

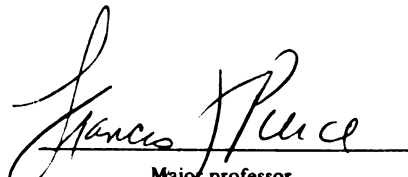
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**THE EFFECT OF ZONE TILLAGE ON THE GROWTH AND
DEVELOPMENT OF RUSSET BURBANK POTATOES**

By

Charlotte Gaye Burpee

A THESIS

**Submitted to
Michigan State University
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ABSTRACT

THE EFFECT OF ZONE TILLAGE ON THE GROWTH AND DEVELOPMENT OF RUSSET BURBANK POTATOES

By

Charlotte Gaye Burpee

Compaction and erosion decrease yields and quality of potatoes (Solanum tuberosum L.). Zone tillage, a system of subsoiling in the row, while leaving a rye cover crop undisturbed for erosion control, increased yields and quality of Russet Burbank potatoes on a central Michigan sandy loam soil. Zone tillage decreased soil bulk density 13% and soil strength 46%, while improving soil air-filled porosity and water retention at the depth of compaction in the zone of root and tuber development. Yields were increased 8 and 19%, but only when plant populations were sufficiently dense (25 cm seed spacings, rather than the standard 30 to 36 cm for this variety). Zone tillage yield increases were due to increased production of larger tubers. Tillage affected the magnitude and temporal patterns of root development. Zone tillage plants produced 100 to 240% more roots at greater depths. Potato plants responded to drought by decreasing production of above-ground biomass, increasing production of roots and senescing later.

In Memoriam

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INTRODUCTION

Due to their stationary nature, plants are subject to a multitude of stresses from which they cannot escape. Man's attempts to lessen the impact of environmental stresses on plants through selection of improved cultivars or through altering cultural practices that ameliorate soil, climatic or other environmental conditions are as old as man's first attempts to grow food. Today increasing population, increasing food deficits and decreasing availability of cultivable land intensify our need to reduce plant environmental stress in order to increase crop productivity, while maintaining or improving the soil resource. A key challenge of the 21st century will be providing more food for expanding human populations without reducing the quality of the physical and biological environments.

Two issues of major concern in protecting the soil resource are compaction, common in industrialized nations and due mainly to use of heavy machinery, and erosion, common throughout the world and associated with pressure on farmers to produce more. Lack of ground cover for

erosion protection is the direct cause, which in Third World nations is the result of increased use of firewood for fuel, decreased fallow periods in slash and burn systems and use of marginal lands for cultivation.

For food deficit (food importing) nations, an additional, but crucial factor is quality of diet and amount of protein in the diet. The world's indigent tend to subsist on high-carbohydrate low-protein diets, resulting in higher rates of infant mortality, greater incidence of disease and malnutrition and shorter lifespans.

The potato, with its short vegetative cycle, high nutritive value and protein content, high productivity, great genetic diversity and wide environmental adaptability is one of the most important food crops grown worldwide and is becoming more so. In Michigan potatoes are produced primarily on sandy soils (95%) and muck soils, which are very susceptible to wind and water erosion. In addition, since potatoes are a lucrative crop, soils planted to potatoes are intensively cultivated. Increasingly heavy wheel traffic year after year compacts the soil just below the depth of normal tillage. Increased soil density and increased mechanical strength in compacted soil layers restrict root growth and reduce yields and potato quality.

Because potatoes have high oxygen requirements and an ethylene-intolerant root system, they are more sensitive to soil physical conditions than other crops. Thus, improving the soil environment in the zone of root growth and tuber development is beneficial to the entire plant. Research with a tillage system of deep tillage in the row while leaving a cover crop of rye undisturbed between rows (zone

tillage), has increased yields and improved quality of Russet Burbank potatoes on compacted sandy loam soils in Michigan.

The objectives of this study were to determine the effect of zone tillage on soil physical properties and soil water relations, on plant biomass production and yields and on root growth and development.

CHAPTER I
LITERATURE REVIEW: POTATO PLANT RESPONSE TO
SOIL PHYSICAL CONDITIONS

Wise management decisions, ones that will improve crop quality and increase yields while maintaining a productive soil environment, are impossible without knowledge of the effect of soil physical properties on plant growth above and below ground. Research concerned with soil-related effects on growth of potatoes fits into six general areas -- soil fertility, soil temperature, soil aeration and gas diffusion, soil moisture, soil mechanical resistance and compaction, and alteration of soil properties by tillage. These factors are inextricably related, and discussion of one involves discussion of the others. While all are important, this review will concentrate on the latter four. Soil fertility and soil temperature will be discussed briefly in light of points important to subsequent discussions. More detailed information on the effect of soil fertility and soil temperature on potatoes can be found in Burton (1967), Harris (1978) and Ivins and Milthorpe (1963).

Soil Fertility

Bushnell (1937) observed that although potato plants are frequently shallow rooted, deep rooting is associated with higher yields. By placing manure in the subsoil, he found that both yields and root growth at depth were increased. Kirkham et al. (1974) discovered that although absorption of nitrate N by potato roots in a sandy soil was most rapid from a depth of 16 cm (as compared to 64 cm), when all the nitrate was injected at the bottom of an 80-cm growth column, roots proliferated there and absorbed nitrogen at that depth. These data showed that when nitrate moved below the zone of maximum root extraction, roots were able to absorb nitrate N, but in decreasing quantities with increasing depth.

Soil Temperature

Optimum soil temperatures for tuber growth, yield and tuber quality range from 16° to 24° C and vary with soil nutrient content and plant growth stage (Yamaguchi et al., 1964; Nielsen et al., 1961; Epstein, 1966). At higher soil temperatures the per cent of deformed tubers increases and internal tuber browning, commonly called "heat" or "drought" necrosis, also increases (Yamaguchi et al., 1964; Lorenz, 1950). At cooler temperatures plant emergence is delayed, and when cooler temperatures are combined with compaction, the delaying effects

become additive (Yamaguchi et al., 1964; Sommerfeldt and Knutson, 1968). Soil temperature also significantly affects potato root concentration with depth, nutrient uptake of potato plants and plant water use efficiency (Epstein, 1966; Nielsen et al., 1961). Soil temperatures are decreased by both increased foliar shading and by increasing soil water content (Lorenz, 1950).

Soil Aeration and Gas Diffusion

Compared to other crops, potatoes have an exceptionally high oxygen requirement. Bushnell (1956a, 1956b) reported that potato roots absorbed oxygen at rates five to a hundred times higher (7 to 12 ml O₂ per hour per gram of oven-dried roots) than that reported for other plants. At less than normal concentrations of soil oxygen, tuber growth decreased and abnormalities increased. Bushnell concluded that potatoes thrive only when supplied with exceptional amounts of oxygen, in quantities that would only be available in more porous soils.

Lemon and Erickson (1952) ascertained that because active root surfaces are covered with a water film, what is crucial to roots is not the total soil oxygen concentration, but the diffusion rate of oxygen through gases and liquids. Gaseous diffusion is much slower through liquids than gases, so thickness of water films around roots or tubers is critical. Soil moisture content also affects oxygen diffusion rate, as does soil density. Dense soils slow oxygen diffusion as compared to loose soils (Bertrand and Kohnke, 1957).

More recent research has shown that the greatest adverse effects of low soil oxygen diffusion rates (ODR) are observed not with roots, but with tubers (Holder and Cary, 1984; Cary, 1985; Cary, 1986). Roots tolerate short periods of reduced ODR without affecting yields, but repeated low ODR levels cause increased deformities and increased tuber initiation, resulting in undersized, knobby tubers.

Jackson (1962) determined that optimum soil physical conditions for emergence and growth of potatoes in a sandy soil required 14% moisture content and a minimum ODR of $63 \times 10^{-8} \text{ g cm}^{-2} \text{ min}^{-1}$ ($105 \mu\text{g m}^{-2} \text{ s}^{-1}$) which was similar to the rate, $56 \times 10^{-8} \text{ g cm}^{-2} \text{ min}^{-1}$ ($93 \mu\text{g m}^{-2} \text{ s}^{-1}$), reported to Jackson by Erickson in a personal communication. Cary (1985) found that growing tubers consume $15 \mu\text{g O}_2 \text{ cm}^{-2} \text{ hr}^{-1}$ ($42 \mu\text{g m}^{-2} \text{ s}^{-1}$). By subtraction and calculation of the mean of Jackson and Erickson's data, potato roots require a minimum of $57 \mu\text{g O}_2 \text{ m}^{-2} \text{ s}^{-1}$, which is $19 \mu\text{g O}_2 \text{ m}^{-2} \text{ s}^{-1}$ more than that reported by Stolzy as the minimum required for corn roots (Stolzy et al., 1961).

In a greenhouse experiment to separate the effects on root development of high soil bulk density from the effect of soil oxygen, Scott and Erickson (1964) found that although soil physical impedance (bulk density of 1.9 Mg m^{-3}) and low oxygen availability both inhibit root elongation, if extra oxygen is present, alfalfa and sugar beet roots are able to penetrate severely compacted soil layers. Their data suggest that low oxygen availability in the root zone, rather than mechanical impedance, is the crucial limiting factor in restriction of root growth. Work by Saini (1976) supports Scott and Erickson's conclusion. In a multiple field experiment, Saini ascertained which

soil physical property or combination of properties was the best predictor of soil productivity for potatoes. At a depth of 20 to 28 cm, where most compacted layers are located, Saini compared the effect on yield of soil texture, ODR, bulk density, soil resistance (as measured by penetrometer) and organic matter content. While there was a significant inverse relationship between either bulk density or penetrometer readings and crop performance (provided no other factor was limiting), the one factor that was highly correlated with marketable yield was oxygen diffusion rate. These data suggest that reduced aeration and ODR due to lower air-filled porosity in compact soils is the soil property which is most deleterious to potatoes.

However, key factors in plant physiology and composition of soil gases under anaerobic conditions were overlooked in these studies. In 1969 two scientific reports about a natural growth hormone were published. The hormone inhibits longitudinal cell expansion while promoting lateral cell expansion. This hormone, ethylene, evolves in its gaseous state in increasing concentrations in anaerobic or waterlogged soils following rapid decreases in oxygen concentration (Smith and Russell, 1969). Smith and Russell reported concentrations of 9 to 10 ppm ethylene under anaerobic conditions, compared to .07 to .14 ppm in aerated soils. Barley root elongation was reduced 50% at ethylene concentrations of 1 ppm and stopped at 10 ppm.

In 1969 Catchpole and Hillman also published results from research on tuber initiation in the presence of ethylene gas. Ethylene inhibited root development, extension growth of sprouts and stolons and caused swelling of all rapidly expanding regions -- the sub-apical regions of

the stolons, stem and axillary buds. Swellings at the end of stolons where tubers were initiating contained little or no starch, though they were similar in morphology and anatomy to normal tubers at a similar stage of development.

Later studies elucidated soil physical conditions under which ethylene is generated (Smith and Restall, 1971; Smith and Dowdell, 1974). Ethylene concentrations of 20 ppm were detected after 10 days in an anaerobic soil at 20° C. When oxygen concentrations decreased, ethylene was produced, and the rate of production rose logarithmically in the spring with increasing soil temperature. Ethylene concentrations also increased with additions of microbial substrates, with increasing soil moisture content, with increasing soil density and with depth from the soil surface. Increasing temperatures were correlated with increased oxygen uptake by roots and aerobic micro-organisms, thus depriving the soil environment of oxygen. Distance from the soil surface, soil density and moisture content all have a great effect on the transfer of gas by diffusion and thus on the rate at which gases such as oxygen and ethylene can diffuse into and out of the soil (Currie, 1984). Smith and Dowdell (1974) concluded that concentrations of ethylene which would inhibit root elongation would occur frequently in "heavy [fine-textured] soils during the spring and early summer and in light [coarse-textured] soils when unusually wet."

Further work examining the effects of ethylene on potato plant physiology has substantiated Catchpole and Hillman's (1969) work. Ethylene inhibits not only starch accumulation in tubers, but also accumulation of red anthocyanin (Cary, 1986). Ethylene inhibits

tuberization even in the presence of CO_2 (Mingo-Castel et al., 1976).

Finally, lowest yields occur with the highest levels of ethylene

(Campbell and Moreau, 1979).

Campbell and Moreau (1979) found that while yields in a sandy loam soil were highest in non-compacted, irrigated treatments, ethylene was present only in the compacted, flooded plots, and was absent in the non-irrigated, compacted plots.

In a comparison of compacted clay soils maintained at field capacity moisture content (soil moisture content at a soil suction of .33 bars), Smith and Restall (1971) found that oxygen concentrations in the less compacted (1.08 g cm^{-3}) soil dropped to 2%, and ethylene was not produced, while oxygen concentrations dropped to less than 1% in the more compact (1.35 g cm^{-3}) soil and ethylene evolved at a concentration of 7 ppm.

Soil Moisture

Compared to other crops, potatoes are very sensitive to water deficits (Singh, 1969; Fulton, 1970; Epstein and Grant, 1973; Phene and Sanders, 1976; Van Loon, 1981; Levy, 1983b). It is commonly thought that potatoes have a shallow, less extensive root system than other crops, which would explain their sensitivity to lack of water (Farris, 1934; Bushnell, 1937; Flocker et al., 1960). However, Fulton (1970)

reported potato root growth in non-compacted soils to a depth of 120 to 130 cm; Van Loon et al. (1985) observed root growth at the base of a subsoiled treatment to 95 cm and Lesczynski and Tanner (1976) cited reports of potato root growth to 90, 120 and 150 cm in non-compacted and muck soils. In addition, McEwen and Johnston (1979) found that subsoiling a non-compacted soil did not increase yields of potatoes. Thus, it seems likely that "shallow rooting" is not a species specific trait and is not the reason for the potato's sensitivity to drought stress.

A possible explanation is the inability of potato roots to penetrate dense layers (De Roo and Waggoner, 1961; Lesczynski and Tanner, 1976; Boone et al., 1978; Van Loon and Bouma, 1978; Van Loon, 1981; Boone et al., 1985; Van Loon et al., 1985). In the presence of a plowpan potato roots are prevented from access to available soil water at greater depths, and thus are more susceptible to soil moisture deficits. Another possibility suggested by Fulton (1970) was that since maximum root extension and amount of root proliferation by depth did not explain the greater need for soil moisture by potatoes over tomatoes and corn, perhaps the root system of potatoes had a lower capacity to absorb water relative to the plant's evapotranspirational demand.

The optimum soil water potential for maximizing potato growth depends on many variables. These factors include plant evapotranspiration rate, soil evaporation rate, soil hydraulic properties, capillary forces in the soil, gravity, rooting depth, age of crop, plant growth stage, potato variety, soil texture, plant and leaf resistance to water flow, solar radiation, air temperature and humidity

(Singh, 1969; Campbell et al., 1976; Van Loon, 1981).

Singh (1969) reported in his review of the literature that the amount of soil moisture needed to obtain maximum potato yields varied widely, from soil moistures of 40% to 70% of crop available water. Comparisons of irrigation rates on sandy soils and loams indicated that evapotranspiration rates needed to be replaced at 100% of evapotranspiration levels on sandy soils and 50 to 75% on loams, with some variation due to potato variety (Martin and Miller, 1980; Martin and Miller, 1983; Miller and Martin, 1983).

Substantial research has also been conducted on potato plant physiological responses to varying and insufficient amounts of soil water (Sparks, 1958; Singh, 1969; Van Loon, 1981). Drought stress decreased yields and per cent of U.S. No. 1's, increased the number of malformed, knobby, constricted tubers ("second-growth"), and in combination with high temperatures, caused sprouting of primary tubers prior to harvest, depriving them of additional carbohydrates (Robins and Domingo, 1956; Martin and Miller, 1980; Levy, 1983a; Wolfe et al., 1983; Susnoschi and Shimshi, 1985; Martin and Miller, 1986). The growth stage at which water deficits occurred caused different plant responses, different varietal responses and different types of deformities (Munns and Pearson, 1974; Painter and Augustin, 1976; Martin and Miller, 1980; Miller and Martin, 1985; Martin and Miller, 1986; Miller and Martin, 1987).

Potato tubers grow from the "eye" end, where the tuber is attached to the stolon. During periods of soil water deficits, tuber growth is retarded or stopped completely. Cells mature, and after water becomes

available again, normal growth does not resume. New growth is restricted to specific regions, occurring at the newer "rose" end, while the older "eye" end becomes stunted. Total yields are not necessarily affected, but total marketable yields, which are more important to farmers, are (Robins and Domingo, 1956; Moorby et al., 1975). Oblong, oval varieties such as Russet Burbank and White Rose are more susceptible to reduced yields and second-growth due to water deficits than are round, white varieties (Sparks, 1958; Martin and Miller, 1983; Wolfe et al., 1983; Martin and Miller, 1986; Miller and Martin, 1987). Water deficits for several days, followed by rewatering can cause more deformities than continuous drought stress (Levy, 1983a).

But the main physiological effect of drought stress is a reduction of the photosynthetic rate and supply of assimilate, rather than reduction of translocation rate (Chapman and Loomis, 1953; Munns and Pearson, 1974; Moorby et al., 1975). Other physiological responses include increased leaf diffusive resistance, decreased relative water content ($[(\text{fresh weight} - \text{dry weight}) / (\text{full turgid weight} - \text{dry weight})] \times 100$), decreased plant dry matter, changes in turgor pressure and stomatal opening/closure, decreased leaf water potential and decreased leaf permeability (Rawitz, 1969; Wilcox and Ashley, 1982; Levy, 1983b; Shimshi et al., 1983; Wolfe et al., 1983; Shimshi and Susnoschi, 1985).

Soil Mechanical Resistance and Compaction

The mechanization of agriculture has meant increased use of heavier machinery. Compacted soils often result, and soil physical properties are altered, particularly when compaction occurs under adverse moisture conditions. Changes include increased soil mechanical resistance (ability of soil to resist applied strength), increased bulk density, reduced pore volume, decreased water infiltration, altered water storage capacity, slowed diffusion of soil atmosphere and decreased air-filled porosity (Blake et al., 1960; Flocker et al., 1960; Struchtmeyer et al., 1963; Timm and Flocker, 1966; Boone et al., 1978). Boone et al. (1978) found that volumetric water content at a given pressure potential increased or decreased, depending on the degree of compaction. Boone et al. (1978) also showed that the potential for capillary rise in the topsoil increased with moderate compaction of the topsoil, but decreased with severe compaction. However, a compacted layer at some depth, as opposed to compacted topsoil, usually decreases the soil's water holding capacity (Flocker et al., 1960; Timm and Flocker, 1966; Campbell et al., 1974; Van Loon and Bouma, 1978). Timm and Flocker (1966) reported that it is easy to under- or over-irrigate soils in poor physical condition. Uncompacted soils with stable structural characteristics and no barrier to abundant, rapid root growth have "greater latitude in soil moisture tension."

Soil mechanical resistance to root and tuber growth depends on bulk

density, soil type and moisture content. Because root tips tend to follow the path of least resistance and bend when obstructed, it is difficult to quantify soil resistance to roots. Root tips encounter less resistance than probes or penetrometers (Barley and Greacen, 1967). Penetration resistance, which is used to measure soil strength, increases with increasing bulk density and decreases with increasing water content (Barley and Greacen, 1967; Campbell et al., 1974). At a given temperature root growth is influenced by mechanical resistance and moisture content, as well as soil oxygen concentration. Roots change their shape in response to soils with high mechanical resistance, increasing their volume per unit length. They then require higher soil oxygen concentrations in order to supply oxygen to interior root cells. Soil water content also affects root cells by supplying water for osmotic turgor, the mechanism by which roots exert pressure. As soil water pressure decreases, turgor is lost and root rigidity is reduced (Barley and Greacen, 1967).

In a study of cotton roots in four soils ranging from medium- to coarse-textured, root penetration was reduced as soil strength increased and was impeded at soil strengths greater than 25 bars, regardless of texture (Taylor et al., 1966). Eavis (1972) compared the separate and combined effects of mechanical impedance, poor aeration and water availability in pea seedling root growth. Roots were shorter and thicker as bulk density increased, as aeration decreased and as soil moisture decreased.

Studies of the effects of soil compaction on potato roots have shown shallow rooting and limited penetration through plowpans, most

rapid penetration at depth in non-compacted soils, slowed or inhibited root growth in compacted treatments, root length densities two to six times greater for non-compacted soils, inability of roots in compacted treatments to maintain capillary transport from mid-season to late-season between groundwater and the deepest roots and greater susceptibility to drought stress in compacted plots (Farris, 1934; De Roo and Waggoner, 1961; Lesczynski and Tanner, 1976; Boone et al., 1978; Van Loon and Bouma, 1978; Boone et al., 1985).

Compaction increases bulk density and soil mechanical resistance. Especially when occurring in the zone of tuber development, this leads to reduced total yields of potatoes and reduced marketable yields, or yields of U.S. No. 1's (Struchtmeyer et al., 1963; Flocker and Timm, 1964; Grimes and Bishop, 1971; Timm and Flocker, 1976). Additional plant-related effects include increased number and weights of deformed and small tubers, delayed emergence and plant stands reduced 30 to 40% (Beveridge, 1966; Flocker et al., 1960; McDole, 1975). Mean tuber size is often decreased, though not tuber numbers, and therefore tuber growth rate, not tuber set, is adversely affected by compaction (Blake et al., 1960; Van Loon and Bouma, 1978). Foliar growth may be slowed and leaf water potential lowered, size and duration of leaf stomatal opening may be decreased, and plants may show drought stress earlier and more severely than plants in non-compacted treatments (Van Loon and Bouma, 1978; Van Loon et al., 1985). Flocker and Timm (1964) reported that in a comparison of three irrigation levels and four fertilizer amounts, neither increased irrigation or increased fertilizer overcame damage to potato yields and tuber quality due to compaction.

The phenomenon of second-growth in compacted soils, which can be severe, is attributed to increased soil temperatures resulting from less foliar cover, which causes greater absorption of solar radiation (Van Loon and Bouma, 1978).

Alteration of Soil Properties by Tillage

Tillage, the mechanical manipulation of soil, has been used for weed control, residue management and altering of surface conditions for planting, irrigation, drainage and harvesting. It is used to mix soil layers, thus incorporating fertilizers, pesticides and organic matter. It is used to create good soil structure, which provides minimum resistance to roots and ensures rapid water infiltration and ample water retention, as well as adequate aeration and gas exchange (Kepner et al., 1982).

Several types of tillage are of importance. Conservation tillage is defined as "any tillage system that reduces loss of soil or water relative to conventional tillage" (Mannering and Fenster, 1983). Conservation tillage leaves a rough surface or surface residue which acts as a mulch to prevent erosion, reduces the amount and speed of runoff, reduces wind speed and evaporation, reduces crusting and increases infiltration and surface water storage capacity. Minimum tillage is a reduced number of tillage operations (compared to conventional tillage) and results in decreased energy use, decreased moisture loss, decreased erosion, fewer trips across the field and

reduced compaction. Minimum tillage may create management problems due to increased weeds or insects (Kepner et al., 1982). A form of minimum tillage, called precision tillage or zone tillage, involves subsoiling in the row.

As a tillage tool moves through the soil, any soil in the tool's path undergoes compressive stress resulting in shearing. Shearing of soils is different from shearing of other solids in that the shearing extends for some distance on either side of the shear plane. This is due to interlocking soil particles and the cohesive action of moisture films (Kepner et al., 1982).

There is a critical depth for all rigid tillage tools above which loosening occurs and below which compaction occurs. This critical depth depends on tine angle, width and lift height, as well as soil moisture and density (Spoor and Godwin, 1978). Thus, in machine-tilled fields, compaction occurs not only from wheel traffic but also from the action of tillage tools.

Tillage research with crops other than potatoes has been extensive. Minimum tillage for corn increased water infiltration 24%, decreased soil loss due to erosion 34% and, in the presence of surface mulch, completely eliminated soil and water losses (Mannering et al., 1966). Precision tillage with cotton increased yields in proportion to average soil strength prior to subsoiling (Carter and Tavernetti, 1968). Deep tillage of wheat resulted in improved soil conditions and increased yields (Kaddah, 1975). Subsoiling of a plowpan in South Carolina increased rooting depth for corn, increased water infiltration and soil-water availability, but did not increase millet yields unless irrigation

was withheld (Campbell et al., 1974). Tillage research with potatoes has produced varied results, which often depend on soil physical conditions and changes other than simple eradication of a compacted layer.

Because they are more sensitive to the soil environment than other cultivars, potatoes are an excellent crop from which to monitor changes in soil physical conditions due to tillage. As discussed earlier, potatoes respond poorly to low soil temperatures, high soil temperatures, low oxygen concentrations, low oxygen diffusion rates and the presence of ethylene. They require more water than other crops, but react poorly to excess water or anaerobic conditions. Potato roots are also less able to penetrate dense layers.

The earliest work on tillage and potatoes involved reduction of excessive cultivation, which caused soil-related effects such as decreased air-filled porosity, decreased aggregation and increased bulk density (Blake and Aldrich, 1955). By reducing pre-emergence tillage and cultivations to no more than one or two trips across the field and by controlling weeds with herbicides, potato yields were maintained at yields similar to those obtained with five or more cultivations (Lombard, 1936; Blake et al., 1962; Grant and Epstein, 1973; Dallyn and Fricke, 1974).

Brasher (1947) found significantly greater yields of potatoes on a loamy sand plowed to 18 cm rather than 10 cm. Jacob and Russell (1952) compared several subsoilers to conventional tillage (moldboard plow followed by disking) in a soil (type unspecified) with a compact zone between 15 and 23 cm. Yields were poorer for subsoiled treatments

unless combined with irrigation, in which case yields were higher. The authors concluded that without irrigation there was no benefit to breaking up the plowpan. They suggested the increased drainage caused "droughty conditions" in a subsoil which was described as "highly permeable sand and gravel."

Bishop and Grimes (1978) reported 8% yield increases and increased root density for White Rose potatoes with precision tillage on a California sandy loam. Subsoiling benefits did not carry over into a second year. Rowse and Stone (1980) cited previous subsoiling work in Great Britain that produced only small yield increases, which they proposed were due either to inadequate loosening of the soil or lack of nutrients at depth. They reported increased potato yields of 13% for surface applied fertilizer in subsoiled treatments and 21% for subsurface applications.

McDole (1975) and Van Loon et al. (1985) also reported yield increases, particularly of marketable tubers, due to subsoiling. Van Loon et al. (1985) eradicated a plowpan on two types of marine loam soils in the Netherlands. One soil had a penetrable subsoil, the other impenetrable. Yield differences were not observed by subsoiling the latter, but were observed in the former during dry years. The greater the drought, the greater the yield difference. However, in wet years, gross tuber yields were not significantly different.

McEwen and Johnston (1979) subsoiled a sandy loam on previously fallow land lacking a plowpan. Subsoiling alone did not improve potato yields unless also accompanied by subsoil applications of fertilizer.

Buxton and Zalewski (1983) compared various combinations of

moldboard plowing to a depth of 30 cm and chisel plowing to 40 cm on silt loams, sandy loams and fine sands with plowpans in eastern Oregon. There were no significant differences in root distributions and no consistent effects on water infiltration, petiole P concentration, percent No. 1's or specific gravity of Russet Burbanks, even though subsoiling reduced penetrometer resistance at greater depths. Thirty-three % of the variability in yield was accounted for by increased rotation time between potato crops, and 18% was accounted for by differences in penetrometer resistance at 20 cm depths. It is important to note, however, that all treatments were irrigated frequently. Ross et al. (1979) found that while deep tillage increased rooting depth; yields, grade and specific gravity of Russet Burbanks were increased only when irrigation was reduced. Buxton and Zalewski (1983) concluded that under irrigated conditions the only advantage to subsoiling was in providing growers with greater flexibility in irrigation scheduling. On the other hand, when irrigation was limited, the increased rooting volume available with subsoiling enabled the plant to extract water from deeper depths and thus improve yields. In a study of three potato varieties Miller and Martin (1987) reached a similar conclusion -- except in the case of drought-sensitive Russet Burbanks, "the benefits from subsoiling may be inadequate to justify the cost if a reliable high-frequency irrigation system is available."

Tanner et al. (1982) studied root length densities in an unreplicated study in Wisconsin in loamy sands with a dense 5 cm plowpan and a six-fold decrease in roots beneath the pan. Russet Burbank yields were not significantly different between plowpan and subsoiled

treatments, and there was no significant increase in root density with depth in subsoiled treatments. Plots in their study were irrigated. The authors attempted to monitor the effect of drought stress on root growth between emergence on May 28th and wilting on June 24th. Plants were watered after June 24th, the end of the stress period, and root length densities were measured, but not until five weeks later. Though root density was greater in the subsoiled stressed treatments, it was well within field variation. The authors concluded that root penetration to deeper layers by stressed plants was insufficient to affect water and nutrient uptake. Their conclusion was based on a sampling time that was at least two weeks late. Root response to drought stress is usually observed within one to three weeks of the end of the stress period (Smucker, personal communication). The authors also concluded that deep plowing "produces insufficient benefits to deep rooting to justify either deep plowing as a practice or further examination, at least for Russet Burbank potatoes on this sandy soil" (Tanner et al., 1982).

From the perspective of gross or marketable yield, these studies indicate that subsoiling potatoes is advantageous only when a compact layer is eradicated and then only when at least one other soil factor is also limiting. If nutrients are supplied and ample water provided, which must be managed carefully to prevent a perched water table above the plowpan, restricted root growth is not damaging to the plant. Yet it is clear that when soil bulk density and mechanical resistance are high enough, they lead to decreased oxygen and increased ethylene concentrations in the soil atmosphere. This "imbalance" in soil gaseous

composition affects potato plants through a host of responses which can ultimately result in reduced yields and unsatisfactory tuber quality. By subsoiling the plowpan, the soil environment is improved for plant, root and tuber growth and development.

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CHAPTER II
CHANGES IN SOIL PHYSICAL PROPERTIES DUE TO ZONE TILLAGE
OF POTATOES (S. tuberosum L.)

ABSTRACT

Compaction restricts rooting and reduces yields and quality of Russet Burbank potatoes (S. Tuberosum L.). Zone tillage, a system of in-the-row subsoiling combined with an interrow rye cover crop for erosion control, increased total yields in a central Michigan sandy loam soil (Alfic Fraglorthod) up to 10, 19, 18 and 8% in 1985 through 1988, respectively. At the depth of compaction zone tillage significantly decreased bulk density 13% and soil strength, as measured by cone penetrometer, 46%. Total air-filled porosity increased up to 31% and the proportion of macropores (pores greater than 24 μm in diameter) doubled. Assuming that aeration stress occurred in these soils at air-filled porosities below 15%, volumetric water contents at 20 to 36 cm depths in conventional treatments (based on moisture release curves of intact soil cores) had to be kept below $.15 \text{ m}^3 \text{ m}^{-3}$ to avoid aeration stress, while moisture contents in zone tillage treatments could go as high as $.22$ to $.25 \text{ m}^3 \text{ m}^{-3}$. Results of previous research indicated that

for optimum growth in a sandy soil, potatoes required volumetric water contents of at least $.14 \text{ m}^3 \text{ m}^{-3}$. Extrapolating to this study, at depths below the plow layer, the range of soil water contents within which conventionally tilled potatoes could maintain optimum growth and still avoid aeration stress was extremely narrow ($.14$ to $.15 \text{ m}^3 \text{ m}^{-3}$).

Whenever soil water approached beneficial amounts, poor aeration may have been limiting to conventional plants in and below the layer of compaction. On six of the eight dates that neutron probe moisture readings were monitored, the air-filled porosities of conventional tillage treatments fell below 15% at 36 cm depths. Therefore, yield differences may have resulted from poorer soil aeration in and below the compacted layer.

INTRODUCTION

Potato producing soils in Michigan are primarily sandy (90 to 95% of total potato producing soils) or organic (5 to 10%). The vast majority of these soils have a compact layer, either naturally occurring and due to the nature of glacial or lacustrine deposits, or man-made and due to intensive crop production and use of heavy farm equipment. These soils are very susceptible to wind and water erosion. As soil erosion exceeds the soil's rate of natural regeneration, productivity is reduced through decreasing soil fertility and degraded soil physical properties, leading to increased production costs.

Michigan farmers are aware of the limitations of degraded soil

structure and erosion. Conventional practices used in potato production in Michigan include use of cover crops for overwinter protection and limiting tillage to spring plowing followed by planting. Yet compacted plowpans persist and erosion continues, especially when the soil is bare and unprotected in the period between tillage or planting and canopy closure. Wind erosion also damages potato seedlings during their most vulnerable period, between emergence and canopy closure.

Sub-surface compaction in potato-producing soils causes reduced aeration, altered water storage capacity, increased soil bulk density and increased soil resistance (Timm and Flocker, 1966; Boone et al., 1978). Since potatoes require high soil oxygen concentrations (Cary, 1985), they perform best in porous soils and are sensitive to the anaerobic, ethylene-producing conditions possible in compacted soils (Campbell and Moreau, 1979). Yet potatoes also appear to require greater amounts of water than other crops (Fulton, 1970). Jackson (1962) determined that optimum soil water contents for emergence and growth of potatoes in a sandy soil was $.14 \text{ m}^3 \text{ m}^{-3}$.

Physiological responses of potato plants to compaction are well-documented, including delayed emergence (McDole, 1975), reduced root penetration and greater susceptibility to drought stress (Van Loon et al., 1985). Bishop and Grimes (1978) observed restricted root growth and reduced yields, and Van Loon and Bouma (1978) found increased number and weights of small and deformed tubers.

In 1985 and 1986 preliminary research was conducted with Russet Burbank potatoes on a sandy loam soil with a compacted layer below 20 cm (Pierce et al., 1986; Pierce et al., 1987). Zone tillage, a system of

subsoiling in the row while leaving an interrow cover of rye undisturbed for erosion control, successfully increased yields and quality of potatoes. Total yields increased up to 10 and 32% in 1985 and 1986, respectively. Marketable yields (U.S. Grade No. 1's), the more important yield to growers, increased up to 7 and 11%.

