physical conditions. On Parkhill loam, yields of sugarbeets, soybeans and dry bean were consistently greater where deep tillage was applied compared to normal fall tillage. Deep tillage may have alleviated water stress on Parkhill loam where rainfall was well below normal for the June to August period.

Deep tillage tended to increase sugarbeet yields during two of three years on Charity clay. Yields of one soybean cultivar were improved by deep tillage during 1983. Physical changes brought about by subsoiling were shown to persist through only one crop year in Chapter 2. In agreement with results of Chapter 2, yield responses to deep tillage were evident only where subsoiling was applied the previous fall.

Soil compaction created by preplant wheel traffic produced soil-dependent crop responses in 1983, a year characterized by a wet spring and dry June to August period. Wheel-induced compaction reduced stands on Parkhill loam but produced the highest soybean yields. The secondary tillage variables had little effect in yields of three other crops.

The effects of preplant wheel traffic were more evident on Charity clay than on Parkhill loam in 1983 as controlled traffic improved seedling emergence, increased dry bean rooting, and increased the yields of four of five crops. Crops were more responsive to controlled traffic on Charity clay because this soil has a greater tendency to develop aeration stress. Dry beans and sugarbeets proved to be most sensitive to wheel-induced compaction as preplant wheel traffic diminished yields of these crops in 1985 as well as in 1983.

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Chapter 5

Evaluation of Tillage Effects on Soil Aeration Using a Simulation Model and the Stress Day Index Approach

INTRODUCTION

The impact of two ameliorative procedures, deep tillage and controlled traffic, were evaluated using conventional approaches up to this point. Taylor and Arkin (1981) described the disadvantages, associated with the approaches utilized in Chapters 2 to 4. First, root observations are costly, time consuming, and destructive. Second, crop response to soil physical changes created by tillage can be masked by other environmental and management factors.

Simulation models, a collection of quantitative relationships designed to describe a system, can be used to evaluate the impact of root zone modifications. Computer simulations derived from these models allow researchers to distinguish crop response to root zone changes from other comfounding responses. More importantly, simulations for long periods of time using recorded or generated weather data can be used to determine probabilities of crop response and benefit (Arkin and Taylor, 1981).

Feddes (1981) reviewed numerous models based on relationships between water use and crop production. The author suggested that few attempts have been made to evaluate the effects of soil manipulation on production through water use. This may be explained in part by our inability to predict physical changes brought about by tillage.

Models based on water use describe only one part of the more complex production system. Soil aeration may be an important part of some production systems, especially in humid regions where soils are poorly drained or prone to compaction. Until recently, few models were available that described the dependence of crop growth on soil aeration.

Whisler et al. (1982) described a cotton growth simulation model (GOSSYM) that was modified to account for the effects of cultivation and wheel traffic on (1) hydraulic properties, (2) mechanical impedance, and (3) changes in root growth due to O_2 stress. The soil O_2 status is evaluated by calculating O_2 concentrations due to one dimensional diffusion into the soil profile. Oxygen deficiency influences cotton growth in GOSSYM through reduced root elongation rates during anaerobiosis.

A quantitative evaluation of aeration stress should include some combination of deficiency duration, intensity (e.g., O_2 concentration), crop species and its growth stage (Erickson, 1982). The stress day index (SDI) concept proposed by Hiler and Clark (1971) meet these requirements. The authors suggested that the SDI concept is applicable to characterization of both water and aeration stresses.

The stress day index for a given period is the product of a stress day factor and a crop susceptibility factor. The stress day factor (SD) is a measure of the degree of water or O_2 deficit. The crop susceptibility factor (CS) quantifies the plant susceptibility to a given stress. Its magnitude depends on the crop species and stage of development. The stress day index for growth period i can be expressed by the following equation:

$$SDI = \sum_{i=1}^{n} (SD_i \times CS_i) \qquad (1)$$

where n represents the number of growth periods.

Stress day index models were incorporated into the water management model, DRAINMOD, to quantify the effect of excessive and deficient soil water conditions (Hardjoamidjojo and Skaggs, 1982). The SDI models of Shaw (1974, 1976) were used to account for yield response to cumulative soil water deficit. The stress day factor originally defined by Sieben (Wesseling, 1974) was used to calculate the SDI for excessively wet conditions. This stress day factor is the sum of excess water in the surface 30 cm of the soil profile and is expressed as:

$$SEW_{30i} = 1/24 \sum_{i=1}^{24} f(x_j) \tag{2}$$

where SEW_{30i} = SEW_{30} for day i and X_j = the water table depth below the surface at the end of the jth hour. The function in equation 2 is evaluated as follows:

$$f(x_j) = 30 - x_j \quad \text{for} \quad x_j < 30 \text{ cm} \tag{3}$$

and

$$f(x_j) = 0 \qquad \text{for} \quad x_j > 30 \text{ cm} \tag{4}$$

The depth of water table has no direct influence on crop growth but it is an indicator of the prevailing soil water conditions (Hardjoamidjojo et al., 1982) and therefore aeration stress.

Air porosity (Pa) of the soil is its physical characteristic that has the greatest influence on gas exchange (Russell, 1977). Thus, a stress day factor based on Pa may account for the degree of soil aeration stress more effectively than water table depth. The air porosity at any soil depth can be calculated if the soil porosity is known, measured or simulated water contents are available, and if the soil volume is relatively constant as water content changes. The crop simulation model CERES-Maize (Jones and Kiniry, 1986) may lend itself to application of the SDI approach in this study because the soil water balance is calculated on a daily basis. Furthermore, soil inputs can be manipulated to account for tillage effects on soil properties.

The objectives of this section were: (1) Evaluate the impact of tillage on soil aeration by simulating profile soil water content under corn and applying the SDI method; and (2) assuming yields are limited by poor aeration on Charity clay, determine the probability of benefit from subsoiling and controlled traffic using generated weather data.

MATERIALS AND METHODS

Soil physical conditions produced by various combinations of primary and secondary tillage were demonstrated in Chapter 2. Conventional fall and spring tillage (NDTMP-CST) produced unfavorable conditions for crop growth. Deep tillage combined with controlled traffic (DTMP-NST) reduced the physical limitations of Charity clay. The DTMP-NST treatment decreased bulk density and increased porosity, especially the volume of large pores. These changes improved internal drainage of the surface and increased air porosity at high soil water potenials. The standard version of CERES-Maize (Jones and Kiniry, 1986) was used to simulate daily water contents under the diverse treatments NDTMP-CST and DTMP-NST. The model was modified to account for the unique conditions that existed at the experiment site.

Model Modifications

Runoff is negligible at the Saginaw Valley Bean and Beet Research Farm because the site is level. The CERES-Maize model uses the "curve number" method to estimate runoff (USDA, Soil Conservation Service, 1972). The user can force zero runoff in the original version of the model by entering the appropriate runoff curve number (CN2).

All precipitation and/or irrigation occuring on a given day enters the soil profile when runoff is zero. This produces an unrealistic situation for Charity clay as ponding can occur when antecedent soil moisture levels are high and rainfall is excessive. A fraction of the rain received on a particular day may not infiltrate until the following day under these conditions.

The water balance subroutine of CERES-Maize (Jones et al., 1986) was altered to permit ponding during excessively wet periods. A storage variable (STOR) was added to quantify the amount of ponding that may occur. The curve number method was retained for calculation of daily runoff (RUNOFF) so that daily infiltration depends on the profile soil water content. This method also provides the user with the opportunity to manipulate CN2 and therefore "adjust" the potential daily infiltration for varying soil conditions.

The STOR value for day i is calculated as follows:

$$STOR_i = RAIN_i + STOR_{i-1} \tag{5}$$

where SOR_{i-i} is the value of STOR on the previous day (usually zero). Daily infiltration (WINF) becomes:

$$WINF_i = STOR_i - RUNOFF_i \tag{6}$$

where $RUNOFF_i$ represents water in the form of rain on day i, plus ponding from the previous day that failed to infiltrate. The new value of STOR becomes:

$$STOR_i = RUNOFF_i \tag{7}$$

The soil evaporation routine was altered for those situations where STOR > 0. Soil evaporation (ES) normally decreases the water content of the first soil depth.

$$SW(1) = SW(1) - ES(.1)/DLAYR(1) \tag{8}$$

Soil water content and depth of layer 1 are represented by SW(1) and DLAYR(1), respectively. The factor, 0.1, facilitates conversion from mm to cm units. When STOR > 0 and STOR < ES, the water content of the first soil depth decreases by the amount:

$$SW(1) = SW(1)-(ES-STOR)(.1)/DLAYR(1) \tag{9}$$

afterwhich STOR is reset to zero. When STOR > ES, the water content of the first soil depth is unchanged by ES. The new STOR value becomes:

$$STOR_i = STOR_i - ES \tag{10}$$

Water balance output produced by the original version of CERES-Maize is illustrated in Appendix Table 19. This version of the model and CERES models in general, evaluate soil water balance using the equation described by Ritchie (1985):

$$S = PRECIP + I - EP - ES - RUNOFF - DRAIN \tag{11}$$

where the quantity of soil water (S) changes with precipitation (PRECIP), irrigation (I), evaporation from plants (EP) and soil (ES), RUNOFF, and drainage from the profile (DRAIN).

Equation 11 is used to evaluate the soil water balance in the modified version of CERES-Maize when STOR = 0. The value of STOR > 0 when ponding occurs and the following relationships hold:

$$S_i = WINF_i - EP_i - DRAIN_i \tag{12}$$

and

$$STOR_i = STOR_{i-1} + PRECIP_i - WINF_i - ES_i \tag{13}$$

The $WINF_i$ term appears in both equations because water that enters the profile diminishes $STOR_{i-1}$ by the same amount. Finally, ponding ceases on day i (i.e., $STOR_i$ becomes zero) when:

$$STOR_{i-1} < WINF_i + ES_i \tag{14}$$

The soil water balance equation can be written:

$$S = WINF_i - DRAIN_i - EP_i - [ES_i - (STOR_{i-1} - WINF_i)] \tag{15}$$

which reduces to:

$$S = STOR_{i-1} - DRAIN_i - ES_i \tag{16}$$

Water balance output was modified to illustrate the relationships in equations 11 to 16 (Appendix Table 20).

Model Inputs

The soil and weather data required by CERES-Maize have been documented (Ritchie et al., 1986). Soil inputs used for the 1983 to 1985 simulations are shown in Appendix Tables 21 to 23, respectively. Variable names are included as column headers but were not part of the actual input data. Seven layers of varying depths, in descending order from the surface, were used to describe the profile under each treatment. Since the texture of Charity clay is uniform throughout the profile, depths of the first four soil layers were chosen to correspond to depths of physical and soil water content measurements. Soil physical properties were evaluated for the first three soil layers (Chapter 2). The neutron probe method was used to monitor soil water content of the second through fourth soil layer (Chapter 3).

The lower limit (LL) of plant extractable water and the drained upper limit (DUL) were determined from measured soil water contents. The lowest water content measured at each depth was assumed to approximate LL. The DUL for each depth was chosen so that simulated water contents matched the measured values during wet periods. A new water content at saturation (SAT) was calculated (Ritchie et al., 1986) whenever the DUL was altered during this fitting process.

Measured and simulated water contents under the NDTMP-CST treatment compared favorably each year from 1983 to 1985 (Appendix Figures 1 to 3). Simulated water contents were within the 95 percent confidence intervals about each measured value except for those produced during the last 30-day period in 1985 (Appendix Figure 3). This descrepancy had no bearing on calculation of the stress day index for 1985.

Soil water content differences measured under the two treatments (Appendix Figures 4 to 6) were duplicated by altering the soil profile data as needed. The LL and DUL, of soil layers 1 and 2, were lower each year for the DTMP-NST treatment than values used for NDTMP-CST. Different root distribution weighting factors (WR) and runoff curve numbers were used for NDTMP-CST and DTMP-NST to account for varying soil conditions created by each treatment. Profile plant-extractable soil water (PESW) was assumed to be the same under the two treatments.

Daily rainfall, maximum and minimum temperatures were recorded at the experiment site. Daily solar radiation was measured at the site but complete records were available for only the 1985 field season.

Solar radiation for 1983 and 1984 were produced using daily percent sunshine as a starting point. Baker and Haines (1969) determined the relationship between percent sunshine and daily insolation for East Lansing, MI. Different relationships were obtained for each 7-day period. These relationships were used to estimate daily solar radiation data for 1985 at East Lansing, MI. Estimated daily solar radiation at East Lansing and measured solar radiation at the experiment site were compared and proved to be highly correlated ($r^2 = 0.935$). The following predictive equation was obtained:

$$SOLRAD_{sc} = -25.4 + (.93)SOLRAD_{el} \qquad (17)$$

where $SOLRAD_{sc}$ is solar radiation at the experiment site (Swan Creek, MI) and $SOLRAD_{el}$ represents solar radiation at East Lansing, MI. Units for equation 17 are arbitrary as long as they are the same for $SOLRAD_{sc}$ and $SOLRAD_{el}$.

A long term study of tillage effects on soil aeration was conducted using 100 years of generated weather data. The weather generator used (Richardson, 1984) produces data that are based on historic weather records from surrounding stations. The original data set consisted of records for each day of the year. This data set was fragmented to include only the 16 April to 31 October period for each year. The profile soil water content was initialized at the drained upper limits (DUL) given in Appendix Table 21 for each year of the 100-year simulation.

Calculation of Stress Day Index

Cumulative stress day index (SDI) was calculated using the equation introduced by Hiler and Clark (1971):

$$SDI = \sum_{i=1}^{n} (SD_i \times CS_i) \tag{18}$$

where i = days after planting, SD_i is the stress day factor for day i, and CS_i is the crop susceptibility factor for day i. Hardjoamidjojo and Skaggs (1982) reported the following empirically derived crop susceptibility factors for corn:

$$CS_i = 0.51 \quad \text{for} \quad 0 < i < 43 \tag{19}$$

$$CS_i = 0.33 \quad \text{for} \quad 42 < i < 81 \tag{20}$$

$$CS_i = 0.02 \quad \text{for} \quad 80 < i \tag{21}$$

Crop susceptibility factors used here were those given in equations 19 to 21 but equation 21 was modified so that:

$$CS_i = 0.02 \quad \text{for} \quad 80 < i < 121 \tag{22}$$

Thus, the SDI was calculated for the 120-day period after planting (i.e., n = 120 in equation 18).

Daily stress day factors were based on air porosity (Pa) of the 0 to 0.10 m soil layer. The exchange of gases between the soil and atmosphere becomes impeded as Pa of this layer decreases. Millington and Quirk (1961) proposed the following model to describe the effect of Pa on gaseous diffusion:

$$Ds/Do = Pa^{3.33}/P^2 \tag{23}$$

where Ds is the gas diffusion coefficient in soil, Do is the diffusion coefficient in air, and P is the soil porosity. At low air porosities, Sallam et al. (1984) found best agreement between calculated and measured relative diffusion coefficients when the Pa exponent was modified as follows:

$$Ds/Do = Pa^{3.1}/P^2 \tag{24}$$

Their model was used to calucalte SD_i in this investigation. Equation 24 was transformed using $-LOG_{10}$ so that SD_i increased as Pa decreased. Stress day factors were calculated only for Pa < 0.15 m m^{-3} as soil aeration was assumed to occur unimpeded at Pa > 0.15 m m^{-3}. The final equation obtained was:

$$SD_i = -LOG_{10}(Pa^{3.1}/P^2) - [-LOG_{10}(0.15^{3.1}/P^2)] \tag{25}$$

The constant on the right hand side of equation 25 was included so that $SD_i = 0$ at Pa = 0.15 m^3 m^{-3}. Equation 25 reduces to:

$$SD_i = LOG_{10}(.15^2) - LOG_{10}(Pa^{3.1}) \tag{26}$$

Thus, SD_i calculated in this way depends only on air porosity. Values produced by equation 26 are demonstrated in Appendix Figure 7.

RESULTS AND DISCUSSION

Evaluation of Model Modifications

Two versions of CERES-Maize, using identical model inputs, were used to produce the simulated water contents illustrated in Figure 30. Water contents produced by the modified version of the model exceeded those produced by the original version but only during excessively wet periods. During dry periods, profile soil water contents are low and the tendency for runoff to occur is diminished. Both versions of the model produce similar water balance output under dry conditions.

The modified version of the model increases the amount of water that enters the profile during the season because runoff is suppressed. Since soil water deficit factors dictate growth rate and eventual yields in CERES-Maize, the water balance modifications increased simulated corn yields for 1983 by decreasing the soil water deficit factors (appendix Tables 24 and 25). Results reported in the remainder of this section were produced exclusively by the modified version of CERES-Maize.

Tillage Effects on Soil Aeration During 1983 to 1985

Simulated water contents under the NDTMP-CST and DTMP-NST treatments for the three years in which field studies were conducted are illustrated in Figures 31 to 33. Differences between treatments are demonstrated primarily in the 0 to 0.10 and 0.10 to 0.20 m soil layers where physical changes created by tillage were most prominent. During one year, 1984, differences also existed in the 0.20 to 0.35 m soil layer. Where differences are evident, simulated water contents were slightly higher under NDTMP-CST than under the DTMP-NST treatment. Treatment effects suggested by the simulated data in Figures 31 to 33 are consistent with those produced by periodic water content measurement during 1983 to 1985 (Appendix Figures 4 to 6).

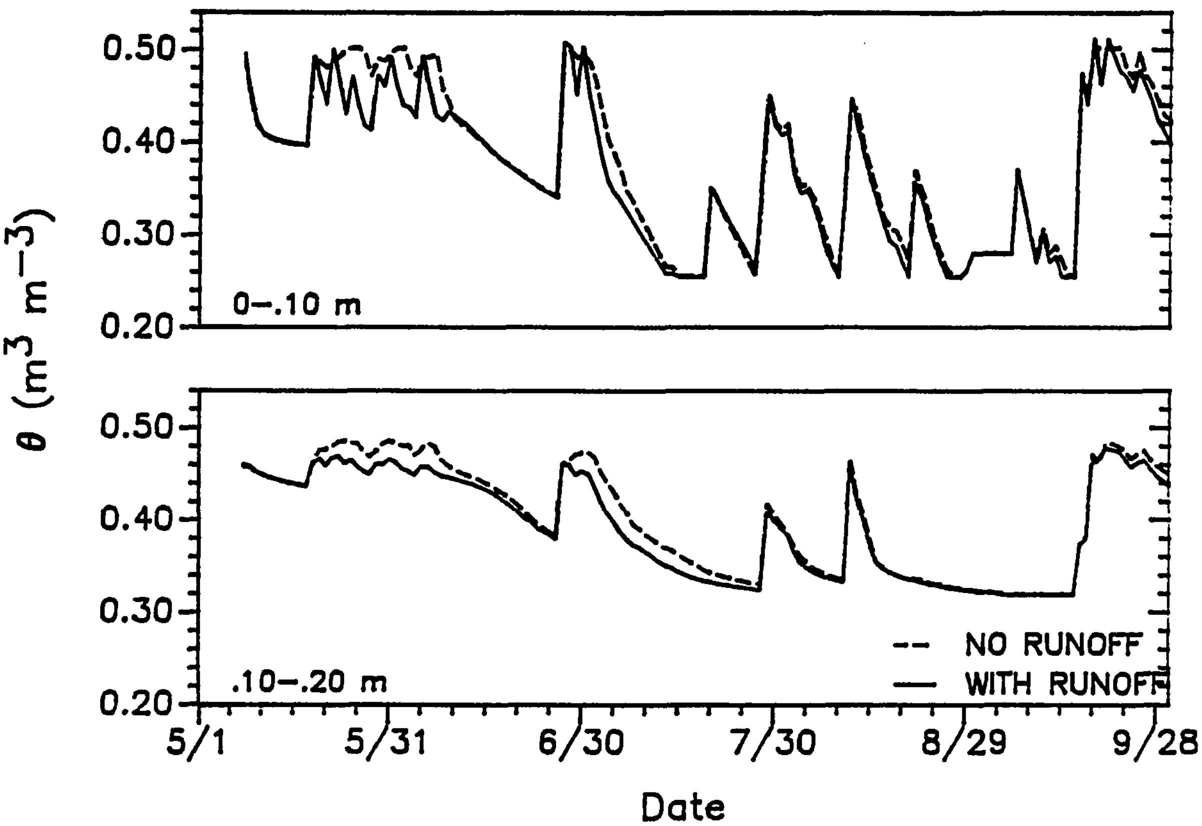

Figure 30. Comparison of simulated water contents at two depths under the NDTMP-CST treatment during 1983 using a version of the model that allows runoff and a modified version that suppresses runoff.

