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PLANT RESPONSE TO INCREASED MOISTURE DUE TO MODIFICATION OF A SAND SOIL WITH COAL FLY ASH

By

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ABSTRACT

PLANT RESPONSE TO INCREASED MOISTURE DUE TO MODIFICATION OF A SAND SOIL WITH COAL FLY ASH

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Field studies were conducted to examine the effectiveness of incorporating coal fly ash into coarse textured sand soils for improving soil moisture retention and plant productivity. Various rates of fly ash were incorporated to a depth of 70 cm with a Towner giant disk plow. Soil moisture was monitored by neutron hydroprobe and gravimetric sampling. Plant growth and dry matter accumulation of corn (Zea mays) was monitored. Corn moisture stress was measured with a leaf porometer, and corn root growth patterns were compared in both an ash modified and an unplowed soil. Grain yields for corn, wheat (Triticum aestivum L.), and soybeans (Glycine max L.) and dry matter accumulation of corn silage and sorghum sudangrass (Sorghum vulgare Pers. x Sorghum vulgare sudanense L.) were monitored.

Soil moisture was increased substantially within the ash band compared to the surrounding sands. Corn plant growth measured by plant height and leaf area showed significant increases on ash modified soils compared to

control treatments. Corn roots were capable of exploring the ash bands fully. Corn drought stress was reduced on the high ash treatments compared to the control treatments. Corn grain and silage yields were improved by ash incorporation. Wheat and sorghum sudangrass yields were also increased. Soybean yield showed no improvement on ash modified soils compared to control treatments.

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INTRODUCTION

Coal fly ash is a by-product of combusting coal by the electrical utility companies. Fly ash is the particulate material which is removed from the flue gas stream by emission control devices. This material accumulates rather quickly and soon becomes a solid waste management problem at the power plants. Sandy soils, prevalent in Michigan, tend to be dry due to a low water holding capacity. Since coal fly ash is composed mainly of silt sized particles, incorporating large quantities of this material into a soil could increase the water holding capacity of sandy soils. This would improve both the productivity of the modified sand and at the same time provide the utility company with a waste management alternative for large quantities of this by-product material.

The goal of this research was to incorporate fly ash in a coarse textured sand soil, using a Towner giant disk plow, and to evaluate the effects of this practice on soil moisture and plant productivity. The primary objective was to quantify soil moisture retention improvement of the ash modified profile. Increased soil moisture would provide a more favorable environment for plant growth and increased yields. Moisture content of both the consolidated and the individual (ash and sand) fractions of the modified profile were monitored.

Evaluation of the benefits provided by increased soil moisture included the monitoring of plant growth and drought stress. Corn plant vegetative growth was monitored by plant height measurements at various times in the season. Plant moisture stress was monitored by measurement of transpiration, diffusive resistance, and leaf temperature deviation from ambient conditions, using a steady state leaf porometer. Root growth was evaluated to determine if corn roots were capable of exploring the fly ash bands in the modified profile. This was thought to be important for utilizing any of the increased moisture held within the ash materials. And finally, corn grain and silage yields, as well as grain yield of soybeans, wheat, and dry matter yield of sorghum sudangrass were recorded to determine the economic benefits of the practice.

LITERATURE REVIEW

Introduction to Coal Fly Ash

Fly ash is the particulate product of combustion which is suspended by the flue gases and carried up the stack. These materials are either collected by emission control equipment or carried into the atmosphere. In April 1977, President Carter announced the National Energy Plan, which included a requirement for the implementation of the best available control technology in all coal fired power plants under construction. Emission control devices are primarily bag filtration systems or electrostatic precipitators. Additional residues from pollution control devices include products of flue gas desulfurization, which can be collected by spraying wet $CaCO_3$ and CaO into the flue gas stream to remove both particulates and SO_2 (Walker & Dowdy, 1980).

Fly ash is amorphous ferro-alumino silicate material (Fisher et al, 1976), in which between 70 and 90% of the particles may be glassy spheres (Hodgson and Holliday, 1966; Fisher et al, 1976). Particle size and chemical composition of this material may vary greatly depending upon the parent coal, fuel processing procedures and combustion conditions, type of emission control devices used, and the collection, handling and storage conditions used (Adriano, et al, 1980). An example particle size distribution of a western U.S. electrostatic precipitator fly ash is as follows: sand fractions (> 0.05 mm), 32.5%; silt fractions (0.05-0.002 mm), 63.2%; and clay fractions (< 0.002 mm), 4.3% (Chang, et al, 1977). Unpublished work by Erickson and Jacobs[1], 1983, reported similar particle sizes in coal fly ashes produced by the Consumers Power Company in Michigan. Virtually every naturally occuring element has been identified in coal fly ash (Klein, et al, 1975).