This chapter summarizes the effects of zone tillage throughout the 1987 and 1988 growing seasons on soil chemical and physical properties and soil water relations.

MATERIALS AND METHODS

Russet Burbank potatoes, Solanum tuberosum L., were grown on a McBride sandy loam (coarse-loamy, mixed, frigid Alfic Fragiorthod) at Michigan State University's Montcalm Experiment Station in central Michigan. The experimental design was a randomized complete block with four replications of four rows each in 1987 and five replications of eight rows each in 1988. Plots consisted of rows 15 meters long spaced 86 cm apart with seed spacings of 25 and 36 cm in 1987 and 25 cm in 1988. Previous crops were alfalfa in 1987, clover in 1988. Plots were plowed and seeded with rye in the fall. Potatoes were planted the following spring -- April 24, 1987 and April 25, 1988. Plots were

hilled May 11, 1987 and May 18, 1988, harvested September 18 and 19, 1987 and September 15 and 16, 1988. Rye was sprayed with Roundup four days after planting. Seed potatoes were mechanically planted in 1987, and hand planted in 1988 to reduce variability in plant stands. Fertilizer, pesticide and fungicide applications followed common practices for Michigan (Table 1). Sprinkler irrigation was scheduled based on tensiometer readings.

Tillage treatments were --

1. Conventional tillage (CT) - spring disking of rye cover crop, moldboard plowing to a depth of 20 to 23 cm followed by planting
2. Spring Bush Hog (BHS) - Spring zone tillage to 33 cm with Bush-Hog Ro-Till, followed immediately by planting (Bush Hog, P.O. Box 1039, Selma, AL 36702-1039)
3. Fall Bush Hog (BHF) - Fall zone tillage to 33 cm with Bush Hog Ro-Till, planting the following spring
4. Spring Paratill (PTS) - Spring zone tillage to 36 cm with Tye Paratill followed immediately by planting (Tye Company, P.O. Box 218, Lockney, Texas 79241)
5. Fall Paratill (PTF) - Fall zone tillage to 36 cm with Tye Paratill followed by planting in the spring (this treatment was conducted in 1987 only)

Table 1. Cultural practices. Montcalm potatoes - 1987 and 1988**A. Irrigation**

1987 Date	Amount	1988 Date	Amount
	--cm--		--cm--
6/10/87	2.0	6/2/88	2.2
6/18/87	2.0	6/10/88	2.0
6/24/87	2.0	6/14/88	2.2
7/2/87	2.0	6/28/88	2.0
7/6/87	2.0	7/1/88	2.0
7/9/87	2.0	7/5/88	2.0
7/14/87	2.0	7/8/88	3.0
7/21/87	2.0	7/14/88	2.0
7/24/87	2.0	7/22/88	1.5
7/28/87	2.0	7/28/88	2.0
7/31/87	2.0	8/2/88	2.0
--	---	8/5/88	2.0
--	---	8/31/88	2.0

B. Fertilizer applications

Date	Amount and Type
4/24/87	500 lbs/A 20-10-10
6/18/87	12.5 gals 28% N as fertigation
7/6/87	12.5 gals 28% N as fertigation
7/28/87	12.5 gals 28% N as fertigation
4/25/88	500 lbs/A 20-10-10
6/22/88	8 gals 28% N as fertigation
7/22/88	8 gals 28% N as fertigation

Table 1. Cultural practices (cont.)**C. Herbicide, pesticide & fungicide applications**

Date	Chemical Applied	Rate
6/23/87	Furadan and Dithane M-45	1 pint/A and 2 lbs/A
7/1/87	Bravo 500 and Furadan	2 pints/A and 1 pint/A
7/16/87	Cygon and Dithane M-45	1 pint/A and 2 lbs/A
7/27/87	Bravo 500	2 pints/A
8/3/87	Dithane M-45 and Furadan	2 lbs/A and 1 pint/A
8/11/87	Bravo 500 and Cygon	2 pints/A and 1 pint/A
8/18/87	Dithane M-45	2 lbs/A
8/24/87	Bravo 500, Furadan and Cygon	2 pts/A, 1 pt/A, 1 pt/A
8/31/87	Dithane M-45	2 lbs/A
6/29/88	Dithane M-45 and Imidan	2 lbs/A and 2 lbs/A
7/12/88	Dithane, Imidan and Ridomil	2 lbs/A, 2lbs/A, 2lbs/A
7/15/88	Pydrin	10 oz/A
7/26/88	Ridomil and Dithane M-45	2 lbs/A and 2 lbs/A
8/3/88	Bravo 500 and Imidan	2 pts/A and 2 lbs/A
8/10/88	Dithane M-45 and Thiodan	2 lbs/A and 2 pts/A
8/13/88	Imidan and PBO	2 lbs/A and 1 qt/A
8/19/88	Bravo 500	2 pts/A
8/26/88	Dithane M-45	2 lbs/A

Soil physical properties (bulk density, total porosity, pore size distribution, moisture retention and saturated hydraulic conductivity) were determined on intact soil cores (7.6 cm in diameter, 7.6 cm in length) sampled in triplicate on September 9, 1987 at three depths from the base of the potato hill -- 0-7.5 cm, 10-17.5 cm and 22.5-30 cm within the zone of fracture for zone tilled treatments. Cores were saturated from the bottom for 48 hours. Saturated hydraulic conductivity (K_{sat}) was determined using the constant head method of Klute (1965). Cores were then resaturated and weighed. Moisture retention for -1, -2, -3, -4 and -6 kPa of matric potential were determined by the blotter paper tension table method (Leamer and Shaw, 1941). Water retention at -10, -33.3 and -100 kPa of matric potential was determined using pressure plates (Richards, 1965). Pore size distribution was calculated by applying the capillary model to the moisture characteristic curve (Vomocil, 1965). Bulk density was determined on a mass per volume basis after oven drying cores for 48 hours at 105° C in a forced air oven.

Soil mechanical resistance was measured September 9, 1987 with a recording cone penetrometer from the top of the hill. Soil moisture samples were also taken at three depths and were subsequently oven dried at 105° C for 48 hours. Gravimetric moisture contents were calculated and converted to volumetric water contents by multiplying by soil bulk density. Soil concentrations of P, K, Ca, Mg, Zn, and Mn, as well as soil pH were determined from composite soil samples (six punch probe cores per composite sample) taken at tillage in April, 1988, at two depths, 0-20 cm and 20-40 cm (Table 2). Soil moisture content was monitored weekly throughout the growing season by tensiometers placed in

Table 2. Soil chemical properties at tillage, 1988

Depth	pH (1:1, soil/CaCl)	pH (1:1, soil/H ₂ O)	P	K	Ca	Mg	Zn	Mn
--cm--			-----g m ⁻³ -----			---mg kg ⁻¹ ---		
0-20	5.9	6.8	326	163	441	86	2.0	23.8
20-40	6.3	7.1	140	63	233	79	0.6	4.8

each replication of each tillage treatment to depths of 15 and 30 cm below the top of the hill (10 cm hill) and bi-weekly by neutron probes at depths of 15, 30, 46, 61, and 76 cm below the top of the 10 cm hill. Tensiometer data were determined with a needle probe inserted in the septum stopper capping the tensiometer and displayed in millibars of water pressure with a Tensimeter (Soil Measurement Systems, 1906 S. Espina St., Suite 6, Las Cruces, N.M. 88001). Neutron probe readings were calibrated to the volumetric moisture content of the McBride sandy loam by excavating around neutron access tubes at each of the five sampling depths and determining volumetric moisture content on intact soil cores at four equidistant points around the tube (Greacen, 1981). Neutron probe calibration curves were then developed and used to predict volumetric water contents at specific neutron probe readings by depth (Fig. 1).

RESULTS AND DISCUSSION

The effectiveness of zone tillage in soil loosening was measured in terms of bulk density and soil strength. Bulk densities were significantly greater below depths of 23 cm for conventional tillage (1.77 Mg m^{-3}), indicating zone tillage effectively broke up the compacted layer, resulting in a mean bulk density for all zone tillage treatments (BHS, BHF, PTS and PTF) of 1.57 Mg m^{-3} (Fig. 2). Above 18 cm there was greater variability in bulk densities with no significant differences due to tillage, though there was a tendency toward lower

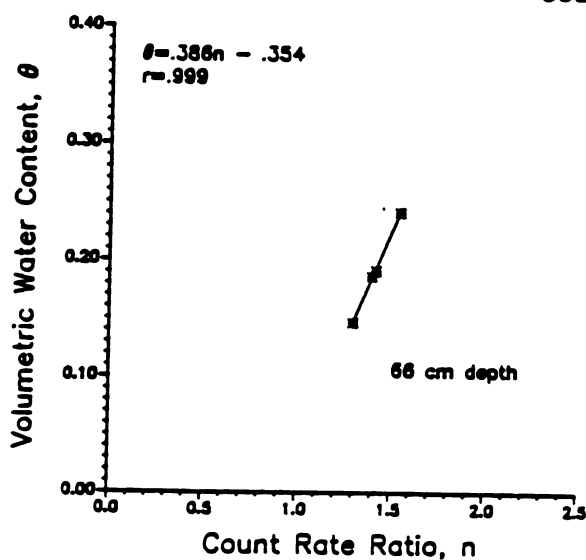
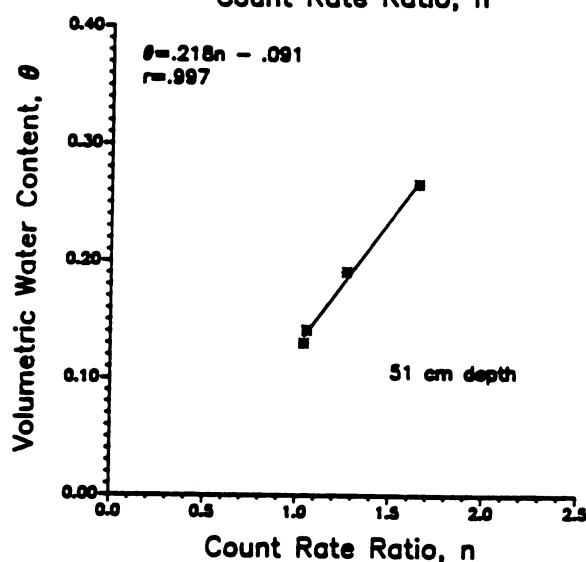
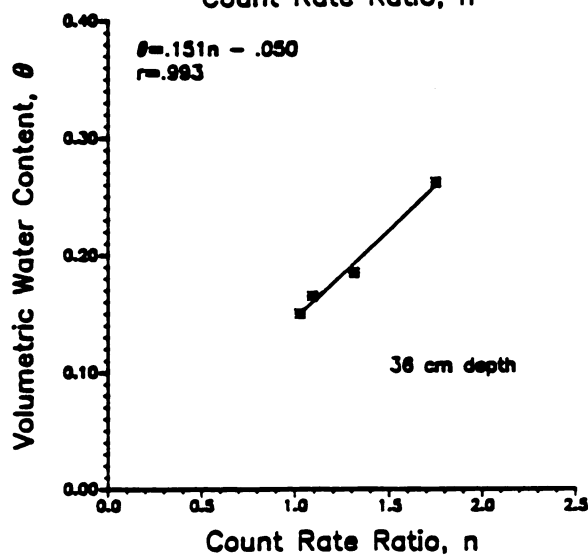
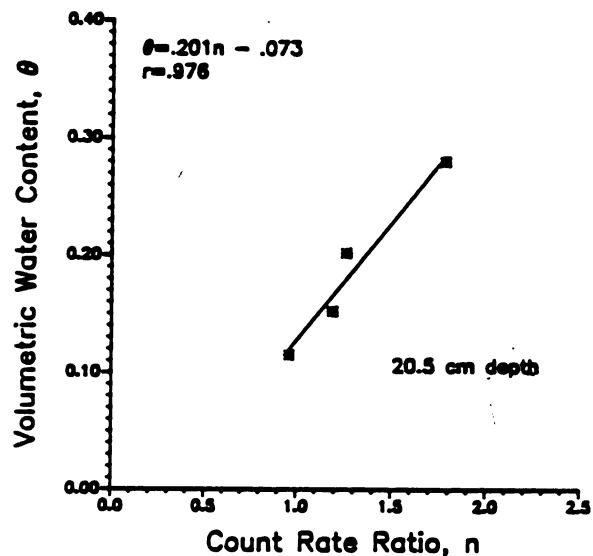
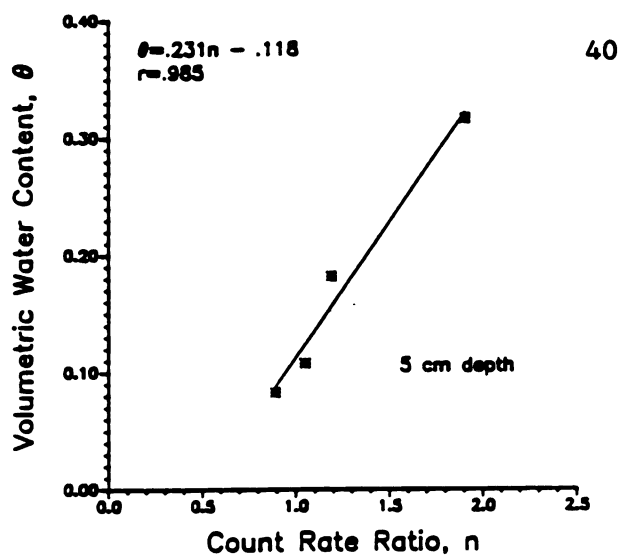


Figure 1. Neutron probe calibration curves for McBride sandy loam, Montcalm Experiment Station

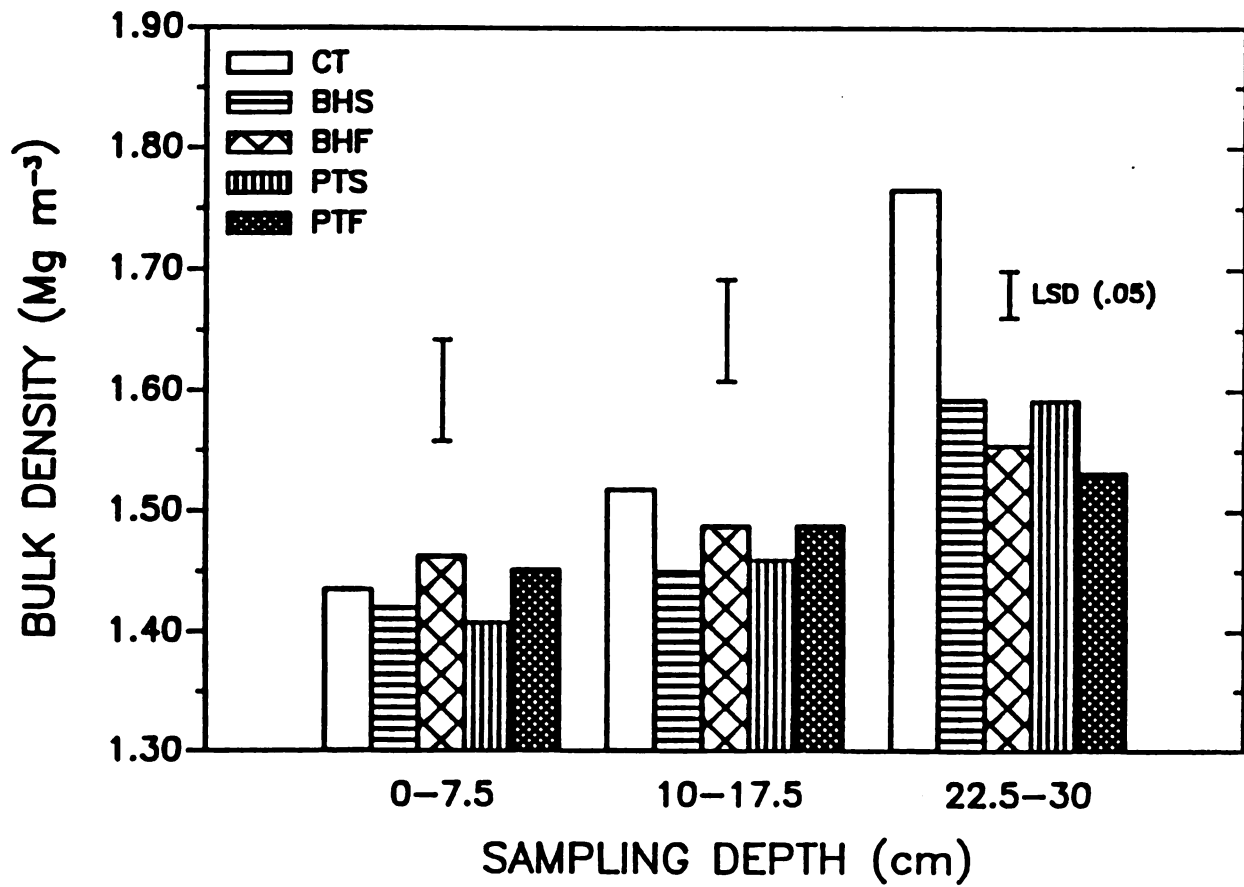


Figure 2. Soil bulk density in Mg m⁻³ at three depths as affected by tillage

bulk densities for spring zone tillage treatments (BHS and PTS) over fall zone tillage treatments (BHF and PTF). By contrast, below 23 cm depths, bulk densities for spring zone tillage were significantly have been due to drier soil conditions in the fall, which were closer to optimum soil water contents for maximum soil fracture by the subsoil tool.

Penetration resistance (cone index) reflects soil impedance to root growth, although it is not an exact measure of soil strength encountered by roots, as root tips bend to follow paths of least resistance (Barley and Greacen, 1967). Figure 3 plots cone index (kPa) by depth from the base of the potato hill for each tillage treatment. Soil moisture contents at time of penetration measurements were similar for each treatment (Table 3). Significantly greater penetration resistance was measured for conventional tillage treatments just below the plow layer (23 cm). Soil strength was so great in conventional treatments below this depth that the cone was unable to penetrate the compacted layer. These data correspond well to bulk density data and indicate the existence of a zone of soil compaction at plow depth. At 2.5 and 5.0 cm above the base of the hill, spring Paratill treatments had significantly greater penetration resistance than all other treatments, at the base of the hill, spring Paratill and fall Bush Hog were significantly greater than all other treatments, at 2.5 and 5.0 cm below the hill, fall Bush Hog had significantly greater resistance than all but spring Paratill treatments, at 12.5 cm fall zone treatments were significantly greater than all other treatments and at 20 cm below the hill, conventional tillage had significantly greater resistance than

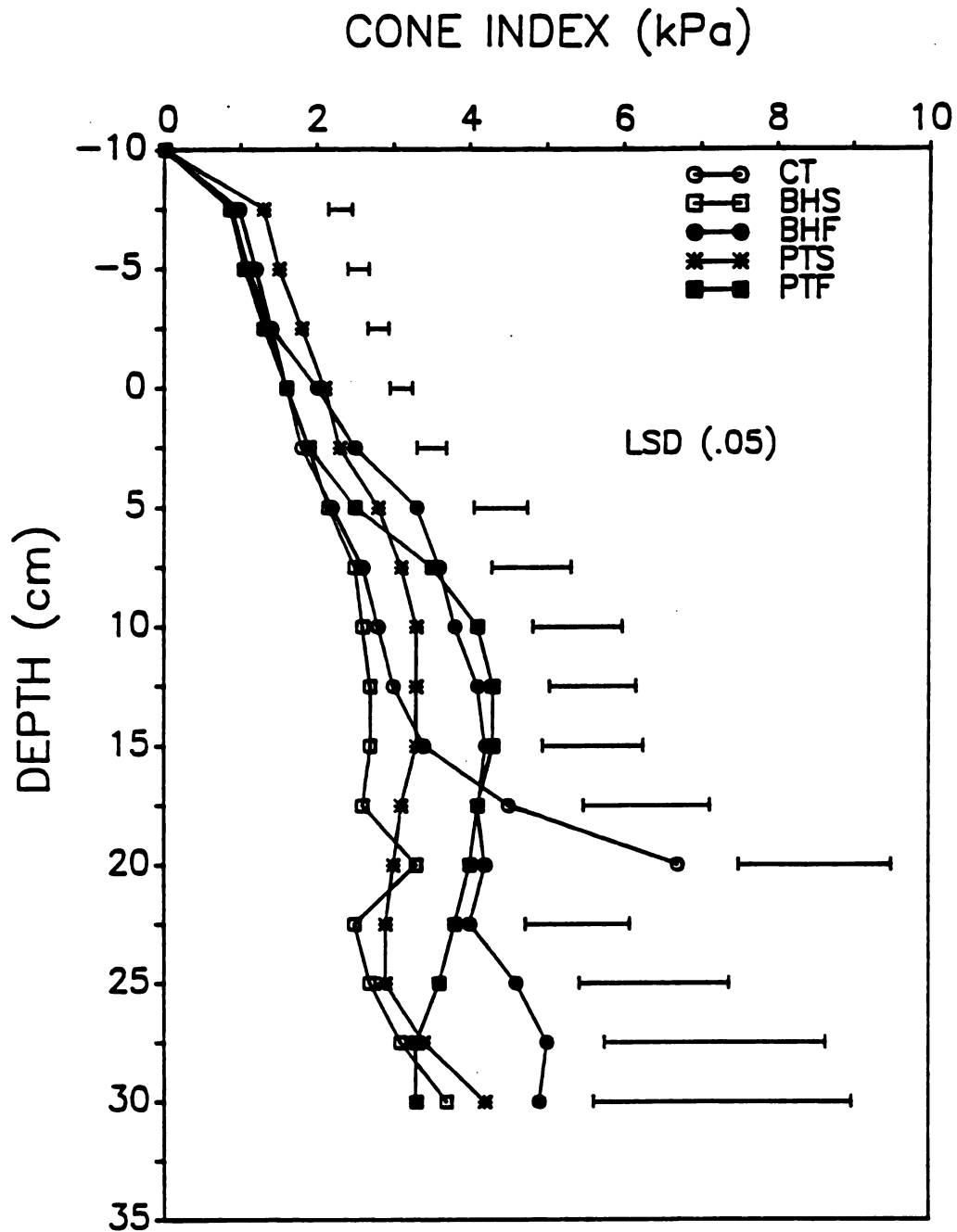


Figure 3. Soil mechanical resistance in kPa as measured by cone penetrometer

Table 3. Soil volumetric moisture content at cone penetrometer reading

Tillage	Volumetric moisture content		
	-10 to -2.5 cm depth (in hill)	0 to 8 cm depth (below hill)	13 to 20.5 cm (below hill)
	-----m ³ m ⁻³ -----		
CT	.19	.20	.19
BHS	.18	.18	.19
BHF	.18	.18	.20
PTS	.21	.22	.22
PTF	.21	.20	.22
LSD (.05)	NS	NS	NS

all zone tillage treatments.

Figures 4, 5 and 6 show total porosity and compare the proportion of pores with radii greater or less than $24\ \mu\text{m}$ (macropores and micropores, respectively) at three depths. The influence of tillage on porosity was generally not significant near the surface, but below 23 cm there was significantly greater total porosity for zone tillage treatments. The critical difference in total porosity lay in the significantly greater proportion of macropores under zone tillage (Fig. 6). Therefore, since macropores are the main pathways for water infiltration, drainage and aeration, below 23 cm zone tillage treatments would have drained more quickly and remained air-filled much of the time, while conventionally tilled treatments would have been subject to more frequent aeration stress.

Pore size distribution curves (which show the percent of pores in each size class and are calculated from soil moisture characteristic curves) indicated similar distributions for all tillage treatments above 18 cm (Figs. 7 and 8). (Pore radii of $144\ \mu\text{m}$ corresponded to matric potentials of $-1.0\ \text{kPa}$ and pore radii of $24\ \mu\text{m}$ corresponded to matric potentials of $-6.0\ \text{kPa}$ in these figures.) There was a trend toward more pores in each size category for spring Bush Hog and fewer pores in each category for conventional tillage. Below 23 cm, however, differences between zone and conventional tillage were conspicuous, with fewer percentages of pores in every size category for conventional treatments, though there was significance ($P=.05$) only at pore radii of $24\ \mu\text{m}$ (Fig. 9). The inflection point of these curves was at $24\ \mu\text{m}$ (matric potentials of $-6.0\ \text{kPa}$). Thus, the percent of pores greater than