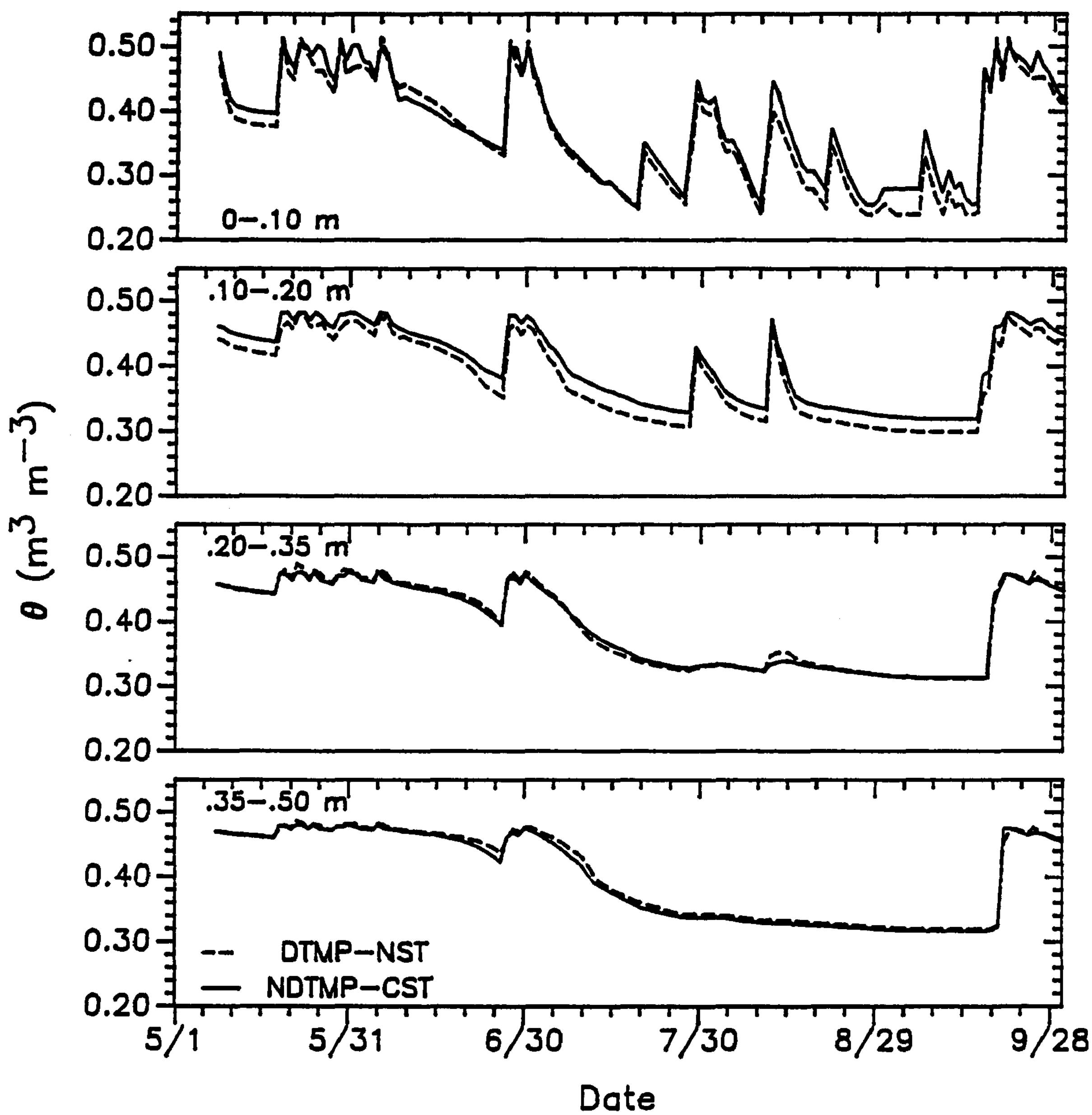

Figure 31. Comparison of simulated water contents at four depths under the NDTMP-CST and DTMP-NST treatments for 1983.

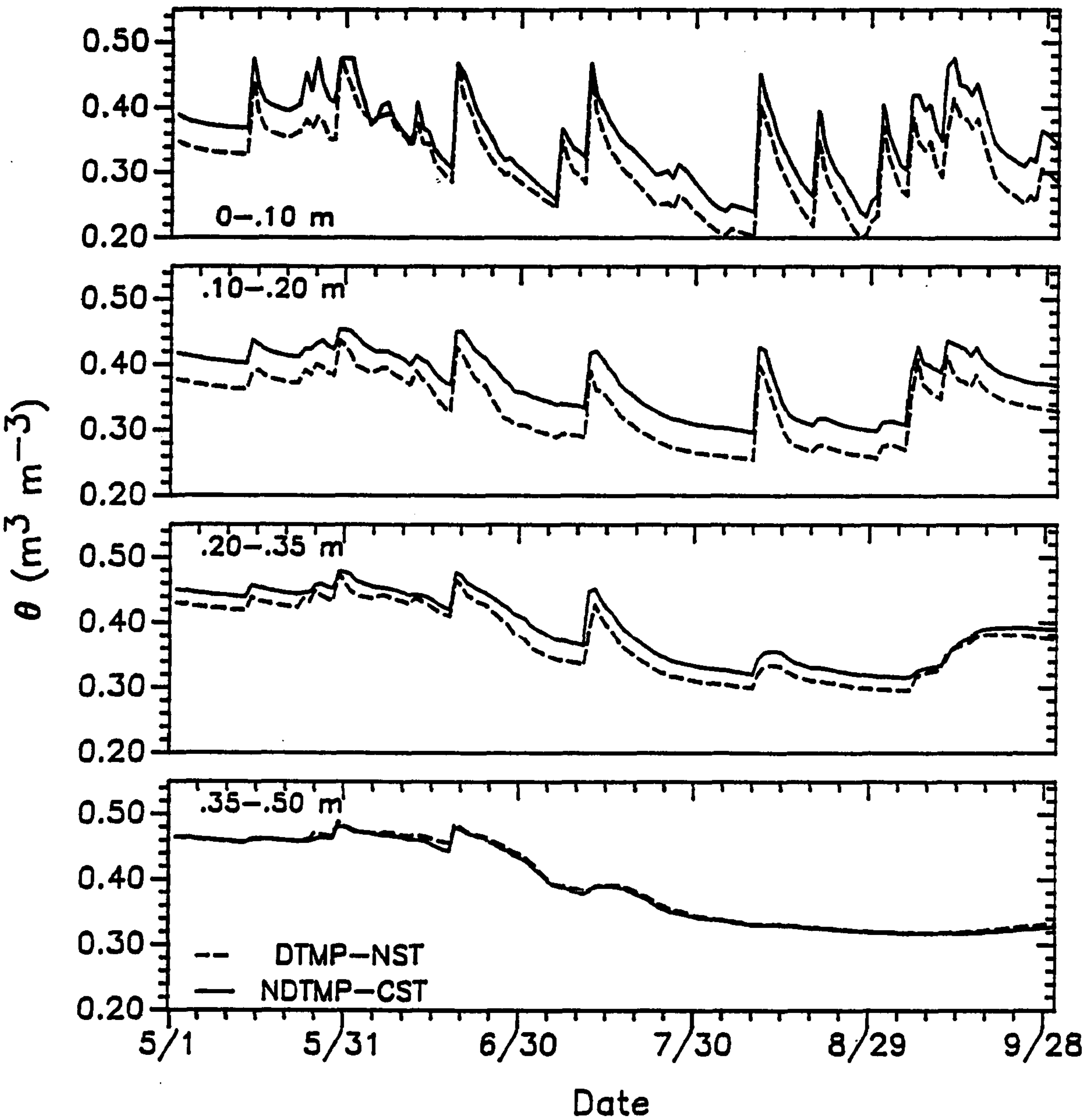

Figure 32. Comparison of simulated water contents at four depths under the NDTMP-CST and DTMP-NST treatments for 1984.

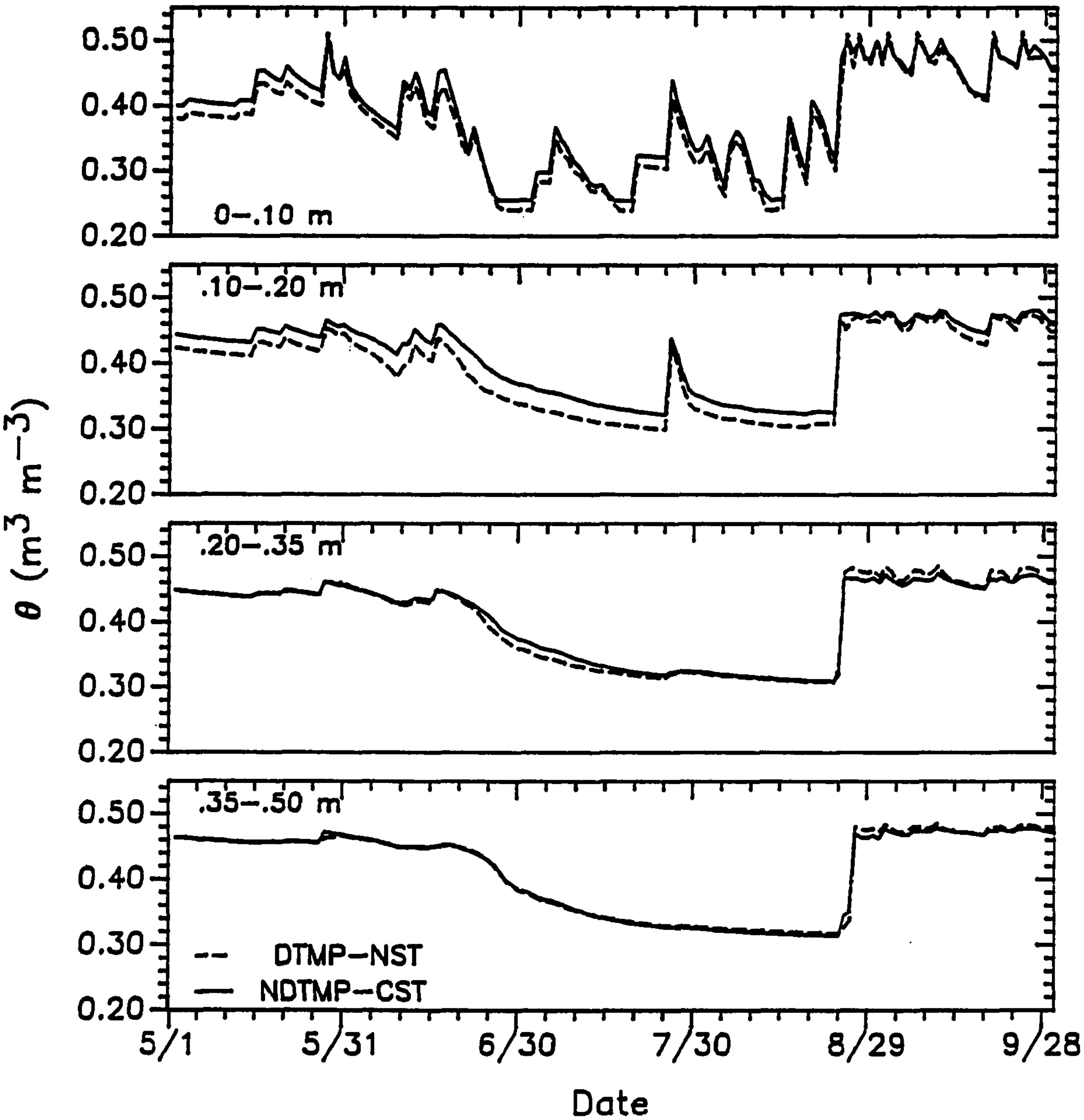

Figure 33. Comparison of simulated water contents at four depths under the NDTMP-CST and DTMP-NST treatments for 1985.

The CERES-Maize model was used primarily to simulate water contents so that soil aeration under each treatment could be assessed. Nevertheless, it is interesting to compare measured and predicted yields for the six simulations illustrated in Figures 31 to 33 (one for each curve). The measured and predicted yields differed by only 55 kg ha^{-1} for the NDTMP-CST treatment in 1983 (Appendix Table 26).

Measured yields exceeded predicted values for each of the five remaining simulations (Appendix Tables 27 to 31). The model underestimated the measured yields by an average of 8.6 percent (standard deviation = 1.5%) for these five simulations. This systematic deviation suggests that CERES-Maize accounted for the year-to-year variation of corn yields.

Simulated air porosity (Pa) at each depth was obtained by subtracting the water content from measured values of soil porosity (Chapter 2). The seasonal variation of simulated Pa during 1983 to 1985 is demonstrated in Figures 34 to 36. The treatments produced large Pa differences despite only subtle water content differences (Figures 31 to 33). The DTMP-NST treatment increased Pa by an amount that that reflects the soil porosity increase.

Note that identical soil porosities (P) were used for the 1983 and 1985 simulations (Figure 34 and 36). The measured water contents in 1984 (Appendix Figure 5) were lower than values measured in 1983 and 1985 (Appendix Figures 4 and 6). This trend is not consistent with seasonal rainfall patterns observed at the experiment site (Chapter 3, Figure 13). Soil inputs (including P) were altered for the 1984 simulations so that water contents under each treatment resembled the measured values. Since measured water contents were suspect in 1984, the Pa curves in Figure 35

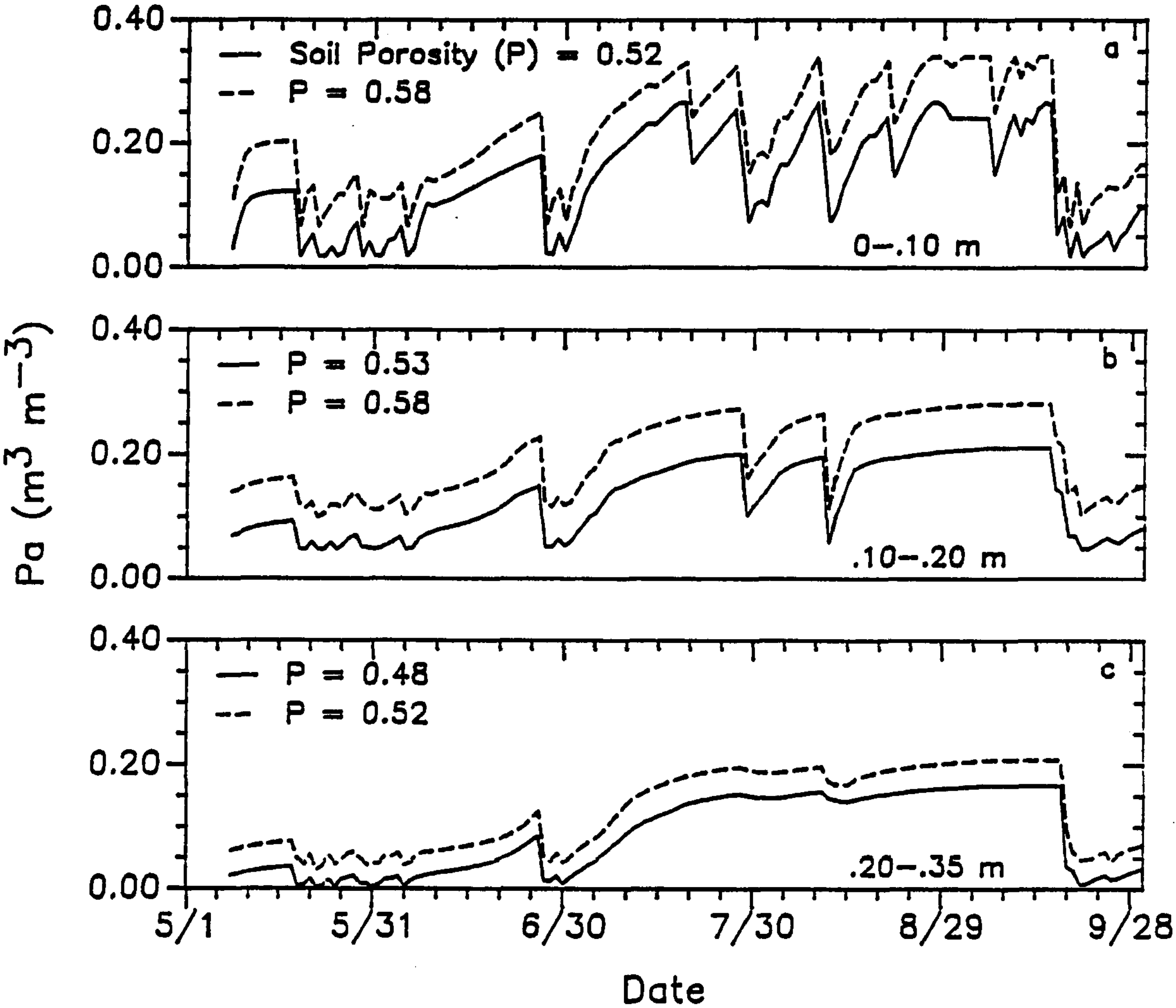

Figure 34. Comparison of simulated air porosities at three depths under the NDTMP-CST (solid line) and DTMP-NST (dashed line) treatments for 1983.