Definition of the Fly Ash Problem

Coal remains one of the United States most valuable energy reserves. In 1985, combustion of coal by the electric power generating utilities produced over 71 million tons of soild by-products each year, 80% of which were fly ashes (Golden, 1987). Although industrial uses may account for up to 50% of some European countries' fly ash production (Brackett, 1967), the total utilization of fly ash in the United States in 1985 was at 27% of the amount produced (Golden, 1987).

The methods most commonly used for coal fly ash management are either sluicing the ash from the plant to large settling ponds or land filling near the power generating station. Many of the currently operating

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[1] (A.E. Erickson and L.W. Jacobs, 1983, personal communication).

facilities have limited storage and disposal areas, and face shutdown if appropriate solid waste management options cannot be found.

Alternative Uses of Coal Fly Ash

Many alternative uses for fly ash exist. Industrially, it has been used for structural fills and in cement mixtures. Many of the bottom ashes have been used in road bed construction, and have a fairly high utilization percentage in comparison to the fly ashes (Golden, 1987).

The idea of utilizing fly ashes in an agricultural capacity as a soil amendment is not new. A great deal of research has been devoted to this goal, because it could create a large scale use for a widely underutilized by-product. Most of the published agricultural research has evaluated the addition of plant nutrients to soils by application of fly ash. While fly ashes generally do not contain N or P in sufficient quantities to satisfy crop requirements, they could be used to supplement Ca, S, B, and Mo in deficient soils (Adriano, et al, 1980). Fly ash applications have been shown to supplement plant-available soil B (Ransome and Dowdy, 1987), Mo (Elseewi and Page, 1984), and S (Elseewi et al, 1978). In addition, fly ash has been utilized as a liming agent on acidic soils (Adriano et al, 1980; Page, et al, 1979).

Physical Amendment for Improved Soil Moisture

Because the texture of the fly ash predominantly lies in the silt fraction (0.05 - 0.002 mm), incorporation of large quantities of this material may change the particle size distribution of amended coarse textured soils. This potential textural shift may affect inherent soil properties such as structure and water holding capacity. Improved soil moisture content may facilitate greater availability of plant extractable water.

Fly ash additions to soils have been shown to increase the water holding capacity for most soil types (Salter, et al, 1971; Chang, et al, 1977). Chang et al (1977) reported that while fly ash applications above 25% by volume consistently increased soil moisture retention, significant increases in plant available water were not found on either a Greenfield sandy loam or a Domino loam, homogeneously mixed with various rates of fly ash. Salter et al (1971) reported that large additions of fly ash (up to 753 t/ha) increased plant available water by as much as 93%. The soil used by Salter et al (1971) was more coarse in texture (54% coarse sand, 23% fine sand, 7% silt, and 14% clay) compared to the sandy loam used by Chang et al (1977) (9% coarse sand, 44% fine sand, 24% silt, and 10% clay). Both of these experiments were conducted with homogeneous mixtures of ash and soil. The disadvantage of homogeneously mixing of fly ashes with soils at high rates are potential reductions in infiltration and hydraulic conductivity, particularly on acidic soils (Chang et al, 1977), as well as potential problems of seedling mortality from salt or B toxicity (Ransome and Dowdy, 1987).

Drought Stress Timing and Corn Productivity

Many factors may play important roles in agricultural productivity. Soil fertility, structure, solar radiation, soil and air temperature, evaporative conditions, and soil moisture are all important components of crop production. Soil moisture has long been noted to be one of the most common limiting factors in plant growth and development. This may particularly hold true on crops such as maize, which are not overly drought tollerant (Jensen and Cavalieri, 1983).

Robins and Domingo (1953) reported that the growth stage of the plant at the time of a water deficit had significant effects on the yield of maize. Depletion of soil moisture to permanent wilting point for 1 or 2 days at tasseling resulted in a 22% yield reduction, and extending periods to 6 to 8 days resulted in a 50% reduction in yield. Denmead and Shaw (1960) noted a 50% yield reduction with water stress prior to silking and a 21% decrease when a stress period was induced after the initiation of silking. Claassen and Shaw (1970b) showed that moisture stress imposed in the silking and early ear development stages caused the maximum reduction in kernel numbers.