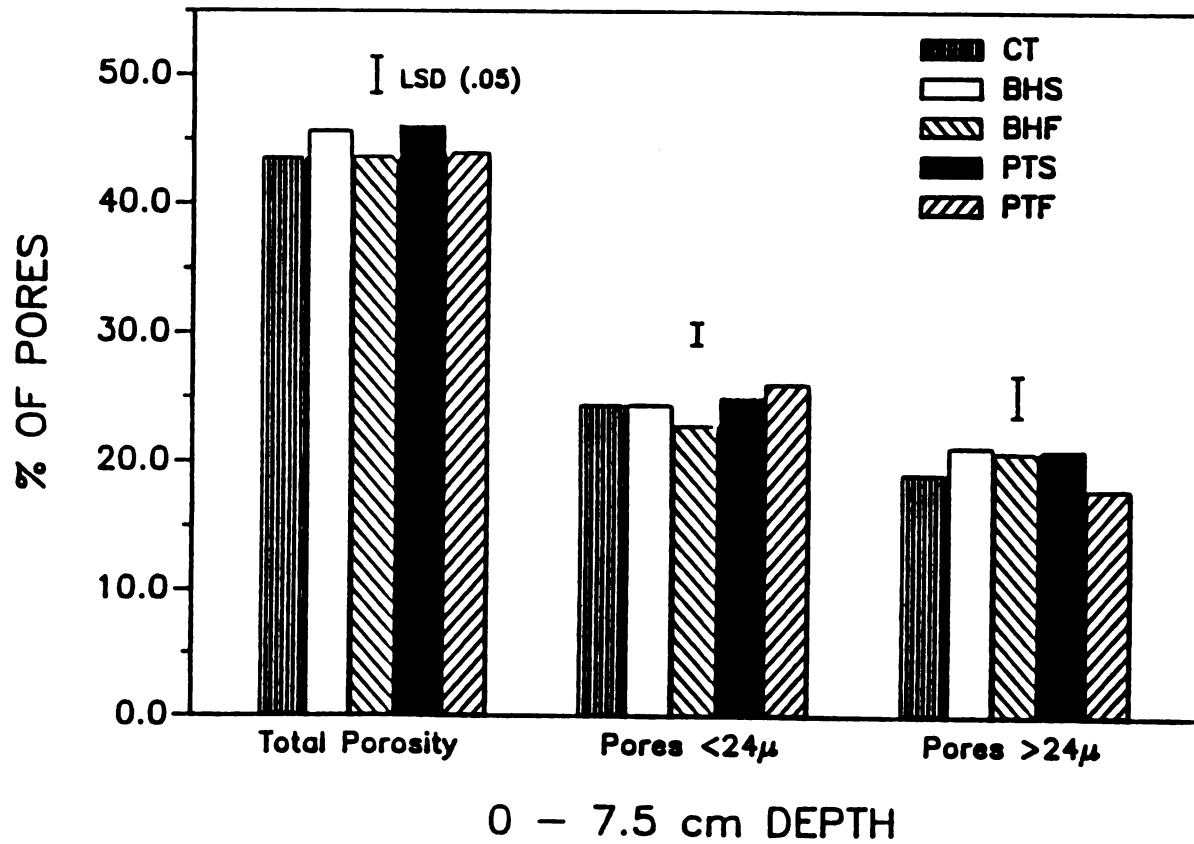


Figure 4. Total porosity, microporosity & macroporosity - 0 to 7.5 cm depths

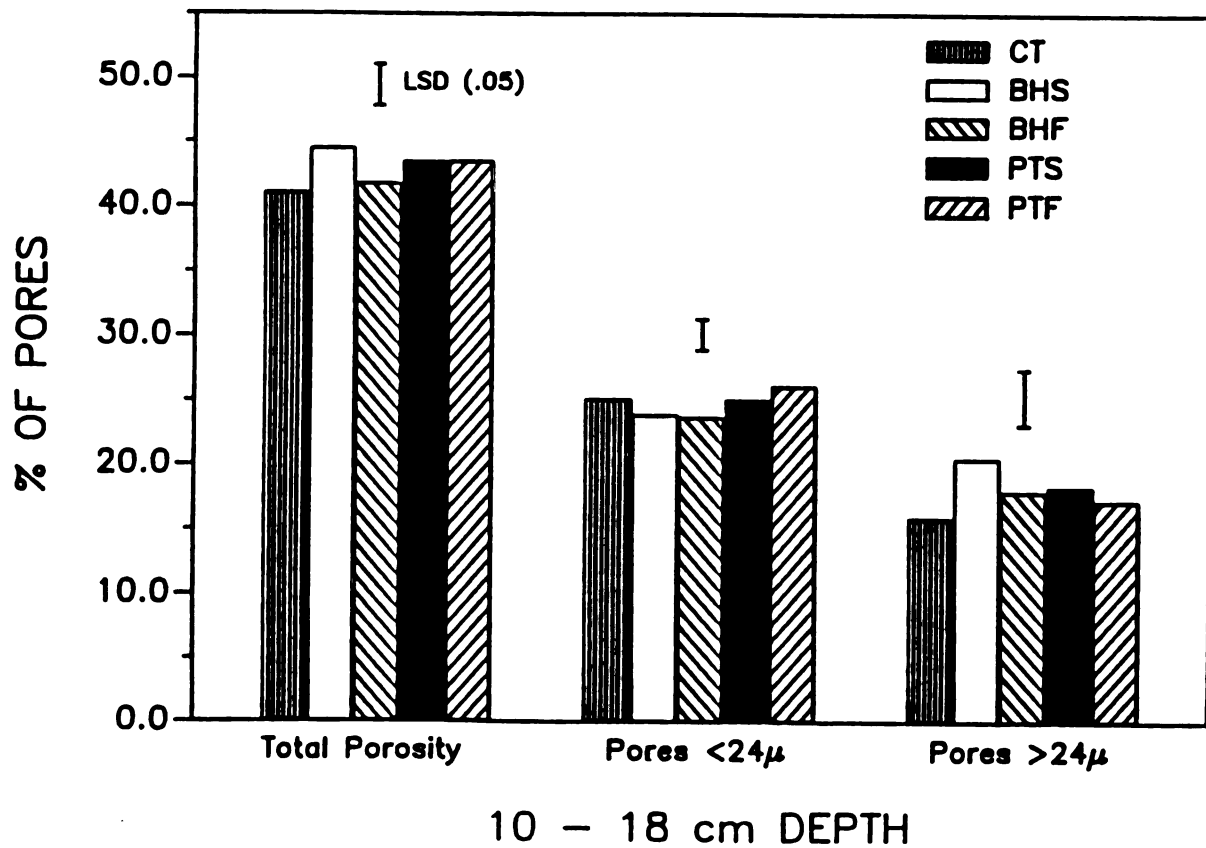


Figure 5. Total porosity, microporosity & macroporosity - 10 to 18 cm depths

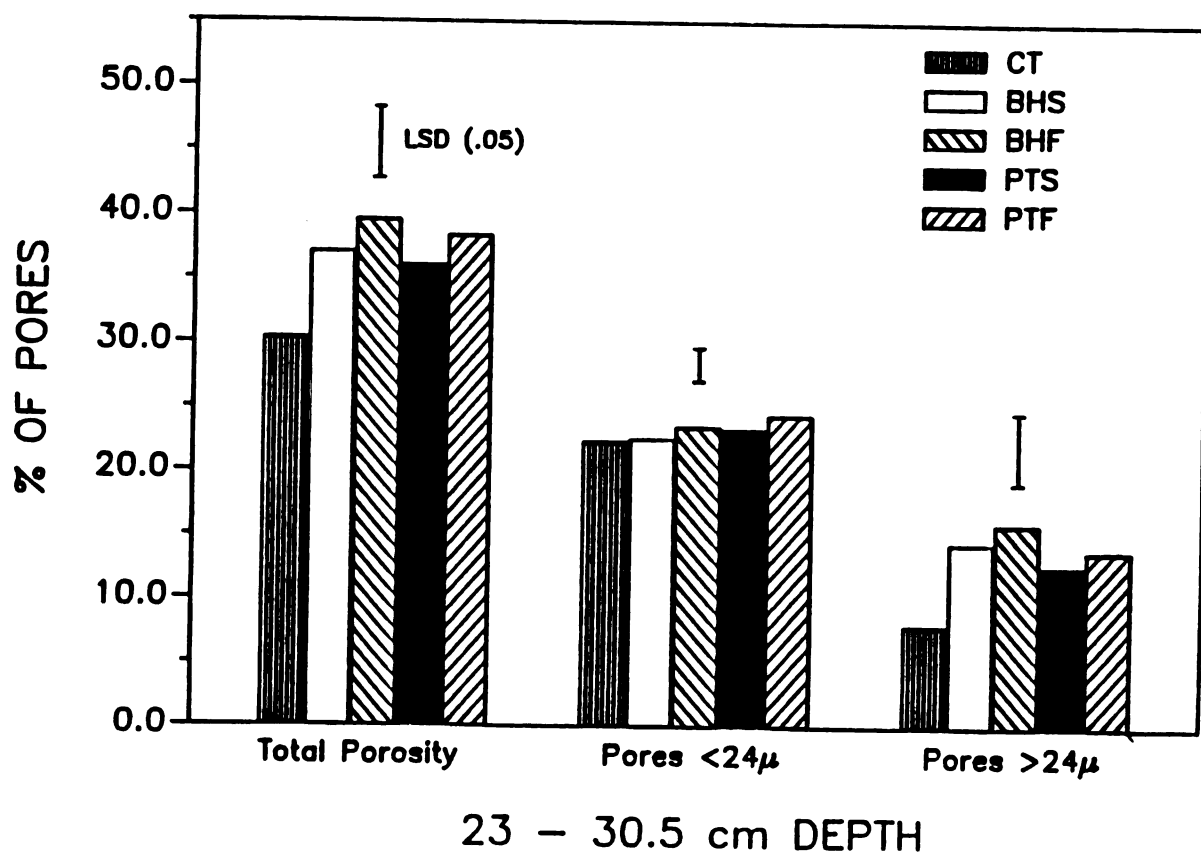


Figure 6. Total porosity, microporosity & macroporosity: 23 to 30.5 cm depths

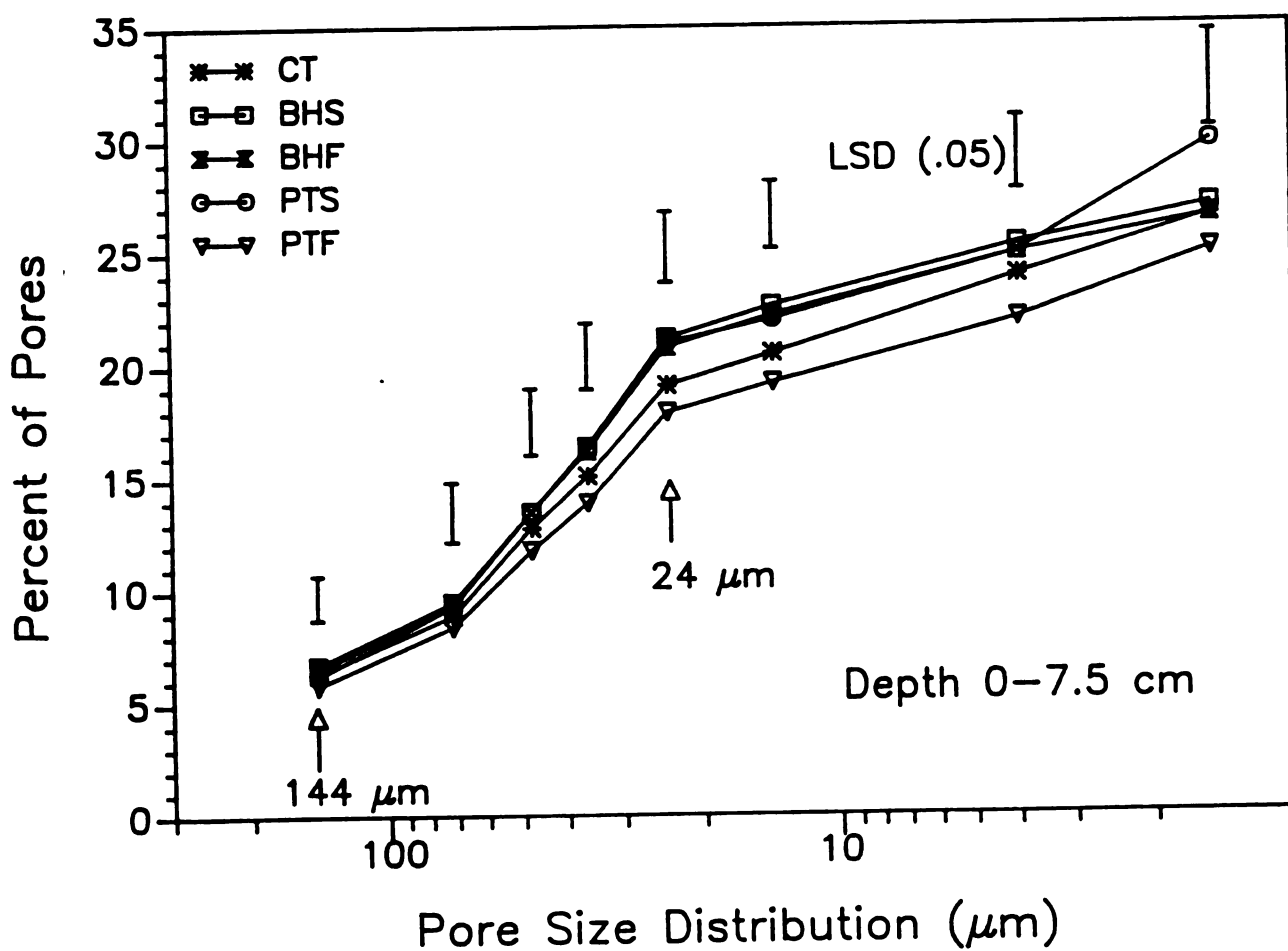


Figure 7. Pore size distribution as affected by tillage at 0 to 7.5 cm depths

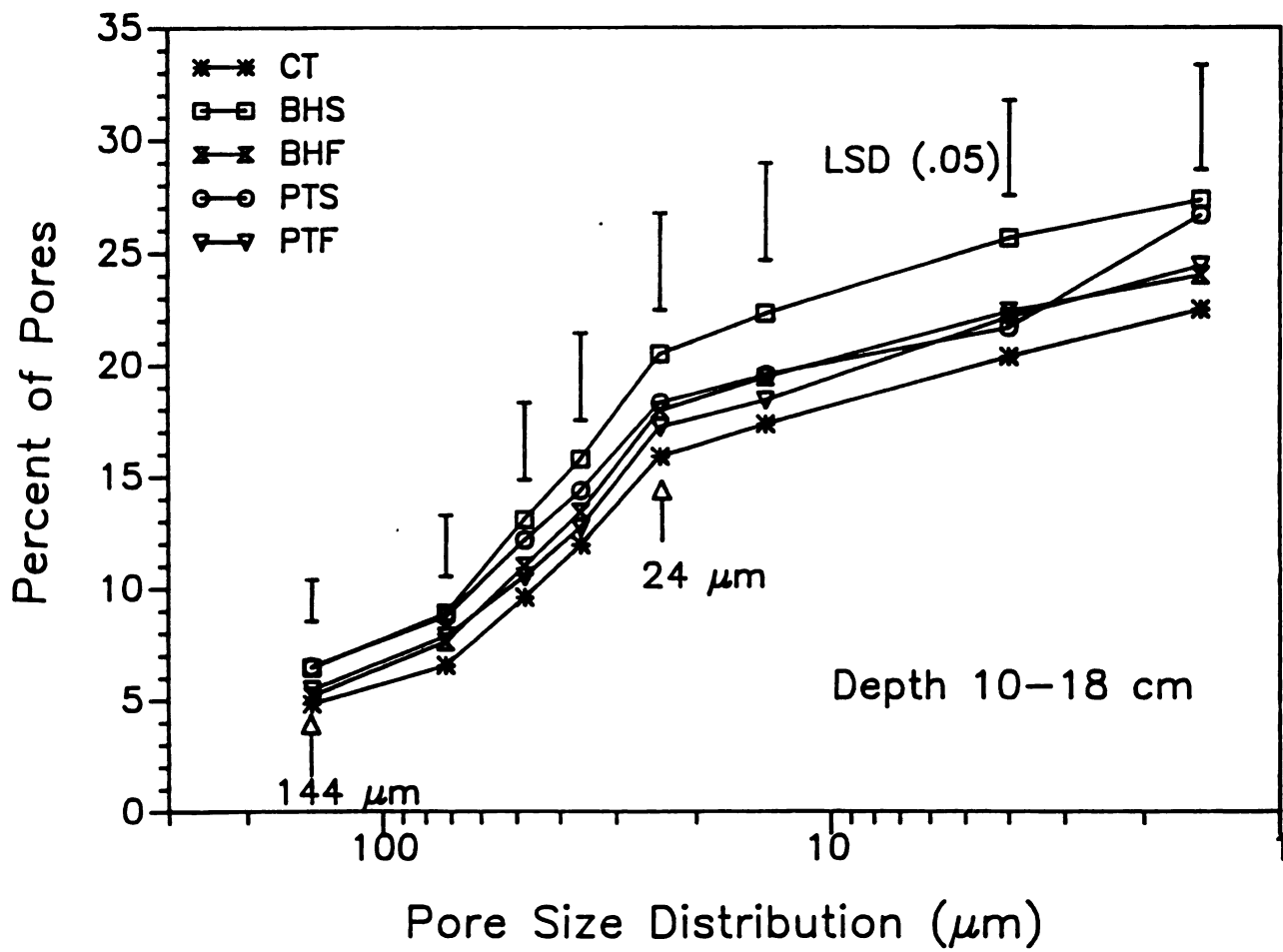


Figure 8. Pore size distribution as affected by tillage at 10 to 18 cm depths

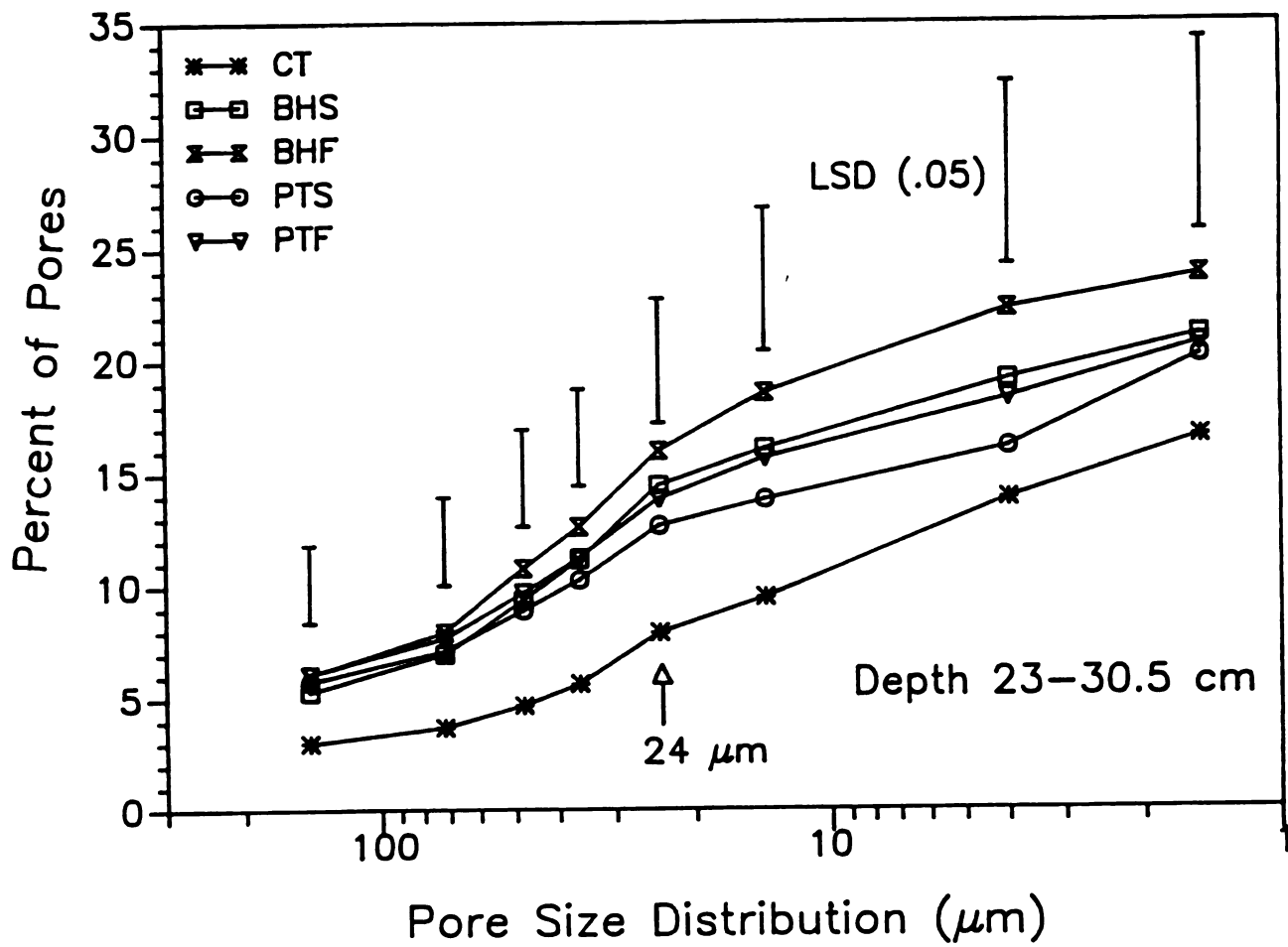


Figure 9. Pore size distribution as affected by tillage at 23 to 30.5 cm depths

24 μm was considered to be a measure of the soil's aeration status and approximated the volume of air-filled pores at field capacity.

Water retention curves and air-filled porosity were obtained for matric potentials between -0.1 and -100.0 kPa, using relationships described by Vomocil (1965). Figures 10, 11 and 12 compare soil water retention and air-filled porosities for three different depth increments beginning from the base of the hill. Above 18 cm soil depths there were no significant differences in water content or air-filled porosity at any matric potential. Below 23 cm all zone tillage treatments had significantly greater moisture contents at -.1 kPa than conventional tillage. Also below 23 cm there was a distinct trend toward less water retention by conventional treatments.

Air-filled porosities showed similar results for all treatments above 18 cm. At the surface there was a trend toward lower porosity under both conventional tillage and fall Paratill treatments. There was also a trend toward greater porosity in the spring Bush Hog treatment at the intermediate sampling depth, though differences were not significant due to field variability. Below 23 cm zone tillage treatments had significantly greater air-filled porosities than conventional treatments at -4.0 kPa of water potential.

In a comparison of Figures 12(a) and 12(b), conventional tillage generally displayed lower volumetric water content, as well as lower air-filled porosity than zone tillage treatments at the depth of compaction. This was a function of the soil's pore size distribution and the proportion of micropores to macropores in the compacted zone. These figures quantify how compaction has reduced some of the soil's

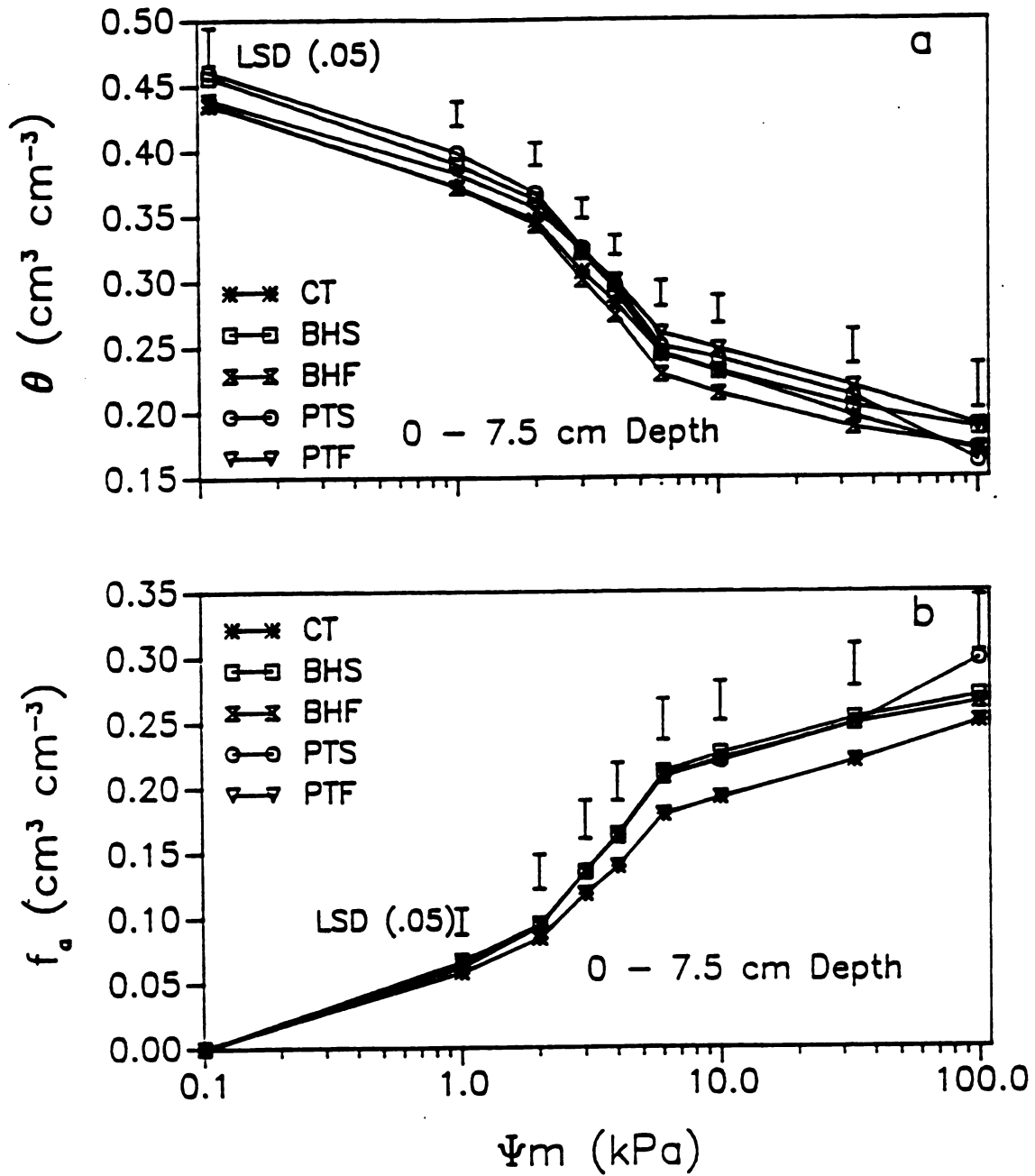


Figure 10(a). Volumetric moisture content - 0 to 7.5 cm

Figure 10(b). Air-filled porosity - 0 to 7.5 cm

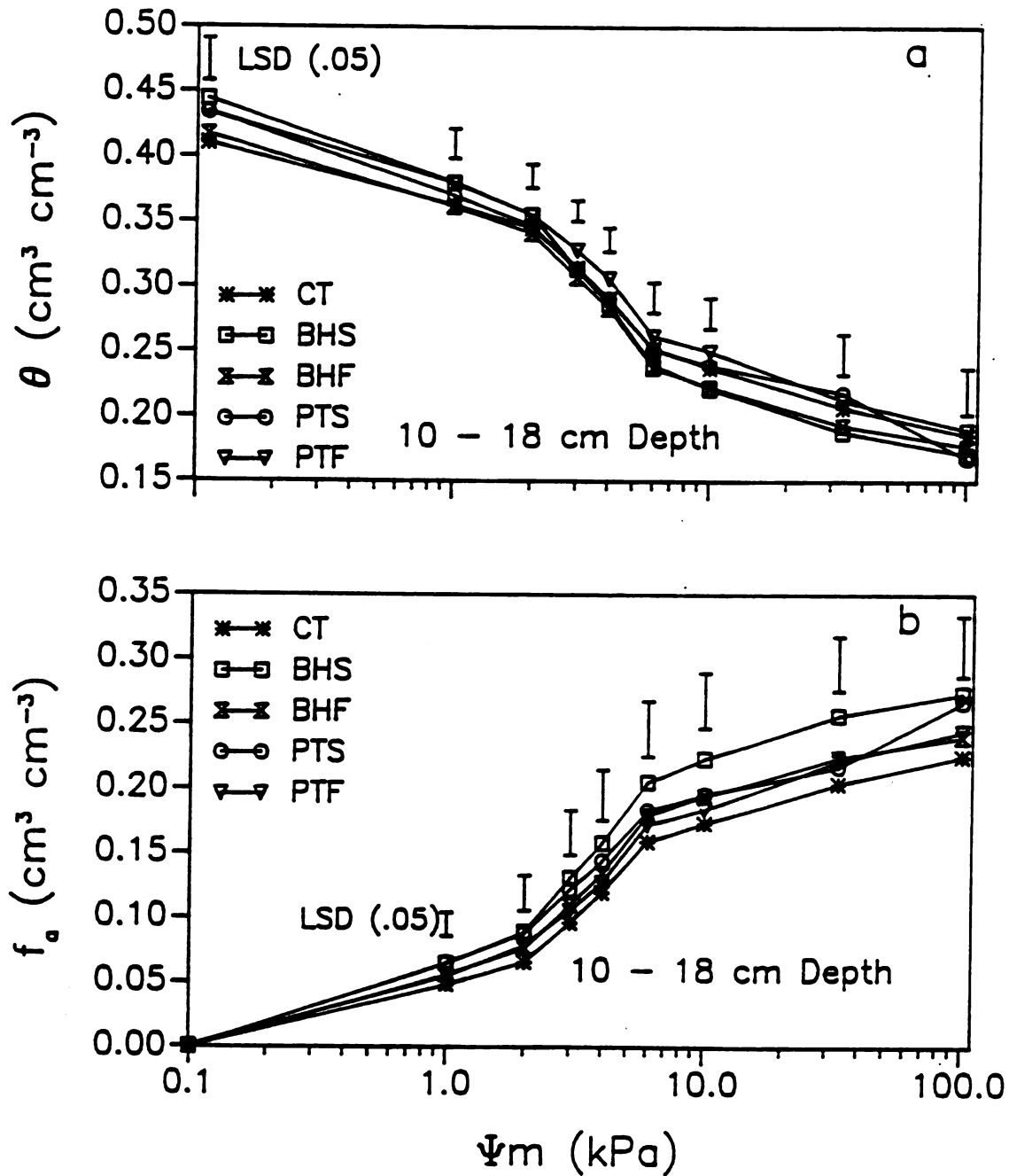


Figure 11(a). Volumetric moisture content - 10 to 18 cm
 Figure 11(b). Air-filled porosity - 10 to 18 cm

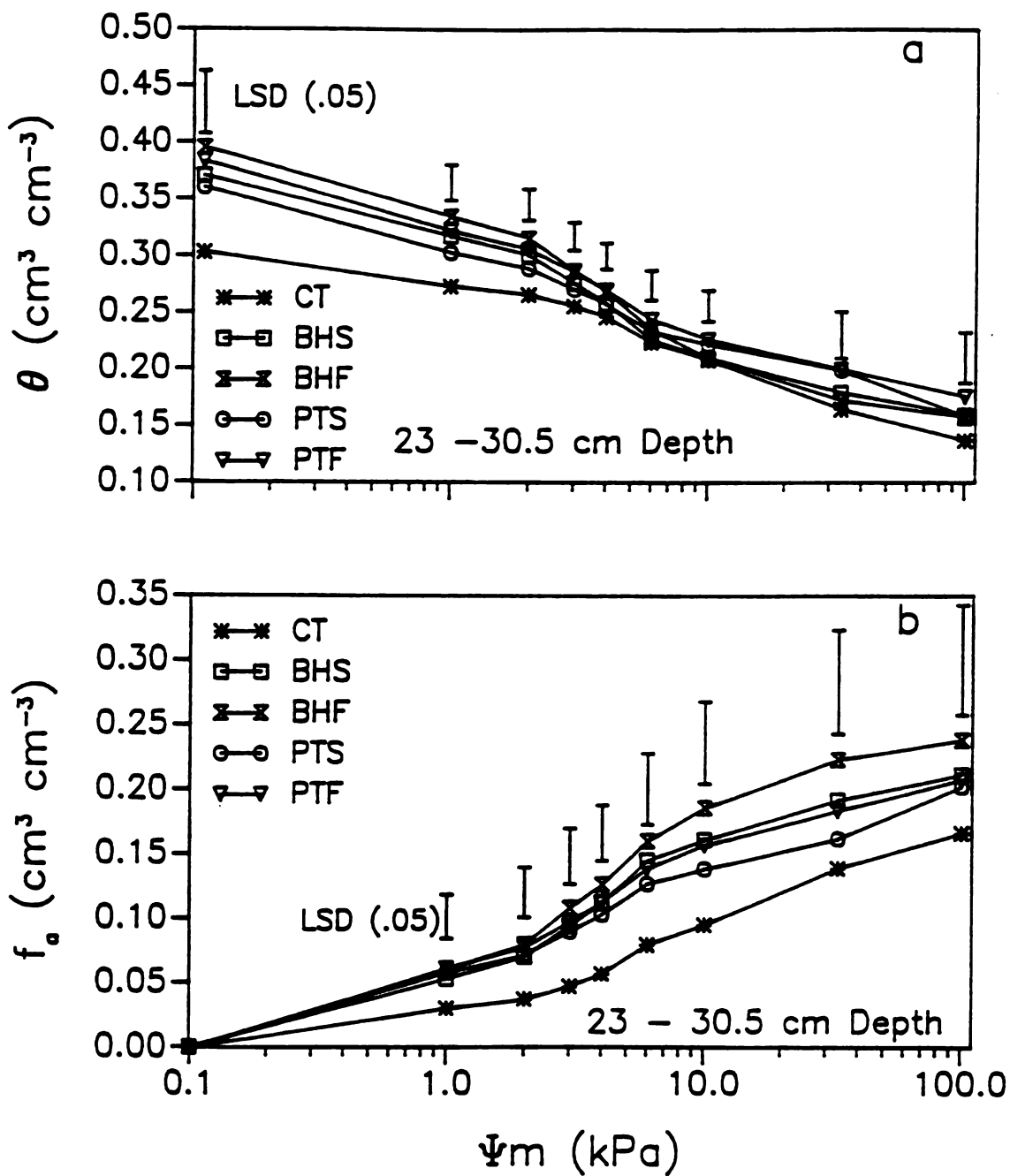


Figure 12(a). Volumetric moisture content - 23 to 30.5 cm

Figure 12(b). Air-filled porosity - 23 to 30.5 cm

water holding capacity and affected its aeration status. They show clearly that zone tillage has alleviated some of the soil's physical limitations, at least temporarily.

Saturated hydraulic conductivity (K_{sat}) is correlated to soil pore size, as well as tortuosity and continuity of pores. Larger pores conduct more water in saturated soils. Data presented in Table 4 show K_{sat} values were not significantly affected by zone tillage. Coefficients of variation were high, ranging from 31 to 104%, with a tendency toward lower K_{sat} values for conventional tillage treatments at 10 to 18 cm and 23 to 30.5 cm. However, though variability in K_{sat} was too high to show significance, there was strong correlation between macroporosity and saturated hydraulic conductivity with a coefficient of determination of .74 at a probability level of .05 (Fig. 13). Each point in Figure 13 represents the mean of data values for twelve cores.

Poor soil aeration is limiting to roots, and thus to plant growth, at air-filled porosities below 5 to 20%, with average values at about 10% (Hillel, 1982). To analyze the effect of variation in soil water content on the plant, assume that air-filled porosities of 15 to 20% are necessary for potatoes, in light of the high oxygen requirements of roots and tubers.

Tensiometer data (Figures 14 and 15) show soil water matric potential for both years. Tensiometers were placed at two depths, 5 and 20.5 cm, below the base of the hill. Spring Paratill treatments were significantly drier at 5 cm depths on 6/2/87 and tended to be drier than all other treatments at this depth early in the 1987 season. Differences were generally not significant in either year at

Table 4. Saturated hydraulic conductivity (K_{sat})

Tillage	K_{sat}		
	0 to 7.5 cm	10 to 18 cm	23 to 30.5 cm
	-----m s ⁻¹ x 10 ⁻³ -----		
CT	2.16	1.45	0.21
BHS	2.45	2.21	0.65
BHF	2.98	1.80	1.23
PTS	2.55	1.81	0.17
PTF	1.93	3.14	0.72

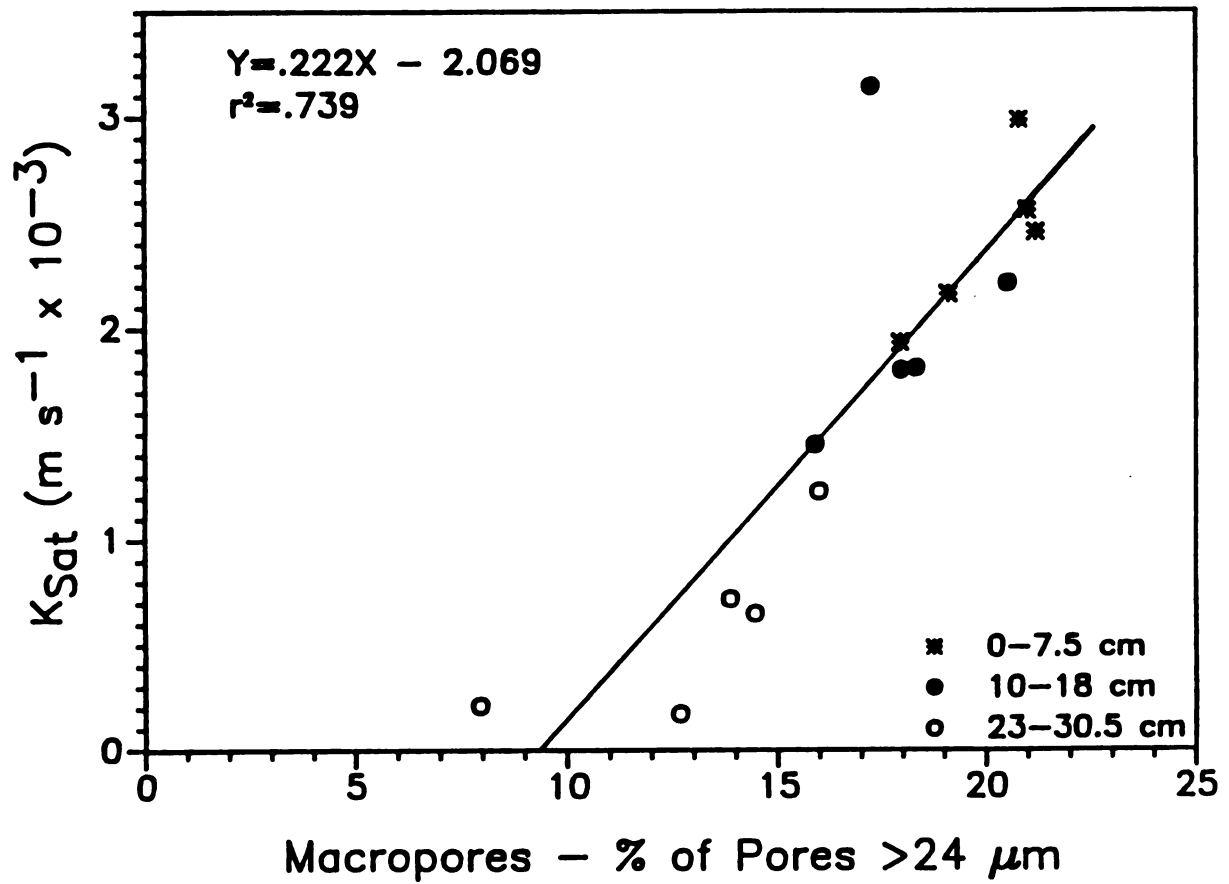


Figure 13. K_{Sat} as a function of macroporosity (pores with radii greater than $24 \mu m$)

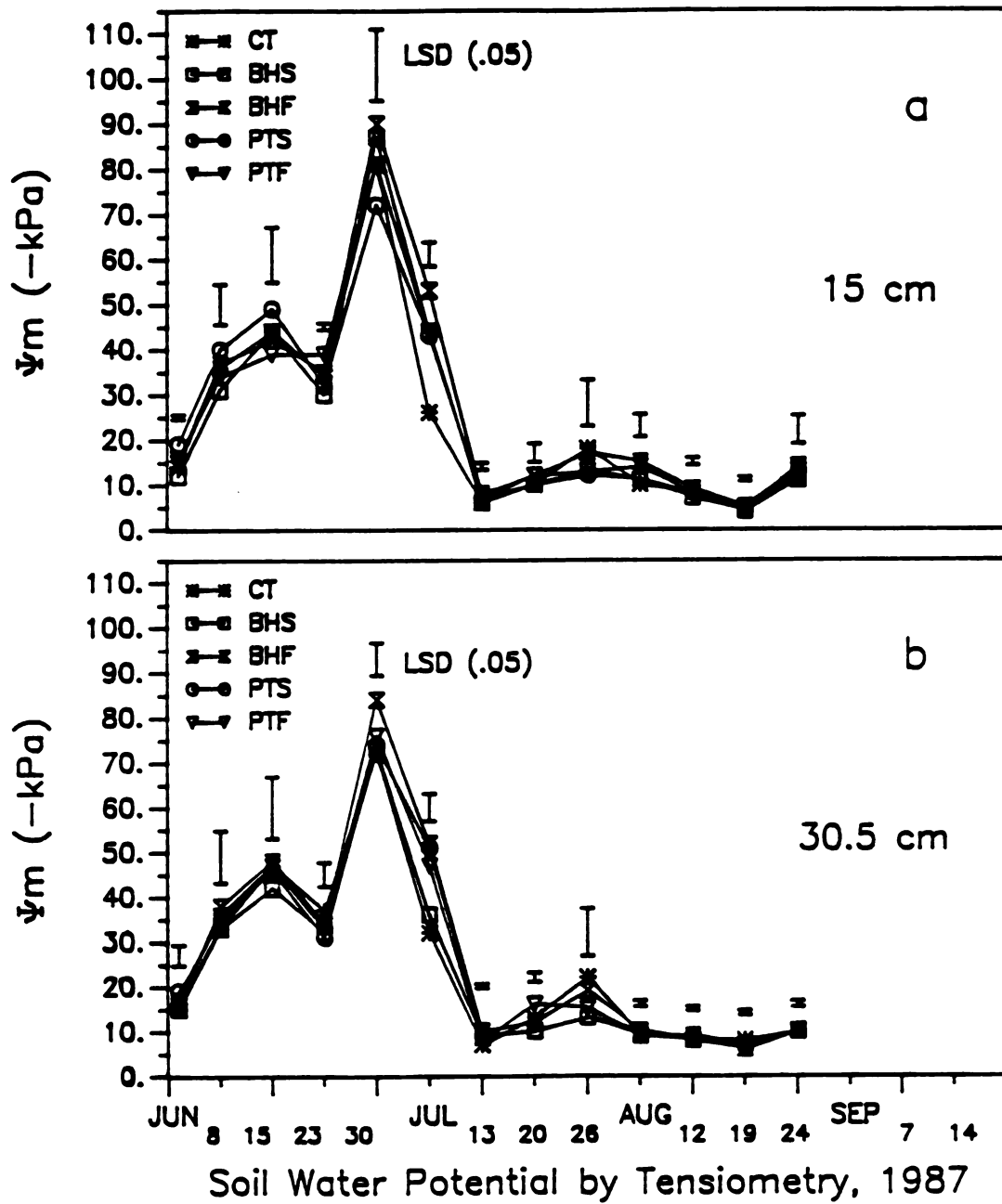


Figure 14(a). 1987 tensiometer data at 5 cm depths
 Figure 14(b). 1987 tensiometer data at 20.5 cm depths

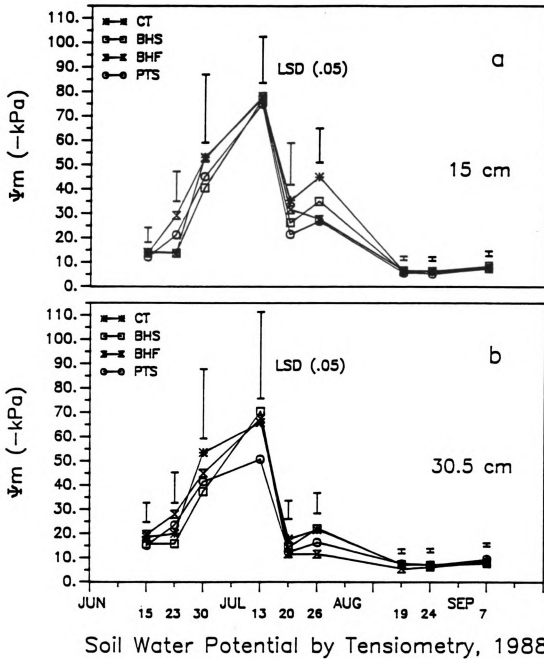


Figure 15(a). 1988 tensiometer data at 5 cm depths

Figure 15(b). 1988 tensiometer data at 20.5 cm depths

either depth with the exception of 7/7/87, 7/20/87 and 7/26/88.