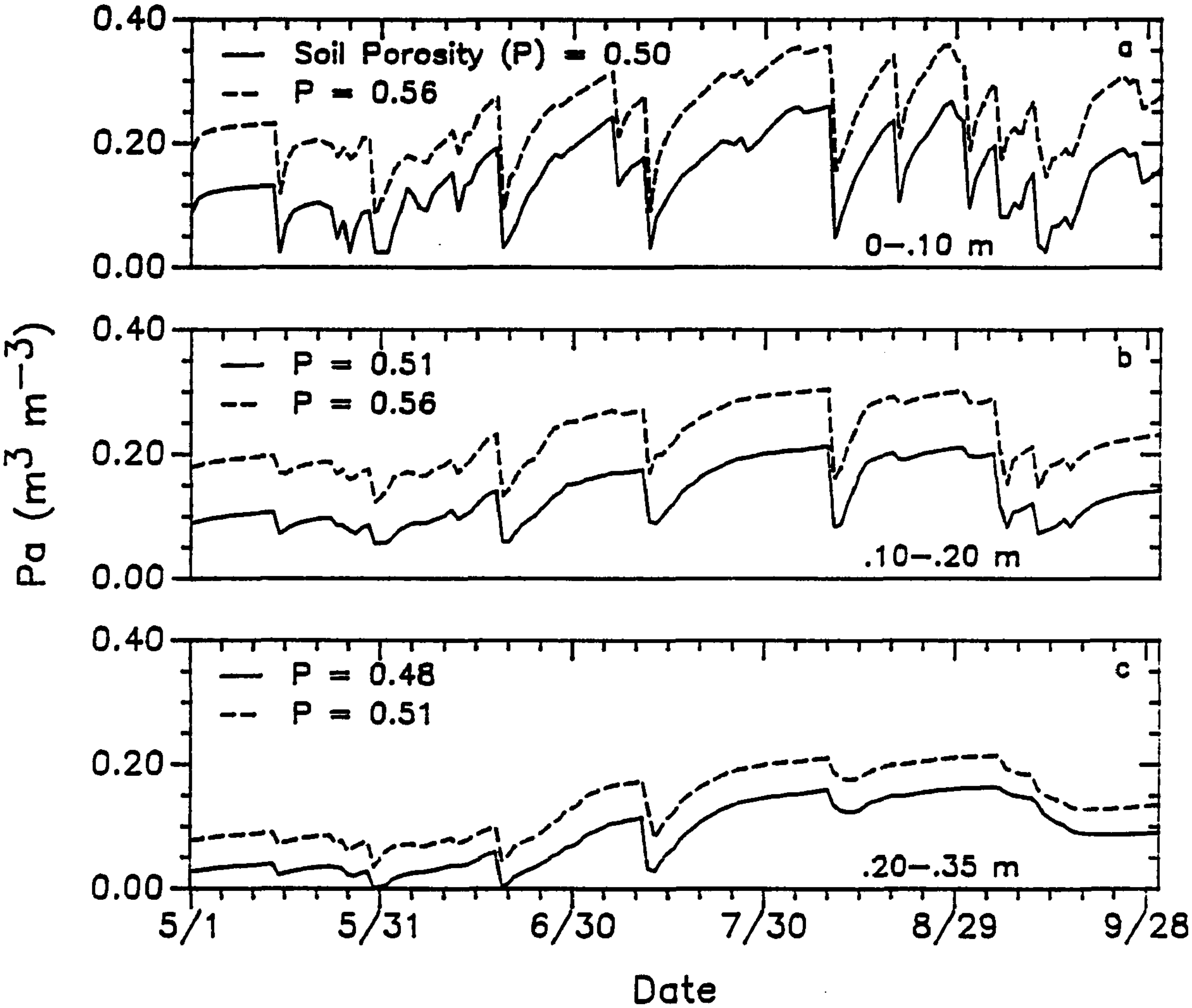

Figure 35. Comparison of simulated air porosities at three depths under the NDTMP-CST (solid line) and DTMP-NST (dashed line) treatments for 1984.

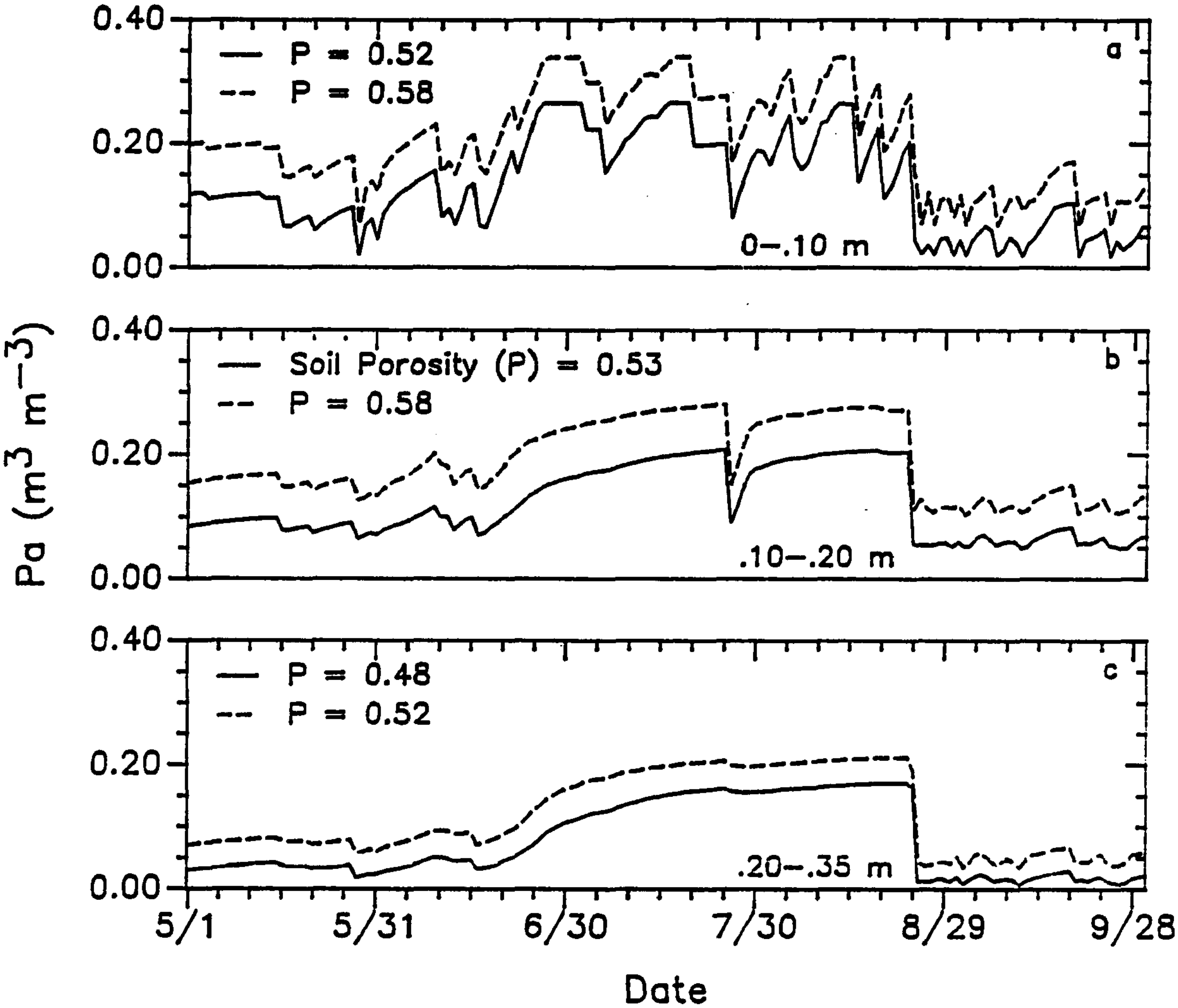

Figure 36. Comparison of simulated air porosities at three depths under the NDTMP-CST (solid line) and DTMP-NST (dashed line) treatments for 1985.

and the cumulative stress day index (SDI) values calculated for 1984 may be unrealistic.

Tillage effects on soil aeration during 1983 to 1985 were assessed by calculating the number of wet days and the SDI for each treatment (Table 20). Air porosity fell below 0.15 m^3 m^{-3} (wet days) most frequently where wheel traffic caused soil compaction. This indicator of soil aeration suggests that the 1984 growing season was the most stressful during the three year study as 61 wet days occured under the NDTMP-CST treatment.

The number of wet days is a poor indicator of soil aeration status. It is not sensitive to the degree of aeration stress or varying crop susceptibility to stress, both of which affect the SDI. Deep tillage and controlled traffic reduced the SDI each year (Table 20). The 1983 growing season was the most stressful in terms of soil water excesses as the SDI corresponding to each treatment exceeded the values obtained for 1984 and 1985.

The SDI approach produced results that are consistent with the observed seasonal rainfall patterns (Chapter 3) and yield responses to the various tillage variables (Chapter 4). The 1983 growing season was characterized by an excessively wet period during the early part of the growing season when corn is most susceptible to soil water excesses (Hardjoamidjojo and Skaggs, 1982). Deep tillage improved yields of two crops during 1983. Controlled traffic increased yields of four out of five crops grown that year, including corn.

Results of this study suggest that yields of crops grown on Charity clay were influenced by soil aeration to a greater extent in 1983 than in 1984 or 1985. Alleviation of soil compaction through deep tillage and

Table 20. Soil aeration stress on Charity clay during 1983 to 1985 as affected by tillage.

	Treatment	Wet Days[1]	SDI
1983			
	NDTMP-CST	56	28.5
	DTMP-NST	29	5.9
1984			
	NDTMP-CST	61	18.4
	DTMP-NST	7	1.3
1985			
	NDTMP-CST	59	15.0
	DTMP-NST	16	1.0
3-Year avg.			
	NDTMP-CST	59	20.6
	DTMP-NST	17	2.7

1 Wet Days = the number of days during the first 120 days after planting when Pa < 0.15 $m^3\ m^{-3}$.

controlled traffic minimized the aeration problem each year based on the stress day indices reported in Table 20.

Long-Term Study of Tillage Effects

Soil inputs given in Appendix Table 21, and 100 years of generated weather data were used in the long-term evaluations. The frequency distribution of predicted grain yield under the two treatments are given in Figure 37. As indicated earlier, soil water deficit factors influence yields predicted by CERES-Maize. The distributions illustrated in Figure 37 suggest that the weather data produced widely varying conditions in terms of soil water deficits.

The frequency distributions of predicted yields were similar for NDTMP-CST and DTMP-NST because the profile plant-extractable soil water was the same for each treatment. Predicted yields averaged about 8.84 Mg ha^{-1} for both treatments. Measured yields, averaged for 1983 to 1985, were 10.3 Mg ha^{-1} for DTMP-NST, and 9.76 Mg ha^{-1} for the NDTMP-CST treatment.

The model predicted total crop failure one year (Figure 37). The number of wet days and SDI values calculated for the same year were omitted from subsequent comparisons because the simulated soil water contents are unrealistic in the absence of plant water extraction.

The number of wet days averaged 67 under NDTMP-CST for the 100-year simulation (Figure 38a). This value suggests that Pa of the 0 to 0.10 m depth is less than 0.15 m^3 m^{-3} during about 50 percent of the 120-day measurement period each year. Wet days may occur only 20 times, on the average, under the DTMP-NST treatment (Figure 38b).

The frequency distribution of SDI under the two treatments are compared in Figure 39. The SDI averaged 23.7 with conventional fall and spring tillage but ranged from 8.8 to 50.8 (Figure 39a). Deep tillage and controlled traffic produced an average SDI of about 2.7 (Figure 39b).

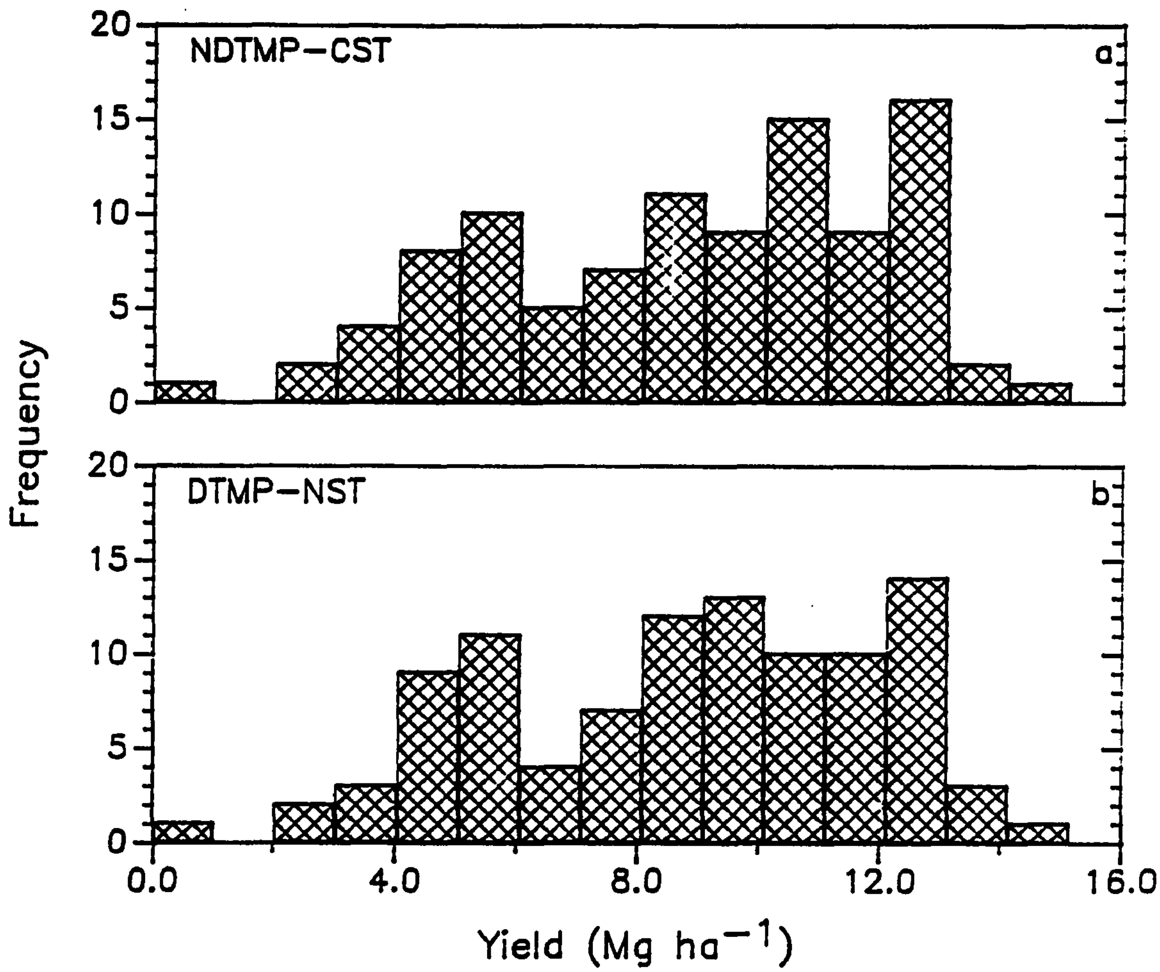

Figure 37. Frequency distribution for 100 years of predicted yields under two tillage treatments.

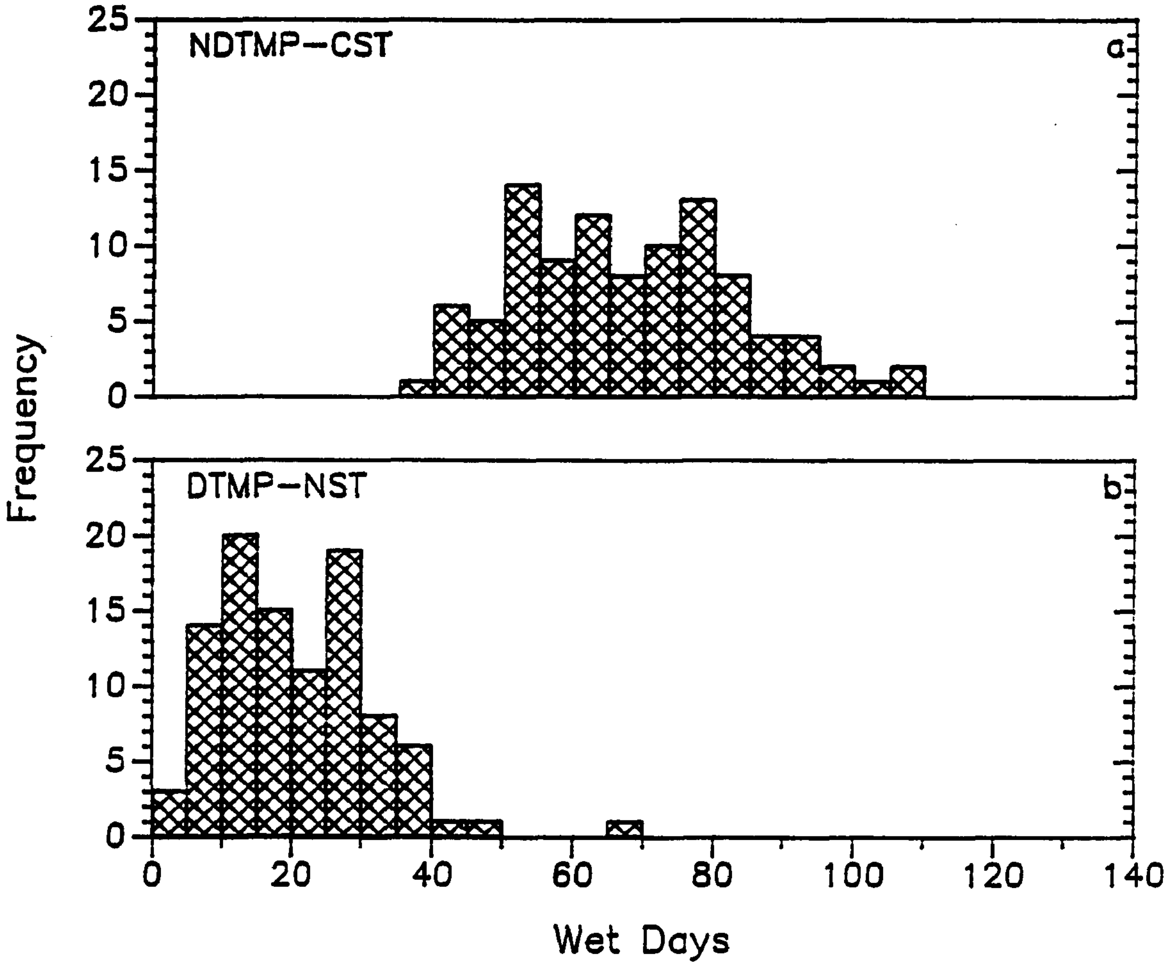

Figure 38. Frequency distribution for the number of wet days under NDTMP-CST and DTMP-NST produced by 100-year simulations for each treatment.