More recent studies dealing with the maize yield component of kernel number suggest that stress during early grain development, rather than silking, results in a reduced number of kernels. Kiniry and Ritchie (1985) described an experiment in which stress was induced through the use of a shading interval. Horizontal panels were used to reduce the light which reached the plant by 79%. Kernel number reduction was closely associated with early kernel development stage (Kiniry and Ritchie, 1985). Grant et al (1989) reported that the interval during which grain set was most sensitive began 2 to 7 days after silking and ended between 16 and 22 days after silking.

While the timing of a drought stress is detrimental during the early reproductive growth stages in maize, stresses occurring early in the vegetative growth stages and later in grain fill stages only marginally affect yields (Robins and Domingo, 1953; Denmead and Shaw, 1960; Claassen and Shaw, 1970a;). Prolonged or severe drought stress that results in leaf desiccation can markedly reduce plant height and vegetative yields, however, significant grain yield reductions by early season stress are only incurred if severe plant wilting takes place (Robins et al, 1967). Yield reductions caused by drought stress during the time of silking are primarily a function of desiccation of either the pollen grains or the organs which transmit or receive the pollen. These yield reductions are the result of pollination failure in which only a portion of the ear is filled with kernels (Robins, et al, 1967).

Drought stress during flowering can also increase the interval between pollination and the onset of silking. In cases of severe drought stress, silking could be delayed until after pollen shed, resulting in kernel number reduction or barren ears (Herrero and Johnson, 1981). Grant et al (1989) demonstrated, however, that drought-induced reduction of kernel number is not absolutely dependent on the prevention of ovule fertilization. Hand pollinated plants, exposed to drought stress conditions during early kernel development, yielded lower kernel numbers than stress during and before pollination (Grant et al, 1989).

Potential Use in Michigan

Michigan is a state that is agriculturally diverse. A wide variety of perennial and annual crops are produced here because of special combinations of climatic factors and soil types. The agricultural productivity of these soils are generally limited by lack of water holding capacity (Erickson, 1972). Jensen and Cavalieri (1983) noted that soil type influences the extent of water deficits, and maize grown in regions with sandy soils may be particularly susceptible to drought stress during short periods without rain.

Soil Moisture

Hillel (1982) uses the term 'soil wetness' to describe the percent moisture content by weight or by volume of a soil. Soil gravimetric or volumetric measurements report the quantity of water in a soil but are not a good measure of the amount of plant-available soil water. Plant-available moisture levels are best characterized by the matric potential of the soil (Hillel, 1982 ; Kramer, 1983).

Matric Potential is the measurement of the free energy which characterizes the tenacity that the soil water is held by the soil matrix. Graphical representation of the relationship between the soil matric potential and the moisture content is known as the soil moisture characteristic curve. Factors affecting the matric potential of a particular soil include soil texture, structure, and organic matter content.

Richards (1965) reported a procedure using a membrane apparatus for the lower matric potential determinations and porous ceramic plates at higher tension levels. Vomocil (1965) described a capillary model representing soil porosity. Initially saturated soil samples of known volume are exposed to increasing suction levels. The volume of water extracted at each suction level 'h' is equal to the volume of pores having an effective radius greater than the 'r' in the capillary rise equation:

$$r=\frac{2\ \lambda\ \cos\ \theta}{g\ D\ h}$$

Where 'λ' is the surface tension, 'θ' is the contact angle (assumed to be zero), 'g' is the acceleration due to gravity, and 'D' is the density of the soil moisture (Vomocil, 1965).

This equation indicates that as suction increases, progressively smaller pores will release their water content (Hillel, 1982). Since porosity is a function of both soil structure and soil texture, both of these components play important roles in soil moisture retention. Hillel (1982) reported that the amount of water retained at lower values of matric suction was primarily a function of soil structure. However, at increased levels of suction, water retention is increasingly affected by adsorbtion, and more directly related to soil texture.

Moisture retention in sandy soils is characteristically low. Pore size in these soils tend to be large, due to larger particle sizes, and are generally more uniform than in other soil types. The moisture characteristic curves for sand show a rapid release of moisture at very low tension compared to clay or loam soils.

Soil moisture availability for plant use is dependent upon the matric potential of the soil water. The relative range of plant-usable water has typically been described as as being between the arbitrary moisture contents known as field capacity and permanent wilting point. Field capacity was defined by Veihmeyer and Hendrickson (1931) as the amount of water held in the soil after excess gravitational moisture had drained away and after the rate of downward movement of water had ended (Peters, 1965). Permanent wilting point was classically described by Briggs and Shantz (1911) as the soil moisture content at which plants growing in that soil first show wilting and cannot recover unless water is added (Kramer, 1983; Peters, 1965).