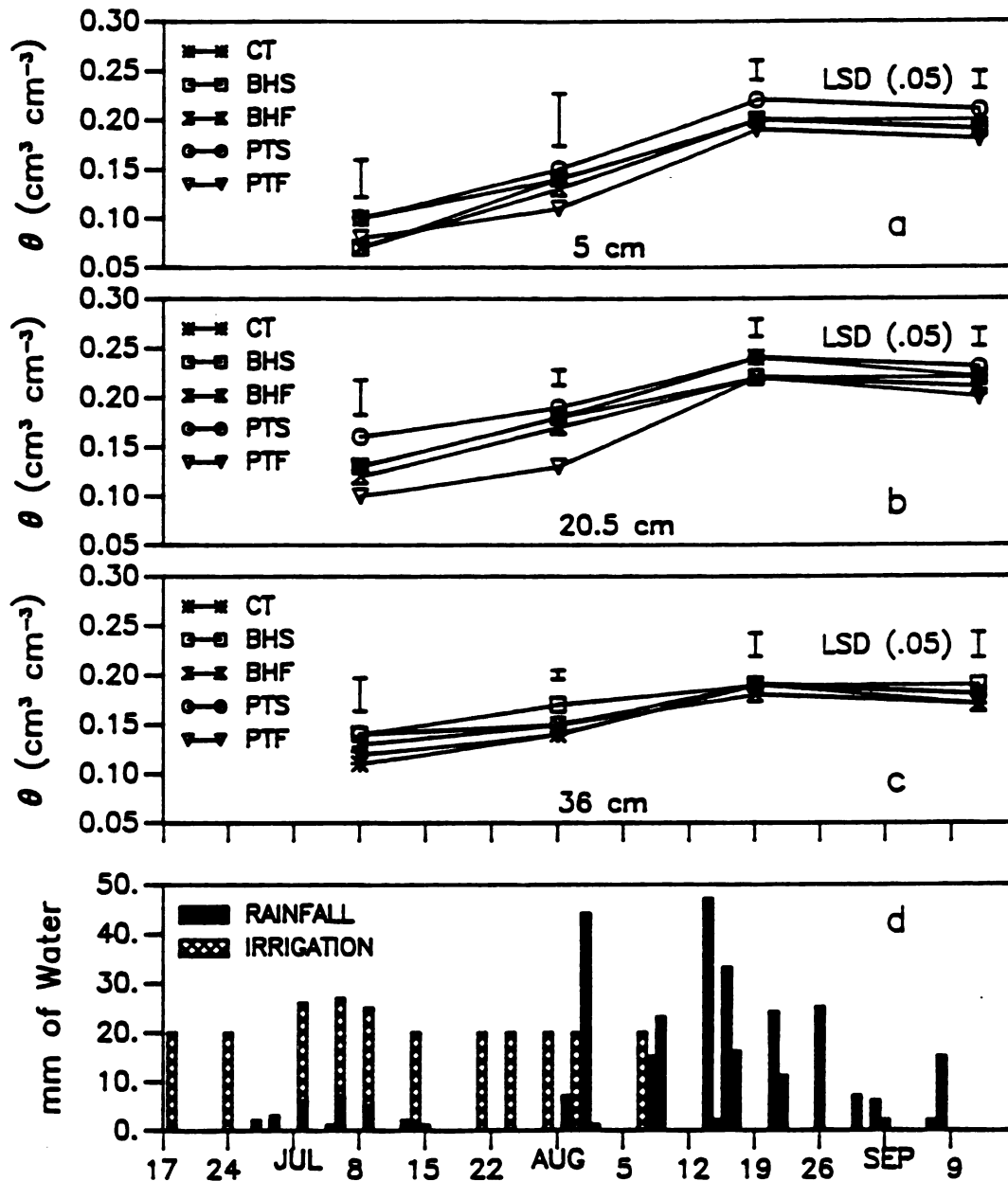
By using Figure 10(b) it is possible to ascertain the range of matric potentials which correspond to specific air-filled porosities at 5 cm depths. Thus, data in Figures 14(a) and 15(a) show tensiometer data at 5 cm depths and indicate that plants in all tillage treatments may have been under aeration stress whenever matric suctions were greater than -4 to -6 kPa (on July 13th and August 19th, 1987, and on August 19th and 24th, 1988), and plants in conventional and fall Paratill treatments may have been under aeration stress somewhere between -5 and -18 kPa (between July 13th and August 24th, 1987, and August 19th to September 7th, 1988). Using Figure 11(b) in the same manner for Figures 14(b) and 15(b), no 1987 or 1988 treatments fell below 15% air-filled porosities at 20.5 cm depths on the dates tensiometer readings were taken. However, if Russet Burbanks in this soil were subject to aeration stress at 20% air-filled porosities, then conventional tillage treatments were stressed at matric suctions of -30 kPa and greater, and all zone tillage treatments except spring Bush Hog were stressed above -12 kPa of matric potential, or most of August, 1987, and August 19th through September 7th, 1988.

Tensiometer data can also be used to monitor stress due to water deficits. Potato plants are usually irrigated at -40 to -50 kPa of matric potential. Tensiometer data indicated that potentials below those levels occurred at both depths on July 1st, 1987, and July 13th, 1988. Irrigation may not have been frequent enough during those periods, especially in 1988 during the drought and higher temperatures when plant evapotranspirational demands would have been much higher. In

conclusion, Figures 14 and 15 show that in both years at depths above 21 cm, aeration and water stress appeared to be generally independent of tillage when measured by tensiometers.

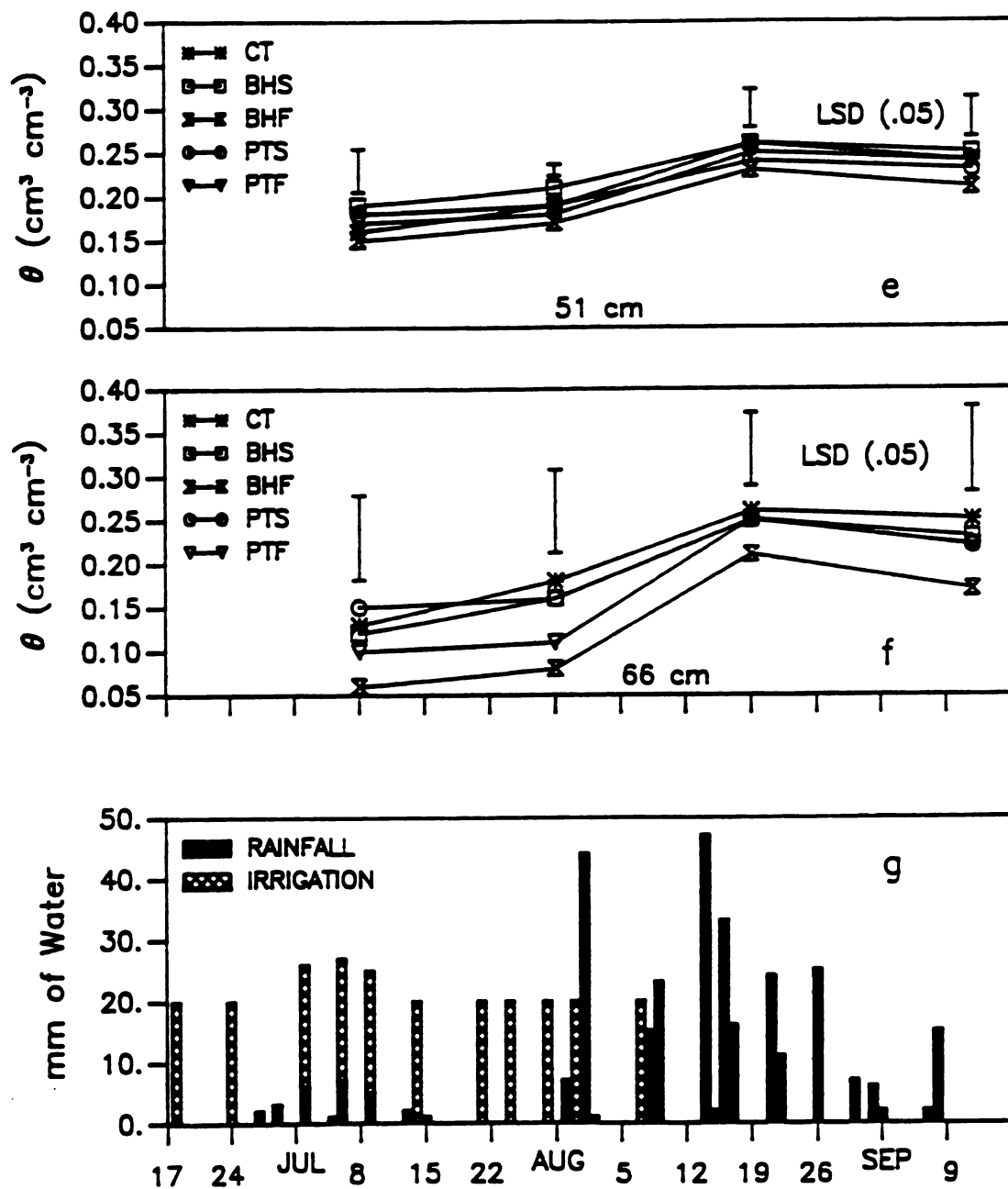
Figures 16 and 17 show irrigation and precipitation data for each year and plot volumetric water contents from neutron probe readings for five depths calculated from the base of the hill. Until August 1, 1987, irrigation was the primary source of water, after which plants were subject to record rainfalls. Climatic conditions were very dry in 1988 through August 5th with the exception of heavy rainfall on July 16th. Though volumetric water contents were generally not significantly different in either year at depths less than 36 cm, spring Paratill was significantly wetter than fall Paratill on 9/9/87 at 5 cm depths (Figure 16(a)), spring Paratill and conventional tillage were significantly wetter on 8/18/87 at 20.5 cm (Figure 16(b)), spring Paratill was significantly wetter than fall Paratill on 9/9/87 at 20.5 cm (Figure 16(b)), spring Paratill and fall Bush Hog were significantly wetter on 7/20/88 at 5 cm (Figure 17(a)) and conventional tillage was significantly drier than zone tillage treatments on 8/2/88 at 5 cm (Figure 18(a)). At 66 cm fall Bush Hog tended to be the driest treatment in both years (Figures 16(f) and 17(f), though variation was high.

Using Figures 10 through 12 to translate volumetric water contents to corresponding values of matric suction, treatments were generally not significantly different and no treatments were under aeration stress (volumetric water contents greater than .25) at 5 cm depths in either year on the four dates. At 20.5 cm depths conventional tillage



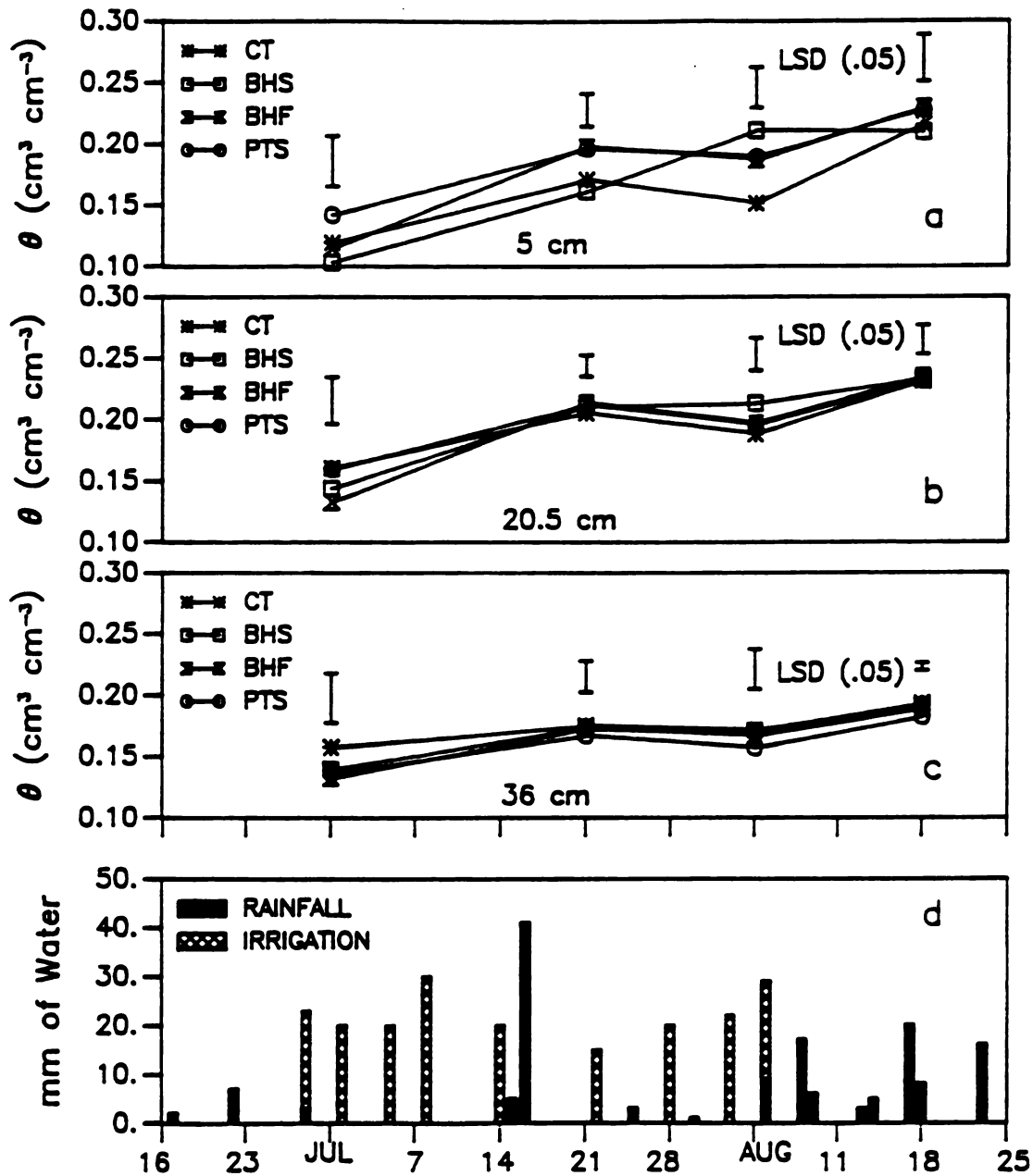
Volumetric Moisture by Neutron Method, 1987

Figure 16. 1987 seasonal soil moisture contents as estimated by neutron probe at (a) 5 cm, (b) 20.5 cm, (c) 36 cm and (d) 1987 precipitation and irrigation data



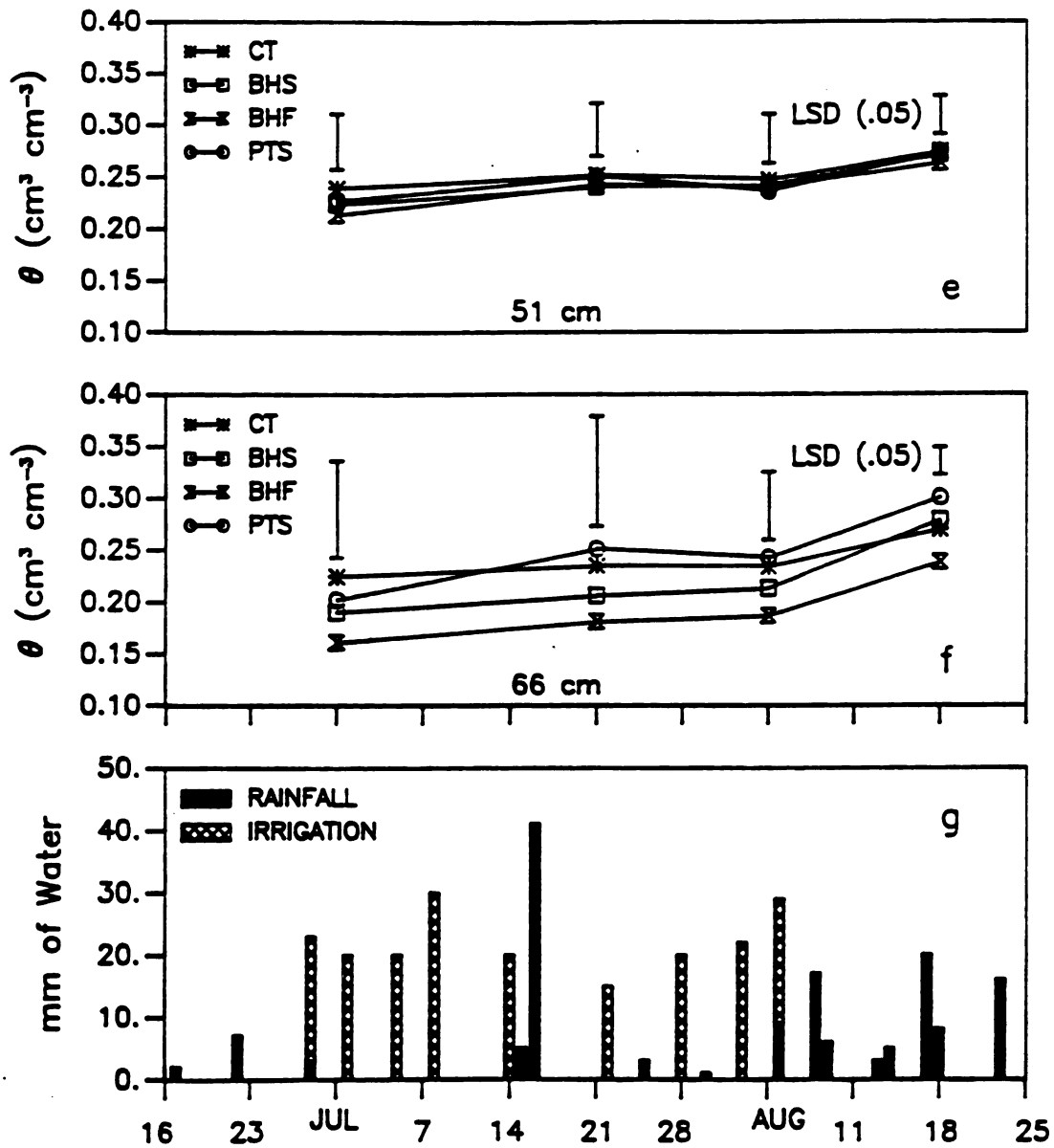
Volumetric Moisture by Neutron Method, 1987

Figure 16 (continued). 1987 seasonal soil moisture contents as estimated by neutron probe at (e) 51 cm, (f) 66 cm and (g) 1987 precipitation and irrigation data



Volumetric Moisture by Neutron Method, 1988

Figure 17. 1988 seasonal soil moisture as estimated by neutron probe at (a) 5 cm, (b) 20.5 cm, (c) 36 cm and (d) 1988 precipitation and irrigation data



Volumetric Moisture by Neutron Method, 1988

Figure 17 (continued). 1988 seasonal soil moisture as estimated by neutron probe at (e) 51 cm and (f) 66 cm and (g) 1988 precipitation and irrigation data

treatments needed volumetric water contents less than .20 to avoid air-filled porosities lower than 20% and may have undergone aeration stress on August 19th and September 9th, 1987, and August 18th, 1988. At 36 cm, using Figures 12, 16(c) and 17(c), conventional tillage treatments needed moisture contents below .15 and approximately .10 to keep air-filled porosities above 15 and 20%, respectively.

Zone tillage treatments needed moisture contents below .22 to .25 and .20 to maintain air-filled porosities of 15 and 20%. Thus, at either porosity zone tillage treatments were not under aeration stress at this depth in either year (except spring Paratill on the last two 1987 dates at 20% air-filled porosity), while conventional treatments may have undergone aeration stress at 15% porosity on all but the first dates and at 20% on all dates in both years. Below 36 cm no treatment effects in moisture content were observed, though at 66 cm fall zone tillage treatments tended to be drier in July and early August, 1987, and Bush Hog treatments drier in 1988, suggesting roots may have been withdrawing water at deeper depths in these treatments. Thus, while water content readings were very similar from treatment to treatment above 36 centimeters, soil air-filled porosity due to tillage-induced textural changes was significantly different. Zone tillage increased soil porosity at both 20.5 and 36 cm depths.

CONCLUSIONS

Over a four-year period Russet Burbank potatoes grown under zone tillage outproduced conventionally tilled plants (see Chapter 3). Based on a review of the literature, two major soil limiting factors in potato production are insufficient soil aeration and ethylene intolerance by tubers and roots. It is likely that yield differences between tillage treatments in this study were related to the negative effects of mechanical impedance due to compaction, since plants were grown in coarse, irrigated, well-drained soils.

Zone tillage improved soil physical conditions by breaking up the layer of compaction. Soil strength and bulk density were significantly decreased at the plowpan, providing an improved environment for water movement and root penetration (Chapter 4). The proportion of macropores was also increased at this depth, resulting in greater total porosity and the potential for greater water retention and improved soil aeration. Tensiometers monitored soil water potential above 20 cm depths where treatment differences in soil physical conditions were usually non-existent. Tensiometer data did flag periods of potential plant stress, however. In early 1987 and 1988 conditions were overly dry, and in late August of both years soil moisture conditions were wet. Neutron probes, which sampled soil moisture content to depths of 66 cm from the base of the hill, were sensitive enough to reveal that at 20 and 36 cm depths, air-filled porosity values were not independent of

tillage. Conventional treatments faced potential aeration stress over a much wider range of volumetric moisture contents than did zone tillage treatments, indicating roots and tubers in the compacted zones may have been more likely to be wet, receive insufficient oxygen and face possible accumulations of ethylene than were plants in subsoiled treatments. Thus, zone tillage caused changes in soil physical properties at the depth of compaction which were reflected in more advantageous soil water and aeration conditions benefitting the plant and resulting in improved yields.

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CHAPTER III:
PLANT RESPONSE TO ZONE TILLAGE OF RUSSET BURBANK
POTATOES (*S. tuberosum* L.)

ABSTRACT

Subsoiling of Russet Burbank potatoes with a minimum tillage system called zone tillage improved soil physical conditions in a McBride sandy loam (Alfic Fragiorthod) in central Michigan. Experiments were conducted to evaluate plant response to decreased bulk density, decreased soil strength and improved air-filled porosity and water retention in the zone of root and tuber development. Yields increased 19 and 8% in 1987 and 1988 when plants were spaced 25 cm apart. No yield increases were observed at 36 cm spacings, and yields were reduced 5% by zone tillage conducted after planting. Destructive plant samplings taken three times each year showed the difference in yield increases between conventional and zone tillage treatments was due to increased production of larger tubers under zone tillage.

INTRODUCTION

Soil physical properties affect plant growth and development, particularly in the case of potatoes, an ethylene-sensitive, high oxygen-requiring cultivar (Campbell and Moreau, 1979; Cary, 1985). By ameliorating the high soil strength, poor aeration and poor water retention common to compacted soils, subsoiling improves the soil environment for plant production. Potatoes perform poorly in compact soils, best in porous soils (Van Loon and Bouma, 1978; Van Loon et al., 1985). Consequently, about 95% of Michigan potatoes are produced on sandy soils (5% on organic soils). These soils are prone to wind and water erosion, and they often contain naturally-occurring or man-made hardpans. Blowing sand often causes severe seedling damage.

Preliminary research with zone tillage, a system of in-the-row subsoiling which leaves an interrow cover of rye undisturbed for erosion control, has resulted in gross yield increases of 10 and 32% in 1985 and 1986, respectively, and marketable yield increases (U.S. Grade No. 1's) of 7 and 11% during the same years (Pierce et al., 1986; Pierce et al., 1987). Subsequent research in 1987 and 1988 was designed to monitor plant response to improved soil physical conditions in the zone of root and tuber development. Though a number of studies have reported on yield and quality of potatoes as affected by subsoiling, previous researchers have neglected the effect of deep tillage on plant dynamics during the growing season. This chapter will evaluate the effect of

improved soil physical conditions on the growth and development of the plant in five areas -- petiole nutrient content, size and number of tubers per plant, dried above-ground biomass per plant, relationship between dried above-ground biomass and dried tuber weights, growth rates and gross and marketable yields.

MATERIALS AND METHODS

Field experiments were conducted in 1987 and 1988 with Russet Burbank potatoes on a McBride sandy loam (coarse-loamy, mixed, frigid Alfic Fragiorthod) in central Michigan at Michigan State University's Montcalm Experiment Station. Experimental design, cultural practices and treatments were discussed in Chapter 2. Soil physical properties were determined from intact soil cores and were also discussed in Chapter 2. Roots were sampled destructively, as well as non-destructively, and data are summarized in Chapter 4.

Three destructive whole plant samplings were taken every three to four weeks each year (on 6/25/87, 7/21/87, 8/10/87, 7/6/88, 7/25/88, 8/19/88). Dates of 1988 samplings were scheduled to monitor plant production during periods of maximum root growth, which occurred between 7/6/87 and 7/25/87 for an April 24th planting, according to 1987 minirhizotron data. In each replication of each treatment 3 meters of row were sampled on each date beginning with the third plant from the end of the row. The number of plants sampled varied in 1987 from six to ten plants per 30.5 meters, due to erratic seed placement by the planter

(36 cm seed spacing). Seed was hand planted in 1988 to reduce variability, and plants were spaced 25 cm apart. Eleven plants were sampled from each 3 meter segment in 1988. (1987 data indicated yield increases due to zone tillage did not occur unless seed spacing was reduced from 36 to 25 cm.) Thus all 1987 samplings were conducted on plants spaced 36 cm apart, and 1988 samplings on plants at 25 cm seed spacings.

Above-ground plant material was cut with machetes at the soil surface, bagged in paper bags, dried in drying ovens at 38° C for two to four weeks until dry and then weighed. Soil in the 30.5 meter rows was excavated by hand and with potato forks to ensure all tubers, including those just initiated, were collected. Tubers were washed, counted, weighed, oven-dried and re-weighed. 1988 tubers were sorted into weight categories (0-56.70 grams, 56.71-85.05 grams, 85.06-170.10 grams, 170.11-226.80 grams, 226.81-283.50 grams, greater than 283.50 grams), counted, weighed, oven-dried up to eight weeks and re-weighed.

Potato petioles (80 to 90 per plot) were sampled at full flowering on 7/8/87 and 7/13/88, dried, ground and analyzed for nitrate N, B, Zn, P, Mn, Cu, Fe, Al, Mg, Ca and K. Tuber yield, quality and specific gravities were determined after mechanical harvesting of two 15-meter rows per replication. Tubers were graded and sorted into the following size categories -- less than 113 grams per tuber, tubers between 113 and 170 grams, 170 to 284 grams, tubers over 284 grams and deformed tubers under and over 284 grams. Subsamples of ten tubers per plot were halved and examined for hollow heart, and specific gravities were determined by the water immersion method.

RESULTS AND DISCUSSION

As discussed in Chapter 2, tillage significantly reduced soil bulk density 10% and penetration resistance 46% at the depth of compaction. Water retention, soil aeration and the proportion of macropores were also increased with zone tillage. Russet Burbank potatoes responded positively to the improved soil physical conditions. Over a four-year period potatoes grown under zone tillage outproduced conventionally tilled plants (Table 1).

Although Pierce et al. (1986) showed significant increases in Zn (14%) and Mn (69%) in zone tillage treatments in 1985, petiole nutrient concentrations were generally unaffected by tillage in 1987 and 1988 (Tables 2 and 3). With the exception of copper concentrations in 1988, petiole concentrations of nitrate N, B, P, Mn, Fe, Al, Mg, Ca and K were not significantly different. The mechanisms behind these yearly variations are not understood.

Figures 1, 2, and 3 illustrate temporal variation within and between years in the number, mean weight and total weight of tubers produced by each plant. 1987 results are inconsistent and generally not significant, though spring Bush Hog treatments significantly outproduced all other treatments in terms of total tuber weight per plant (Fig. 3). This may have been due to the fact that rye in these plots was destroyed by the tillage system the previous fall, leaving no rye in the spring to compete for soil moisture. 1988 results showed trends toward more

Table 1. Russet Burbank yields as affected by tillage at 25 cm seed spacings

Tillage	Gross Yields			
	1985	1986	1987	1988
	-----Mg ha ⁻¹ -----			
CT	39.3	38.8	42.3	39.0
BHS	40.9	45.9	47.7	42.0
BHF	----	46.3	----	40.6
PTS	43.2	46.1	50.1	41.9
PTF	----	47.4	----	----
LSD (.05)	NS	3.5	5.3	1.8

Table 2. Concentration of nitrate N in petioles

Tillage	Petiole N Concentrations	
	1987	1988
	-----g kg ⁻¹ -----	
CT	3.01 x 10 ⁻²	2.44 x 10 ⁻²
BHS	3.05 x 10 ⁻²	2.22 x 10 ⁻²
BHF	3.33 x 10 ⁻²	2.13 x 10 ⁻²
PTS	3.76 x 10 ⁻²	2.17 x 10 ⁻²
LSD (.05)	NS	NS

Table 3. Petiole Nutrient Concentrations

[illegible]

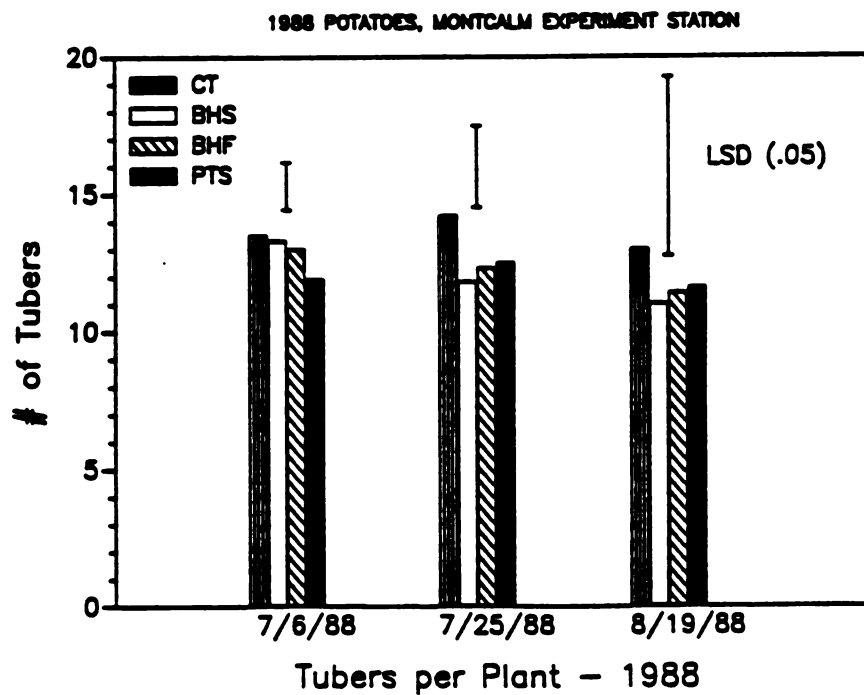
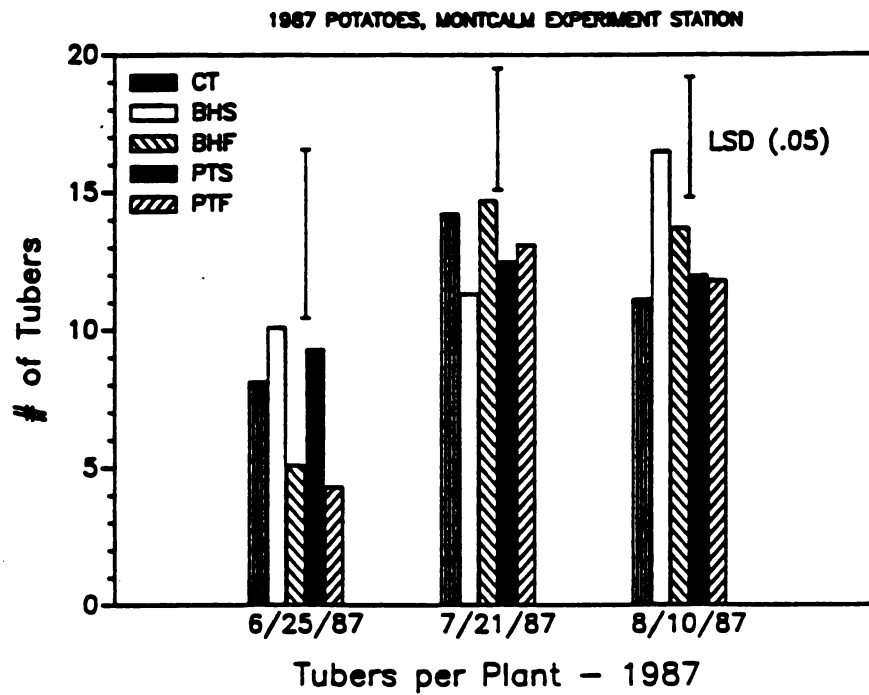