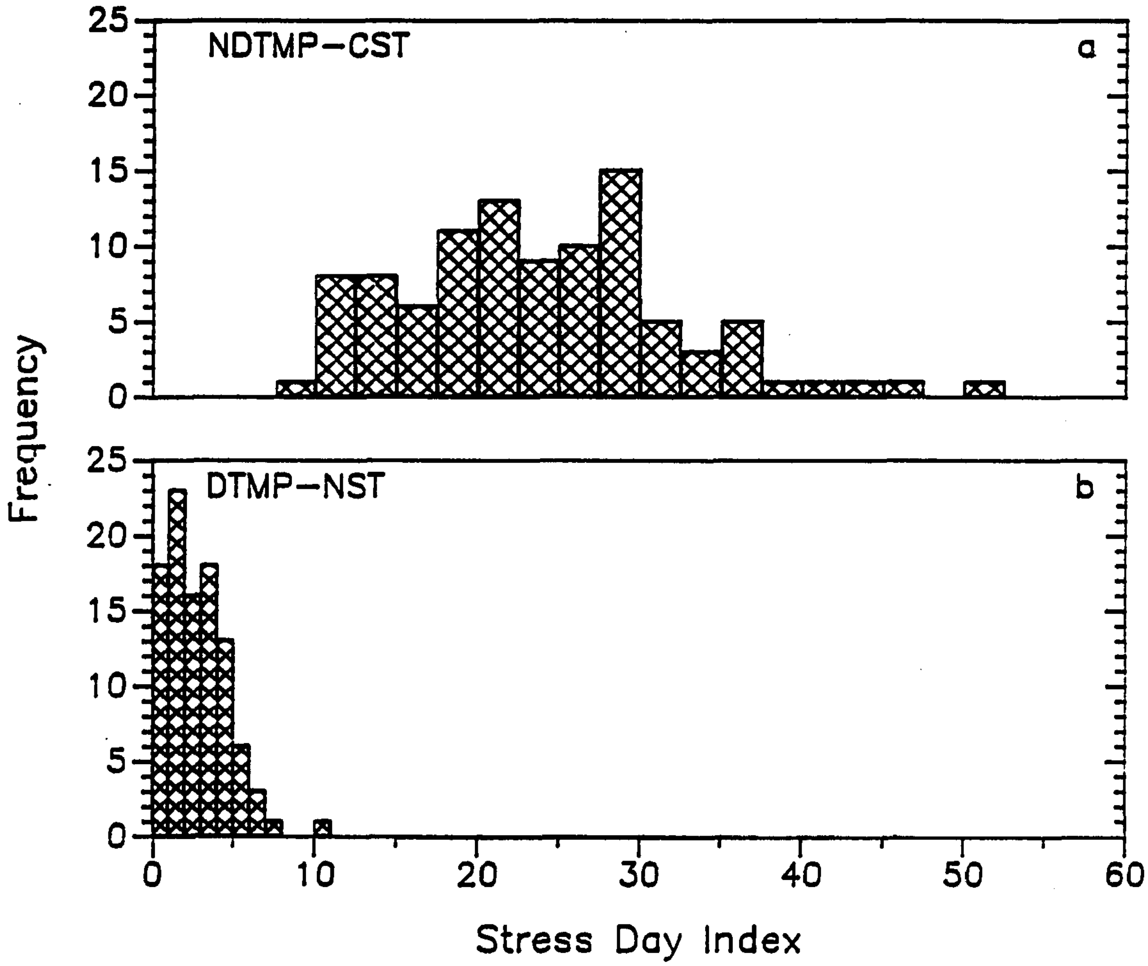

Figure 39. Frequency distribution for stress day index under NDTMP-CST and DTMP-NST produced by 100-year simulations for each treatment.

The SDI averaged 2.7 for the same treatment during the three years of field study (Table 20).

The probability of benefit from deep tillage and controlled traffic can be determined using the frequency distribution of SDI produced by 99 years of simulated data. We start by assuming yield reductions under NDTMP-CST in 1983 were due in part to impeded soil aeration at certain times during the growing season. Fifteen SDI values occur in the class containing the SDI of 28.5 (Figure 39a), the value calculated for the NDTMP-CST treatment in 1983. Another 18 observed values occur in classes containing SDI values of > 30. This suggests that 33 of the 99 years (33 percent) were at least as stressful as 1983 in terms of soil water excesses. Using the same approach, SDI for NDTMP-CST exceeded the value for 1985 (15.0) 83 percent of the time.

The SDI index values used here were based on crop susceptibility factors (CS) for corn. The CS factors varied from 0.51 for the first 42-day period after planting to 0.02 for day 81 to 120 after planting. The SDI approach would likely produce different results for crops that are planted at different times or exhibit different susceptibility to aeration stress.

CONCLUSIONS

The water balance output of the CERES-Maize model simulated measured soil water contents under corn reasonably well. The diverse treatments, NDTMP-CST and DTMP-NST, produced similar water contents at each depth but differing air porosities.

The cumulative stress day index, based on seasonal variation of air porosity in the 0 to 0.10 m depth, was a sensitive measure of soil aeration. Deep tillage and controlled traffic improved soil aeration each year (i.e., decreased SDI). Soil water excesses under conventional fall and spring tillage may cause yield reductions on Charity clay during at least one of three years.

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Chapter 6

SUMMARY AND CONCLUSIONS

Normal fall and spring tillage operations on charity clay create unfavorable physical conditions for crop growth as internal drainage is poor and soil aeration may be impeded at certain critical times. Physical conditions of Charity clay were improved below the normal depth of plowing by subsoiling in the fall when it was relatively dry. Soil physical measurements revealed that changes brought about by subsoiling may persist through only one crop year even when post-subsoiling traffic is controlled. Results also indicate that shallow chiseling after subsoiling may be more beneficial than the normal fall tillage practice moldboard plowing.

Wheel traffic associated with conventional spring tillage recompacted soil loosened by subsoiling but also increased the density of the subsoil where normal fall tillage was applied. Effects of wheel traffic on physical properties below the normal depth of plowing were evident each year but were not cumulative when applied three years in succession.

The unstable surface of Charity clay proved to be extremely susceptible to wheel-induced compaction. Saturated hydraulic conductivity and pore size distribution were the most sensitive indicators of compaction in the Ap horizon. Subsoiling followed by controlled preplant wheel traffic produced the most favorable soil environment for root growth in terms of aeration.

Since aeration can be impeded at times on Charity clay, daily precipitation and weekly profile soil water contents were monitored to determine the occurrence of this environmental stress under various combinations of primary and secondary tillage. The influence of tillage on water content of Parkhill loam was also evaluated in 1983, the only year in which the experiment was conducted at a second site.

The distribution of growing season precipitation varied greatly during the three year study at the Saginaw Valley Bean and Beet Research Farm. Rainfall patterns during April and May were similar at the two study sites in 1983. During the critical June to August period of 1983, precipitation was 92 mm below normal at the second study site (on Parkhill loam) compared to only 19 mm below normal at the Bean and Beet Research Farm.

Water content of Charity clay and Parkhill loam, determined by neutron scattering, were related to the rainfall patterns each year. The seasonal variation of soil water content could have been assessed more effectively each year by obtaining measurements more frequently. However, water content measured at weekly intervals verified that preplant wheel traffic altered the physical conditions of the plow layer such that water content was consistently greater under conventional spring tillage than in plots where traffic was controlled. Preplant wheel traffic decreased air porosity accordingly indicating that controlled traffic diminished the aeration problem. The primary tillage variables had negligible effects on the water content of of Parkhill loam in 1983 and on water content of Charity clay during 1983 to 1985.

Plant responses to tillage substantiate the results of physical measurements which demonstrated that subsoiling and controlled traffic improved soil conditions. On Parkhill loam, sugarbeet, soybean and dry bean yields were consistently greater where subsoiling was applied compared to normal fall tillage. This deep tillage practice may have alleviated water stress on Parkhill loam where rainfall was well below normal for the June to August period in 1983

Deep tillage tended to increase sugarbeet yields during two of three years on Charity clay. Yields of one soybean cultivar were improved by subsoiling during 1983. Yield responses to deep tillage were evident only where subsoiling was applied the previous fall just as physical changes were evident only during the first crop year after subsoiling.

Soil compaction created by preplant wheel traffic produced soil-dependent crop responses in 1983, a year characterized by a wet spring and dry June to August period. Wheel-induced compaction reduced stands on Parkhill loam but produced the highest soybean yields. The secondary tillage variables had little effect in yields of three other crops.

The effects of preplant wheel traffic were more evident on Charity clay than on Parkhill loam in 1983 as controlled traffic improved seedling emergence, increased dry bean rooting, and increased the yields of four of five crops. Crops were more responsive to controlled traffic on Charity clay because this soil has an unstable surface and is therefore susceptible to the damaging effects of excessive or untimely tillage practices. Dry beans and sugarbeets proved to be most sensitive to wheel-induced compaction as preplant wheel traffic diminished yields of these crops in 1985 as well as in 1983.

Tillage effects on soil aeration were evaluated further using the CERES-Maize model and the stress day index method. The water balance output of the CERES-Maize model simulated measured soil water contents under corn reasonably well. The diverse treatments, NDTMP-CST and DTMP-NST, produced similar water contents at each depth but differing air porosities.

The cumulative stress day index, based on seasonal variation of air porosity in the 0 to 0.10 m depth, was a sensitive measure of soil aeration. Deep tillage and controlled traffic improved soil aeration each year (i.e., decreased SDI). Soil water excesses under conventional fall and spring tillage may cause yield reductions on Charity clay during at least one of three years.

Recommendations

Results of this investigation indicate that deep tillage is a beneficial operation during some years on fine-textured Michigan soils. Results of the computer simulation study suggest that subsoiling may increase yields in at least one of three years on Charity clay through improved soil aeration. Deep tillage is not feasible after harvest of some crops commonly grown in the Saginaw Valley but it should be applied whenever possible on soils where a recognized problem exists. Soil conditions (i.e., water content) may be suitable for deep tillage after the final cutting of forage crops and are almost always suitable following small grain harvest.

Where normal fall tillage (i.e., moldboard plowing) is necessary, secondary tillage can be reduced or eliminated for several crops without yield loss. Minimization of preplant wheel traffic associated with secondary tillage is important for the sensitive dry bean and sugarbeet crops as yields of these crops can be increased dramatically in some years. Management of problem soils must include occasional ameliorative procedures and compaction prevention by controlling or reducing preplant wheel traffic.

APPENDIX TABLES

Table 1. Crop cultivars, planting dates, row spacings, seeding rates, and fertilizer application rates used at two study sites in 1983.

Crop	Cultivar[1]	Site[2]	Planting Date	Row spacing	Seeding[3] rate	Desired[4] population	Fertilizer Rates[5] N band	N post	P	K	Micro-nutrients
				m	seeds m^{-1}	plants	kg ha^{-1}				
beets	US-H20,US-H23	1	4/28	0.51	11	96.9	30	0	62	0	Mn,Zn
corn	P3901,GL422	1	5/12	0.51	3.3	64.5	22	174	44	0	Zn
soybeans	H78,C79	1	5/11	0.51	21	420	18	0	35	0	Mn,Zn
dry beans	C20,SV	1	6/09	0.51	15	292	27	0	52	0	Mn,Zn
oats	Her,Mar	1	4/28	0.18	90		13	0	26	0	Mn,Zn
beets	US-H20,US-H23	2	5/10	0.51	11	96.9	22	0	46	67	B
corn	P3901,P3744	2	5/10	0.51	3.3	64.5	16	152	31	116	Zn
soybeans	H78,C79	2	5/10	0.51	21	420	18	0	34	29	Mn,Zn
dry beans	C20,SV	2	6/08	0.51	15	292	27	0	52	0	Mn,Zn

1 P3901 = Pioneer hybrid 3901; GL422 = Great Lakes 422; H78 = Hodgson 78; C79 = Corsoy 79; SV = Swan Valley; Her = Heritage; Mar = Mariner.

2 Site 1 = Charity clay, Saginaw Valley Bean and Beet Research Farm, Swan Creek, MI; site 2 = Parkhill loam, Ithaca, MI.

3 Sugarbeets were planted at the indicated rate but later thinned to a spacing of approximately 5 seeds m^{-1}; the seeding rate for oats is given in kg ha^{-1}.

4 Actual units for plant population are 10^{-3} plants ha^{-1}.

5 Fertilizers were applied in a band at planting; Postemergence N was applied as ammonium nitrate.

Table 2. Herbicide program used for 1983.

		Herbicide		Application	
Crop	site[1]	common name	chemical name	rate	method
				kg ha^{-1} a.i.	
sugarbeets	1,2	Pyrazon	5-amino-4-chloro-2-phenyl-3(2H)-pyridazone	4.5	Pre-e[2]
		Diethatylethyl	N-chloroacetyl-N-(2,6-diethyl phenyl) -glycine ethyl ester	2.8	Pre-e
corn	1,2	Cyanazine	2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2 -yl]amino]-2-methylpropanenitrile	2.2	Pre-e
		Alachlor	2-chloro-N-(2,6-diethylphenyl)-N -(methoxymethyl)acetamide	2.2	Pre-e
soybeans	1,2	Linuron	N'-(3,4-dichlorophenyl)-N-methoxy-N-methylurea	1.2	Pre-e
		Alachlor	2-chloro-N-(2,6-diethylphenyl)-N -(methoxymethyl)acetamide	2.2	Pre-e
dry beans	1	Chloramben	3-amino-2,5-dichlorobenzoic acid	2.2	Pre-e
		Dinoseb	2-(1-methylpropyl)-4,6-dinitrophenol	3.4	Pre-e
dry beans	2	Chloramben	3-amino-2,5-dichlorobenzoic acid	2.2	Pre-e
		Dinoseb	2-(1-methylpropyl)-4,6-dinitrophenol	1.7	Pre-e
oats	1	None			

1 site 1 = Charity clay, Saginaw Valley Bean and Beet Research Farm, Swan Creek, MI; site 2 = Parkhill loam, Ithaca, MI.

2 Pre-e = preemergence nonincorporated.

Table 3. Crop cultivars, planting dates, row spacings, seeding rates, and fertilizer application rates used in 1984.

Crop	Cultivar[1]	Crop Year[2]	Planting Date	Row spacing	Seeding rate[3]	Desired population[4]	Fertilizer Rates[5] N band	N post	P	Micro-nutrients
				m	seeds m^{-1}	plants	- - kg ha^{-1}		- -	
beets	US-H20,US-H23	1,2	4/27	0.51	11	96.9	37	0	17	Mn,Zn
corn	P3901,P3744	1	5/03	0.51	3.3	64.5	58	157	26	Zn
		2	5/03	0.51	3.3	64.5	58	202	26	Zn
soybeans	H78,C79	1,2	5/18	0.51	21	420	44	0	20	Mn,Zn
dry beans	C20,SV	1,2	6/07	0.51	15	292	31	0	14	Mn,Zn
wheat	Fran	2	10/20/83	0.18	135		0	57	0	none
oats	Her,Mar	1	4/12	0.18	90		37	0	17	Mn,Zn

1 P3901 and P3744 = Pioneer hybrids 3901 and 3744, respectively; H78 = Hodgson 78; C79 = Corsoy 79; SV = Swan Valley; Fran = Frankenmuth; Her = Heritage; Mar = Mariner.

2 Crop year = 1 indicates that the crop appeared only in plots where the primary tillage variables were applied the previous fall; 2 indicates that the crop appeared only in plots established for the second crop year; 1,2 indicates that the crop appeared in plots representing both the first and second crop year.

3 Sugarbeets were planted at the indicated rate but later thinned to a spacing of approximately 5 seeds m^{-1}; seeding rates for wheat and oats are given in kg ha^{-1}.

4 Actual units for plant population are 10^{-3} plants ha^{-1}.

5 Fertilizers were applied in a band at planting; Postemergence N was applied as ammonium nitrate.

Table 4. Herbicide program used for the experiment on Charity clay in 1984.

	Herbicide		Application	
Crop	common name	chemical name	rate	method
			$kg\ ha^{-1}$ a.i.	
sugarbeets	Pyrazon	5-amino-4-chloro-2-phenyl-3(2H)-pyridazone	4.5	Pre-e[1]
	Diethatylethyl	N-chloroacetyl-N-(2,6-diethyl phenyl) -glycine ethyl ester	2.8	Pre-e
corn	Cyanazine	2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2 -yl]amino]-2-methylpropanenitrile	2.2	Pre-e
	Alachlor	2-chloro-N-(2,6-diethylphenyl)-N -(methoxymethyl)acetamide	2.2	Pre-e
soybeans	Linuron	N'-(3,4-dichlorophenyl)-N-methoxy-N-methylurea	2.2	Pre-e
	Alachlor	2-chloro-N-(2,6-diethylphenyl)-N -(methoxymethyl)acetamide	2.2	Pre-e
dry beans	Chloramben	3-amino-2,5-dichlorobenzoic acid	2.8	Pre-e
	Alachlor	2-chloro-N-(2,6-diethylphenyl)-N -(methoxymethyl)acetamide	2.2	Pre-e
oats	None			
wheat	None			

1 Pre-e = preemergence nonincorporated.

Table 5. Crop cultivars, planting dates, row spacings, seeding rates, and fertilizer application rates used in 1985.

Crop	Cultivar[1]	Crop Year[2]	Planting Date	Row spacing	Seeding rate[3]	Desired population[4]	Fertilizer Rates[5]: N band	Fertilizer Rates[5]: N post	Fertilizer Rates[5]: P	Micro-nutrients
				m	seeds m^{-1}	plants	- - kg ha^{-1} - -			
beets	US-H20,US-H23	1	4/23	0.51	11	96.9	30	0	14	Mn,B
		2,3	4/23	0.51	11	96.9	77[6]	0	35	Mn,B
corn	P3901,P3744	1,3	5/03	0.51	3.3	64.5	73	188	33	Zn
soybeans	H78,C79	1,2,3	5/14	0.51	21	420	49	0	22	Mn,Zn
dry beans	C20,SV	1,2,3	5/21	0.51	15	292	62	0	28	Mn,Zn
wheat	Fran	2	10/15/84	0.18	135		0	48	0	none
oats	Her,Mar	1	4/12	0.18	86		37	0	17	Mn,Zn
		3	4/12	0.18	86		44	0	20	Mn,Zn

1 P3901 and P3744 = Pioneer hybrids 3901 and 3744, respectively; H78 = Hodgson 78; C79 = Corsoy 79; SV = Swan Valley; Fran = Frankenmuth; Her = Heritage; Mar = Mariner.

2 Crop year = 1 indicates that the crop appeared only in plots where the primary tillage variables were applied the previous fall; 2 indicates that the crop appeared only in plots established for the second crop year; 1,3 the first and third; and 1,2,3 the first, second, and third crop year.

3 Sugarbeets were planted at the indicated rate but later thinned to a spacing of approximately 5 seeds m^{-1}; seeding rates for wheat and oats are given in kg ha^{-1}.

4 Actual units for plant population are 10^{-3} plants ha^{-1}.

5 Fertilizers were applied in a band at planting; postemergence N for wheat was applied as ammonium nitrate; postemergence N for corn was applied by spraying a liquid consisting of 28% N between the rows.

6 Due to an error, the indicated rates of N and P were doubled for the US-H20 sugarbeets planted in plots established for the third crop year.

Table 6. Herbicide program used for the experiment on Charity clay in 1985.

Crop	Herbicide: common name	Herbicide: chemical name	Application rate	Application method
			kg ha^{-1} a.i.	
sugarbeets	Pyrazon	5-amino-4-chloro-2-phenyl-3(2H)-pyridazone	3.4	Pre-e[1]
	Ethofumesate	(+)-2-ethoxy-2,3-dihydro-3,3-dimethyl -5-benzofuranyl methanesulfonate	2.2	Pre-e
	Diethatylethyl	N-chloroacetyl-N-(2,6-diethyl phenyl) -glycine ethyl ester	2.2	Pre-e
	Ethofumesate	(+)-2-ethoxy-2,3-dihydro-3,3-dimethyl -5-benzofuranyl methanesulfonate	0.8	Post
	Desmedipham+ Phenmedipham	ethyl[3-[[(phenylamino)carbonyl]oxy]phenyl]carbamate 3-[(methoxycarbonyl)amino]phenyl(3 -methylphenyl)carbamate	1.1	Post
	Endothal	7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid	0.6	Post
corn	Cyanazine	2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2 -yl]amino]-2-methylpropanenitrile	2.5	Pre-e
	Alachlor	2-chloro-N-(2,6-diethylphenyl)-N -(methoxymethyl)acetamide	2.8	Pre-e
soybeans	Metribuzin	4-amino-6-(1,1-dimethylethyl)-3-(methylthio) -1,2,4-triazin-5(4H)-one	0.4	Pre-e
	Metolachlor	2-chloro-N-(2-ethyl-6-methylphenyl)-N -(2-methoxy-1-methylethyl)acetamide	2.2	Pre-e
	Acifluorfen	5-[2-chloro-4-(trifluoromethyl)phenoxyl] -2-nitrobenzoic acid	0.3	Post

Table 6 (Cont'd).