Both field capacity and permanent wilting point tend to be variable, particularly the latter. Slatyer (1957) criticized the use of permanent wilting point as it is dependent upon the osmotic properties of the plants grown on these soils (Kramer, 1965). While there may not be a definitive point at which plants wilt, plant-available water is generally considered to exist between the ranges of 0.3 bar and 15 bars (Hillel, 1982 ; Kramer, 1983).

Soil Amendments to Improve Soil Moisture Retention

Sand soils are notoriously short of soil moisture. Unger et al (1981) stated that any method which increased the water retention ability of these soils would be beneficial, and this can be accomplished by adding materials which retain more water than sand alone. Several procedures have been used to increase the water holding capacity of sandy soils. Where coarse textured soils are overlying a fine textured subsoil, deep tillage has been used to mix the two horizons together and increase the water holding capacity in the rooting zone. Unger et al (1981) reported that deep plowing of sandy soils in Washington (Miller and Aarstad, 1972), and in Oklahoma (Harper and Brensing, 1950) increased the clay content of the surface soils, and hence the water holding capacity.

Additions of organic matter have been shown to increase the water retention of sandy soils (Jamison, 1953). While there may be an increase in soil moisture associated with organic matter additions, generally associated with better soil structure, it may not be practical as a sand soil moisture retention amendment.

The ability of incorporated organic material to increase water holding capacity in coarse textured soils can be limited by the volume of material needed to significantly increase soil organic matter percentage. This may especially be a problem on droughty sand soils where the breakdown of organic matter can be rapid. Lucas and Vitosh (1978) estimated a humus decomposition rate of bare loamy sand to be at 4.5 percent annually, and reported levels as high as 7 percent decay for Metea loamy sand treated with 30 tons of manure per year under corn production.

Another approach to increasing the water holding capacity on droughty sand soils is to prevent the rapid downward movement of water through the use of an impermeable barrier. A system described by Erickson and Hansen (1968) reduces the infiltration through and out of the root zone, creating a perched water zone above the barrier. Asphalt films applied at a 60 cm depth showed the ability to maintain a zone of low tension plant-available moisture in a 20 cm band above the barrier while allowing sufficient infiltration and aeration in the surface 15-20 cm of soil. Plant-available moisture in the barriered profile was increased by 50 to 200% over the original sand solum (Erickson, 1972).

Erickson reported significant increases in the yields of cucumbers and cabbage grown on barriered treatments without irrigation over the 'control' and the 'control with irrigation' on a field site composed of Ottawa fine sand in Allegan county MI (Unger et al, 1981). Saxena et al (1973) reported that the water stored in a profile in Florida was increased by at least 2.5 cm, and yields were increased from 0 to more than 150% depending upon the crop and season.

MATERIALS AND METHODS

Experimental Sites and Treatment Design

The first field experiment, the Miller Trust site (Figure 1), was established in the spring of 1985 on a Boyer loamy sand (Typic Hapludalf coarse-loamy, mixed, mesic) soil series located in T. 1 North, R. 3 West, Section 2, south of the Eaton Rapids middle school, Eaton County, MI. Soils of the Boyer Series are noted as being moderately suited to farming, with moderate permeability, and low available water holding capacity (Soil Survey of Eaton County, 1978). The experimental design at the Miller Trust site was a randomized complete block design (Steel and Torrie, 1960). The site was divided into 20 units, 12.2 m by 24.4 m in size, which established 4 replications of 5 treatments: unplowed and plowed controls, 5 centimeters (605 Mg/ha), 7.5 centimeters (908 Mg/ha), and 10 centimeters (1,210 Mg/ha) of fly ash incorporated into the soil.

A second area, the Cuda site (Figure 2), located adjacent to the Miller Trust site, was established as an addition to this field experiment in 1986. The Cuda site contained the same soil series and was also designed as a