Figure 1. 1987 and 1988 tubers per plant as affected by tillage

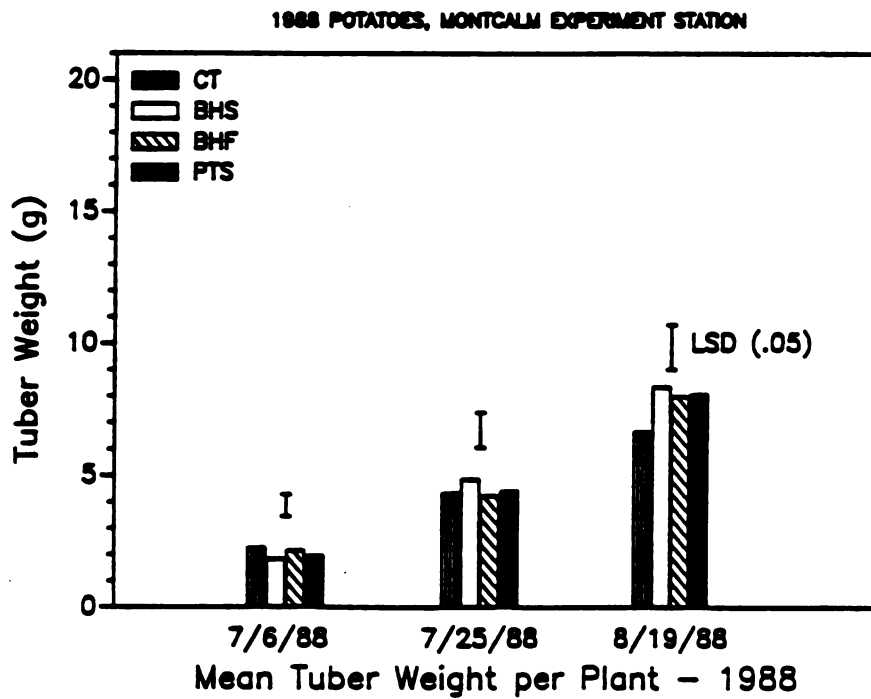
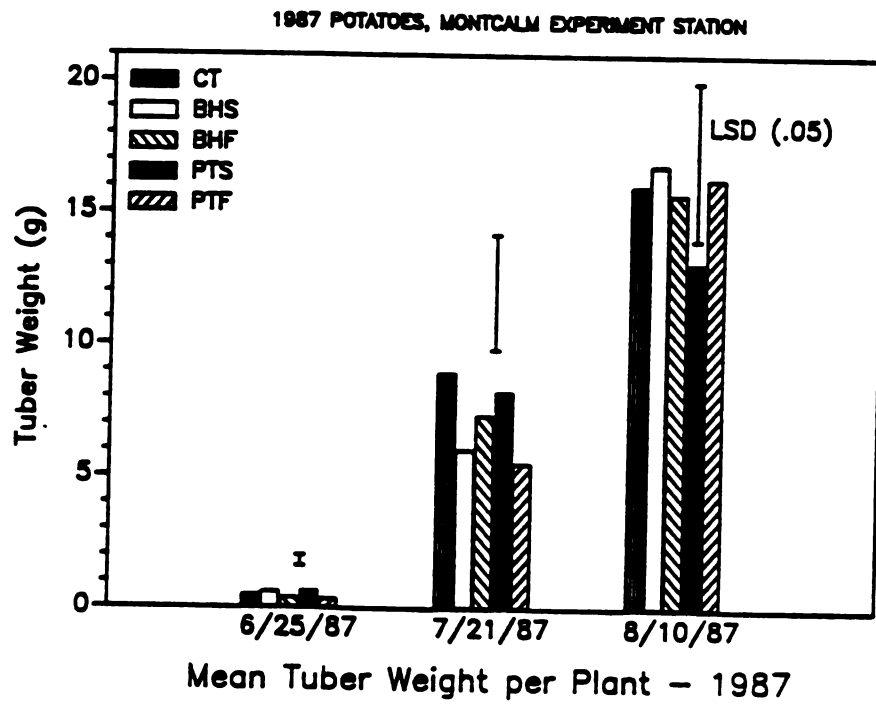


Figure 2. 1987 and 1988 mean tuber weight per plant as affected by tillage

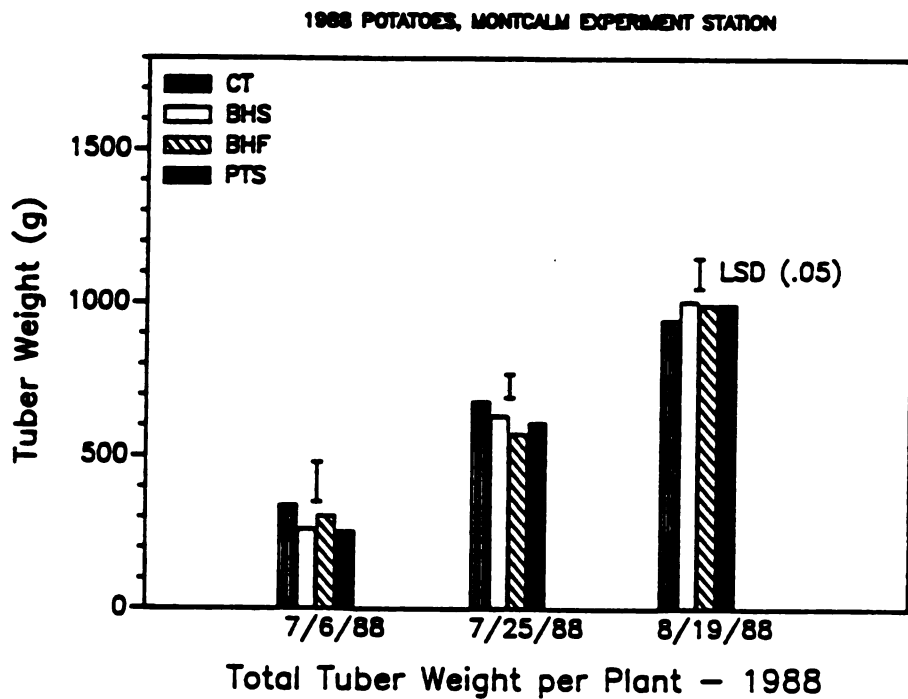
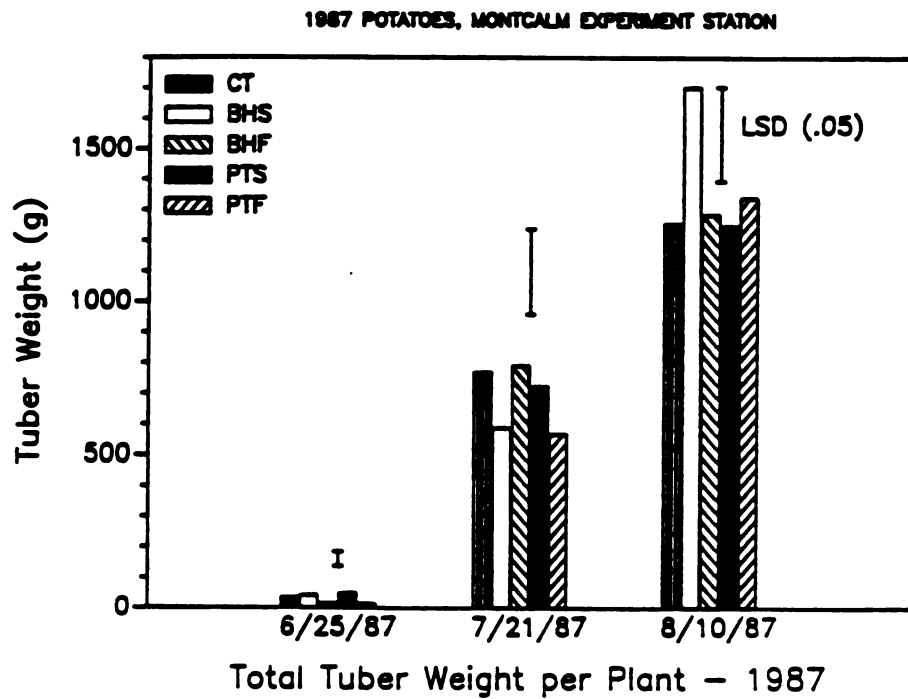


Figure 3. 1987 and 1988 total tuber weight per plant as affected by tillage

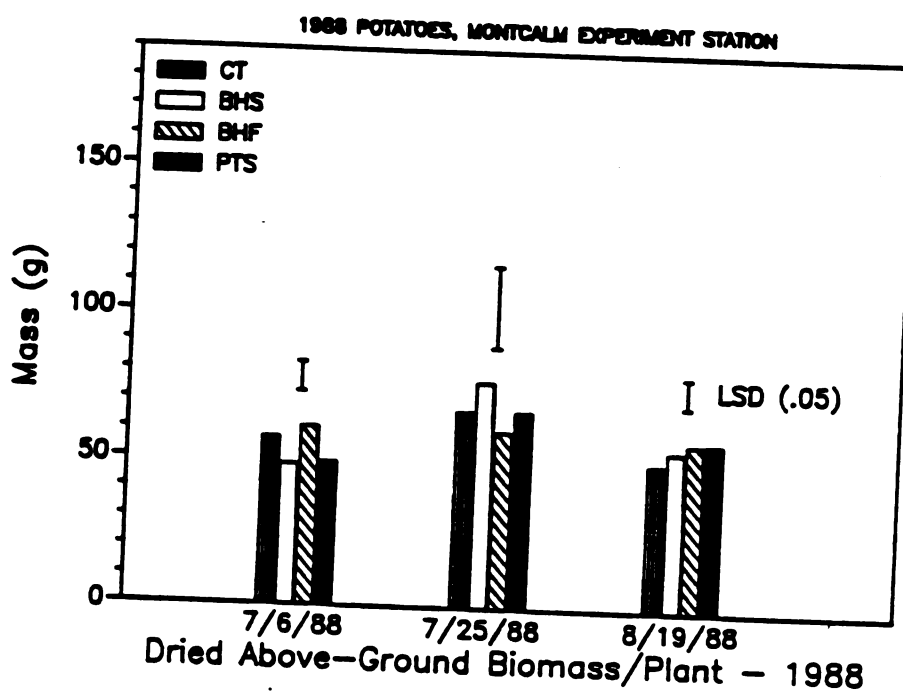
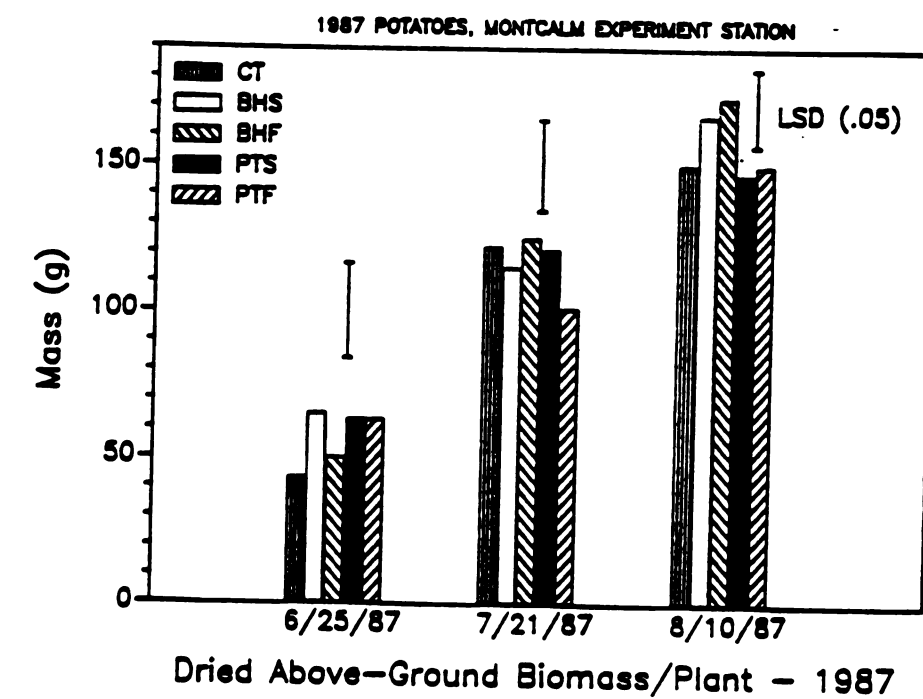


Figure 4. 1987 and 1988 above-ground biomass per plant as affected by tillage

tubers per plant at all dates for conventional treatments (Figure 1) and lower mean tuber weights for conventional treatments as the season progressed (Fig. 2). Looking at total tuber weight per plant in 1988, conventional treatments tended to produce greater tuber weights early in the season and mid-season, though zone tillage treatments were beginning to overtake conventional treatments by August 19th (Fig. 3). Figure 4 shows no obvious trends in above-ground plant production within year in 1987 or 1988, though growth patterns tended to mirror patterns observed in production of total tuber weight in Figure 3.

The striking difference in these data lies in the magnitude of overall plant production in 1987 and 1988. Figure 1 shows generally similar numbers of tubers initiated and produced each year, ranging from 12 to 17 tubers per plant in July and August, with some variation due to tillage. Yet for every other measure of plant production --mean tuber weight, total tuber weight and weight of above-ground plant material -- 1987 plants substantially outproduced 1988 plants (Table 4). The most likely explanation for these differences was the 1988 drought, which occurred in conjunction with unusually high temperatures. Since evapotranspiration is the only cooling mechanism available to plants that is also controlled by plants, it is possible that substantial carbohydrates were diverted from tuber bulking and production of above-ground biomass to production of roots and to water absorption and transpiration in 1988. Note, though, that plant stress due to weather did not seem to affect tuber initiation, just tuber bulking. These results corroborate previous research which found that the main physiological effect of drought on potatoes was a reduction of

Table 4. Mean per plant production by year averaged over all treatments

Mean per Plant Production	Late July Sampling		Mid-August Sampling	
	1987	1988	1987	1988
# of Tubers	13.2	12.7	13.0	11.8
Mean Tuber Weight (g)	7.2	4.5	15.6	7.8
Total Tuber Weight (g)	689	622	1368	985
Dried Above-Ground Biomass (g)	117	68	157	55

photosynthetic rate and thus, the supply of photoassimilate (Munns and Pearson, 1974; Moorby et al., 1975). A corollary effect was a decrease in dried above-ground biomass (Wolfe et al., 1983).

Another difference in 1987 and 1988 biomass data was that 1987 data patterns were erratic with no distinct trends. For example, in Figure 2 1987 zone tillage treatments had widely different mean tuber weights on 7/21/87 and 8/16/87. Yet 1988 data showed definite trends. In the same figure, mean tuber weights for 1988 zone tillage treatments were similar to each other and showed a small, but steady increase in weight over conventional treatments. 1988 data appeared muted, with less dramatic differences between treatments, but there were clear trends. Conventional treatments produced more tubers at lower mean weights and lower total weights. Yield data later in this chapter will suggest that plant population density may have affected response to zone tillage. If this hypothesis is true, then erratic results in 1987 may have been due to erratic seed placement by the planter.

In 1988 tuber biomass data were recorded in more detail than in 1987. Rather than simply collecting information on total numbers of tubers and total wet tuber weights from the destructively sampled tubers, tubers were divided into size categories of 56.7 gram increments and then counted and weighed. Table 5 presents number of tubers per plant in each size category for the three sampling dates, illustrating a trend in conventional treatments toward greater numbers of small tubers and fewer large tubers as the season progressed. Looking at some of the more illustrative data on tuber weight per plant, Figure 5 shows tuber

Table 5. Number of tubers per plant in different size categories
as affected by tillage in 1988

Number of Tubers per Plant by Size Category & Date						
<u>7/6/88</u>						
Tillage	0-56.7g	56.7-113.4g	113.4-170.1g	170.1-226.8g	226.8-283.5g	283.5-340
----- # plant ⁻¹ -----						
CT	13.0	0.5	---	---	---	---
BHS	12.9	0.4	---	---	---	---
BHF	12.4	0.5	---	---	---	---
PTS	11.4	0.5	---	---	---	---
LSD (.05)	NS	NS				
<u>7/25/88</u>						
CT	9.1	4.3	0.6	0.2	---	---
BHS	6.8	3.6	1.1	0.2	---	---
BHF	7.6	3.6	0.9	0.1	---	---
PTS	7.8	4.0	0.6	0.2	---	---
LSD (.05)	NS	NS	NS	NS	---	---
<u>8/19/88</u>						
CT	6.3	3.7	2.1	0.6	0.3	0.1
BHS	4.4	2.5	2.4	0.8	0.5	0.3
BHF	4.7	3.4	1.8	0.9	0.4	0.2
PTS	4.7	3.6	1.8	0.9	0.4	0.3
LSD (.05)	NS	0.7	NS	NS	NS	NS

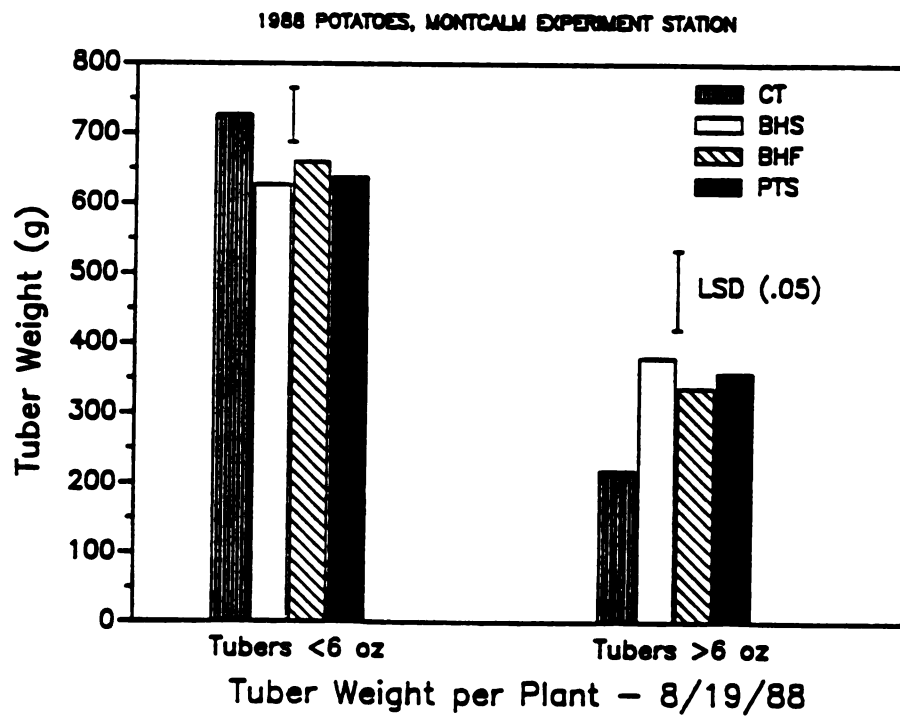
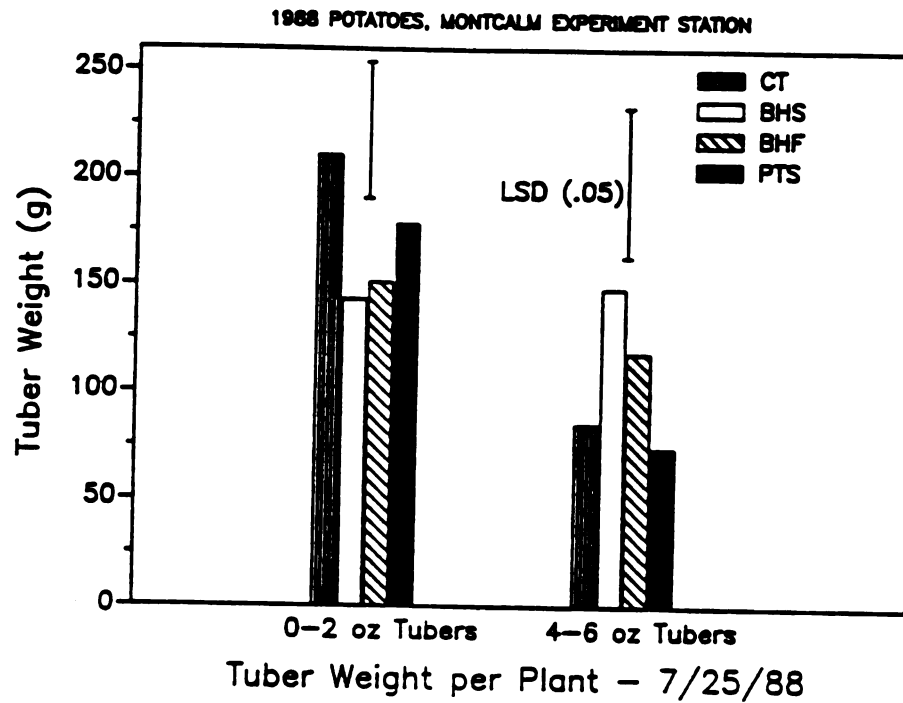


Figure 5. Tuber weight per plant on 7/25/88 and 8/19/88 as affected by tillage

weight per plant from two sampling dates. On 7/25/88 conventional treatments produced significantly greater tuber weights per plant in the smallest size category with lower weights in the larger size category. On 8/19/88 tillage significantly affected tuber weight per plant again, with conventional tillage treatments having significantly greater total tuber weights of tubers under 6 ounces (170.10 g) and significantly lower weights of tubers over 6 ounces. These data showed a propensity toward greater production of small tubers by conventionally tilled plants throughout the summer and may be a response by conventional plants to low oxygen diffusion rates in and above the layer of compaction. Holder and Cary (1984) and Cary (1985, 1986) found that the greatest adverse effects of low soil oxygen diffusion rates were on tubers, rather than roots. Also, tuber initiation and deformities were increased when low oxygen diffusion rates increased, resulting in undersized, knobby tubers.

In order to evaluate the degree of effectiveness with which plants produced tubers, ratios of dried tuber weight to dried above-ground plant biomass were calculated (Fig. 6). The ratio might then be used to elucidate the plant's efficiency in capture of solar energy, production of carbohydrates and diversion to tubers as opposed to leaves, stems, roots and plant physiological processes. 1987 results vary, though significantly higher ratios for spring Bush Hog over conventional tillage and for fall Paratill over fall Bush Hog suggest either different growth stages or more efficient carbohydrate allocation by conventional tillage and fall Bush Hog treatments. 1988 data showed trends toward lower ratios for conventional tillage in early July with

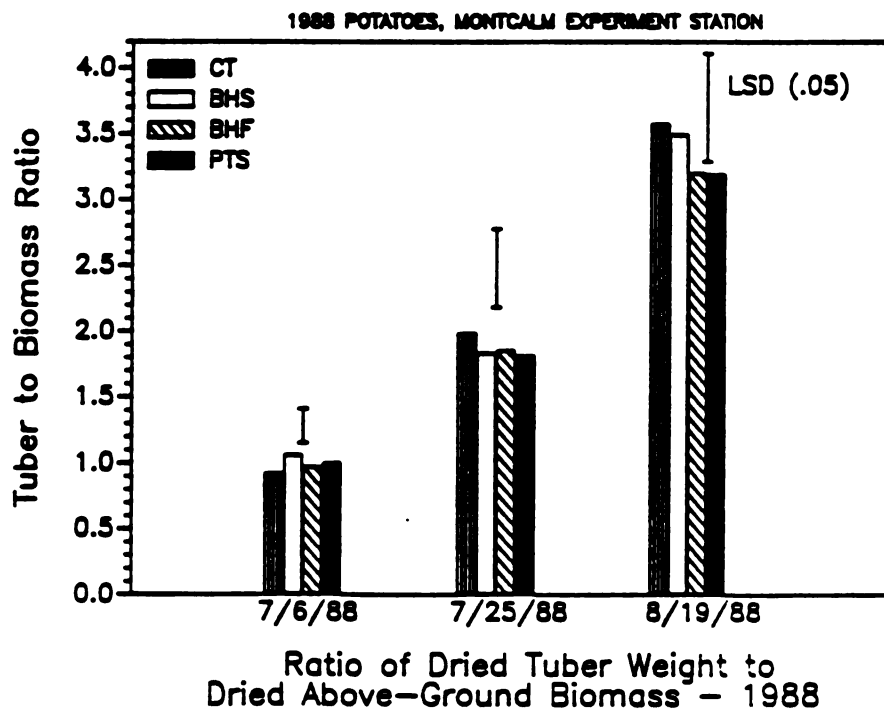
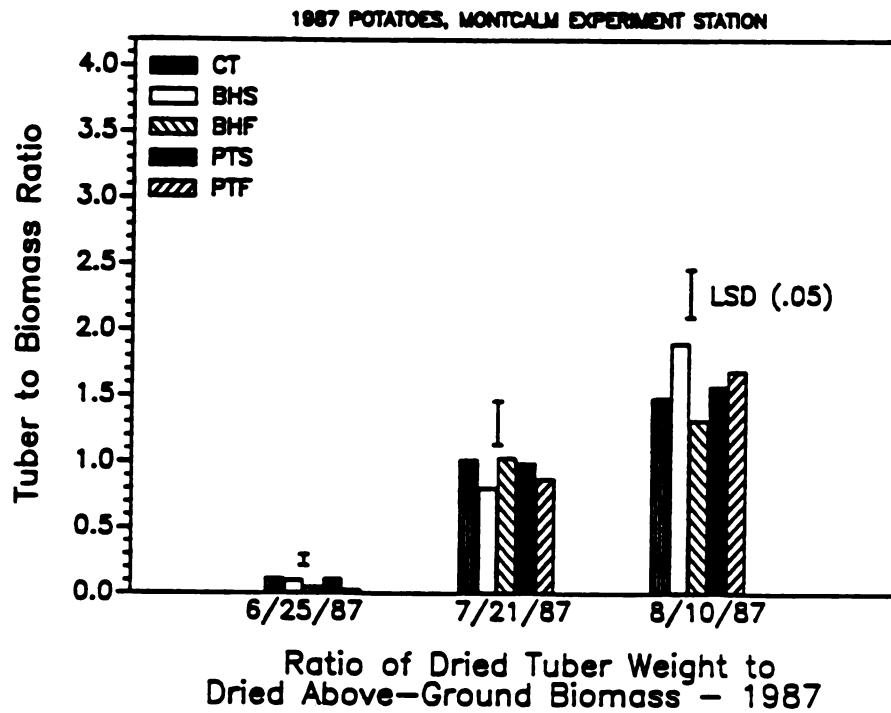
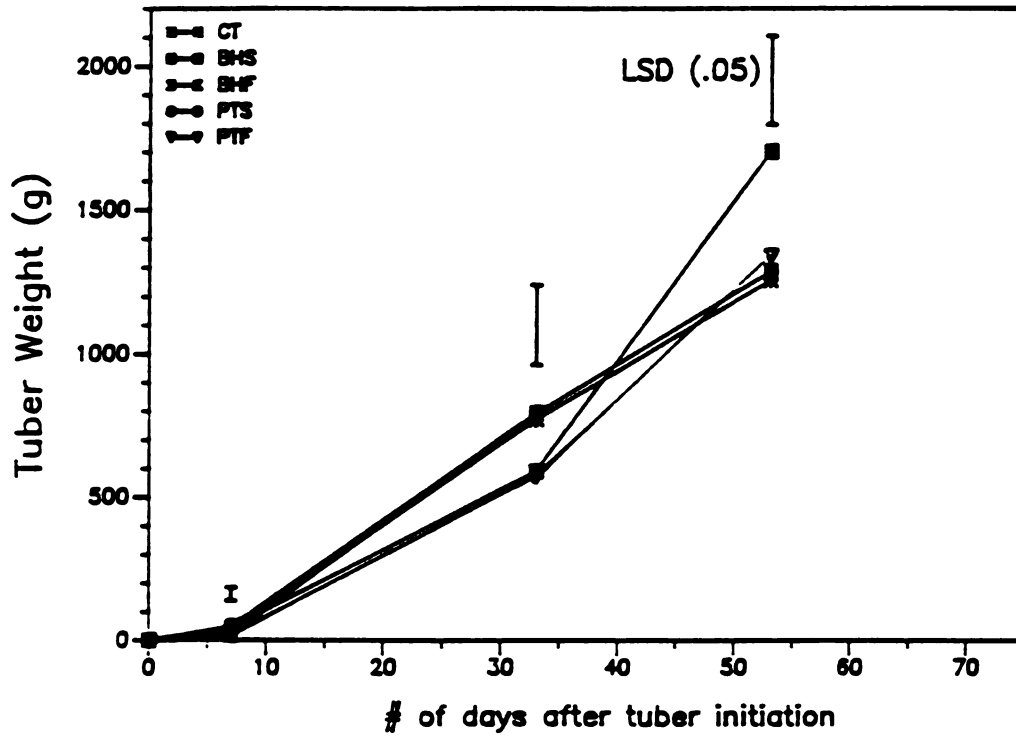


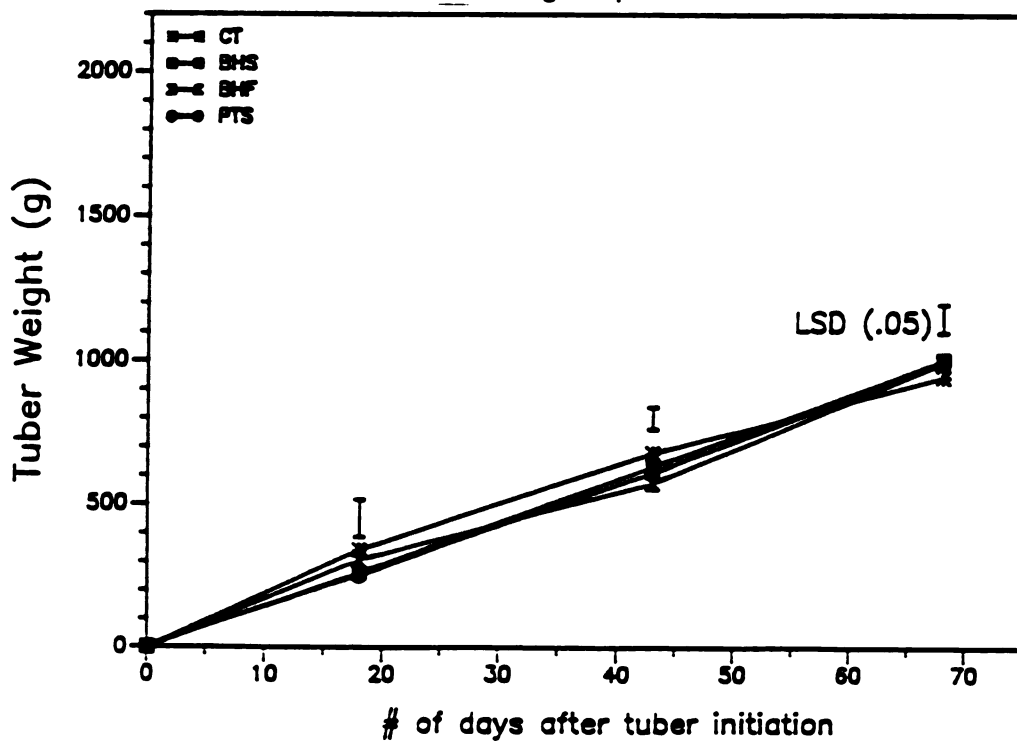
Figure 6. 1987 and 1988 ratios of dried tuber weight to dried above-ground plant biomass as affected by tillage

lower ratios for zone tillage in late July and mid-August. Also, in late July and mid-August each year, 1988 plants were up to two times as efficient at tuber production as 1987 plants on a per plant basis, based on production of above-ground biomass. Total per plant tuber production was greater in 1987, however (Fig. 3). Ultimately, this was reflected in yield differences, though margins were not as dramatic as one might expect, in light of the 1988 drought. Total 1987 yields showed increases over 1988 yields of 8% for conventional tillage, 14% for Bush Hog and 20% for Paratill. Recall that at 36 cm seed spacings, 1987 plots contained approximately 42 plants per 15 meters of row, while 1988 plants contained 17 more plants in the same length of row. Therefore, while individual plants were more productive in 1987, 1988 plants outnumbered 1987 plants per unit area. When total tuber weights from mid-August samplings were calculated on a per unit area basis, total tuber weights were almost identical in the two years. (1987 dried above-ground biomass was 2.9 times greater than 1988 data on a per plant basis and 2.0 times greater on a per unit area basis.)