Crop	Herbicide common name	Herbicide chemical name	Application rate	Application method
			kg ha^{-1} a.i.	
dry beans	Glyphosate	N-(phosphonomethyl)glycine	1.7	Pre-p
	Chloramben	3-amino-2,5-dichlorobenzoic acid	2.2	Pre-e
	Metolachlor	2-chloro-N-(2-ethyl-6-methylphenyl)-N -(2-methoxy-1-methylethyl)acetamide	2.2	Pre-e
oats	None			
wheat	None			

1 Pre-p = preplant nonincorporated; Pre-e = preemergence nonincorporated; Post = postemergence.

Table 7. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on corn grain moisture at harvest from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C[2]	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		percent											
P-3901	DTMP	34.0Aa[3]	31.6Aa	23.3	23.8	22.6	22.2	28.7Aa	31.4Aa	missing		26.2	24.7
	DTCH			23.5	22.9			28.5Aa	30.6Aa	"			
	NDTMP	34.5Aa	32.3Aa	23.1	22.8	22.5	22.4	29.7Aa	29.8Aa	"		24.2	26.5
	NDTCH			23.3	23.0			30.4Aa	31.8Aa	"			
P-3744	DTMP	31.5Ba	27.6Aa	23.8	24.3	22.0	22.7	28.1Aa	31.0Aa	"		27.6	26.1
	DTCH			23.6	23.1			29.7Aa	31.2Aa	"			
	NDTMP	29.2Aa	27.8Aa	22.9	24.0	22.9	21.7	29.8Aa	29.5Aa	"		29.5	28.0
	NDTCH			24.1	23.7			28.1Aa	30.1Aa	"			

Statistics:[4]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	NS	NS	NS		NS
S	**	NS	NS	**		NS
P x S	NS	NS	NS	NS		NS
C	**	NS	NS	NS		NS
P x C	NS	NS	NS	NS		NS
S x C	NS	NS	NS	NS		NS
P x S x C	NS	NS	NS	NS		NS
LSDp(.05)	2.9	1.7	1.5	3.0		5.2
LSDs(.05)	2.4	1.6	1.4	2.9		5.1

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 P-3901 = Pioneer hybrid 3901; P-3744 = Pioneer 3744 except for 1983 when H No. 2 was Great Lakes 422.

3 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

4 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 8. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on corn plant population from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C[2]	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
						10^{-3} plants ha^{-1}							
P-3901	DTMP	56.5	56.5	70.1Aa[3]	66.2Aab	62.6	65.5	49.7	53.6	missing		47.8	52.6
	DTCH			72.0Aa	70.7Ab			45.5	52.9	"			
	NDTMP	53.6	57.8	69.4Aa	58.5Aa	65.2	68.8	45.5	50.9	"		48.1	47.5
	NDTCH			66.5Aa	66.5Aab			47.5	50.0	"			
P-3744	DTMP	42.6	45.2	70.1Aa	73.3Ab	70.4	64.9	52.9	53.3	"		46.8	43.6
	DTCH			74.9Aa	70.4Aab			51.7	57.1	"			
	NDTMP	44.9	43.6	67.8Aa	63.0Aa	64.6	65.5	49.1	51.3	"		45.2	40.0
	NDTCH			73.9Aa	67.5Aab			54.9	47.5	"			

Statistics:[4]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	NS	NS	NS		NS
S	NS	*	NS	NS		NS
P x S	NS	NS	NS	NS		NS
C	**	NS	NS	NS		NS
P x C	NS	NS	NS	NS		NS
S x C	NS	NS	NS	NS		NS
P x S x C	NS	NS	NS	NS		NS
LSDp(.05)	9.2	9.4	7.5	14.6		12.0
LSDs(.05)	5.9	8.6	7.2	14.2		11.6

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 P-3901 = Pioneer hybrid 3901; P-3744 = Pioneer 3744 except for 1983 when C No. 2 was Great Lakes 422.

3 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

4 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 9. Mean squares from analysis of variance for two measures of root density of soybeans (SB), dry beans (DB), and corn grown on Charity clay from 1983 to 1985.

	1983					1984			1985			
	df	SB	DB	df	Corn	df	SB	DB	df	SB	df	DB
RLD[1]												
P[2]	1	0.17977	0.26761	1	0.2779	1	0.50069	0.02059	1	0.32842	1	0.85474
Error a	3	0.24722	0.41939	2	0.2535	3	0.11539	0.33262	3	0.46489	3	1.32053
S	1	0.00210	0.92158*	1	0.1089	1	0.23990	0.00194	1	0.10901	1	0.15029
PxS	1	0.20430	0.53467	1	0.5791	1	0.30206	0.00327	1	0.17966	1	0.10143
Error b	6	0.30912	0.12006	4	0.3250	6	0.36232	0.3119	6	0.26122	5(1)	0.10033
D	5	3.66945**	1.36465**	5	3.0119**	5	1.94008**	2.26657**	5	3.10461**	5	1.99942**
PxD	5	0.07428	0.09967	5	0.0473	5	0.13413*	0.01915	5	0.03853	5	0.05116
SxD	5	0.04382	0.29740*	5	0.2103	5	0.08446	0.02998	5	0.02821	5	0.10626
PxSxD	5	0.07306	0.05282	5	0.1816	5	0.14329*	0.07528	5	0.02619	5	0.09246
Error c	60	0.05995	0.09412	40	0.2721	60	0.04282	0.04989	60	0.05803	55(5)	0.06336
RWD												
P	1	0.019601	0.00838	1	0.001410	1	2.1670	0.03242	1	0.23876	1	0.34291
Error a	3	0.008384	0.01622	2	0.004833	3	4.3117	0.03076	3	0.39089	3	0.20965
S	1	0.000941	0.05899	1	0.031746	1	0.0003	0.03985	1	0.00603	1	0.20064*
PxS	1	0.010067	0.00159	1	0.010623	1	2.3654	0.37206	1	0.00209	1	0.01435
Error b	6	0.005676	0.01611	4	0.006023	6	1.6814	0.19078	6	0.00342	5(1)	0.02274
D	2	0.083961*	0.9253**	2	0.120252**	2	1.5037	0.38706**	2	0.08741*	2	0.09775
PxD	2	0.023923**	0.00760	2	0.015522	2	1.1163	0.01570	2	0.00976	2	0.02558
SxD	2	0.003231	0.02227	2	0.002047	2	0.6485	0.01827	2	0.00859	2	0.01255
PxSxD	2	0.009782*	0.00158	2	0.000117	2	2.8495	0.03453	2	0.04046	2	0.00480
Error c	24	0.002625	0.01132	16	0.004865	24	0.9000	0.04677	24	0.01579	22(2)	0.03629

1 RLD = Root length density; RWD = Root weight density (i.e., dry weight of roots per unit volume).

2 P = primary tillage; S = secondary tillage; D = depth; *,** significant at the 0.05 and 0.01 levels, respectively; degrees of freedom enclosed in ( ) indicate the number of df lost due to missing values.

Table 10. Influence of primary tillage (P), secondary tillage (S), and depth on root weight density of soybean (SB), dry bean (DB), and corn roots during 1983 to 1985 on Charity clay.

		1983						1984				1985			
		SB		DB		Corn		SB		DB		SB		DB	
Depth	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
- - m - -		10^{-6} g cm^{-3}						10^{-5} g cm^{-3}		10^{-6} g cm^{-3}					
0.23-0.31	DTMP	292	222	202	289	316	350	123	126	507	672	494	472	488	653
	NDTMP	146	185	125	259	241	333	119	167	753	428	216	381	208	418
0.31-0.38	DTMP	124	126	122	147	182	195	260	75	270	372	332	377	365	482
	NDTMP	111	156	132	150	215	272	45	136	605	281	209	197	208	342
0.38-0.46	DTMP	105	132	115	128	160	166	90	136	224	313	253	337	336	338
	NDTMP	117	114	102	123	155	205	47	41	328	276	271	145	161	310
	LSDp(.05)[1]	81		135		106		235		429		590		481	
	LSDs(.05)	68		126		99		171		505		160		272	
averaged over P:															
0.23-0.31		219	203	164	274	279	341	121	146	630	550	355	427	348	535
0.31-0.38		118	141	127	149	198	233	152	106	438	327	271	287	287	412
0.38-0.46		111	123	108	125	157	185	68	88	276	295	262	241	249	324
	LSD(.05)[2]	48		89		70		121		357		113		192	

1 LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and depth; LSDs(.05) = LSD for comparison of two S means at the same level of P and depth.

2 LSD for comparison of two S means at a particular depth but averaged over levels of P.

Table 11. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on sugarbeet sucrose content (SC), clear juice purity (CJP), recoverable sucrose content (RSC), and alpha-amino-N content (AAN) during 1983 on Parkhill loam.

C	P/S	SC		CJP		RSC		AAN	
		CST	NST	CST	NST	CST	NST	CST	NST
		- kg Mg^{-1} -		- percent -		- kg Mg^{-1} -		- mmol kg^{-1} -	
US-H20	DTMP	177	180	95.9	96.1	154	157	92	87
	NDTMP	173	177	96.0	95.8	150	154	103	101
US-H23	DTMP	179	180	96.0	95.8	156	156	81	76
	NDTMP	174	176	95.4	95.7	150	152	70	90

Statistics[1]

	SC	CJP	RSC	AAN
P	NS	NS	NS	NS
S	NS	NS	NS	NS
P x S	NS	NS	NS	NS
C	NS	NS	NS	NS
P x C	NS	NS	NS	NS
S x C	NS	NS	NS	NS
P x S x C	NS	NS	NS	NS
LSDp(.05)	0.99	0.68	9.6	54
LSDs(.05)	0.43	0.58	8.5	50

1 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 12. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on sugarbeet plant density from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		plants m^{-1}											
US-H20	DTMP	4.50Ba[2]	3.57Aa	3.67Aa	4.21Bb	3.26Aa	4.02Ba	missing		3.32	3.40	2.79Aa	3.18Aa
	DTCH			3.75Aa	3.67Aa			"		3.57	3.37		
	NDTMP	4.00Aa	3.45Aa	3.81Aa	4.23Bb	3.51Aa	3.78Aa	"		2.93	3.29	2.33Aa	2.95Ba
	NDTCH			3.69Aa	3.63Aa			"		2.90	3.44		
US-H23	DTMP	3.79Aa	3.84Aa	4.08Ab	4.37Ab	3.57Aa	3.75Aa	"		3.50	3.09	3.08Aa	3.30Aa
	DTCH			3.96Aab	4.16Ab			"		3.75	3.40		
	NDTMP	3.55Aa	2.99Aa	4.14Ab	4.13Ab	3.65Aa	3.59Aa	"		3.78	3.13	2.80Aa	3.01Aa
	NDTCH			3.57Aa	3.61Aa			"		3.55	3.49		

Statistics:[3]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	*	NS		NS	*
S	*	NS	*		NS	*
P x S	NS	NS	NS		NS	NS
C	NS	**	NS		NS	NS
P x C	NS	*	NS		NS	NS
S x C	NS	NS	NS		NS	NS
P x S x C	NS	NS	NS		NS	NS
LSDp(.05)	1.58	0.46	0.75		0.91	0.52
LSDs(.05)	0.75	0.40	0.55		0.98	0.50

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 13. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on sucrose content of sugarbeets from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		kg Mg^{-1}											
US-H20	DTMP	184	183	177	177	183	182	175	174	167	168	168	177
	DTCH			179	179			173	175	173	175		
	NDTMP	179	182	181	177	175	182	172	172	174	177	170	171
	NDTCH			178	180			174	173	172	172		
US-H23	DTMP	181	183	170	173	176	180	172	174	165	169	176	181
	DTCH			177	176			173	167	169	176		
	NDTMP	178	180	176	172	179	182	171	168	170	173	178	178
	NDTCH			178	178			172	171	170	173		

Statistics:[2]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	NS	NS	NS	NS	NS
S	NS	NS	NS	NS	NS	NS
P x S	NS	NS	NS	NS	NS	NS
C	NS	**	NS	**	NS	**
P x C	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	12	7	9	5	9	7
LSDs(.05)	10	5	9	4	9	8

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 14. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on clear juice purity of sugarbeets from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		percent											
US-H20	DTMP	96.2	96.4	96.1	96.3	96.4Ab[2]	96.7Aa	95.6	96.0	95.3Aa	95.8Aa	95.1Aa	95.3Aa
	DTCH			96.1	96.2			96.0	96.0	94.9Aa	95.6Aa		
	NDTMP	96.4	96.1	96.5	96.4	95.3Aa	96.2Aa	95.5	96.0	95.3Aa	95.7Aa	94.3Aa	95.0Aa
	NDTCH			96.0	96.5			95.6	96.0	95.1Aa	95.0Aa		
US-H23	DTMP	95.9	95.9	95.8	96.1	96.0Aa	96.1Aa	95.7	96.1	95.4Aa	95.6Aa	95.5Aa	95.8Aa
	DTCH			96.0	96.1			95.7	95.3	95.4Aa	96.0Aa		
	NDTMP	95.7	95.8	96.1	96.5	96.0Aa	96.1Aa	95.6	95.5	95.1Aa	95.8Aa	95.4Aa	96.2Aa
	NDTCH			96.2	96.5			97.2	95.3	95.0Aa	95.3Aa		

Statistics:[3]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	NS	*	NS	NS	NS
S	NS	NS	NS	NS	*	*
P x S	NS	NS	NS	NS	NS	NS
C	*	NS	NS	NS	NS	**
P x C	NS	NS	*	NS	NS	NS
S x C	NS	NS	NS	*	NS	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	0.6	0.6	0.8	1.2	1.1	1.0
LSDs(.05)	0.6	0.6	0.9	1.1	1.0	0.9

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 15. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on recoverable sugar content of sugarbeets from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		kg Mg^{-1}											
US-H20	DTMP	160	160	155	155	160	161	151	151	143Aa[2]	145Aa	144	152
	DTCH			156	156			151	152	148Aa	151Aa		
	NDTMP	157	159	159	155	151	159	148	149	149Aa	154Aa	144	146
	NDTCH			155	158			150	151	147Aa	147Aa		
US-H23	DTMP	157	159	147	150	153	157	149	151	141Aa	146Aa	152	157
	DTCH			154	154			150	146	145Aa	153Aa		
	NDTMP	154	156	153	151	156	159	148	145	145Aa	150Aa	153	155
	NDTCH			156	156			153	147	145Aa	149Aa		

Statistics:[3]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	NS	NS	NS	NS	NS
S	NS	NS	NS	NS	**	NS
P x S	NS	NS	NS	NS	NS	NS
C	NS	**	NS	*	NS	**
P x C	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	12	7	9	6	10	8
LSDs(.05)	9	5	10	5	10	9

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 16. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on alpha-amino-N content of sugarbeets from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		mmol kg^{-1}											
US-H20	DTMP	81	79	96Ab[2]	101Ab	69Aa	69Aa	104Aa	111Aa	125	115	155Aa	142Aa
	DTCH			91Aab	99Ab			93Aa	106Aa	158	130		
	NDTMP	67	93	71Aa	86Ab	117Ab	85Aa	109Aa	106Aa	123	113	186Ba	154Aa
	NDTCH			92Ab	77Aa			106Aa	99Aa	141	154		
US-H23	DTMP	80	91	95Aab	99Ab	75Aa	73Aa	101Aa	100Aa	111	106	119Aa	104Aa
	DTCH			106Ab	95Ab			92Aa	121Ba	128	97		
	NDTMP	75	88	76Aa	74Aa	75Aa	72Aa	90Aa	118Ba	122	113	106Aa	102Aa
	NDTCH			88Aab	72Aa			82Aa	107Ba	136	118		

Statistics:[3]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	**	*	NS	NS	NS
S	NS	NS	NS	**	NS	*
P x S	NS	NS	NS	*	NS	NS
C	NS	NS	NS	NS	*	**
P x C	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	*	NS	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	36	21	32	22	45	41
LSDs(.05)	33	24	35	20	44	32

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 17. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on soybean grain moisture at harvest from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		percent											
Hodgson	DTMP	12.6	12.5	16.6	16.9	16.7Aa[2]	18.0Aa	11.5	11.4	11.9	11.8	11.6	11.5
-78	DTCH			16.5	16.5			11.6	11.6	11.7	11.8		
	NDTMP	12.6	12.6	16.9	16.8	16.7Aa	17.6Aa	11.5	11.4	12.3	11.8	11.6	11.4
	NDTCH			16.5	16.7			11.6	11.4	12.3	12.0		
Corsoy	DTMP	13.3	13.9	16.9	17.0	18.3Aa	17.4Aa	11.6	11.5	12.2	12.1	11.7	11.6
-79	DTCH			17.2	17.1			11.6	11.5	12.2	12.0		
	NDTMP	13.3	13.5	17.2	17.0	18.3Aa	17.6Aa	11.6	11.7	11.8	11.9	11.6	11.6
	NDTCH			17.3	17.0			11.7	11.6	12.2	11.9		

Statistics:[3]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	NS	NS	NS	NS	NS
S	NS	NS	NS	NS	NS	NS
P x S	NS	NS	NS	NS	NS	NS
C	**	**	NS	*	NS	NS
P x C	NS	NS	NS	NS	NS	NS
S x C	NS	NS	*	NS	NS	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	0.7	0.7	1.3	0.3	0.6	0.3
LSDs(.05)	0.5	0.8	1.5	0.3	0.7	0.3

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 18. Influence of primary tillage (P), secondary tillage (S), and cultivar (C) on dry bean grain moisture at harvest from 1983 to 1985 on Charity clay.

		1983		1984				1985					
		CY1[1]		CY1		CY2		CY1		CY2		CY3	
C	P/S	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST	CST	NST
		-------------------------						percent					-------------------------
C20	DTMP	20.4Ba[2]	18.9Aa	16.9	17.4	15.2Aa	15.2Aa	19.6Aa	19.2Aa	23.4Ba	21.0Aa	19.4	19.7
	DTCH			17.0	17.1			19.5Aa	18.3Aa	25.8Bc	20.8Aa		
	NDTMP	21.3Ba	18.9Aa	18.7	17.8	15.6Aa	15.1Aa	19.5Aa	18.1Aa	25.0Bbc	21.2Aa	18.6	19.1
	NDTCH			17.5	17.6			20.4Aa	19.0Aa	24.2Bab	21.3Aa		
Swan-Valley	DTMP	20.2Ba	18.9Aa	17.3	17.5	16.0Ba	15.0Aa	20.1Aa	19.8Aa	23.0Aa	22.6Aa	21.3	20.7
	DTCH			16.2	17.4			19.6Aa	19.3Aa	23.2Aa	22.7Aa		
	NDTMP	20.4Aa	19.2Aa	17.4	17.8	15.7Ba	14.8Aa	23.2Ab	23.1Ab	23.4Aa	22.8Aa	21.2	20.6
	NDTCH			17.3	16.9			23.4Ab	22.8Ab	23.7Aa	22.6Aa		

Statistics:[3]	1983	1984		1985		
	CY1	CY1	CY2	CY1	CY2	CY3
P	NS	NS	NS	NS	NS	NS
S	**	NS	*	**	**	NS
P x S	NS	NS	NS	NS	NS	NS
C	NS	NS	NS	**	NS	**
P x C	NS	NS	NS	**	NS	NS
S x C	NS	NS	NS	NS	NS	NS
P x S x C	NS	NS	NS	NS	NS	NS
LSDp(.05)	1.4	1.2	0.9	2.5	1.5	2.1
LSDs(.05)	1.5	0.9	0.7	1.6	1.5	1.7

1 CY1 = crop year 1; CY2 = crop year 2; CY3 = crop year 3.

2 Pairs of CST and NST means in each row followed by the same upper-case letter are not different using LSD as the criterion for significance. Means in each column and within the same cultivar followed by the same lower-case letter are not different.