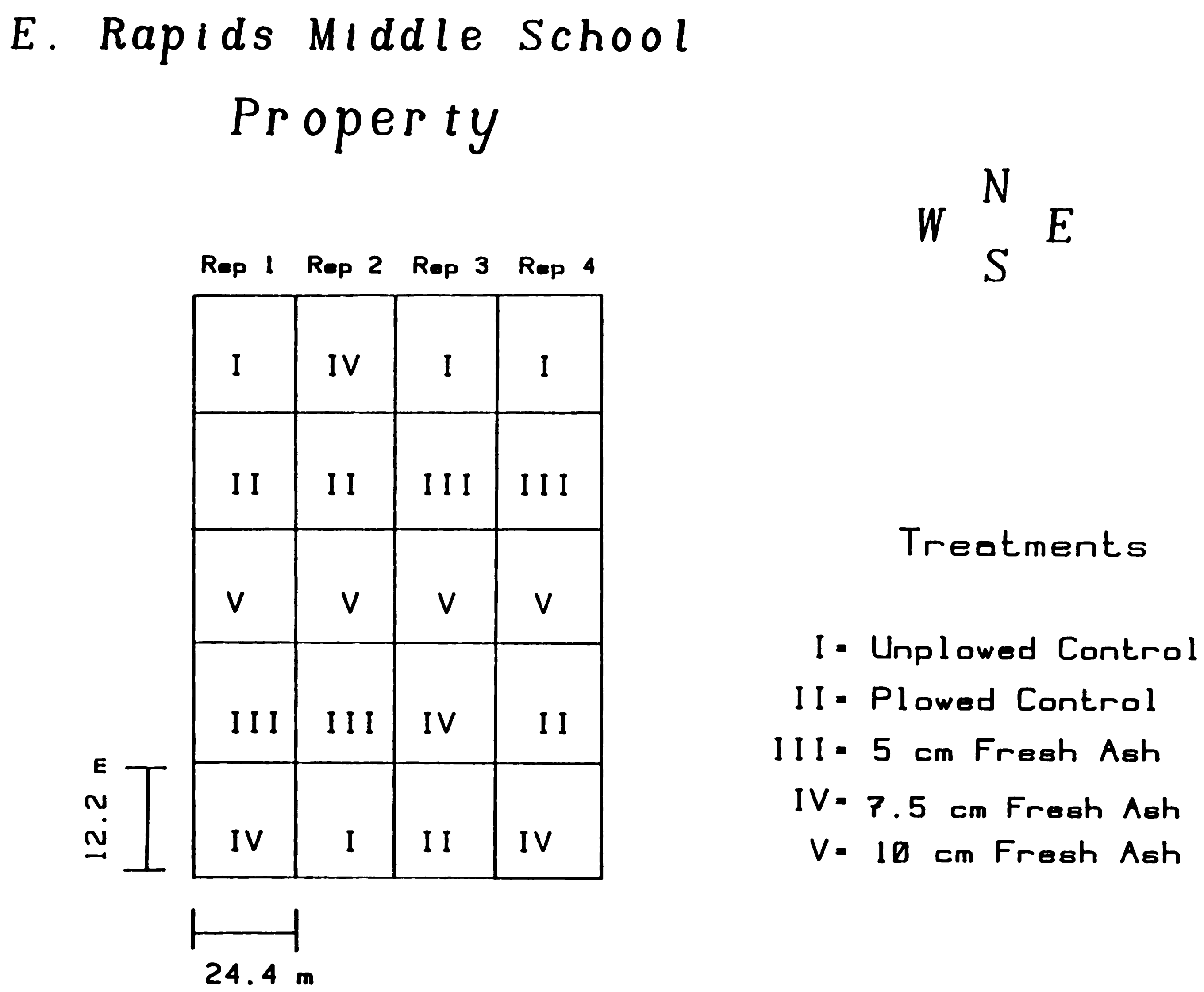


Figure 1. Plot diagram, Miller Trust site, Eaton Rapids MI.