Figure 7 compares growth curves for total tuber production as measured by weight. Assuming tuber initiation began at approximately 55 days after planting, growth increased linearly in both years, and the 1987 curve was much steeper. Spring Bush Hog treatments produced significantly greater weights of tubers on day 52. Growth curves for production of above-ground biomass increased linearly in 1987, but peaked in 1988 at a lower level early in the season and then levelled off (Fig. 8). Day zero in this figure was the appropriate date plants re-emerged after hilling (7 days post-hilling), which was 30 days

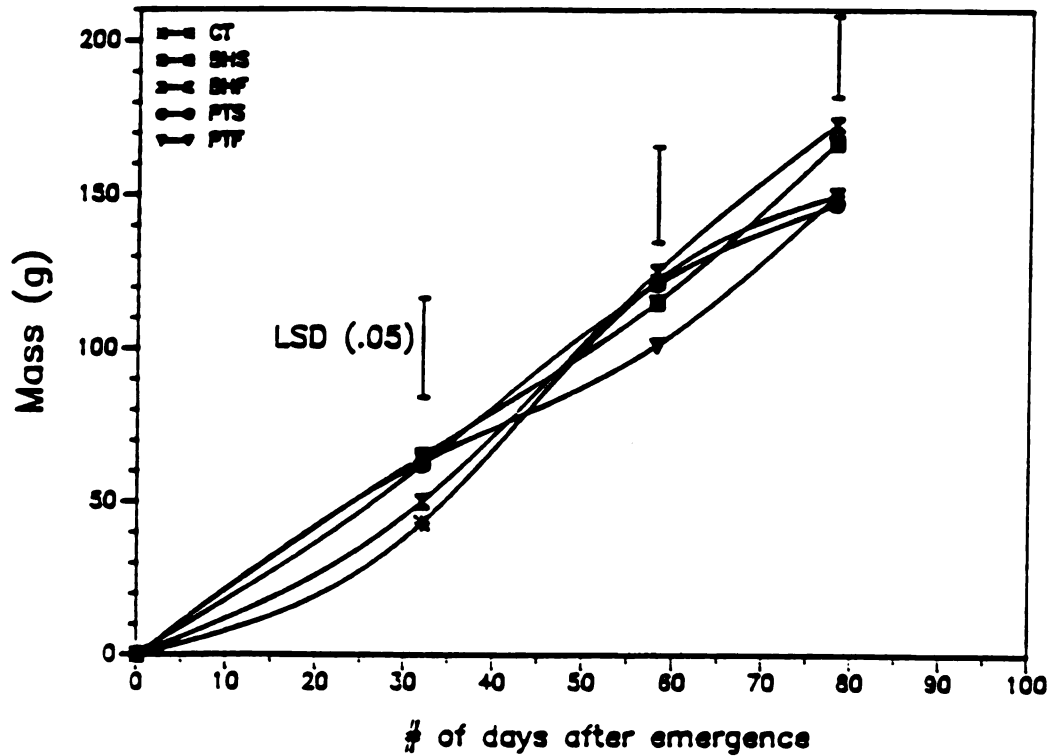


Total Tuber Weight per Plant – 1987

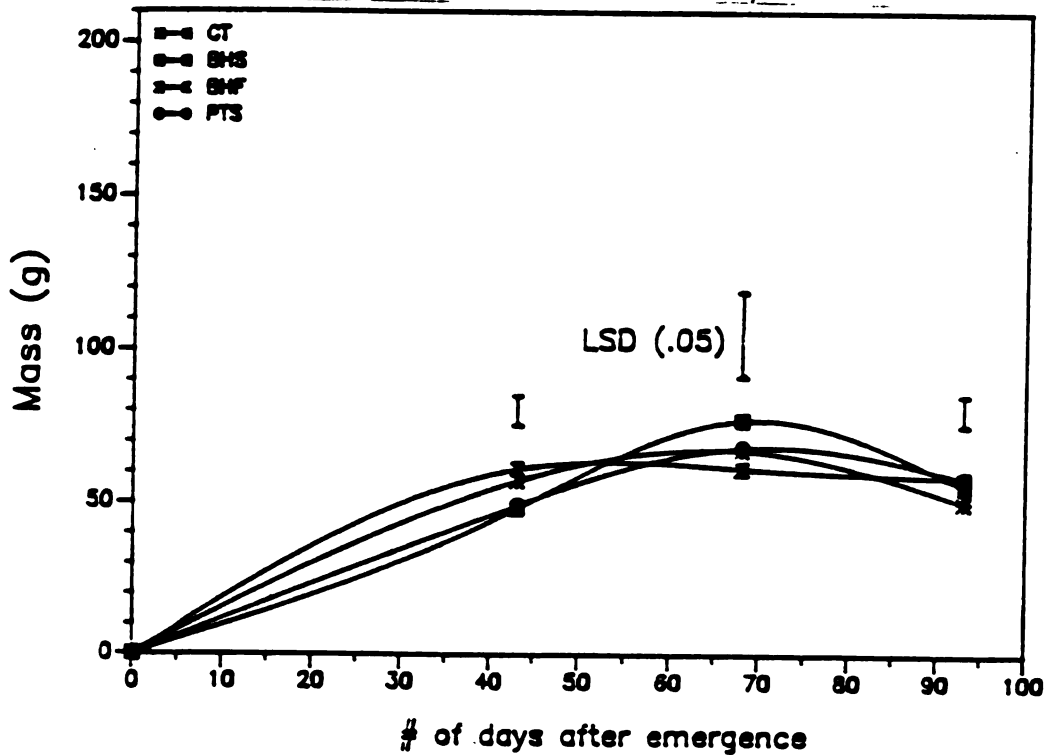


Total Tuber Weight per Plant – 1988

Figure 7. 1987 and 1988 growth curves: tuber weight/plant as affected by tillage



Dried Above-Ground Biomass/Plant - 1987



Dried Above-Ground Biomass/Plant - 1988

Figure 8. 1987 & 1988 growth curves: above-ground biomass/plant as affected by tillage

after planting. Though growth patterns were generally similar from treatment to treatment within year, in Figure 8 both 1987 spring Bush Hog and 1987 fall Paratill appeared to be increasing linearly in above-ground biomass production on day 77, while the other treatments were beginning to level off. In Figure 7 both spring Bush Hog and fall Paratill were also increasing tuber production in 1987 at a faster rate than the other treatments. These differences in growth stage and rate could explain the significantly higher 1987 ratios of spring Bush Hog and fall Paratill over the other two treatments. The growth curves also clearly illustrate differences between years, showing 1988 plants had reached near peak production of above-ground biomass early in the season, by day 43.

Ultimately treatment differences in plant growth and development affect plant production in terms of yield. The tendency toward greater production of small tubers by conventional treatments during the growing season was also evident in 1988 per plant harvest data. (Because precision planting was not conducted in 1987, and harvest populations were not taken, 1987 per plant harvest data is not available.) In terms of marketable yield per plant, spring zone tillage tended to be more productive than conventional tillage (Fig. 9). A comparison of yields of all non-deformed tubers above and below 6 ounces showed zone tillage conducted after planting (PTP) produced the smallest yields in every category. Conventional treatments showed greatest yields of tubers less than 6 ounces and, with the exception of PTP treatments, smallest yields of tubers over 6 ounces. Paratill post-planting also produced significantly smaller gross and marketable yields and

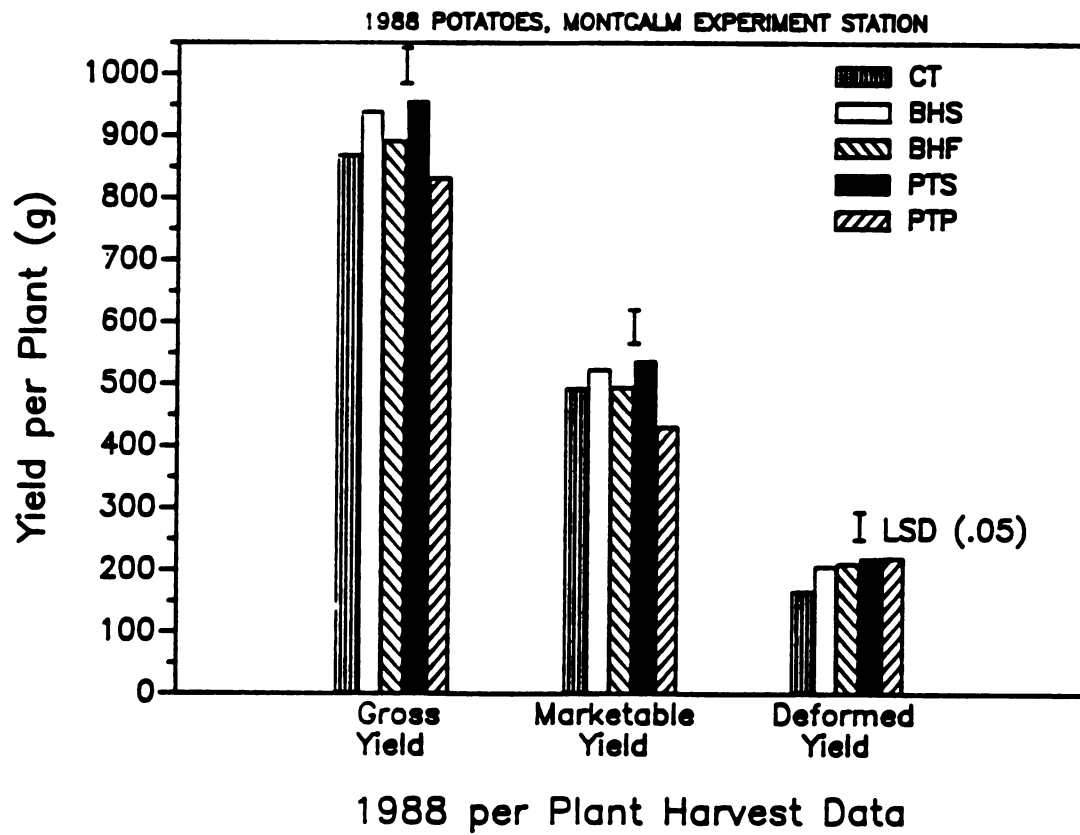


Figure 9. 1988 per plant harvest data as affected by tillage

Table 6. Yield and quality of potatoes at 25 cm seed spacing as affected by tillage

Tillage	Gross Yield		Marketable Yield (U.S. Grade #1's)		Specific Gravity		Hollow Heart	
	1987	1988	1987	1988	1987	1988	1987	1988
	-----Mg ha ⁻¹ -----						----#/10--	
CT	42.2	39.0	25.8	22.1	1.068	1.066	1.0	0.4
BHS	47.7	42.0	31.0	23.4	1.068	1.069	1.0	0.4
BHF	----	40.6	----	22.5	---	1.066	---	0.2
PTS	50.1	41.9	28.0	23.7	1.067	1.067	0.3	0.4
PTP	----	37.2	----	19.3	---	1.067	---	0.0
LSD(.01)		2.7		2.4				
LSD(.05)	5.3		3.8		NS	.002	NS	NS

produced the greatest yields of unmarketable tubers, suggesting zone tillage conducted after planting may be detrimental to yields. Spring zone tillage tended to produce greater total and marketable yields than conventional tillage, though differences were not significant in 1988. Conventional tillage tended to produce fewer malformed tubers in 1988, though this may very well have been related to the decreased overall production in conventional treatments of large tubers.

Differences in specific gravity and incidence of hollow heart were not consistent in either year (Table 6). Specific gravities of 1988 spring Bush Hog treatments were significantly higher than all other treatments. In 1987 spring Paratill treatments tended to have lower incidence of hollow heart, and in 1988 fall Bush Hog tended to have the lowest incidence of hollow heart.

In contrast to these data showing improved quality and yields under zone tillage, Ross et al. (1979), Buxton and Zalewski (1983) and Miller and Marin (1987) observed no yield increases after subsoiling Russet Burbanks in irrigated plots. Though Miller and Martin (1987) reported seed spacings of about 23 cm, neither Ross et al. nor Buxton and Zalewski mentioned seed spacing. Assuming standard seed spacings of 30 to 36 cm for Russet Burbanks were used, plants may not have taken advantage of improved soil physical conditions at greater depths unless crowding occurred at the surface. Table 7 compares 1987 yields at two seed spacings, 25 and 36 cm. Only when the standard seed spacing of 30 to 36 cm for Russet Burbanks was reduced to 25 cm did Russet Burbanks respond with increased yields. Therefore, plant response to zone tillage, as measured by quality and yields of Russet Burbanks, was

Table 7. Effect of seed spacing and tillage on gross yields of potatoes in 1987 as affected by tillage

1987 Gross Yields		
Tillage	25.4 cm spacing	35.6 cm spacing
	-----Mg ha ⁻¹ -----	
CT	42.2	41.8
BH	47.7	41.0
PT	50.1	40.1
LSD (.05)	5.3	NS

significant and positive only at higher plant populations.

CONCLUSIONS

By eliminating a compact subsoil layer, zone tillage improved soil physical conditions. However, Russet Burbank potatoes did not take advantage of the benefits resulting from subsoiling unless the subsoiling was conducted prior to planting and plants were sufficiently crowded at the surface. It appears that tuber set was not affected by drought or heat stress, and was not affected by stress due to compaction in 1987, but may have been affected by compaction in 1988 when conventional treatments tended to produce more tubers per plant. Total weight of tubers and above-ground biomass were affected by all three types of stress. Plant production of tubers, leaves and stems were substantially reduced from 1987 to 1988, a year of drought and high temperatures. Total 1987 tuber weights per plant (with the exception of one zone tillage treatment) were not significantly different, but 1987 plants used in the destructive samplings had been planted at the wider 36 cm seed spacing, where no yield increases were observed. At higher population densities, 1988 zone tillage plants were producing greater above-ground plant material in August and greater numbers of larger tubers throughout the summer, resulting in increased total and marketable yields in September.

Growth rates and magnitude of plant production were greatly decreased by climatic stress. An additional destructive sampling

between mid-August and harvest in mid-September would have been useful in providing more definitive information on growth rates. Plant efficiency in terms of tuber production was greatly decreased in 1988 when carbohydrates were probably reallocated from production of tuber and above-ground plant biomass to production of roots. Plants compensate for and respond to soil water deficits by conservation and prevention of water loss through stomatal closure, leaf senescence and decreased production of new leaves, thereby reducing the leaf surface area through which evapotranspirational water loss can occur. At the same time net root production is increased, expanding the volume and depth of soil explored by roots. This then increases the amount of water roots are able to extract (see Chapter 4). Leaf and stomatal responses result in decreased carbon uptake and thus, decreased photoassimilate production.

Because of improved soil water relations and improved soil aeration, 1988 zone tilled plants were better able to compensate for drought. They did not senesce as early as conventional plants, enabling them to continue producing carbohydrates and bulking tubers for a longer period of time.

Because no yield increases were observed in their studies, several researchers have argued that subsoiling is unnecessary if irrigation is available and water is applied frequently (Buxton and Zalewski, 1983; Miller and Martin, 1987). Yet potatoes have a high nitrogen requirement and receive frequent chemical applications throughout the growing season. They are usually planted in porous, easily leachable soils. To ignore the environmental consequences of groundwater pollution due to

unrestricted irrigation is shortsighted and unwise.

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CHAPTER IV:

ROOT RESPONSE TO ZONE TILLAGE OF RUSSET BURBANK

POTATOES (*S. tuberosum* L.)

ABSTRACT

Using a subsoiling system called zone tillage, potato yields were increased in a central Michigan sandy loam soil 10, 32, 19 and 8% in 1985 through 1988. Two types of root measurements were taken in 1987 and 1988 to monitor and better understand root responses to improved soil physical conditions in the root zone. Both traditional destructive core sampling and non-destructive videotaping through clear plastic minirhizotron tubes inserted at a 45° angle beneath potatoes in the row were used. In 1987 zone tillage did not result in increased yields unless seed spacing was reduced from 36 cm to 25 cm and plants faced stress due to surface crowding. 1988 plants, hand planted at 25 cm seed spacings to reduce variability, produced significantly greater yields and minirhizotron root counts below 38 cm for two zone tillage treatments. Between 95 and 240% greater total root counts were observed for these zone tillage treatments over conventionally tilled treatments. 1988 plants, subject to drought and high temperature stress, produced

greater overall root counts and greater root counts at deeper depths over a longer period of time than 1987 plants, regardless of treatment. Minirhizotron data showed temporal variation in root turnover rates and allowed for more accurate scheduling of destructive root sampling.

INTRODUCTION

Potatoes are often described as having more fragile, shallower rooting systems than other crops (Flocker et al., 1960; Lesczynski and Tanner, 1976), which, if true, would explain the potato's sensitivity to water deficits (Epstein and Grant, 1973; Phene and Sanders, 1976; Van Loon, 1981; Levy, 1983) and the inability of its roots to penetrate compact layers (Boone et al., 1978; Van Loon and Bouma, 1978; Van Loon, 1981; Boone et al., 1985; Van Loon et al., 1985). Root growth of potatoes has also been reported to depths of 90 to 150 cm in non-compacted soils (Fulton, 1970; Van Loon et al., 1985; Lesczynski and Tanner, 1976), suggesting that compaction inhibits potato root growth. Potatoes may be sensitive to water deficits, not only because their roots are often more shallow in the presence of a plowpan, but because they require more water than other crops, which is not explained by differences in total root proliferation or maximum root extension (Fulton, 1970). Fulton found that potato, corn and tomato roots all had very similar patterns of root proliferation and similar maximum depths of root penetration (between 120 and 130 centimeters) in a non-compacted

sandy loam soil. In the presence of a plowpan the sensitivity of potatoes to lack of water was exacerbated, as root access to deeper soil water was restricted.

Scott and Erickson (1964) showed that the crucial factor limiting root growth in alfalfa and sugar beets was low availability of oxygen in the compacted layer, not soil mechanical resistance. Saini (1976) found that while a significant inverse relationship existed between either bulk density or soil strength and crop performance, the one soil physical factor that was highly correlated with marketable yield of potatoes was oxygen diffusion rate.

Thus, reduced aeration due to the absence of air-filled pores in compact soils is a most plausible explanation for lack of potato root penetration through plowpans. It is not the complete picture, however. There is an additional variable which plays a key role and is correlated to soil oxygen concentrations.

The natural growth hormone, ethylene, which inhibits longitudinal cell expansion while promoting lateral cell expansion, evolves in increasing concentrations in anaerobic or waterlogged soils following rapid decreases in soil oxygen concentrations (Smith and Russell, 1969). Furthermore, soil ethylene concentrations increase with increasing soil moisture content, with increasing soil density, with depth from soil surface and with increasing temperature as oxygen uptake by roots and micro-organisms increases (Smith and Restall, 1971; Smith and Dowdell, 1974).

Potatoes are unusually sensitive to low concentrations of ethylene. They respond to its presence by inhibiting root elongation,

as well as tuberization and starch accumulation in tubers (Catchpole and Hillman, 1969; Mingo-Castel et al., 1976; Cary, 1986). Lowest yields occur with the highest levels of ethylene (Campbell and Moreau, 1979). Thus, it appears the deleterious effects of compaction on potatoes are related more to the potato's combined need for unusually high amounts of water and soil oxygen coupled with its ethylene intolerance, rather than an inherently weaker root system.

Research with potatoes and compacted subsoils has shown very limited penetration of potato roots through plowpans (Boone et al., 1978; Van Loon and Bouma, 1978). Lesczynski and Tanner (1976) reported 85% of potato roots grew above the plowpan, and total root production in terms of root length densities (cm of root length per cm^3 of rooted soil volume) was found to be two to six times greater in uncompacted soils (Boone et al., 1978).

In the presence of dense subsoil layers, roots are forced to deplete soil water more completely at the surface during dry years and are prevented from extracting groundwater by capillary transport resulting in greater susceptibility to drought stress (Boone et al., 1985). During dry weather, plowpans can also become absolute barriers to roots by forming a rigid soil matrix in which soil pore diameters are smaller than root diameters (Boone et al., 1985). In contrast, during wet periods, plowpans may support a perched water table, promoting anaerobic conditions, lower oxygen diffusion rates and increased ethylene concentrations. Smith and Dowdell (1974) concluded that concentrations of ethylene which would inhibit root elongation occurred frequently in "heavy soils [fine-textured] during the spring and early

summer and in light soils [coarse-textured] when unusually wet."

By improving soil physical conditions through eradication of a compact subsoil layer to a depth of 35 to 40 cm, potato yields were increased 8 to 32% in four years of field experiments between 1985 and 1988. Under zone tillage (a system of in-the-row subsoiling with an interrow rye cover crop left undisturbed for erosion control), soil strength and bulk density were significantly decreased 46% and 10%, soil air-filled porosity increased up to 31% and the number of soil macropores increased up to 101% in a sandy loam soil (see Chapter 2). The objective of this study was to evaluate the response of potato roots to fracturing of dense subsoil layers with zone tillage. As no previous studies have monitored potato root growth using minirhizotron tubes, two further objectives were to ascertain the extent to which minirhizotrons would quantify temporal variation in potato root growth and whether or not patterns of minirhizotron root counts were comparable to destructive root sampling data (Taylor, 1986).

MATERIALS AND METHODS

Field experiments were conducted in 1987 and 1988 with Russet Burbank potatoes on a McBride sandy loam (coarse-loamy, mixed, frigid Alfic Fragiorthod) in central Michigan at Michigan State University's Montcalm Experiment Station. Experimental design, cultural practices and treatments were discussed in Chapter 2.

Destructive root samples were taken on June 25th, 1987, August

12th, 1987, July 7th, 1988, and July 26th, 1988, using the method described by Srivastava et al. (1982). Roots were sampled from one plant in each replication of each treatment. Plant material above the hill was removed with a machete. Each plant was bagged, oven-dried at 38°C and weighed. In 1988 hill roots were also collected and counted. A rectangular metal core placed over the center of the plant at the base of the hill and perpendicular to the row was driven into the soil by a hammer driven profile sampler mounted on a tractor (Srivastava et al., 1982). A grid of eighteen soil cubes 7.5 cm (443 cc) per side (three across, six down) was extracted from the 22.5 x 45.0 cm of soil in the metal core. Soil cubes were refrigerated (1987) or frozen (1988), then washed in a hydropneumatic elutriator (Gillison's, Inc., 3033 Benzie Hwy., Benzonia, MI 49616) which separated soil from roots (Smucker et al., 1982). Samples were stored in a 10% methyl alcohol solution and refrigerated at 4°C until counted, stained with a 1% malachite green solution to aid in distinguishing roots from organic matter, counted on a 2.4 cm grid and converted to root length densities by the line-intersect method (Tennant, 1975), which was a modification of Newman's method (Newman, 1966). These data are reported as root length densities (cm of root length per cm³ of soil).

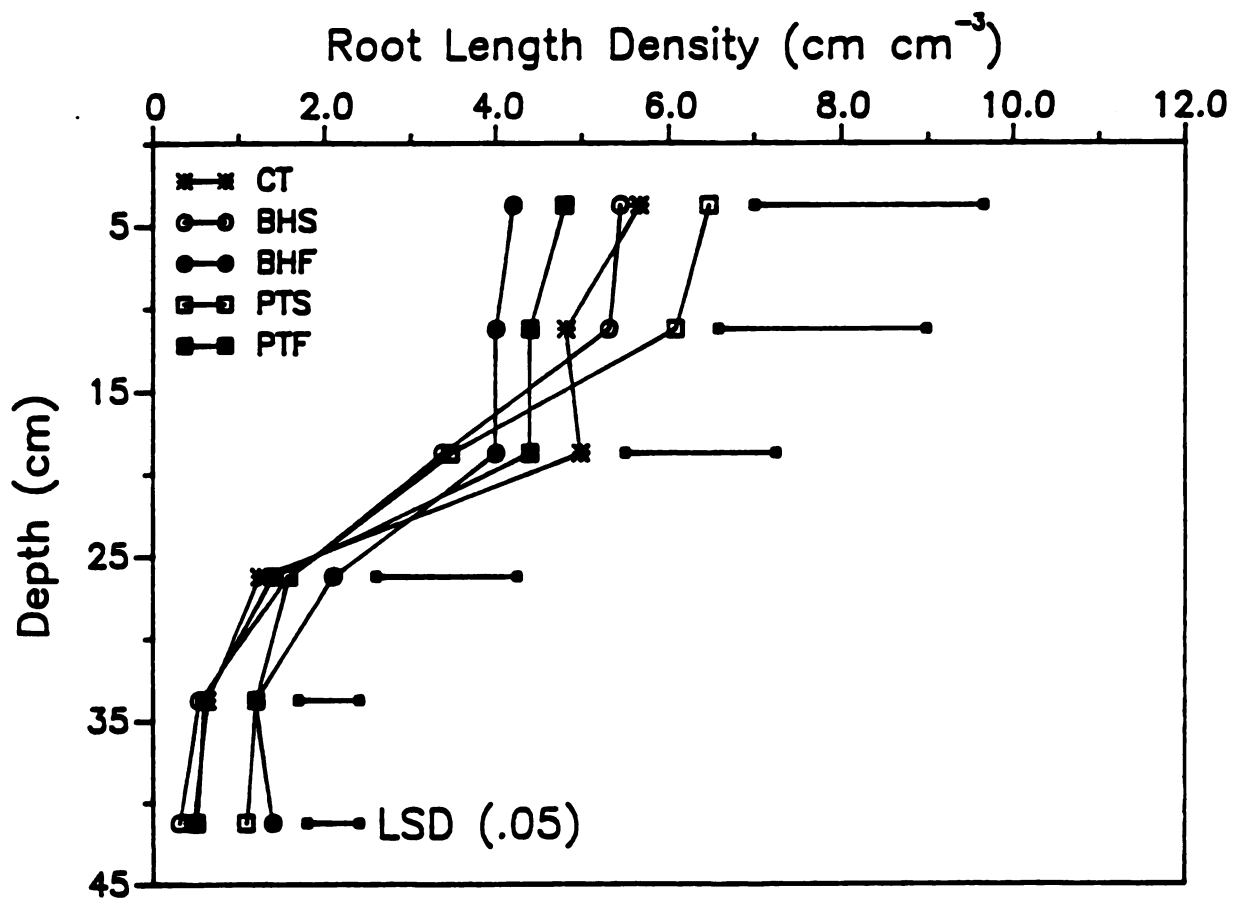
Non-destructive root sampling was conducted by inserting clear plastic (butyrate) minirhizotron tubes 5.4 cm in diameter, 183 cm in length at a 45° angle in the soil (Upchurch and Ritchie, 1983). Holes were bored with a hydraulically driven soil sampling probe (Giddings Model GSRP-ST) fitted with a cutting bit designed to compact soil inward rather than outward (Box et al., 1989). Holes were then cleaned with a

round wire brush that was gently rotated as the brush was pulled up and down the hole. Tubes were installed by hand between the third and fourth plants from the end of the row parallel to and beneath the row, one week after planting. Tubes were capped at both ends with No. 11 neoprene stoppers. The portion of the tube protruding above the soil was spray-painted black to exclude light and then spray painted white to reflect solar rays and reduce heating. Three tubes were inserted in adjacent rows in each replication of each treatment each year to capture the variability associated with minirhizotron data. A miniature video camera (Model MV-9011 Agricultural camera, Circon, Santa Barbara, CA.) was inserted in the tube to the depth of the deepest observable roots and then brought up the tube at 1.2 cm depth increments while filming occurred for three seconds at each depth. Each frame corresponded to a 1.2 by 1.8 cm area, or 2.16 cm². Video images of the roots were recorded with a modified Hitachi monitor-viewfinder, portable video cassette recorder (Panasonic Model NV-8420) and portable computer to store data on date, time, tube number and depth. Roots were filmed on June 19th, July 6th, July 20th, August 5th and August 19th in 1987 and June 15th, June 23rd, July 7th, July 13th, July 20th, August 1st and August 30th in 1988. Videotapes were later viewed and roots counted frame by frame. Each root was given a count of one, regardless of its origin. Where tubes were not filmed due to mechanical failure of instruments, mean root counts from replications of the same treatment were used. The data were analyzed as root counts per cm² of frame.

RESULTS AND DISCUSSION

Root length densities versus soil depth for destructive, mechanical root sampling were plotted in Figures 1, 2 and 3 showing results for two dates in 1987 and one in 1988. At both 1987 sampling dates there was a proliferation of roots in conventional tillage (CT) treatments just above the base of the conventional plow layer, located at about 20 cm. On June 25th, 1987, conventional tillage root length densities were significantly greater than spring zone tillage treatments (BHS and PTS, or spring Bush Hog and spring Paratill) at this depth. Early in the 1987 season fall zone tillage treatments (BHF and PTF, or fall Bush Hog and fall Paratill) tended to have fewer roots near the surface, though differences were significant only below 30 cm, where zone loosening took place in the zone tillage treatments. Later in the season, conventional tillage and fall zone tillage tended to produce least roots overall, with significant differences at 10 to 30 cm depths, indicating the possibility of earlier senescence in these treatments than spring zone tillage treatments (BHS and PTS).

The June and August samplings in 1987 were too early and too late to catch maximum total root growth, according to 1987 minirhizotron data which showed maximum root growth occurred between July 6th and 25th for seed planted April 24th (discussed later). Thus, 1988 destructive root samplings were scheduled to monitor the peak period. Figure 3 shows generally greater net root production on July 26th, 1988, than on either



6/25/87 ROOT SAMPLING

Figure 1. Root length density responses to zone tillage treatments by the destructive method of root sampling, conducted 62 days after planting (6/25/87)

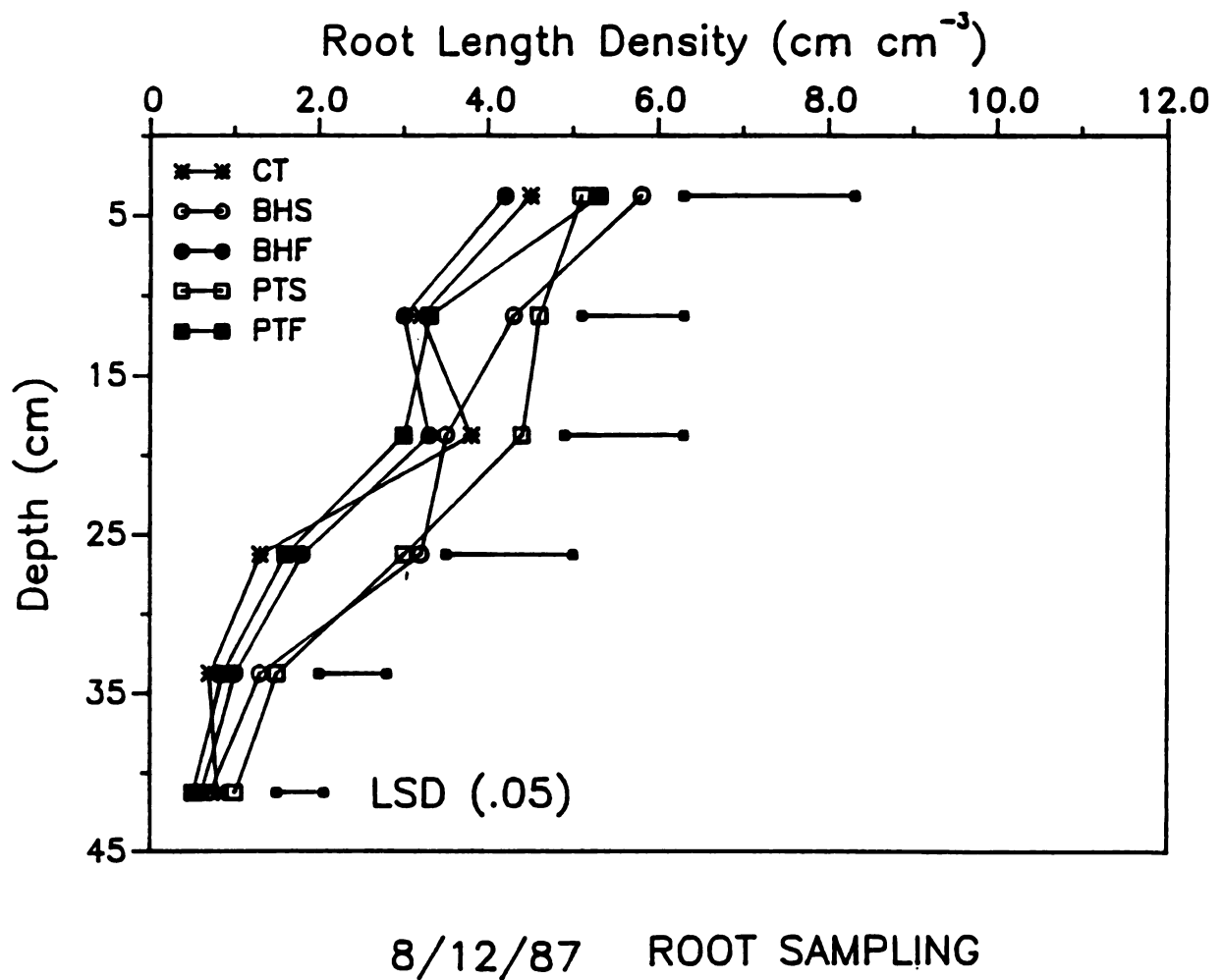
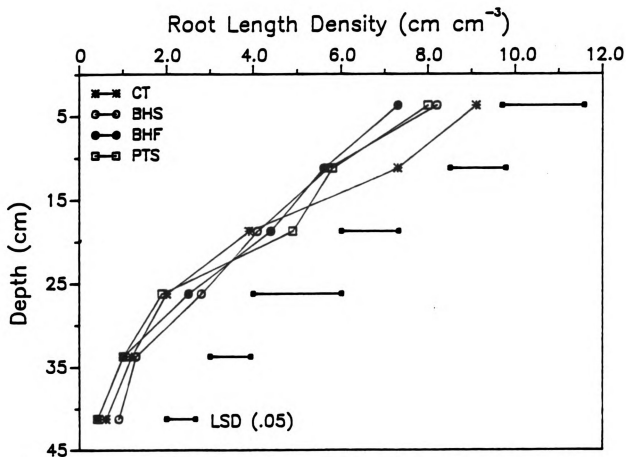


Figure 2. Root length density responses to zone tillage treatments by the destructive method of root sampling, conducted 110 days after planting (8/12/87)



7/26/88 ROOT SAMPLING

Figure 3. Root length density responses to zone tillage treatments by the destructive method of root sampling, conducted 92 days after planting (7/26/88)

of the 1987 dates. Root length densities of up to 7 to 9 cm cm⁻³ were present near the base of the hill in 1988, as opposed to densities of 4 to 7 cm cm⁻³ in 1987, which may have indicated the 1988 July sampling date was closer to peak root production. However, since the 1987 above-ground biomass was greater than 1988 biomass, there may have been greater carbon allocation to roots in 1988 during the drought. While conventional tillage produced significantly more roots than zone tillage at 11 cm, it did not show the pattern of sharp increases above the plow layer observed in 1987. Between 25 and 45 cm root counts in 1987 and 1988 were similar in magnitude.

Compared to dry edible beans, where average root length densities in a clay soil peaked at about 3.5 cm cm⁻³ (King, 1988), Russet Burbank potatoes produced greater quantities of roots overall. Lesczynski and Tanner (1976) reported 2 to 6 cm of potato roots per cm⁻³ of soil in the plow layer, with decreasing densities below. Their data agreed well with our 1987 data in Figures 1 and 2, where root length densities at depths less than 20 cm ranged from 3 to 6.5 cm cm⁻³. 1988 data, however, produced substantially greater root length densities in the plow layer, ranging from 4 to 9 cm cm⁻³. Drought conditions may have caused greater root proliferation near the surface where irrigation water was more plentiful. Zone tillage treatments tended to produce fewer roots above 11 cm, perhaps because they were able to produce more roots deeper in the profile, from 15 to 25 cm beneath the base of the hill.