3 *,** = significant at the 0.05 and 0.01 levels, respectively; NS = nonsignificant; LSDp(.05) = LSD for comparison of two P means at the same or different levels of S and C; LSDs(.05) = LSD for comparison of two S means at the same level of P and C.

Table 19. Sample water balance output produced by the original version of CERES-Maize.

	JUL	AVERAGE							PERIOD			SOIL WATER CONTENT WITH DEPTH							TOTAL
DAY	DAY	ES	EP	ET	EO	SR	MAX	MIN	RUNOFF	DRAIN	PREC	SW1	SW2	SW3	SW4	SW5	SW6	SW7	PESW
5/ 8/83	128	4.8	.0	4.8	4.8	659.	10.6	1.7	.00	.00	.00	.47	.44	.46	.47	.47	.47	.47	14.0
5/ 9/83	129	5.0	.0	5.0	5.0	688.	12.2	-.6	.00	.00	.00	.43	.44	.46	.47	.47	.47	.47	13.5
5/10/83	130	4.3	.0	4.3	5.6	694.	19.4	-1.1	.00	.00	.00	.40	.43	.45	.47	.47	.47	.47	13.1
5/11/83	131	2.0	.0	2.0	6.1	685.	23.3	2.8	.00	.00	.00	.39	.43	.45	.47	.47	.47	.47	12.9
5/12/83	132	1.3	.0	1.3	5.4	559.	26.1	6.7	.00	.00	.00	.38	.43	.45	.47	.47	.47	.47	12.8
5/13/83	133	1.0	.0	1.0	5.3	539.	26.1	9.4	.00	.00	.00	.38	.42	.45	.46	.47	.47	.47	12.7
5/14/83	134	1.4	.0	1.4	1.6	181.	20.6	8.9	.00	.00	.50	.38	.42	.45	.46	.47	.47	.47	12.6
5/15/83	135	.8	.0	.8	5.1	621.	16.1	5.6	.00	.00	.00	.38	.42	.45	.46	.47	.47	.47	12.5
5/16/83	136	.7	.0	.7	3.5	488.	10.0	.6	.00	.00	.00	.38	.42	.44	.46	.47	.47	.47	12.4
5/17/83	137	.7	.0	.7	4.8	626.	16.1	-2.8	.00	.00	.00	.38	.42	.44	.46	.47	.47	.47	12.4
5/18/83	138	.6	.0	.6	3.4	410.	18.9	1.7	.00	.00	.00	.38	.42	.44	.46	.46	.47	.47	12.3
5/19/83	139	1.7	.0	1.7	1.7	187.	19.4	11.1	.00	.00	26.90	.52	.46	.47	.47	.47	.47	.47	14.8
5/20/83	140	1.2	.0	1.2	1.2	146.	15.6	8.3	.00	.00	.00	.46	.47	.48	.48	.47	.47	.47	14.7
5/21/83	141	4.4	.0	4.4	4.4	491.	22.2	5.6	.00	.00	.00	.45	.46	.46	.47	.47	.47	.47	14.2
5/22/83	142	2.3	.0	2.3	2.3	242.	20.0	12.8	3.52	1.09	21.60	.52	.48	.48	.48	.48	.47	.47	15.7
5/23/83	143	1.9	.0	1.9	1.9	219.	15.6	11.7	.00	2.17	.00	.48	.47	.48	.48	.48	.47	.47	15.3
5/24/83	144	5.6	.0	5.6	5.6	609.	24.4	4.4	.00	2.35	.00	.46	.46	.46	.47	.47	.47	.47	14.5
5/25/83	145	3.6	.0	3.6	3.6	450.	12.8	8.3	2.01	.04	11.90	.51	.46	.47	.48	.48	.47	.47	15.1
5/26/83	146	4.8	.0	4.8	4.8	612.	13.9	2.8	.00	1.03	.00	.46	.46	.47	.48	.47	.47	.47	14.6
5/27/83	147	4.5	.0	4.5	5.1	619.	19.4	.6	.00	.52	.00	.44	.45	.46	.47	.47	.47	.47	14.1
5/28/83	148	2.7	.0	2.7	3.2	356.	20.6	7.8	.00	.02	.00	.42	.44	.46	.47	.47	.47	.47	13.8
5/29/83	149	3.8	.0	3.8	3.8	431.	17.8	10.6	.00	.02	16.80	.52	.45	.47	.48	.47	.47	.47	15.1
5/30/83	150	1.3	.0	1.3	1.3	167.	13.3	7.2	.00	.35	.00	.45	.46	.48	.48	.48	.47	.47	14.9
5/31/83	151	2.6	.0	2.6	2.6	318.	14.4	7.8	6.60	2.05	13.50	.47	.47	.48	.48	.48	.47	.47	15.1

Table 20. Sample water balance output produced by the modified version of CERES-Maize.

	JUL	AVERAGE							PERIOD				SOIL WATER CONTENT WITH DEPTH							TOTAL
DAY	DAY	ES	EP	ET	EO	SR	MAX	MIN	INF	DRAIN	PREC	STOR	SW1	SW2	SW3	SW4	SW5	SW6	SW7	PESW
5/ 8/83	128	4.8	.0	4.8	4.8	659.	10.6	1.7	.00	.00	.00	.00	.47	.44	.46	.47	.47	.47	.47	140.2
5/ 9/83	129	5.0	.0	5.0	5.0	688.	12.2	-.6	.00	.00	.00	.00	.43	.44	.46	.47	.47	.47	.47	135.2
5/10/83	130	4.3	.0	4.3	5.6	694.	19.4	-1.1	.00	.00	.00	.00	.40	.43	.45	.47	.47	.47	.47	130.9
5/11/83	131	2.0	.0	2.0	6.1	685.	23.3	2.8	.00	.00	.00	.00	.39	.43	.45	.47	.47	.47	.47	128.9
5/12/83	132	1.3	.0	1.3	5.4	559.	26.1	6.7	.00	.00	.00	.00	.38	.43	.45	.47	.47	.47	.47	127.6
5/13/83	133	1.0	.0	1.0	5.3	539.	26.1	9.4	.00	.00	.00	.00	.38	.42	.45	.46	.47	.47	.47	126.6
5/14/83	134	1.4	.0	1.4	1.6	181.	20.6	8.9	.50	.00	.50	.00	.38	.42	.45	.46	.47	.47	.47	125.7
5/15/83	135	.8	.0	.8	5.1	621.	16.1	5.6	.00	.00	.00	.00	.38	.42	.45	.46	.47	.47	.47	124.9
5/16/83	136	.7	.0	.7	3.5	488.	10.0	.6	.00	.00	.00	.00	.38	.42	.44	.46	.47	.47	.47	124.2
5/17/83	137	.7	.0	.7	4.8	626.	16.1	-2.8	.00	.00	.00	.00	.38	.42	.44	.46	.47	.47	.47	123.5
5/18/83	138	.6	.0	.6	3.4	410.	18.9	1.7	.00	.00	.00	.00	.38	.42	.44	.46	.46	.47	.47	122.9
5/19/83	139	1.7	.0	1.7	1.7	187.	19.4	11.1	26.90	.00	26.90	.00	.51	.46	.47	.47	.47	.47	.47	148.1
5/20/83	140	1.2	.0	1.2	1.2	146.	15.6	8.3	.00	.00	.00	.00	.46	.47	.48	.48	.47	.47	.47	146.8
5/21/83	141	4.4	.0	4.4	4.4	491.	22.2	5.6	.00	.00	.00	.00	.45	.46	.46	.47	.47	.47	.47	142.4
5/22/83	142	2.3	.0	2.3	2.3	242.	20.0	12.8	18.13	1.06	21.60	1.21	.51	.48	.49	.49	.48	.48	.47	159.5
5/23/83	143	1.9	.0	1.9	1.9	219.	15.6	11.7	1.15	3.84	.00	.00	.49	.48	.48	.48	.48	.47	.47	155.0
5/24/83	144	5.6	.0	5.6	5.6	609.	24.4	4.4	.00	2.35	.00	.00	.48	.46	.47	.47	.47	.47	.47	147.0
5/25/83	145	3.6	.0	3.6	3.6	450.	12.8	8.3	2.58	.06	11.90	5.67	.46	.46	.48	.48	.48	.47	.47	149.5
5/26/83	146	4.8	.0	4.8	4.8	612.	13.9	2.8	2.21	1.98	.00	.00	.46	.47	.47	.48	.48	.47	.47	148.5
5/27/83	147	5.1	.0	5.1	5.1	619.	19.4	.6	.00	1.25	.00	.00	.44	.45	.46	.47	.47	.47	.47	142.1
5/28/83	148	3.1	.0	3.1	3.2	356.	20.6	7.8	.00	.02	.00	.00	.43	.44	.46	.47	.47	.47	.47	139.0
5/29/83	149	3.8	.0	3.8	3.8	431.	17.8	10.6	16.79	.02	16.80	.00	.51	.46	.47	.48	.47	.47	.47	152.0
5/30/83	150	1.3	.0	1.3	1.3	167.	13.3	7.2	.00	.85	.00	.00	.46	.47	.48	.48	.48	.47	.47	149.8
5/31/83	151	2.6	.0	2.6	2.6	318.	14.4	7.8	2.63	2.05	13.50	8.25	.47	.47	.48	.48	.48	.47	.47	150.3

Table 21. CERES-Maize soil inputs for the 1983 simulations and the long term simulation runs using the generated weather data.

TRT=NDTMP-CST							
			SALB	U		SWCON	CN2
1			.11	12.00		.020	70.00
DLAYR(L)	LL(L)	DUL(L)		SAT(L)	WR(L)		
10.	0.340	0.490		0.502	0.900		
10.	0.340	0.500		0.512	0.200		
15.	0.334	0.464		0.470	0.150		
15.	0.344	0.470		0.474	0.150		
20.	0.344	0.470		0.474	0.100		
20.	0.344	0.470		0.474	0.050		
20.	0.344	0.470		0.474	0.010		
00.0							
TRT=DTMP-NST							
2			.11	12.00		.020	50.00
10.	0.320	0.470		0.514	0.900		
10.	0.320	0.480		0.520	0.600		
15.	0.334	0.464		0.486	0.300		
15.	0.344	0.470		0.474	0.150		
20.	0.344	0.470		0.474	0.100		
20.	0.344	0.470		0.474	0.050		
20.	0.344	0.470		0.474	0.010		
00.0							

Table 22. CERES-Maize soil inputs for the 1984 simulations.

TRT=NDT-MP CST						
			SALB	U	SWCON	CN2
1			.11	12.00	.020	70.00
DLAYR(L)	LL(L)	DUL(L)		SAT(L)	WR(L)	
10.	0.310	0.460		0.476	0.900	
10.	0.310	0.470		0.486	0.200	
15.	0.334	0.464		0.470	0.150	
15.	0.344	0.470		0.474	0.150	
20.	0.344	0.470		0.474	0.100	
20.	0.344	0.470		0.474	0.050	
20.	0.344	0.470		0.474	0.010	
00.0						
TRT=DT-MP NST						
2			.11	12.00	.020	50.00
10.	0.270	0.420		0.476	0.900	
10.	0.270	0.430		0.482	0.600	
15.	0.314	0.444		0.470	0.300	
15.	0.344	0.470		0.474	0.150	
20.	0.344	0.470		0.474	0.100	
20.	0.344	0.470		0.474	0.050	
20.	0.344	0.470		0.474	0.010	
00.0						

Table 23. CERES-Maize inputs for the 1985 simulations.

TRT=NDT-MP CST						
			SALB	U	SWCON	CN2
1			.11	12.00	.020	20.00
DLAYR(L)	LL(L)	DUL(L)		SAT(L)	WR(L)	
10.	0.340	0.490		0.502	0.900	
10.	0.340	0.500		0.512	0.200	
15.	0.334	0.464		0.470	0.150	
15.	0.344	0.470		0.474	0.150	
20.	0.344	0.470		0.474	0.100	
20.	0.344	0.470		0.474	0.050	
20.	0.344	0.470		0.474	0.010	
00.0						
TRT=DT-MP NST						
2			.11	12.00	.020	20.00
10.	0.320	0.470		0.514	0.905	
10.	0.320	0.480		0.520	0.600	
15.	0.334	0.464		0.486	0.300	
15.	0.344	0.470		0.474	0.150	
20.	0.344	0.470		0.474	0.100	
20.	0.344	0.470		0.474	0.050	
20.	0.344	0.470		0.474	0.010	
00.0						

Table 24. Model output produced by the original version of CERES-Maize.

VARIETY NUMBER 27 VARIETY NAME PIO 3901

LAT =43.3 , SOWING DEPTH = 5.0 CM , PLANT POP = 5.4 PLANTS/M**2

GENETIC CONSTANTS P1 =154. P2 =.30 P5=685. G2 =560. G3 =11.
SOIL ALBEDO= .11 U=12.0 SWCON= .02 RUNOFF CURVE NO.=90. SOIL NO.= 2

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 10.	.320	.470	.514	.150	.470	.900
10.- 20.	.320	.480	.520	.160	.480	.600
20.- 35.	.334	.464	.486	.130	.464	.300
35.- 50.	.344	.470	.474	.126	.470	.150
50.- 70.	.344	.470	.474	.126	.470	.100
70.- 90.	.344	.470	.474	.126	.470	.050
90.- 110.	.344	.470	.474	.126	.470	.010
110.0	37.2	51.7	53.2	14.5	51.7	TOTAL PROFILE

THE PROGRAM STARTED ON JULIAN DATE 128

DAY	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	CUMULATIVE BIOMASS	LAI	CSD1	WATER BALANCE COMPONENTS AFTER GERMINATION ET	PREC	PESW
5/12/83	132	7.	SOWING						
5/13/83	133	14.	GERMINATION				18.	0.	12.7
5/28/83	148	45.	EMERGENCE				34.	61.	12.8
6/15/83	166	156.	END JUVENILE STAGE	5.	.14	.00	78.	116.	12.1
6/21/83	172	223.	TASSEL INITIATION	16.	.34	.00	91.	116.	10.8
7/20/83	201	644.	SILKING, LNO= 16.0	560.	2.44	.05	229.	183.	2.9
8/ 1/83	213	823.	BEGIN GRAIN FILL	789.	2.34	.07	282.	230.	1.5
9/ 5/83	248	1295.	END FILL, GPP=438.	1296.	.67	.51	377.	294.	-2.7
9/ 8/83	251	1327.	PHYSIO MATURITY	1296.	.67				

	PREDICTED VALUES	MEASURED VALUES
SILKING JD	201	206
MATURITY JD	251	267
GRAIN YIELD KG/HA (15)	7601.	9130.
KERNEL WEIGHT G (DRY)	.2718	.2200
FINAL GPSM	2363.	4672.
GRAINS/EAR	438.	584.
MAX. LAI	2.44	4.00
BIOMASS G/SM	1296.	1008.

CROP MATURE FOR SINGLE YEAR RUN

Table 25. Model output produced by the modified version of CERES-Maize.

VARIETY NUMBER 27 VARIETY NAME PIO 3901

LAT =43.3 , SOWING DEPTH = 5.0 CM , PLANT POP = 5.4 PLANTS/M**2

GENETIC CONSTANTS P1 =154. P2 =.30 P5=685. G2 =560. G3 =11.
SOIL ALBEDO= .11 U=12.0 SWCON= .02 RUNOFF CURVE NO.=90. SOIL NO.= 2

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 10.	.320	.470	.514	.150	.470	.900
10.- 20.	.320	.480	.520	.160	.480	.600
20.- 35.	.334	.464	.486	.130	.464	.300
35.- 50.	.344	.470	.474	.126	.470	.150
50.- 70.	.344	.470	.474	.126	.470	.100
70.- 90.	.344	.470	.474	.126	.470	.050
90.- 110.	.344	.470	.474	.126	.470	.010
110.0	37.2	51.7	53.2	14.5	51.7	TOTAL PROFILE

THE PROGRAM STARTED ON JULIAN DATE 128

DAY	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	CUMULATIVE		WATER BALANCE COMPONENTS AFTER GERMINATION			
				BIOMASS	LAI	CSD1	ET	PREC	PESW
5/12/83	132	7.	SOWING						
5/13/83	133	14.	GERMINATION				18.	0.	12.7
5/28/83	148	45.	EMERGENCE				38.	61.	14.2
6/15/83	166	156.	END JUVENILE STAGE	6.	.14	.00	97.	116.	12.6
6/21/83	172	223.	TASSEL INITIATION	17.	.35	.00	110.	116.	11.2
7/20/83	201	644.	SILKING, LNO= 16.0	634.	2.71	.01	258.	183.	4.3
8/ 1/83	213	823.	BEGIN GRAIN FILL	882.	2.48	.01	315.	230.	2.4
9/ 5/83	248	1295.	END FILL, GPP=448.	1477.	.70	.46	419.	294.	-2.3
9/ 8/83	251	1327.	PHYSIO MATURITY	1477.	.70				

	PREDICTED VALUES	MEASURED VALUES
SILKING JD	201	206
MATURITY JD	251	267
GRAIN YIELD KG/HA (15)	8789.	9130.
KERNEL WEIGHT G (DRY)	.3069	.2200
FINAL GPSM	2420.	4672.
GRAINS/EAR	448.	584.
MAX. LAI	2.71	4.00
BIOMASS G/SM	1477.	1008.

CROP MATURE FOR SINGLE YEAR RUN

Table 26. CERES-Maize output for the conventional fall and spring tillage treatment (NDTMP-CST) using the 1983 weather data.

VARIETY NUMBER 27 VARIETY NAME PIO 3901

LAT =43.3 , SOWING DEPTH = 5.0 CM , PLANT POP = 5.4 PLANTS/M**2

GENETIC CONSTANTS P1 =154. P2 =.30 P5=685. G2 =560. G3 =11.
SOIL ALBEDO= .11 U=12.0 SWCON= .02 RUNOFF CURVE NO.=70. SOIL NO.= 1

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 10.	.340	.490	.502	.150	.490	.900
10.- 20.	.340	.500	.512	.160	.500	.200
20.- 35.	.334	.464	.470	.130	.464	.150
35.- 50.	.344	.470	.474	.126	.470	.150
50.- 70.	.344	.470	.474	.126	.470	.100
70.- 90.	.344	.470	.474	.126	.470	.050
90.- 110.	.344	.470	.474	.126	.470	.010
110.0	37.6	52.1	52.7	14.5	52.1	TOTAL PROFILE

THE PROGRAM STARTED ON JULIAN DATE 128

DAY	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	WATER BALANCE COMPONENTS CUMULATIVE AFTER GERMINATION					
				BIOMASS	LAI	CSD1	ET	PREC	PESW
5/12/83	132	7.	SOWING						
5/13/83	133	14.	GERMINATION				18.	0.	12.7
5/28/83	148	45.	EMERGENCE				38.	61.	13.8
6/15/83	166	156.	END JUVENILE STAGE	6.	.14	.00	90.	116.	12.6
6/21/83	172	223.	TASSEL INITIATION	16.	.34	.00	103.	116.	11.3
7/20/83	201	644.	SILKING, LNO= 16.0	652.	2.76	.01	255.	183.	4.0
8/ 1/83	213	823.	BEGIN GRAIN FILL	898.	2.51	.00	312.	230.	2.2
9/ 5/83	248	1295.	END FILL, GPP=449.	1472.	.71	.47	415.	294.	-2.5
9/ 8/83	251	1327.	PHYSIO MATURITY	1472.	.71				

	PREDICTED VALUES	MEASURED VALUES
SILKING JD	201	206
MATURITY JD	251	267
GRAIN YIELD KG/HA (15)	8575.	8520.
KERNEL WEIGHT G (DRY)	.2987	.2200
FINAL GPSM	2426.	4672.
GRAINS/EAR	449.	584.
MAX. LAI	2.76	4.00
BIOMASS G/SM	1472.	1008.

CROP MATURE FOR SINGLE YEAR RUN

Table 27. CERES-Maize output for the deep tillage - controlled traffic treatment (DTMP-NST) using the 1983 weather data.

VARIETY NUMBER 27 VARIETY NAME PIO 3901

LAT =43.3 , SOWING DEPTH = 5.0 CM , PLANT POP = 5.7 PLANTS/M**2

GENETIC CONSTANTS P1 =154. P2 =.30 P5=685. G2 =560. G3 =11.
SOIL ALBEDO= .11 U=12.0 SWCON= .02 RUNOFF CURVE NO.=50. SOIL NO.= 2

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 10.	.320	.470	.514	.150	.470	.900
10.- 20.	.320	.480	.520	.160	.480	.600
20.- 35.	.334	.464	.486	.130	.464	.300
35.- 50.	.344	.470	.474	.126	.470	.150
50.- 70.	.344	.470	.474	.126	.470	.100
70.- 90.	.344	.470	.474	.126	.470	.050
90.- 110.	.344	.470	.474	.126	.470	.010
110.0	37.2	51.7	53.2	14.5	51.7	TOTAL PROFILE

THE PROGRAM STARTED ON JULIAN DATE 128

DAY	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	BIOMASS	LAI	CSD1	ET	PREC	PESW
				WATER BALANCE COMPONENTS CUMULATIVE AFTER GERMINATION					
5/12/83	132	7.	SOWING						
5/13/83	133	14.	GERMINATION				18.	0.	12.7
5/28/83	148	45.	EMERGENCE				38.	61.	13.9
6/15/83	166	156.	END JUVENILE STAGE	6.	.15	.00	88.	116.	13.1
6/21/83	172	223.	TASSEL INITIATION	17.	.36	.00	101.	116.	11.8
7/20/83	201	644.	SILKING, LNO= 16.0	676.	2.89	.01	254.	183.	4.4
8/ 1/83	213	823.	BEGIN GRAIN FILL	925.	2.63	.03	310.	230.	2.8
9/ 5/83	248	1295.	END FILL, GPP=443.	1546.	.75	.45	417.	294.	-2.4
9/ 8/83	251	1327.	PHYSIO MATURITY	1546.	.75				

	PREDICTED VALUES	MEASURED VALUES
SILKING JD	201	206
MATURITY JD	251	267
GRAIN YIELD KG/HA (15)	9157.	10200.
KERNEL WEIGHT G (DRY)	.3067	.2200
FINAL GPSM	2523.	4672.
GRAINS/EAR	443.	584.
MAX. LAI	2.89	4.00
BIOMASS G/SM	1546.	1008.

CROP MATURE FOR SINGLE YEAR RUN

Table 28. CERES-Maize output for the conventional fall and spring tillage treatment (NDTMP-CST) using the 1984 weather data.

VARIETY NUMBER 27 VARIETY NAME PIO 3901

LAT =43.3 , SOWING DEPTH = 5.0 CM , PLANT POP = 6.9 PLANTS/M**2

GENETIC CONSTANTS P1 =154. P2 =.30 P5=685. G2 =560. G3 =11.
SOIL ALBEDO= .11 U=12.0 SWCON= .02 RUNOFF CURVE NO.=70. SOIL NO.= 1

DEPTH-CM		LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.-	10.	.310	.460	.476	.150	.460	.900
10.-	20.	.310	.470	.486	.160	.470	.200
20.-	35.	.334	.464	.470	.130	.464	.150
35.-	50.	.344	.470	.474	.126	.470	.150
50.-	70.	.344	.470	.474	.126	.470	.100
70.-	90.	.344	.470	.474	.126	.470	.050
90.-	110.	.344	.470	.474	.126	.470	.010
	110.0	37.0	51.5	52.2	14.5	51.5	TOTAL PROFILE

THE PROGRAM STARTED ON JULIAN DATE 118

DAY	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	CUMULATIVE BIOMASS	LAI	CSD1	WATER BALANCE COMPONENTS AFTER GERMINATION ET	PREC	PESW
5/ 3/84	124	1.	SOWING						
5/ 4/84	125	3.	GERMINATION				20.	1.	12.6
5/19/84	140	54.	EMERGENCE				23.	24.	12.6
6/ 6/84	158	155.	END JUVENILE STAGE	6.	.16	.00	87.	104.	13.4
6/12/84	164	244.	TASSEL INITIATION	27.	.54	.00	111.	124.	12.4
7/20/84	202	691.	SILKING, LNO= 17.0	869.	4.06	.00	290.	249.	5.6
8/ 3/84	216	860.	BEGIN GRAIN FILL	1213.	3.67	.00	354.	255.	-.2
9/11/84	255	1334.	END FILL, GPP=439.	1967.	.00	.26	493.	407.	.2
9/14/84	258	1366.	PHYSIO MATURITY	1967.	.00				

	PREDICTED VALUES	MEASURED VALUES
SILKING JD	202	206
MATURITY JD	258	267
GRAIN YIELD KG/HA (15%)	11301.	12600.
KERNEL WEIGHT G (DRY)	.3150	.2200
FINAL GPSM	3031.	4672.
GRAINS/EAR	439.	584.
MAX. LAI	4.06	4.00
BIOMASS G/SM	1967.	1008.

CROP MATURE FOR SINGLE YEAR RUN

Table 29. CERES-Maize output for the deep tillage - controlled traffic treatment (DTMP-NST) using the 1984 weather data.

VARIETY NUMBER 27 VARIETY NAME PIO 3901

LAT =43.3 , SOWING DEPTH = 5.0 CM , PLANT POP = 6.6 PLANTS/M**2

GENETIC CONSTANTS P1 =154. P2 =.30 P5=685. G2 =560. G3 =11.
SOIL ALBEDO= .11 U=12.0 SWCON= .02 RUNOFF CURVE NO.=50. SOIL NO.= 2

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 10.	.270	.420	.476	.150	.420	.900
10.- 20.	.270	.430	.482	.160	.430	.600
20.- 35.	.314	.444	.470	.130	.444	.300
35.- 50.	.344	.470	.474	.126	.470	.150
50.- 70.	.344	.470	.474	.126	.470	.100
70.- 90.	.344	.470	.474	.126	.470	.050
90.- 110.	.344	.470	.474	.126	.470	.010
110.0	35.9	50.4	52.2	14.5	50.4	TOTAL PROFILE

THE PROGRAM STARTED ON JULIAN DATE 118

DAY	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	BIOMASS	LAI	CSD1	ET	PREC	PESW
				WATER BALANCE COMPONENTS CUMULATIVE AFTER GERMINATION					
5/ 3/84	124	1.	SOWING						
5/ 4/84	125	3.	GERMINATION				20.	1.	12.6
5/19/84	140	54.	EMERGENCE				23.	24.	12.6
6/ 6/84	158	155.	END JUVENILE STAGE	6.	.15	.00	80.	104.	14.0
6/12/84	164	244.	TASSEL INITIATION	26.	.52	.00	103.	124.	13.1
7/20/84	202	691.	SILKING, LNO= 17.0	840.	3.91	.00	282.	249.	5.7
8/ 3/84	216	860.	BEGIN GRAIN FILL	1156.	3.53	.00	346.	255.	-.1
9/11/84	255	1334.	END FILL, GPP=443.	1889.	.00	.26	484.	407.	.4
9/14/84	258	1366.	PHYSIO MATURITY	1889.	.00				

	PREDICTED VALUES	MEASURED VALUES
SILKING JD	202	206
MATURITY JD	258	267
GRAIN YIELD KG/HA (15)	10926.	11700.
KERNEL WEIGHT G (DRY)	.3160	.2200
FINAL GPSM	2922.	4672.
GRAINS/EAR	443.	584.
MAX. LAI	3.91	4.00
BIOMASS G/SM	1889.	1008.

CROP MATURE FOR SINGLE YEAR RUN

Table 30. CERES-Maize output for the conventional fall and spring tillage treatment (NDTMP-CST) using the 1985 weather data.

VARIETY NUMBER 27 VARIETY NAME PIO 3901

LAT =43.3 , SOWING DEPTH = 5.0 CM , PLANT POP = 4.6 PLANTS/M**2

GENETIC CONSTANTS P1 =154. P2 =.30 P5=685. G2 =560. G3 =11.
SOIL ALBEDO= .11 U=12.0 SWCON= .02 RUNOFF CURVE NO.=20. SOIL NO.= 1

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 10.	.340	.490	.502	.150	.490	.900
10.- 20.	.340	.500	.512	.160	.500	.200
20.- 35.	.334	.464	.470	.130	.464	.150
35.- 50.	.344	.470	.474	.126	.470	.150
50.- 70.	.344	.470	.474	.126	.470	.100
70.- 90.	.344	.470	.474	.126	.470	.050
90.- 110.	.344	.470	.474	.126	.470	.010
110.0	37.6	52.1	52.7	14.5	52.1	TOTAL PROFILE

THE PROGRAM STARTED ON JULIAN DATE 117

DAY	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	BIOMASS	LAI	CSD1	ET	PREC	PESW
				WATER BALANCE COMPONENTS CUMULATIVE AFTER GERMINATION					
5/ 3/85	123	3.	SOWING						
5/ 4/85	124	7.	GERMINATION				21.	0.	12.6
5/12/85	132	59.	EMERGENCE				5.	3.	12.1
5/31/85	151	167.	END JUVENILE STAGE	5.	.13	.00	46.	49.	13.6
6/ 6/85	157	218.	TASSEL INITIATION	14.	.29	.00	63.	58.	11.9
7/15/85	196	654.	SILKING, LNO= 16.0	538.	2.36	.00	235.	124.	1.1
7/28/85	209	816.	BEGIN GRAIN FILL	673.	1.88	.25	285.	162.	-.2
9/ 7/85	250	1305.	END FILL, GPP=441.	1210.	.55	.26	417.	440.	14.5
9/ 9/85	252	1334.	PHYSIO MATURITY	1210.	.55				

	PREDICTED VALUES	MEASURED VALUES
SILKING JD	196	206
MATURITY JD	252	267
GRAIN YIELD KG/HA (15)	7702.	8170.
KERNEL WEIGHT G (DRY)	.3206	.2200
FINAL GPSM	2030.	4672.
GRAINS/EAR	441.	584.
MAX. LAI	2.36	4.00
BIOMASS G/SM	1210.	1008.

CROP MATURE FOR SINGLE YEAR RUN

Table 31. CERES-Maize output for the deep tillage - controlled traffic treatment (DTMP-NST) using the 1985 weather data.

VARIETY NUMBER 27 VARIETY NAME PIO 3901

LAT =43.3 , SOWING DEPTH = 5.0 CM , PLANT POP = 5.4 PLANTS/M**2

GENETIC CONSTANTS P1 =154. P2 =.30 P5=685. G2 =560. G3 =11.
SOIL ALBEDO= .11 U=12.0 SWCON= .02 RUNOFF CURVE NO.=20. SOIL NO.= 2

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 10.	.320	.470	.514	.150	.470	.905
10.- 20.	.320	.480	.520	.160	.480	.600
20.- 35.	.334	.464	.486	.130	.464	.300
35.- 50.	.344	.470	.474	.126	.470	.150
50.- 70.	.344	.470	.474	.126	.470	.100
70.- 90.	.344	.470	.474	.126	.470	.050
90.- 110.	.344	.470	.474	.126	.470	.010
110.0	37.2	51.7	53.2	14.5	51.7	TOTAL PROFILE

THE PROGRAM STARTED ON JULIAN DATE 117

DAY	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	BIOMASS	LAI	CSD1	ET	PREC	PESW
				CUMULATIVE		WATER BALANCE COMPONENTS AFTER GERMINATION			
5/ 3/85	123	3.	SOWING						
5/ 4/85	124	7.	GERMINATION				21.	0.	12.6
5/12/85	132	59.	EMERGENCE				5.	3.	12.1
5/31/85	151	167.	END JUVENILE STAGE	6.	.16	.00	46.	49.	13.6
6/ 6/85	157	218.	TASSEL INITIATION	16.	.34	.00	64.	58.	11.8
7/15/85	196	654.	SILKING, LNO= 16.0	587.	2.64	.01	239.	124.	.8
7/28/85	209	816.	BEGIN GRAIN FILL	731.	2.06	.32	285.	162.	-.1
9/ 7/85	250	1305.	END FILL, GPP=421.	1299.	.62	.26	417.	440.	14.8
9/ 9/85	252	1334.	PHYSIO MATURITY	1299.	.62				

	PREDICTED VALUES	MEASURED VALUES
SILKING JD	196	206
MATURITY JD	252	267
GRAIN YIELD KG/HA (15)	8200.	9130.
KERNEL WEIGHT G (DRY)	.3048	.2200
FINAL GPSM	2273.	4672.
GRAINS/EAR	421.	584.
MAX. LAI	2.64	4.00
BIOMASS G/SM	1299.	1008.

CROP MATURE FOR SINGLE YEAR RUN

APPENDIX FIGURES

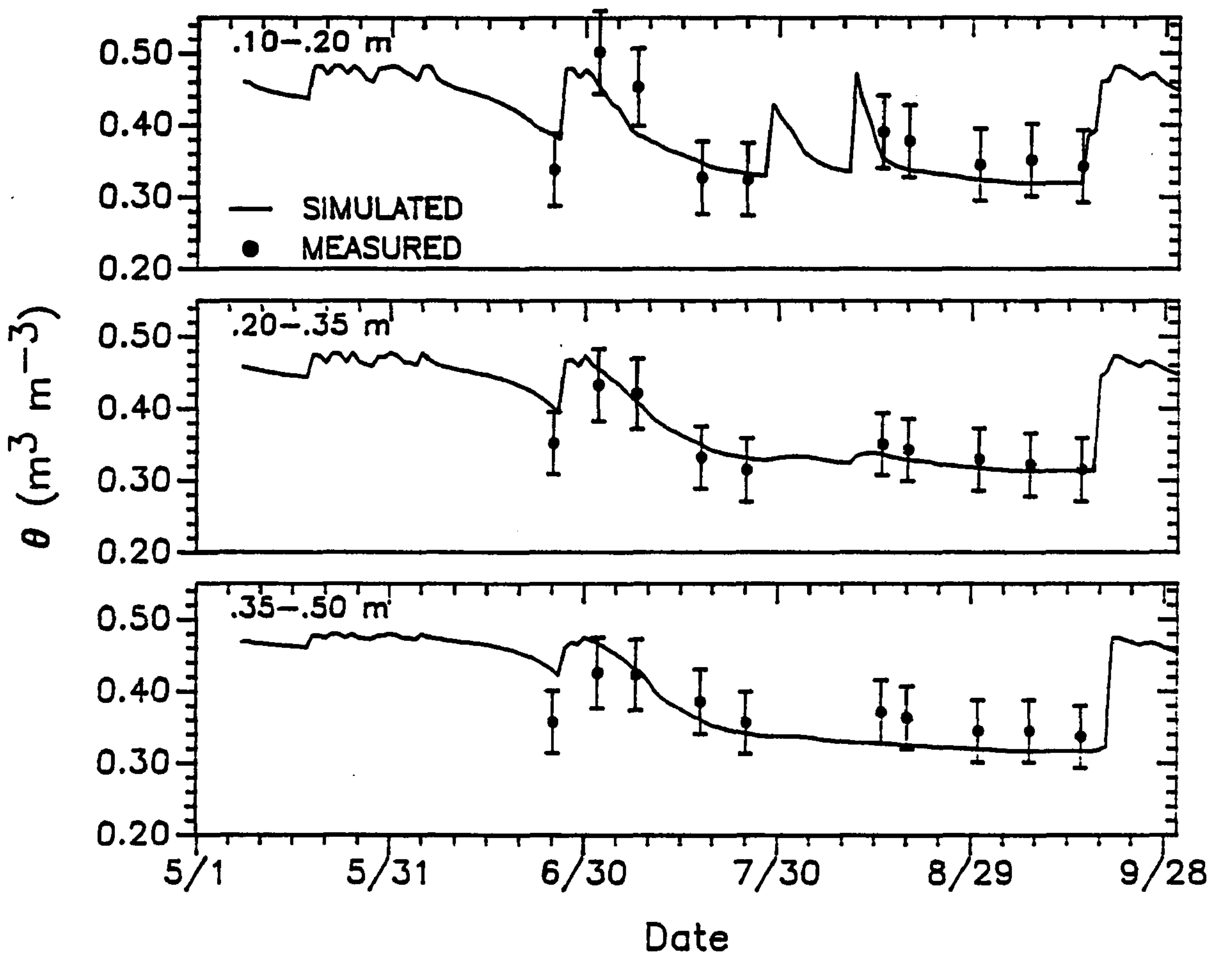

Figure 1. Comparison of measured and simulated water contents at three depths under the NDTMP-CST treatment in 1983.

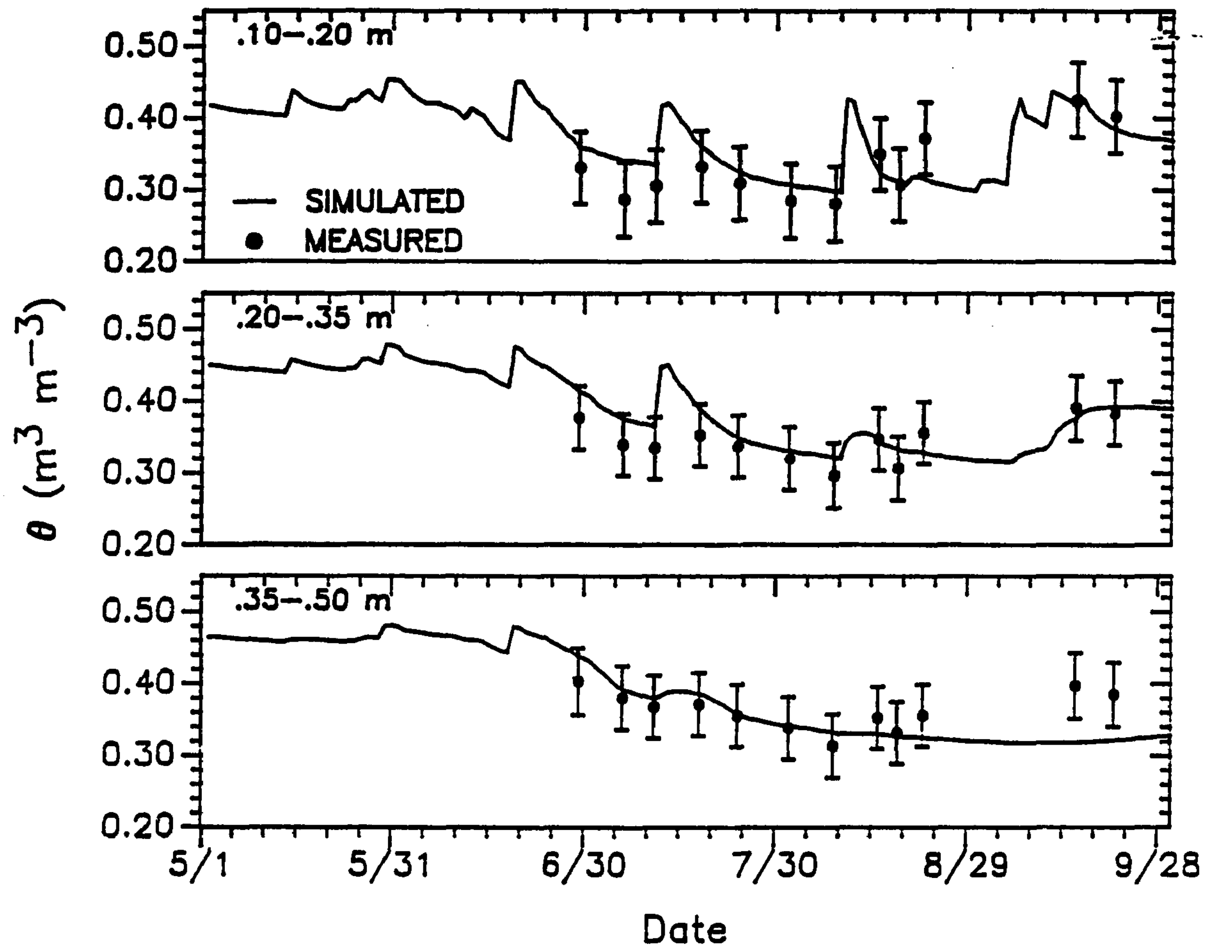

Figure 2. Comparison of measured and simulated water contents at three depths under the NDTMP-CST treatment in 1984.