Early in the growing seasons between planting on April 24th/25th and July, climatic conditions were very different during the two years

of the study. Potatoes grew under normal temperatures and rainfall for central Michigan in 1987. On the other hand, in 1988, potatoes were subject to drought and unusually high temperatures.

Figures 4 through 15 highlight certain aspects of 1987 and 1988 minirhizotron data. In Figures 5 to 8 statistical comparisons were not made because root counts at different times or depths are not independent of each other. Therefore, the discussion for these figures focuses on a qualitative description of the minirhizotron data. However, data were also analyzed quantitatively using two different depth increments for analytic purposes. Figures 9 to 15 present mean root counts per cm^2 of video frame aggregated by 7.5 cm depth increments and analyzed statistically at each depth for differences among treatments. Tables 1 and 2 present total root counts per cm^2 of frame at four depths, which are meaningful in terms of tillage treatments (discussed later).

Figure 4 shows plant response to weather differences in terms of maximum depth of root penetration. No basic differences due to tillage were seen in 1987 in either pattern or depth of root proliferation. With the exception of spring Paratill treatments (PTS), the maximum measurable depths of penetration were achieved by July 6th. (Minirhizotron tubes used in this study measured roots to a depth of approximately 110 cm from the top of a 10 cm hill.) By contrast, marked differences existed in 1988 data. Fall Bush Hog treatments penetrated deeper and more quickly much earlier in the season. Roots in all treatments took longer to reach maximum depths in 1988, and two treatments (conventional tillage and spring Bush Hog) penetrated to

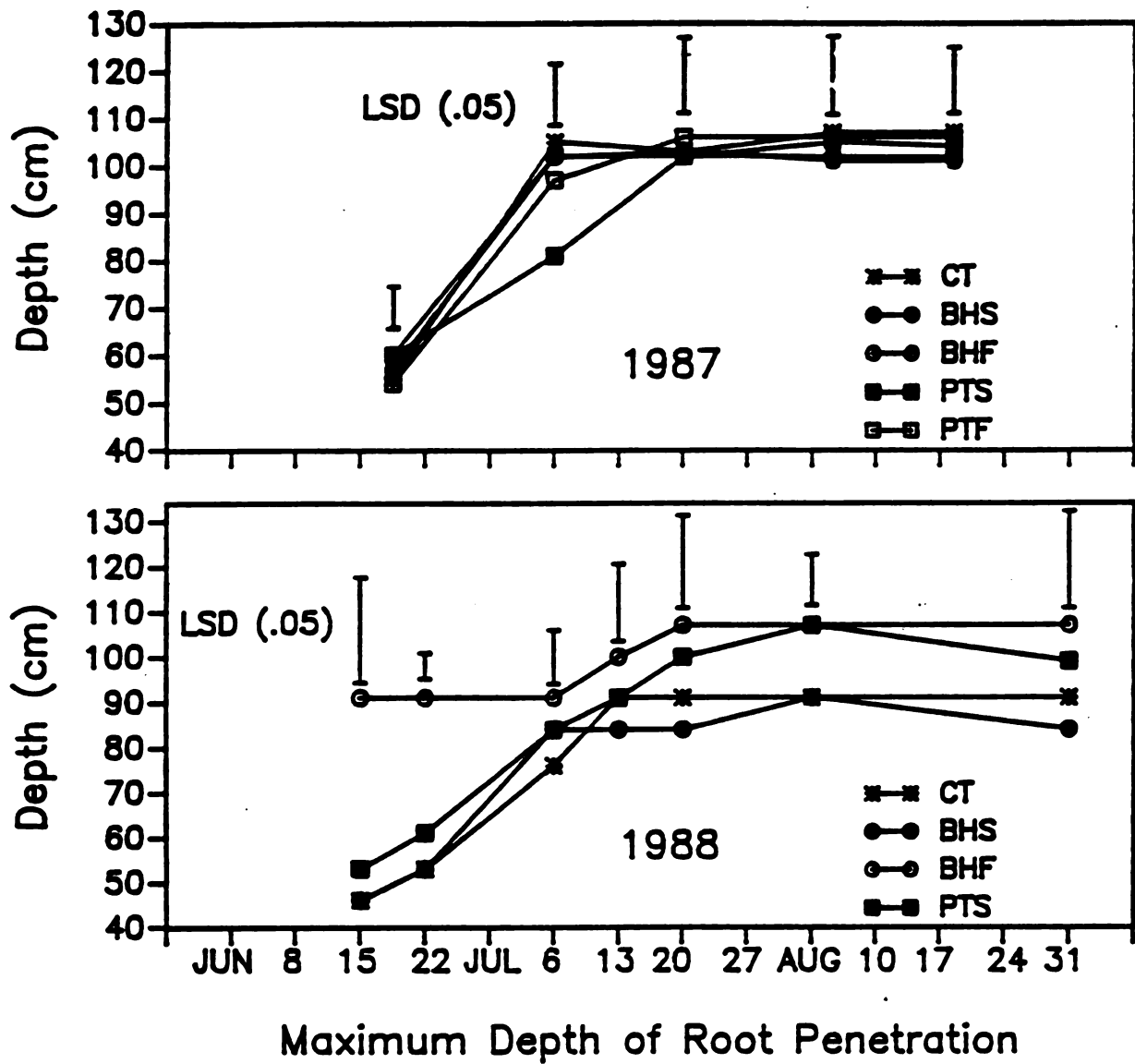


Figure 4. Maximum depth of potato root penetration in 1987 and 1988 on a McBride sandy loam soil as affected by tillage

depths of only 90 cm from the top of the hill.

Figures 5 and 6 illustrate the temporal variation of 1987 minirhizotron data in mean root counts at each depth increment for conventional and fall Bush Hog treatments. Both figures show that maximum root growth occurred between July 6th and July 20th and that the great bulk of root growth occurred above 50 cm and in the hill. In similar fashion to 1987 mechanical root sampling data, on each of these dates greatest root counts for conventional tillage occurred above the compact layer at 20 cm. In direct contrast to previous work by other researchers (Flocker et al., 1960; review in Lesczynski and Tanner, 1976), Figure 5 shows substantial root penetration occurred below the pan to a depth of 46 cm. It is possible, though unlikely, that roots may have followed the tube-soil interface. If this had been the case, one would not expect the differences in root counts from 20 to 50 cm compared to 50 cm and below. Fall Bush Hog root counts in Figure 6 followed a more distinct pattern than conventional tillage root counts with root growth clustered in a smaller range of root counts per cm² of frame. Senescence appeared to have begun by August 5th, when net root loss overtook net root production.

Figures 7 and 8 show temporal variation in mean root counts for the same two treatments in 1988. Patterns were much more consistent and clearly delineated here than in Figures 5 and 6. Each 1988 minirhizotron tube lay beneath identical numbers of evenly spaced plants which were handplanted, while 1987 plant numbers and spacings, which were planted mechanically with a planter, may have varied considerably. Data discussed earlier indicated yield of Russet Burbanks was affected

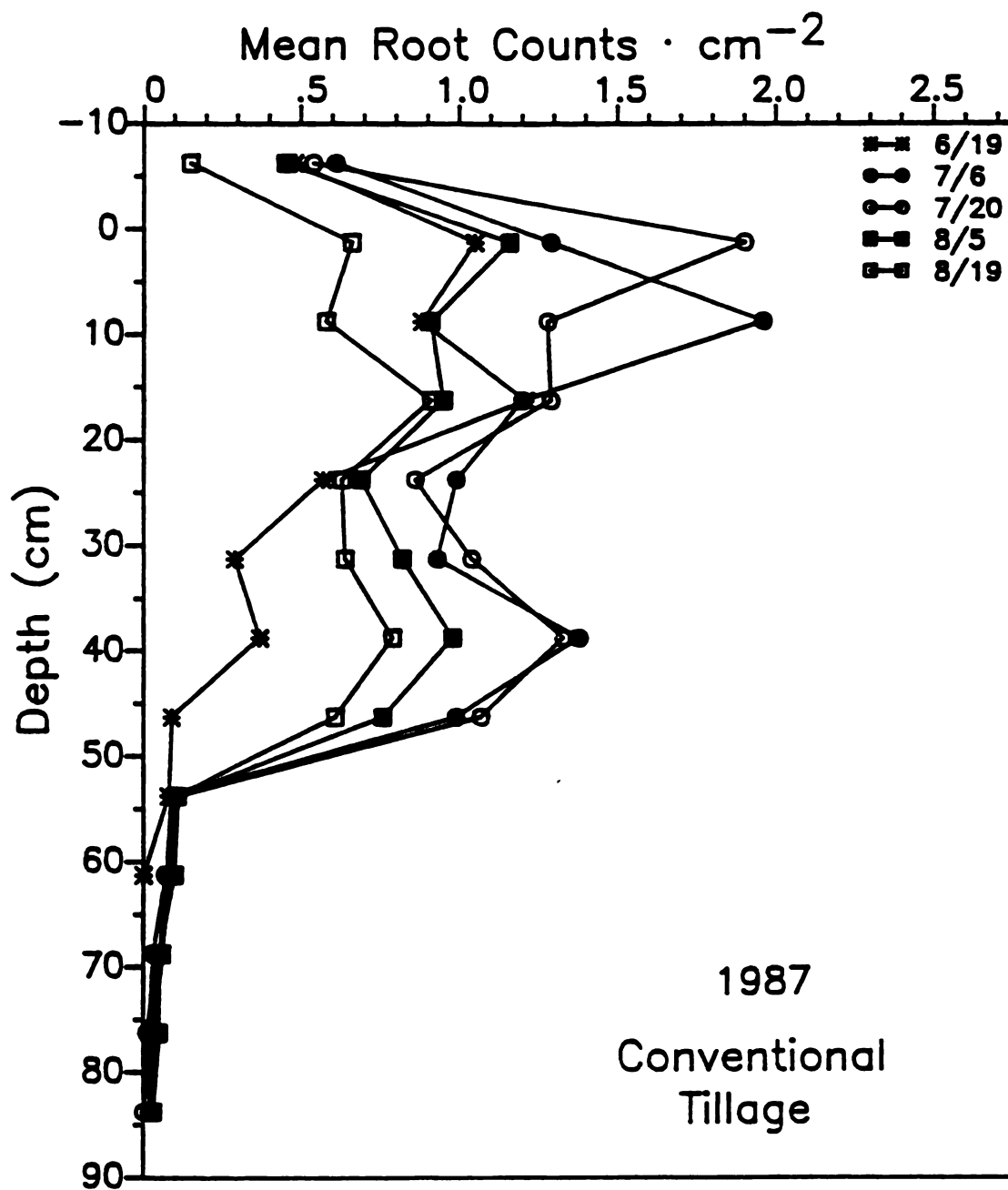


Figure 5. 1987 minirhizotron data - potato root counts per cm² of video frame for conventional tillage treatments

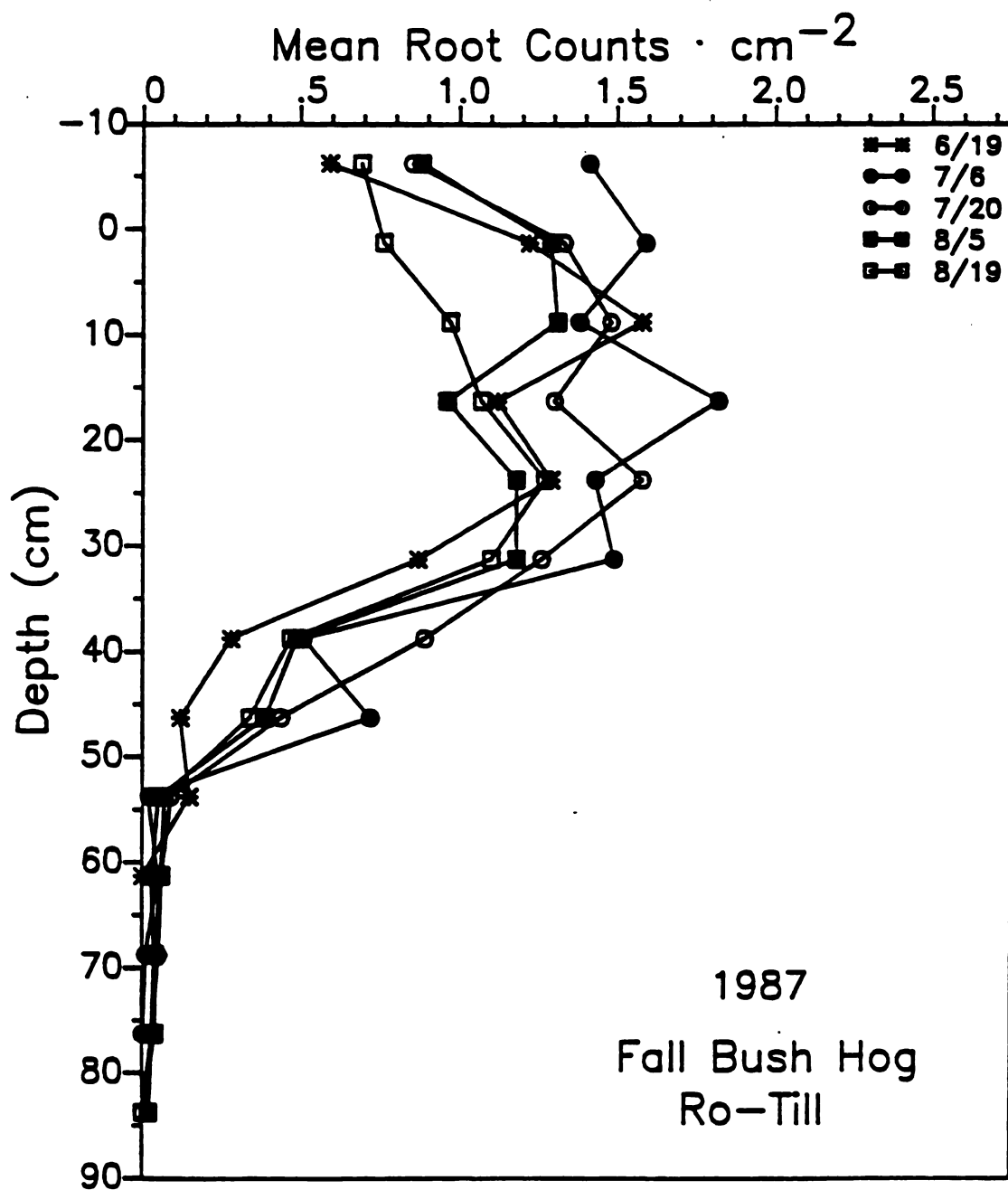


Figure 6. 1987 minirhizotron data - potato root counts per cm² of video frame for fall Bush Hog treatments

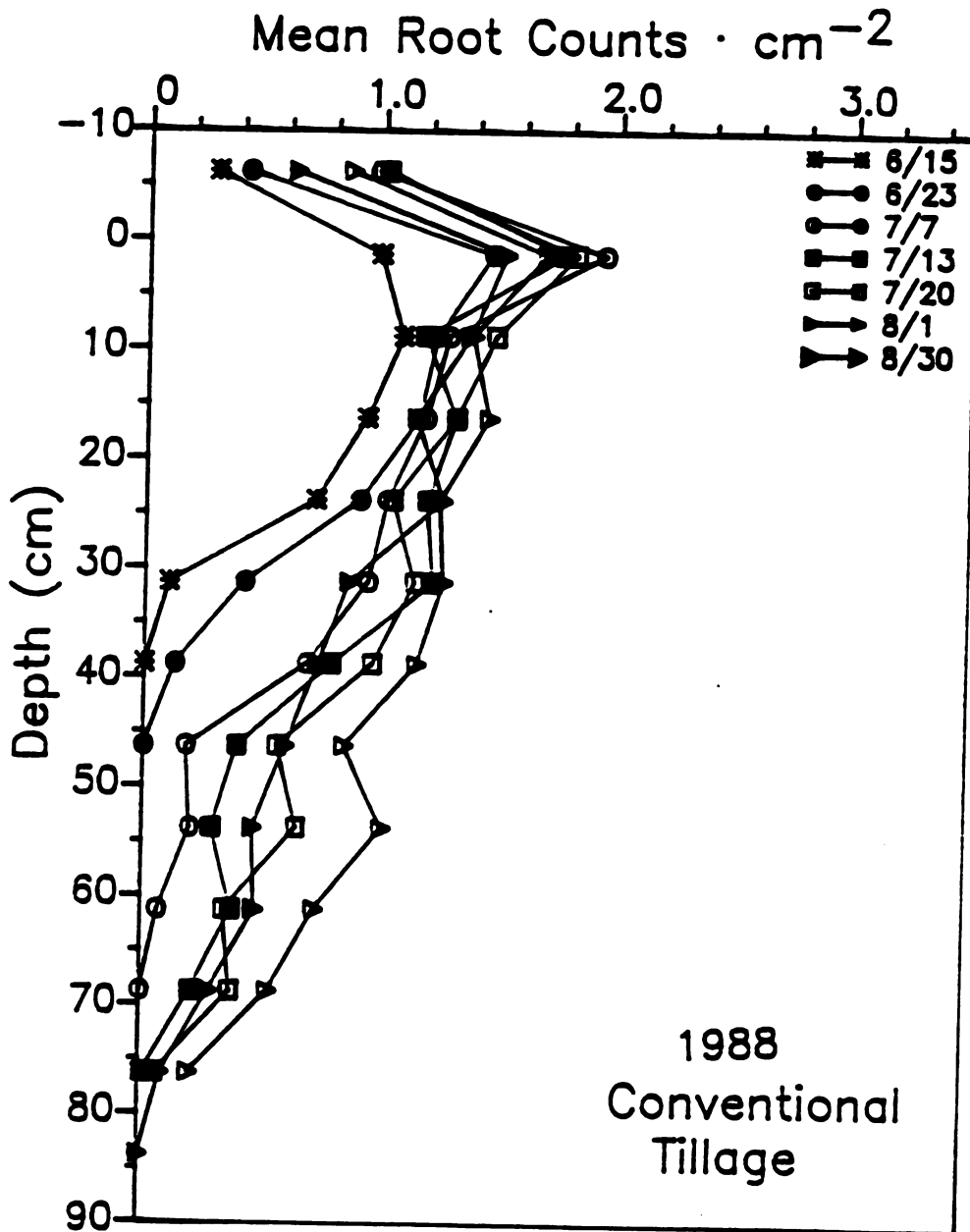


Figure 7. 1988 minirhizotron data - potato root counts per cm^2 of video frame for conventional tillage treatments

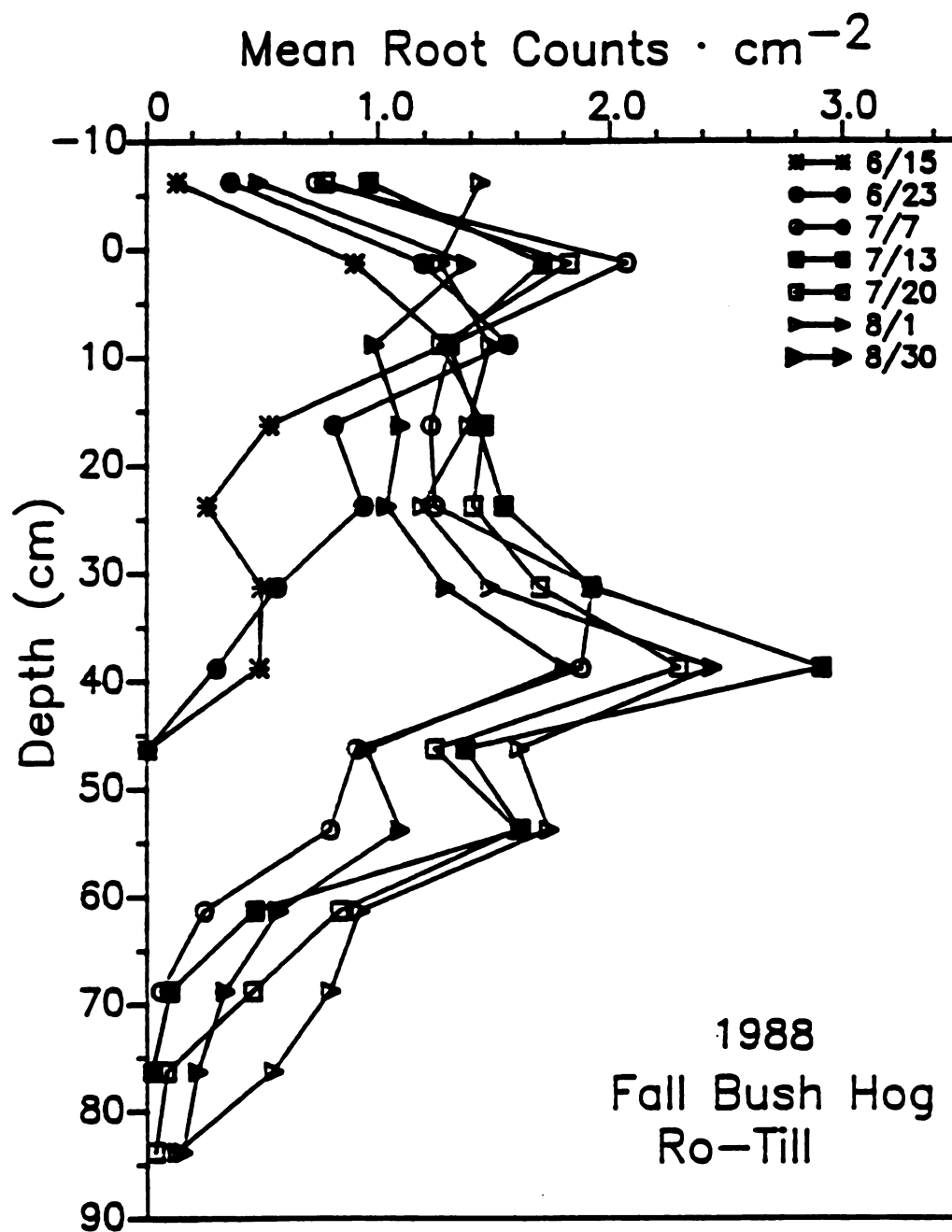


Figure 8. 1988 minirhizotron data - potato root counts per cm^2 of video frame for fall Bush Hog treatments

by surface spacing of seed potatoes (see Chapter 3) and should also affect root response.

The increased proliferation of roots in conventional treatments above the conventional plow layer that was observed in 1987 was absent in 1988 (Figure 7), as it was in the 1988 mechanical root sampling data (Fig. 3). There was much greater root activity at depth beginning earlier and lasting for a much longer period of time for both treatments in the dry 1988 season. Yet the magnitude of mean 1988 root counts was not quite as great at most depths as in 1987. A striking difference between Figures 7 and 8 is the much greater root activity by the fall Bush Hog treatment at 30 to 60 centimeters from the base of the hill. It appears that under stressful conditions (e.g., dry weather, high temperatures and greater population densities), roots in the zone tillage treatment were able to take advantage of improved soil physical conditions at depth. (1987 minirhizotron measurements were made on plots where Russet Burbank seed was spaced 36 cm apart. In these plots zone tillage treatments showed no yield increases over conventionally tilled treatments. However, yield increases were observed in plots planted at 25 cm seed spacings, as plant population was increased.)

In order to illustrate temporal patterns of root growth and development quantitatively, Figures 9 through 15 are presented to compare mean root counts per cm² of rhizotron frame for the four 1988 tillage treatments between June 15th and August 30th. Two major temporal patterns are evident: (1) the progression of roots through the soil profile to depths of 77 cm by July 13th and (2) the pattern of senescence by the spring Bush Hog treatment before August 30th. Unlike

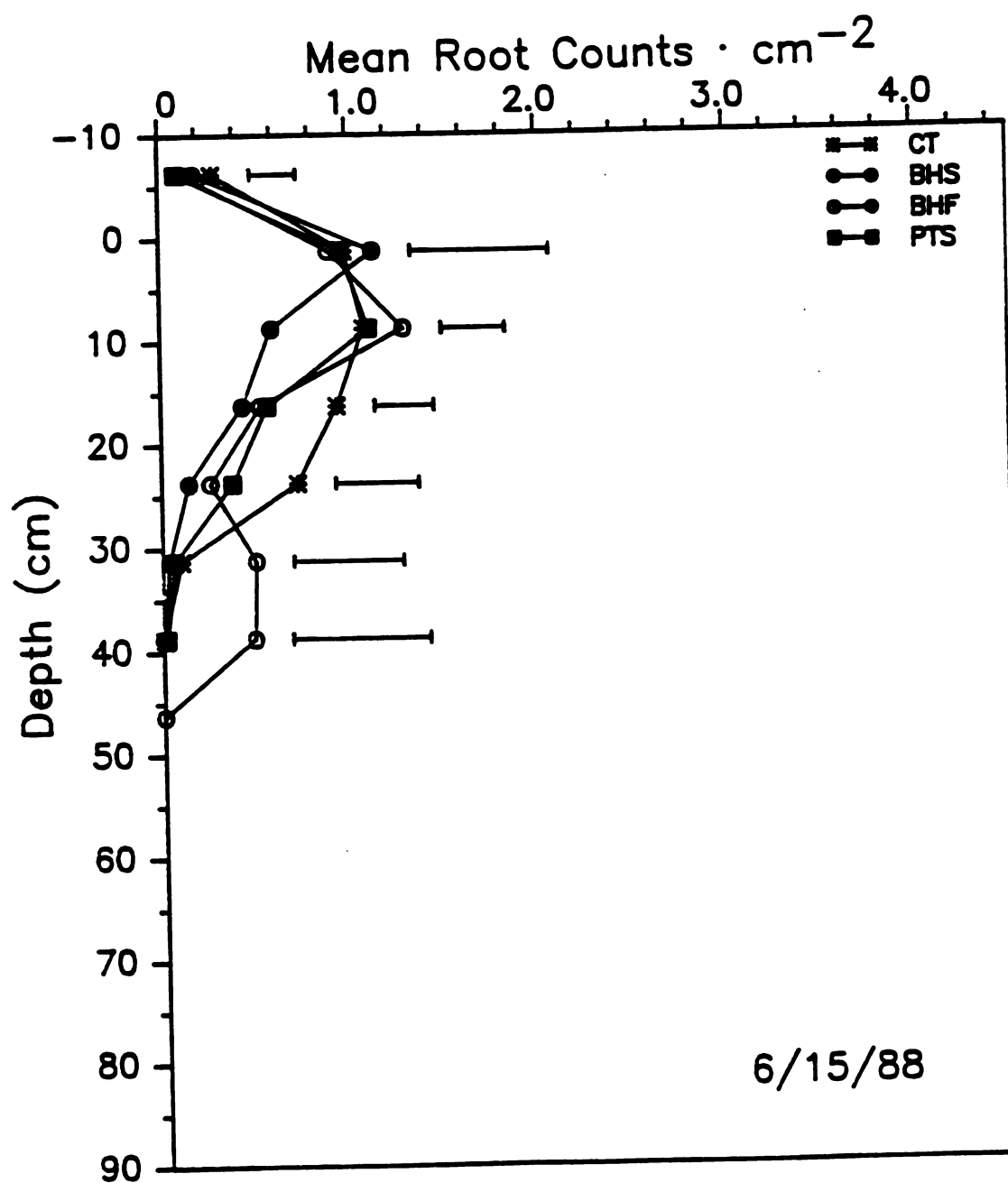


Figure 9. 1988 minirhizotron data by date - root counts per cm² of video frame as affected by tillage, 51 days after planting (6/15/88)

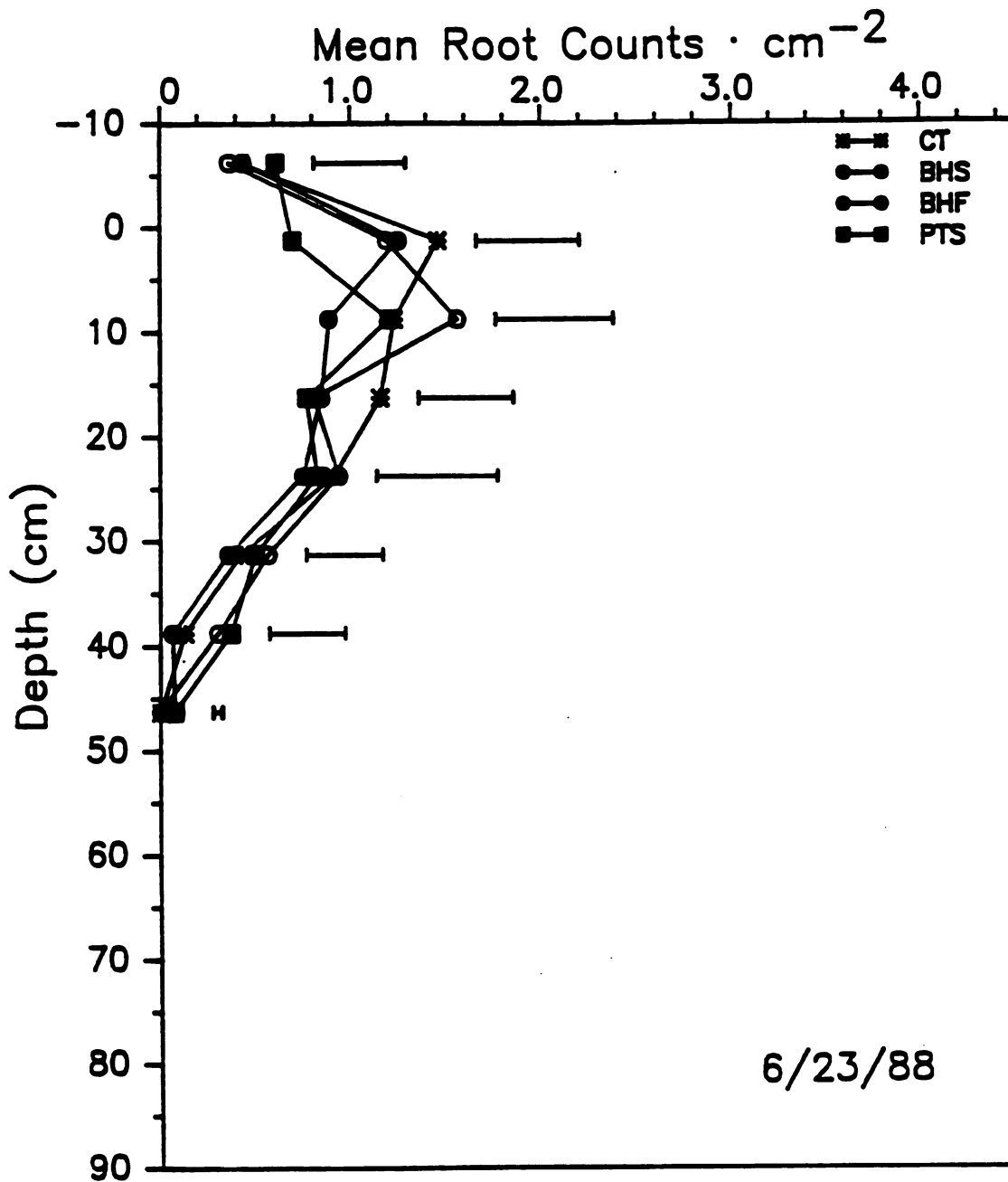


Figure 10. 1988 minirhizotron data by date - root counts per cm² of video frame as affected by tillage, 59 days after planting (6/23/88)

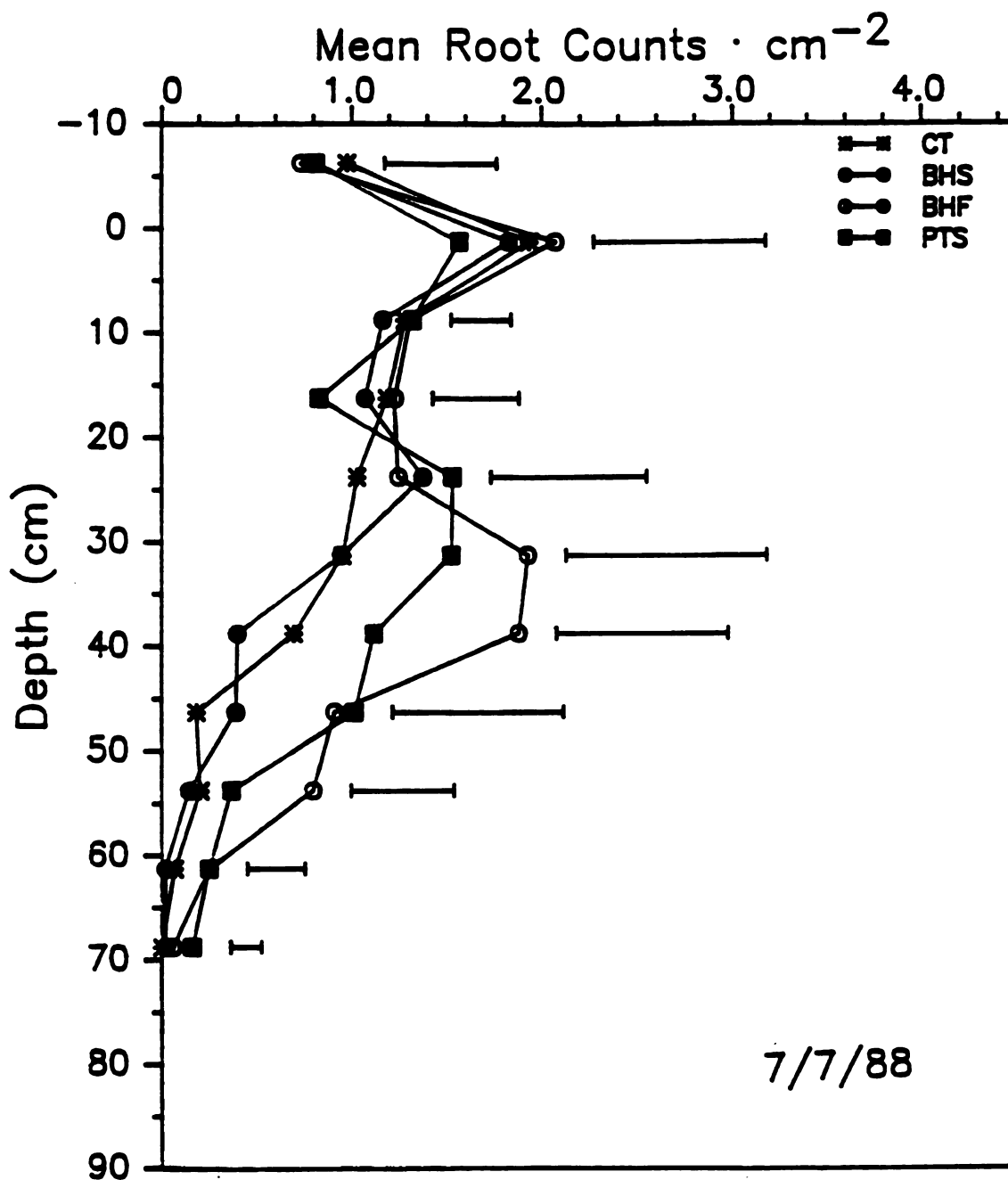


Figure 11. 1988 minirhizotron data by date - root counts per cm² of video frame as affected by tillage, 73 days after planting (7/7/88)