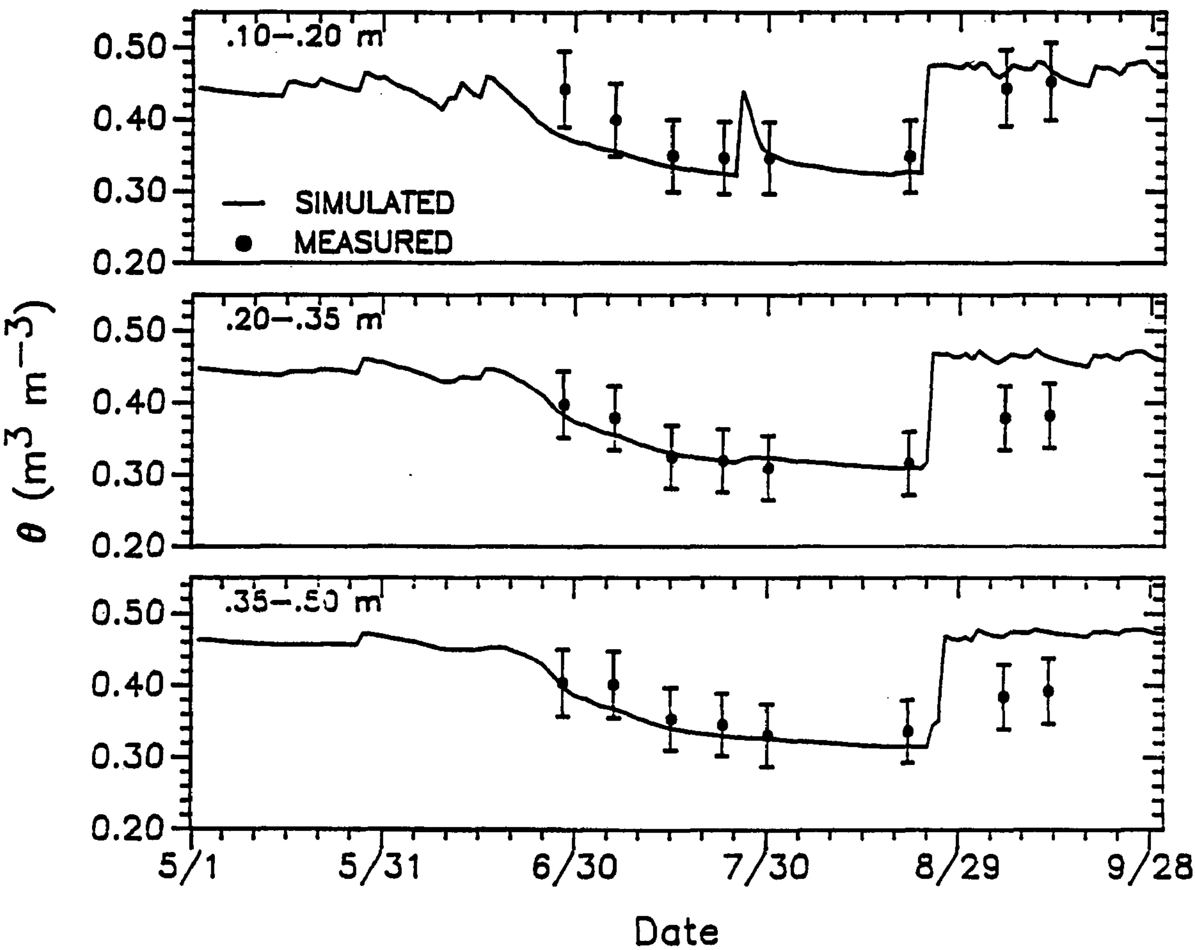

Figure 3. Comparison of measured and simulated water contents at three depths under the NDTMP-CST treatment in 1985.

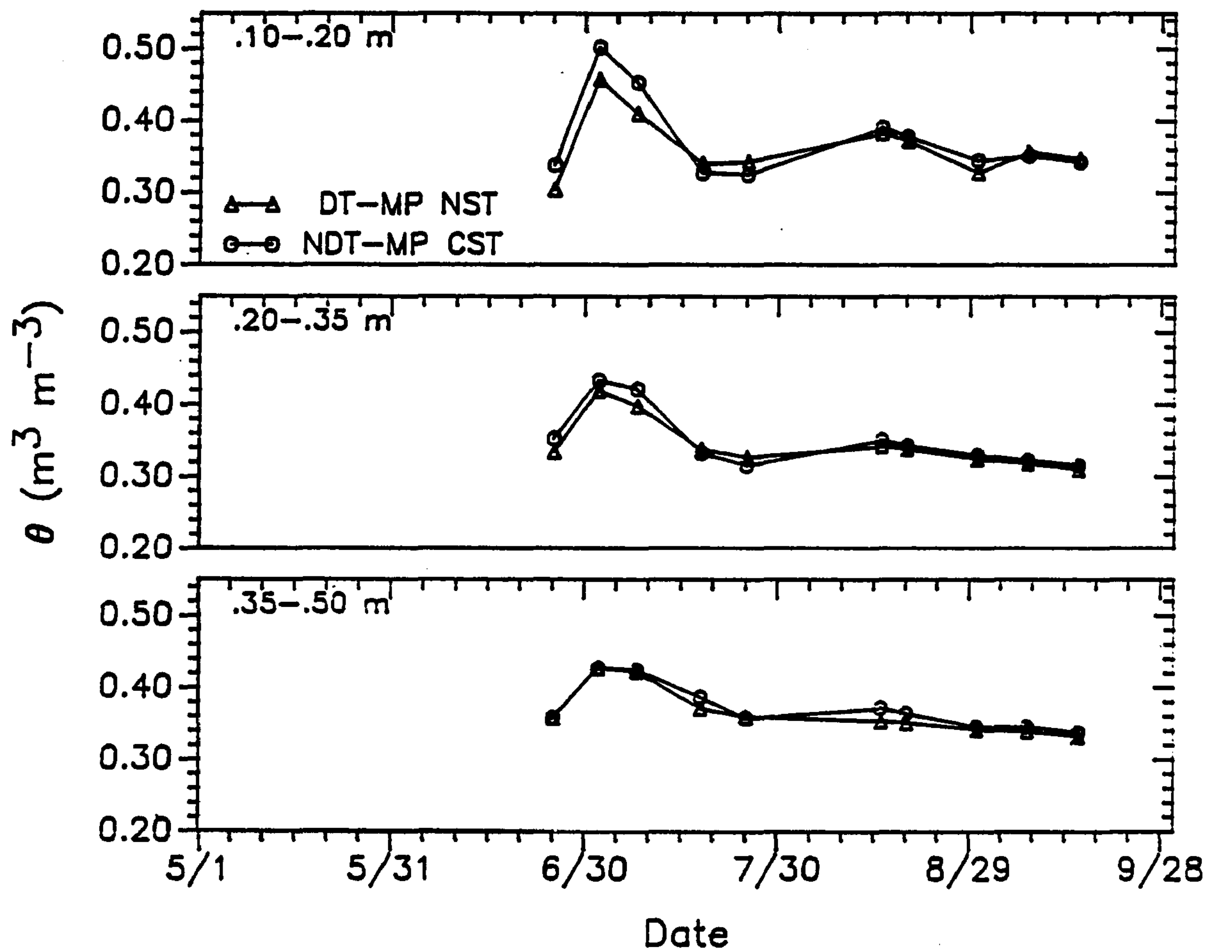

Figure 4. Comparison of measured water contents under the NDTMP-CST and DTMP-NST treatments for 1983.

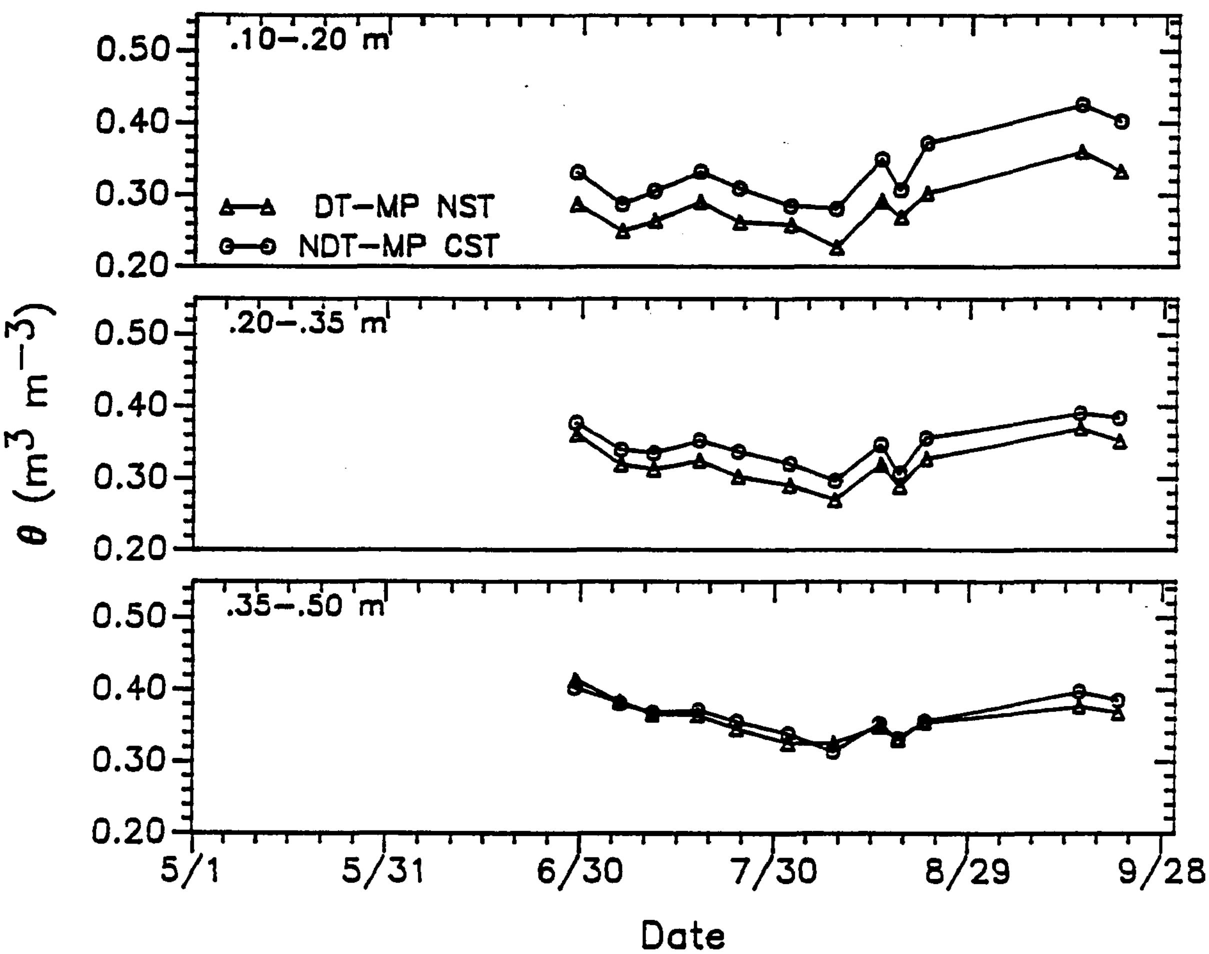

Figure 5. Comparison of measured water contents under the NDTMP-CST and DTMP-NST treatments for 1984.

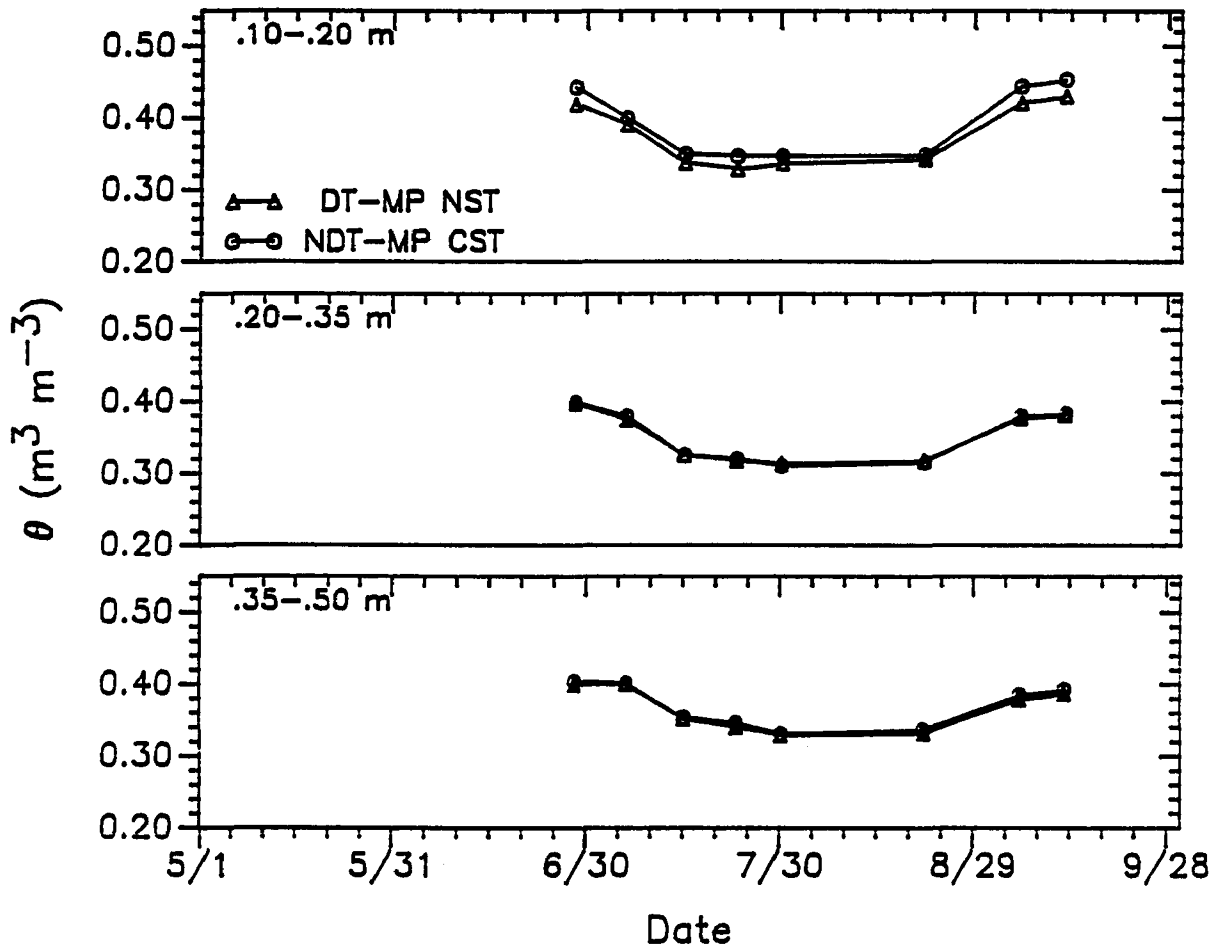

Figure 6. Comparison of measured water contents under the NDTMP-CST and DTMP-NST treatments for 1985.

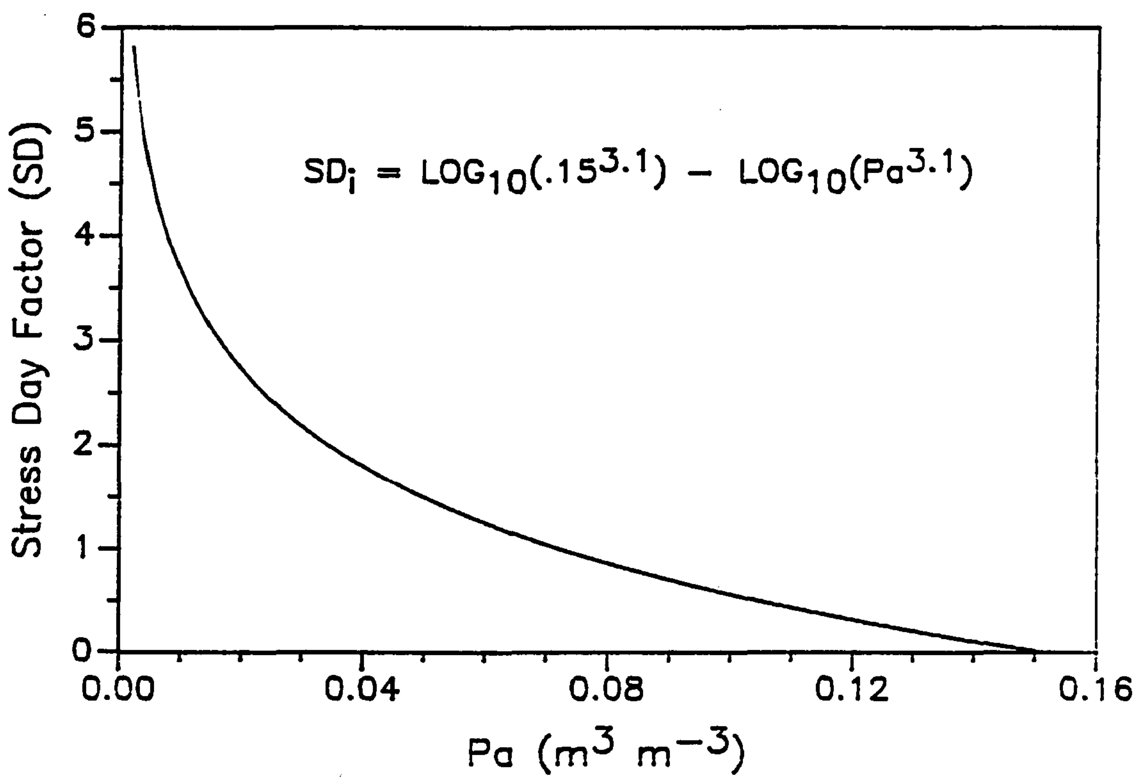

Figure 7. Variation of the stress day factor with soil air porosity (Pa).