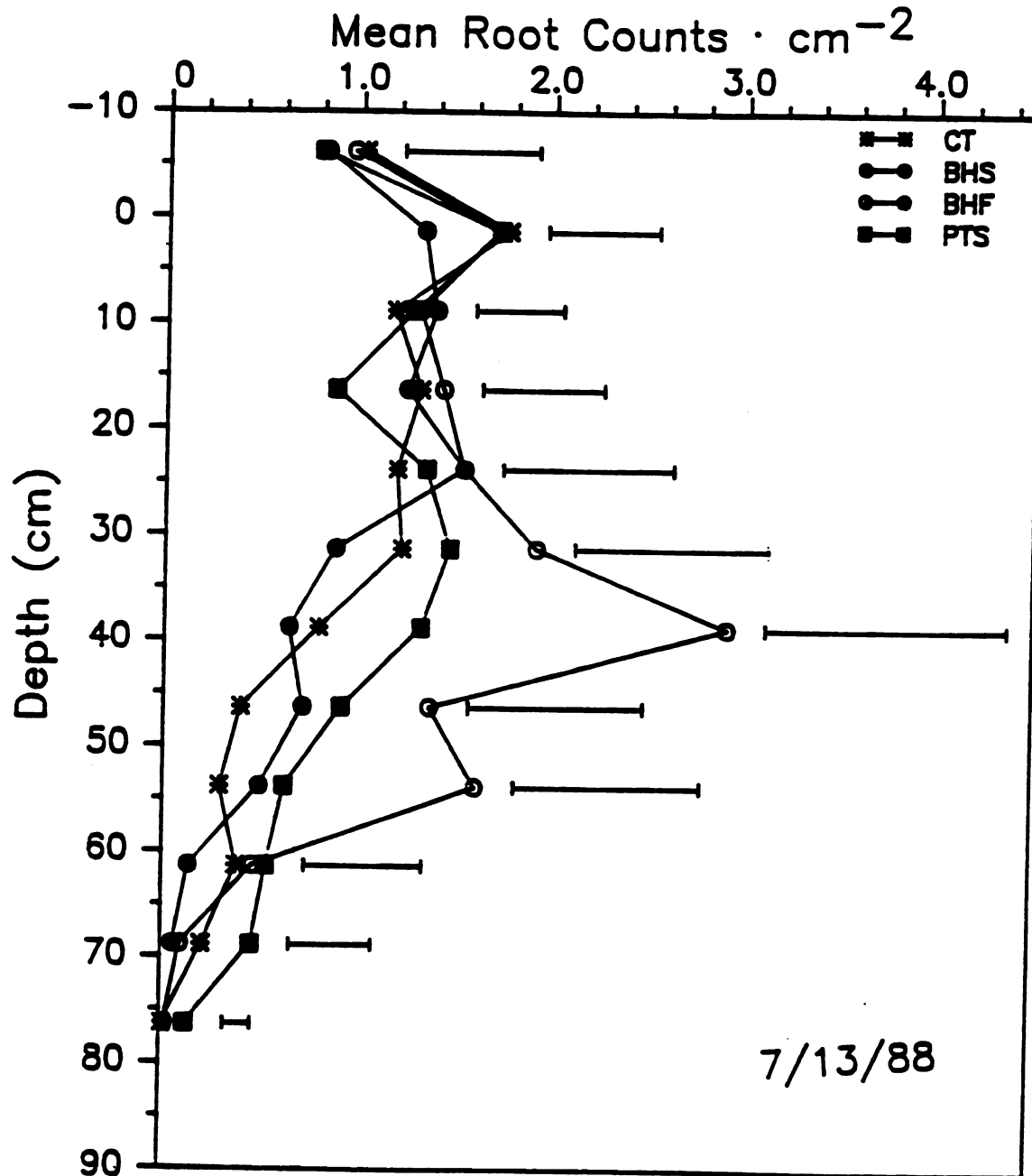


Figure 12. 1988 minirhizotron data by date - root counts per cm^2 of video frame as affected by tillage, 79 days after planting (7/13/88)

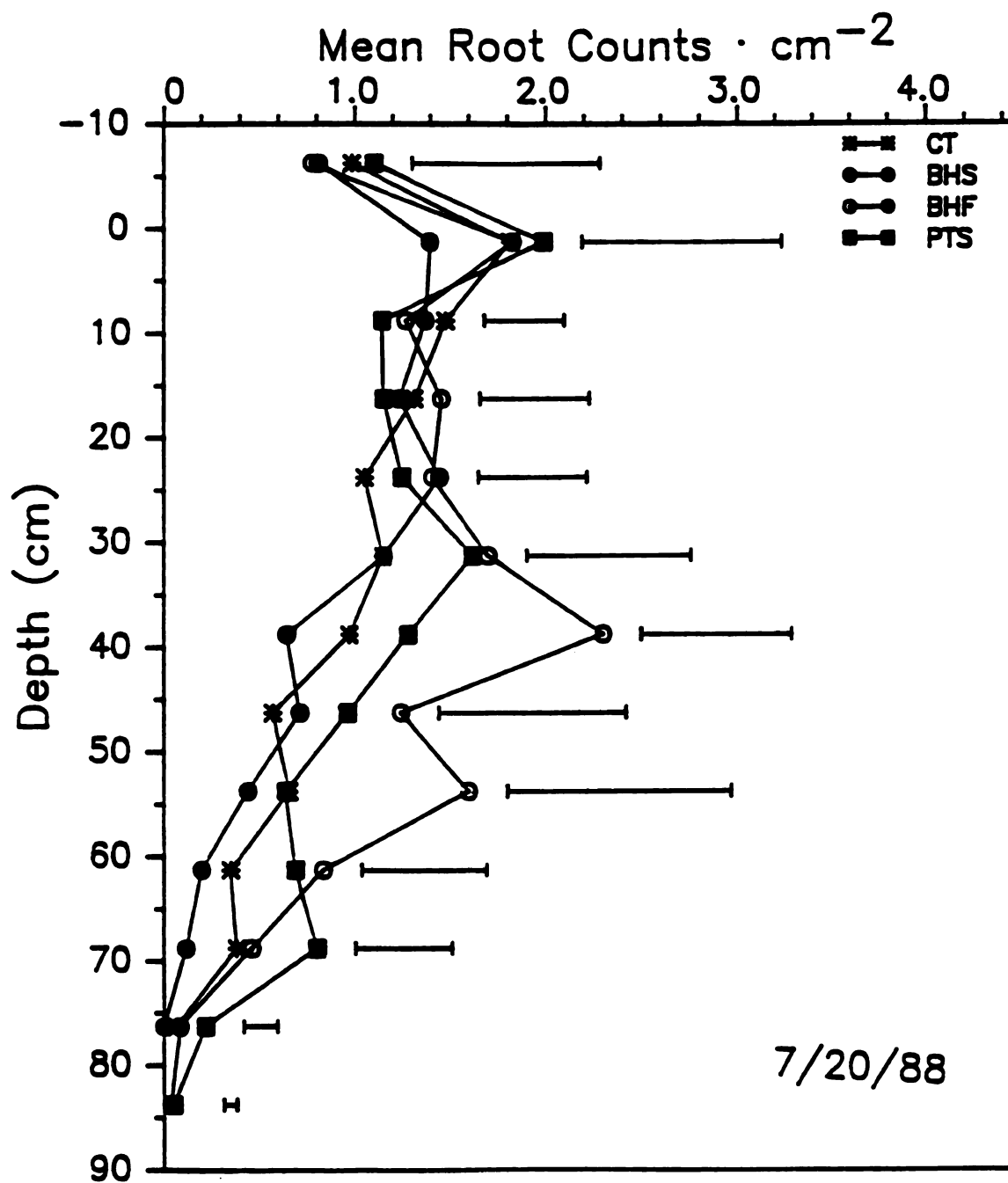


Figure 13. 1988 minirhizotron data by date - root counts per cm² of video frame as affected by tillage, 86 days after planting (7/20/88)

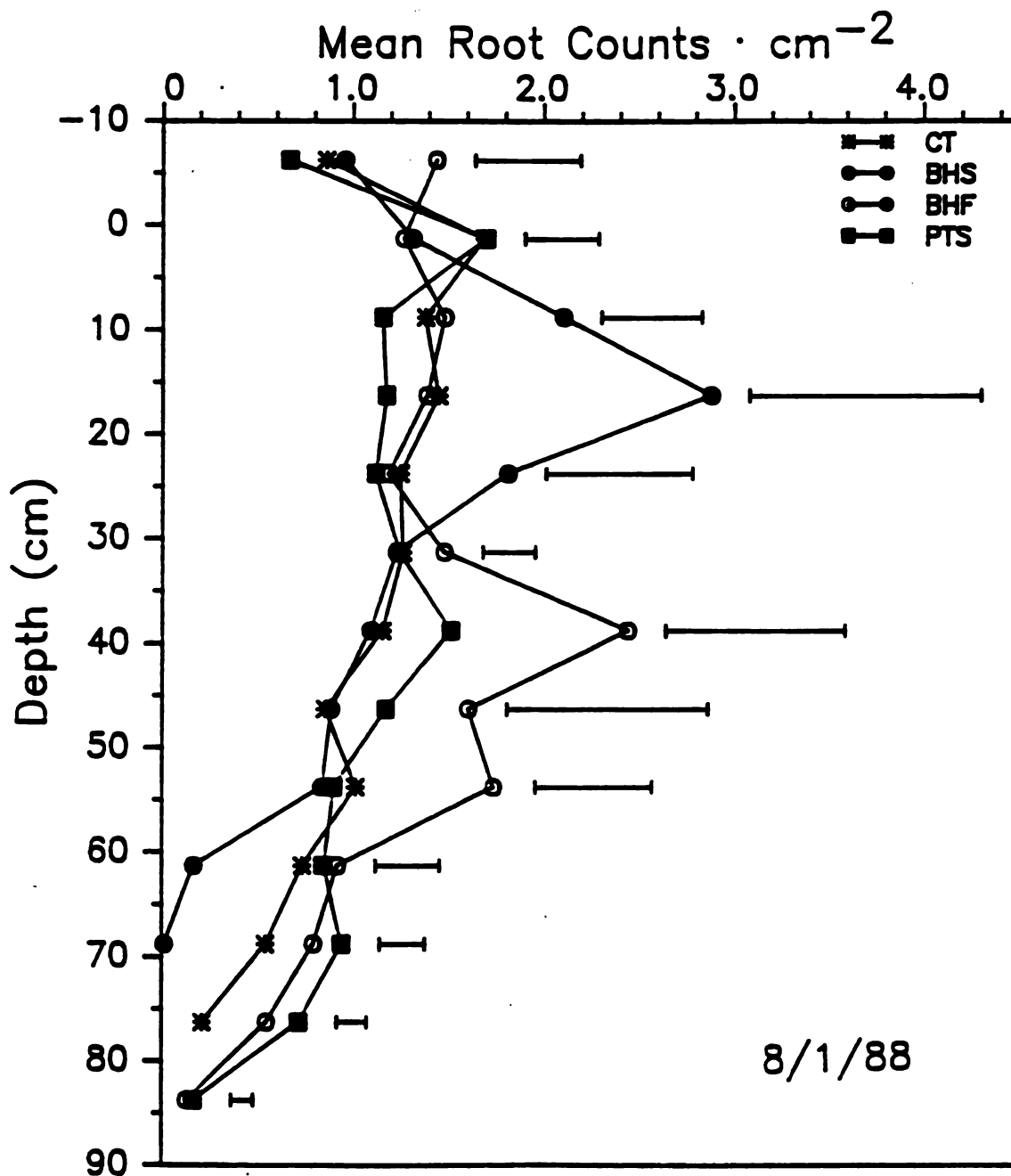


Figure 14. 1988 minirhizotron data by date - root counts per cm^2 of video frame as affected by tillage, 98 days after planting (8/1/88)

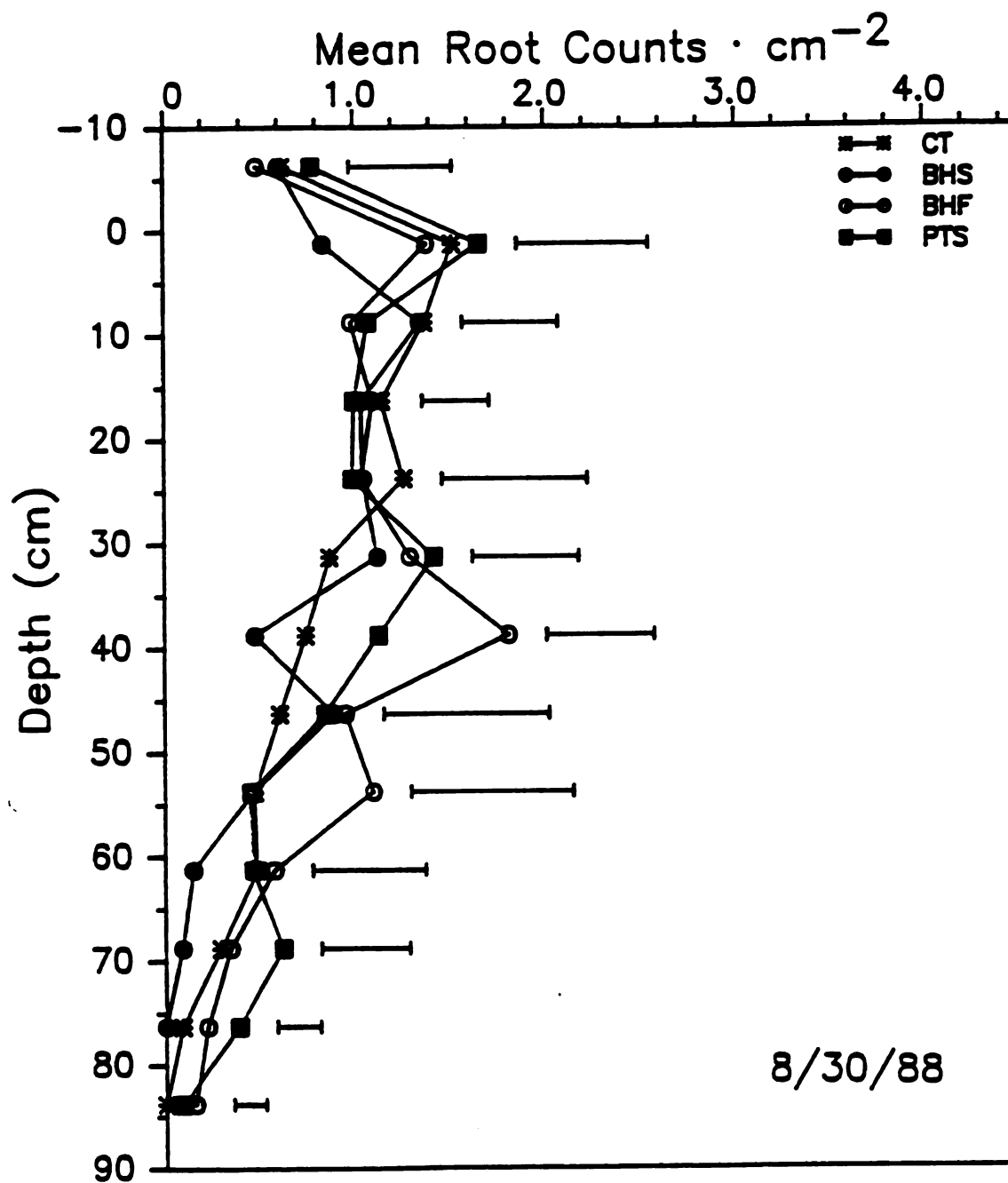


Figure 15. 1988 minirhizotron data by date - root counts per cm^2 of video frame as affected by tillage, 127 days after planting (8/30/88)

1987, when roots were beginning to senesce by July 26th (Table 1), new roots continued to grow and develop through August, 1988. Another striking difference occurred below 25 cm depths, where tillage affected root counts per cm² of frame. Fall Bush Hog treatments outproduced all other treatments from July 7th to August 1st. In contrast spring Bush Hog and conventional tillage treatments produced the least roots at deeper depths. Differences were significant at 9 and 16 cm on 6/15/88; at 39 cm on 7/7/88, 7/13/88, and 7/20/88; at 9, 16, 39 and 54 to 84 cm on 8/1/88 and at 39 and 76 cm on 8/30/88. Tillage did not significantly affect root counts in the hill (-10 to 0 cm) or root counts in the plow layer (0 to 25 cm), except on June 15th when spring Bush Hog treatments produced significantly fewer root counts and on August 1st when spring Bush Hog treatments produced significantly greater root counts below 60 cm.

Tables 1 and 2 summarize 1987 and 1988 total root counts per cm² of minirhizotron frame for depth groupings relevant to the different tillage treatments -- in the potato hill, in the conventionally tilled plow layer (0 to 23 cm), from the base of the conventional tillage plow layer to the base of the zone tilled plow layer (23 to 38 cm), below the base of zone tillage (38 to 99 cm) and finally, total root counts overall between 0 and 99 cm. Except in the hill, total root production did not vary significantly from one treatment to the next in 1987, though fall Bush Hog treatments tended to produce more roots overall, as well as between 0 to 23 and 23 to 38 cm depths. In July, 1988, fall Bush Hog and spring Paratill produced more roots in the area of zone loosening (23 to 38 cm) and produced significantly greater root counts

Table 1. 1987 total minirhizotron root counts/cm² of frame by date

Tillage	Hill roots	Roots at 0-23 cm depths	Roots at 23-38 cm depths	Roots below 38 cm	Total roots: 0-99 cm depths
-----counts cm ⁻² -----					
<u>6/19/87</u>					
CT	4.4	28.2	7.8	3.6	39.5
BHS	1.7	25.6	11.6	3.1	40.3
BHF	5.3	35.2	19.4	3.5	58.1
PTS	5.3	18.9	15.6	6.7	41.3
PTF	7.5	30.5	6.3	0.3	37.1
LSD (.05)	2.9	NS	NS	NS	NS
<u>7/6/87</u>					
CT	5.5	31.0	17.3	23.4	71.8
BHS	2.5	29.4	20.0	20.1	69.5
BHF	12.7	42.3	26.3	11.7	80.4
PTS	8.2	28.1	14.5	11.9	54.5
PTF	6.7	27.9	19.6	17.5	64.9
LSD (.01)	3.9	NS	NS	NS	NS
<u>7/20/87</u>					
CT	4.9	36.2	17.1	23.9	77.2
BHS	3.3	26.7	16.1	15.7	58.5
BHF	7.6	40.9	25.6	14.0	80.5
PTS	8.2	28.1	14.5	11.9	54.5
PTF	8.0	31.2	19.1	17.8	68.1
LSD (.05)	NS	NS	NS	NS	NS
<u>8/5/87</u>					
CT	4.1	27.2	13.6	18.7	59.5
BHS	3.6	20.7	15.8	15.7	52.2
BHF	7.9	32.1	21.2	9.4	62.7
PTS	4.6	20.6	14.8	19.5	54.9
PTF	6.0	19.1	14.7	15.9	49.6
LSD (.05)	NS	NS	NS	NS	NS
<u>8/19/87</u>					
CT	1.4	19.4	11.5	15.4	46.3
BHS	1.2	17.4	12.5	14.0	43.9
BHF	6.3	25.2	21.3	9.3	55.9
PTS	4.6	20.6	14.8	19.5	54.9
PTF	6.0	19.1	14.7	15.9	49.6
LSD (.01)	2.4	NS	NS	NS	NS

Table 2. 1988 total minirhizotron root counts/cm² of frame by date

Tillage	Hill roots	Roots at 0-23 cm depths	Roots at 23-38 cm depths	Roots below 38 cm	Total roots: 0-99 cm depths
-----counts cm ⁻² -----					
<u>6/15/88</u>					
CT	2.8	29.4	8.0	0.0	37.4
BHS	1.8	21.0	1.7	0.0	22.7
BHF	1.3	26.6	7.3	4.8	38.7
PTS	0.9	25.7	4.3	0.2	30.2
LSD (.05)	NS	NS	NS	NS	NS
<u>6/23/88</u>					
CT	4.1	37.4	13.0	1.3	51.6
BHS	4.2	28.9	10.8	0.7	56.8
BHF	3.5	34.6	14.7	3.0	48.8
PTS	5.9	34.6	13.0	3.9	49.7
LSD (.05)	NS	NS	NS	NS	NS
<u>7/7/88</u>					
CT	9.4	42.8	19.2	11.2	73.2
BHS	7.6	39.5	22.5	9.5	71.3
BHF	7.1	44.7	30.9	37.8	113.4
PTS	7.9	36.1	29.6	28.3	94.0
LSD (.05)	NS	NS	NS	17.3	30.7
<u>7/13/88</u>					
CT	9.8	41.5	23.5	20.5	85.3
BHS	7.9	38.4	23.5	20.1	82.1
BHF	9.3	43.2	33.7	63.1	140.0
PTS	7.7	37.6	27.4	39.1	103.9
LSD (.01)	NS	NS	NS	16.9	23.8
<u>7/20/88</u>					
CT	9.5	44.7	21.4	29.2	95.3
BHS	7.8	38.9	25.3	20.5	84.7
BHF	7.5	44.3	30.2	64.4	138.7
PTS	10.6	41.7	27.9	45.4	114.7
LSD (.05)	NS	NS	NS	25.9	31.5
<u>8/1/88</u>					
CT	8.3	43.8	24.4	51.2	119.7
BHS	9.3	61.1	29.6	23.8	114.5
BHF	14.0	40.2	25.9	80.8	146.9
PTS	16.5	39.1	23.1	62.0	124.2
LSD (.05)	NS	14.3	NS	25.5	NS

Table 2 (Cont'd). 1988 total minirhizotron counts/cm² by date

Tillage	Hill roots	Roots at 0-23 cm depths	Roots at 23-38 cm depths	Roots below 38 cm	Total roots: 0-99 cm depths
-----counts cm ⁻² -----					
<u>8/30/88</u>					
CT	6.0	39.1	20.5	26.1	86.0
BHS	5.8	31.1	21.0	20.1	72.4
BHF	4.7	33.7	22.7	50.5	106.7
PTS	7.5	36.3	23.3	38.7	98.3
LSD (.05)	NS	NS	NS	NS	NS

below 38 cm in July and early August, and therefore indicated greater use by potato roots of soil at depth in these two zone loosened treatments. In 1988 root counts for spring Bush Hog treatments were very similar to conventional tillage root counts. The one exception to this occurred in early August when spring Bush Hog treatments produced significantly more root counts at 0 to 23 cm and significantly fewer root counts below 38 cm.

In a comparison of total root counts on similar dates each year, all treatments but conventional tillage were producing fewer root counts on June 15, 1988, than on June 19, 1987. Yet by June 23, 1988, all 1988 treatments except fall Bush Hog were outproducing 1987 plants. On July 6, 1987, and July 7, 1988, conventional tillage and spring Bush Hog were producing similar numbers of root counts, while 1988 fall Bush Hog and spring Paratill were producing substantially greater root counts. By July 20th each year, all 1988 treatments had greater total root counts than 1987 treatments, especially fall Bush Hog (1.7:1) and spring Paratill (1.6:1). Comparing August 5, 1987 to August 1, 1988, 1988 treatments outproduced 1987 treatments by at least 200%. Similar differences occurred between August 19, 1987, and August 31, 1988. 1987 root growth had peaked between July 20th and August 5th, while 1988 root growth did not peak until sometime in August. If minirhizotron root counts reflect actual root production, then these data suggest that in order to meet plant nutrient and water requirements under the abnormally stressful growing conditions of 1988, plants compensated by producing deeper roots and more roots overall at all depths for substantially longer periods of time than did 1987 plants, which were grown under less

stressful conditions. As might be expected when more plant carbohydrates are diverted to root production and root physiological processes, and fewer are routed to tubers, 1988 yields were lower than 1987 yields (see Chapter 3). In both years zone tillage treatments produced significantly greater gross yields than conventional tillage, though significant increases in marketable yields were measured only in 1987.

CONCLUSIONS

By using both destructive and non-destructive methods to monitor growth of Russet Burbank potato roots, it was possible to determine that root penetration occurred below the compacted layer (bulk density of 1.77 Mg m^{-3}) in conventionally tilled treatments to the base of 110 cm deep minirhizotron tubes. Roots in zone tillage treatments also penetrated at greater depths and generated greater overall root production than conventional treatments in the subsoiled zone. These data contradict a common conception that potatoes are a shallow rooted cultivar (Flocker et al., 1960; Lesczynski and Tanner, 1976).

During 1987, a relatively normal rainfall year, conventionally tilled treatments showed increased accumulations of roots just above the plowpan, while spring zone tillage treatments generated greater root production just below the plowpan using destructive sampling methods (Fig. 2).

During the high temperatures and drought of 1988, plants produced

many more roots at depth than 1987 plants. 1988 root counts below 38 cm were 120 to 240% greater for fall Bush Hog treatments than for conventional treatments. Differences were significant or highly significant at these depths. Spring Paratill treatments also outproduced conventional treatments, by margins of 95 to 160%.

In 1988, potato plants compensated for early season drought and temperature stress by producing greater numbers of roots at greater depths for a longer period of time than did 1987 plants. Not surprisingly, 1988 yields were reduced somewhat from 1987, though zone tillage treatments continued to maintain significantly higher yields than conventional tillage treatments both years. These data support our hypothesis that tillage affected the magnitude and temporal patterns of root development. Because of the variability observed in root data, the number of tubes per plot and the number of replications is important in being able to ascertain significant differences.

The major advantage of minirhizotron methods over traditional, mechanical methods of root sampling lies in the ability to monitor temporal variation of root growth and development non-destructively with minirhizotrons. Minirhizotron data made it possible to ascertain times of minimum and maximum net root growth. This in turn enabled more appropriate scheduling of destructive root samplings. Minirhizotron techniques also facilitated monitoring of root development much deeper in the profile than that obtained with destructive sampling methods. In a comparison of root data from the two methods (6/19/87 minirhizotron data versus 6/25/87 root length densities), there was poor correspondence above 13 cm depths. When data values were ranked from

highest to lowest, minirhizotron data and destructive mechanical data were in reverse order above 13 cm. Below 13 cm, however, there was good correspondence between rank order of data for each treatment.

Several researchers have reported results that contradict those presented here. Buxton and Zalewski (1983) subsoiled to 40 cm in eastern Oregon and reduced penetrometer resistance at the plowpan depth, but did not find differences in root distribution of Russet Burbanks (by digging pits across rows) compared to conventional treatments. Though plant spacing was not mentioned by the authors, the 1987 data from this study showed no significant yield increases for Russet Burbanks under zone tillage unless spacing of seed potatoes was reduced from the standard 30 to 36 cm for this variety (see Chapter 3). Also, 1987 minirhizotron tubes, which were placed in the wider 36 cm seed spacing plots, rarely showed significant differences in patterns of root growth. The implication is that Russet Burbanks may not take advantage of the benefits of subsoiling through increased rooting and increased yields unless sufficiently crowded at the surface. It was only in 1988 at 25 cm seed spacings that significant differences and consistent patterns in root distribution were observed.

Buxton and Zalewski's field plots were frequently irrigated ensuring no need on the part of roots to explore the subsoil. Ross et al. (1979) found that while deep tillage increased rooting depth, yields were not increased unless irrigation was reduced.

Tanner et al. (1982) also studied root length densities of Russet Burbanks in Wisconsin on loamy sands. The authors found no significant differences in yields, bulk densities or root length densities between

plowpan and subsoiled treatments. Yet the study was unreplicated, seed was spaced 30 cm apart and treatments were irrigated frequently. In order to monitor the effect of drought stress on root growth, the researchers withheld water from a subplot between plant emergence and drought-induced wilting one month later. Plants were re-watered and root length densities measured, but not until five weeks after wilting. Root response to drought stress usually occurs within one to three weeks of the end of the stress period (Smucker, personal communication). Stressed treatments showed "increased rooting," that was "well within normal field variation," and the authors stated root penetration by the water-deficit plants was insufficient to "affect water and nitrogen uptake from deeper layers significantly." They concluded that "deep plowing produced insufficient benefits . . . to justify either deep plowing as a practice or further experimentation." Buxton and Zalewski reached a similar conclusion, saying that the only advantage to subsoiling of irrigated potatoes was in giving farmers greater flexibility in the scheduling of irrigation.

Both studies overlooked an important point. Kirkham et al. (1974) found that when nitrate N moved below the zone of maximum extraction by potato roots, roots absorbed nitrogen in decreasing quantities with increasing depth. Because of the potential environmental effects and the possibility of groundwater pollution, frequent irrigation of chemically-treated potatoes grown on sandy, easily leachable soils should no longer be an acceptable practice.

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SUMMARY

The objective of this study was to quantify the effects of zone tillage on soil physical conditions at the layer of compaction, and its subsequent effect on potato growth and yields. Field studies were conducted over a two-year period on a McBride sandy loam at Michigan State University's Montcalm Experiment Station with Russet Burbank potatoes. Tillage treatments included conventional tillage to a depth of 20 to 23 cm and zone tillage to a depth of 33 cm with the Bush Hog Ro-Till and to a depth of 36 cm with the Tye Paratill. In zone tilled treatments, a fall-seeded cover crop of rye remained undisturbed in the interrow area for erosion control. To summarize, the following are the major findings of this study as presented in Chapters 2, 3 and 4:

- Bulk density and soil strength were significantly decreased at the plowpan, while air-filled porosity, volume of macropores and water retention capacity were increased. This provided an improved soil environment for water movement, root penetration and tuber growth.
- Zone tillage caused significant increases in gross yields and marketable yields in 1987 and 1988, which were consistent with 1985 and 1986 data.
- Yield increases in zone tilled treatments were due to increased production of larger tubers.
- Zone tillage resulted in yield increases of Russet Burbanks only when the standard seed spacing of 30 to 36 cm for this variety was reduced to 25 cm.

- Zone tillage conducted after planting in 1988 was detrimental to gross yields and marketable yields.
- Plants reacted to drought stress in 1988 by reducing production of above-ground biomass and increasing production of roots at deeper depths for a longer period of time. Per plant tuber production was also decreased. Closer spacing of 1988 plants resulted in yields that were only 8 to 20% less than 1987, in spite of the drought.
- Leafy vegetative growth senesced earlier in 1988 in conventionally tilled plants, while zone tilled plants continued producing photoassimilates and bulking tubers for an extended period of time.
- Tuber set was generally the same for both years and was therefore apparently unaffected by drought or heat. However, tuber set was affected by compaction, with greater numbers of tubers being initiated in conventional treatments, where the plowpan was not broken up by tillage.
- In 1988, zone tillage plants produced 100 to 240% more total roots than conventionally tilled plants.
- In 1987 destructive root samples showed stratification of root length densities above the plow layer in conventional plots.
- Warm, dry conditions during the early growth period in both 1987 and 1988 resulted in low soil water contents, suggesting that irrigation was not initiated soon enough or applied often enough early in the season.

Future research needs and issues raised by this study include the following:

- Root biomass was increased with zone tillage. Is there a direct relationship between increased root biomass and tuber yield?
- Minirhizotron root counts and destructively sampled root data appeared positively correlated at depth, but negatively correlated near the surface. More definitive data are needed to elucidate the relationship between the two types of root measurements.
- Root counts presented here vary in both space and time, and tend to be auto-correlated. Therefore, there is a need for

definitive statistical procedures with which to analyze time- and depth-dependent minirhizotron data.

- Widely divergent shoot to root ratios were observed in 1987 and 1988, and zone tilled plants showed yield increases when planted at closer seed spacings. Future research should investigate the mechanisms by which tuber crops allocate carbon when subjected to stress and ascertain why stressed plants produce and apportion photoassimilates below ground for longer periods of time.
- Video frames of minirhizotron data allowed for the determination of time at which roots began to senesce, as well as for patterns of root branching and root morphology. More detailed study of these parameters may elucidate how tillage and drought stress affect potato roots.
- Roots and tubers overlapped in the soil volume they explored. What is the appropriate root sampling technology for tuber crops?
- When a tuber is aborted, are its carbohydrates re-utilized by the plant?
- Previous research reported that roots, and especially tubers, were negatively affected by sustained periods of low oxygen diffusion rates. Future research should determine how long soil oxygen diffusion rates stay below minimum levels in zone tillage vs. conventional tillage treatments and how oxygen diffusion rates are related to soil moisture contents at different soil bulk densities.
- Research with other varieties in Michigan (not reported here) did not show the impact of zone tillage on yields. Further work on varietal response to stress due to compaction and drought is needed.
- Compaction and erosion are not just Michigan problems. They affect the sustainability of potato production domestically, as well as abroad. What are the global implications of this research? What are the implications for use of zone tillage under non-irrigated conditions? What are the labor requirements in countries where machinery is impractical or unavailable?
- Potatoes can be an important protein source, as they contain the amino acid lysine, lacking (or present only in small quantities) in grains such as millet, rice and corn. Thus, potatoes provide an inexpensive, complete source of protein when combined with grains. How does zone tillage affect the nutritional content of potatoes?

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