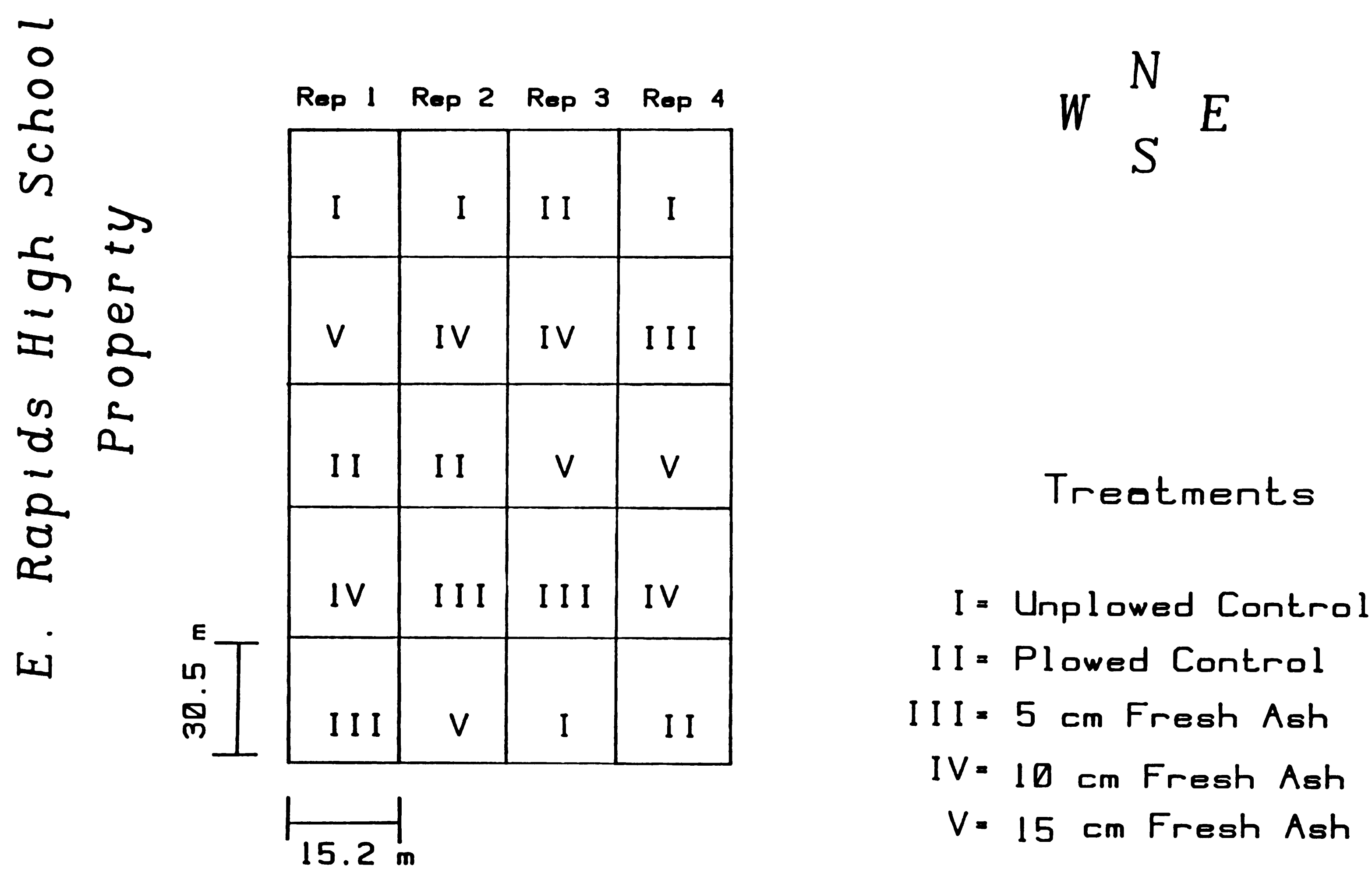


Figure 2. Plot diagram, Cuda site, Eaton Rapids MI.

randomized complete block experiment, with 4 replications of 5 treatments. The experimental area was divided into 20 units, 15.2 m by 30.5 m in size. The treatments consisted of: unplowed and plowed controls, 5 centimeters (605 Mg/ha), 10 centimeters (1,210 Mg/ha), and 15 centimeters (1820 Mg/ha) of fresh ash incorporated into the soil.

Fly ashes used on these sites were supplied by the Lansing Board of Water and Light (BWL). The ash used on the Miller Trust site was a fresh ash that was transported from a landfill site by BWL personnel in covered semi-tractor trailer trucks. These trucks were specially fitted with a hydraulic ram to push the load of ash out the back of the trailer. Ash was spread on the appropriate plot area and then leveled out to the treatment depth with the front end blade of a D-7 Caterpillar tractor.

The fly ash was incorporated with a Towner giant disk plow. This plow, which was manufactured in California, is typical of the type of equipment used for deep tillage of heavily compacted soils (Unger et al, 1981). The Towner plow was selected because of its potential depth of tillage. The four bottom plow, with disk blades 127 cm in diameter, was capable of incorporating ash to a depth of 65 to 75 cm.

Fly ash was applied to an individual replication and incorporated on the same day to prevent wind erosion of the exposed ash. The experimental site was plowed from south to north in one direction to avoid creating a huge dead furrow. The depth of plowing was 60 to 65 centimeters. This was partially determined by the power and traction capabilities of the D-7 caterpillar tractor used. The goal of this procedure was to find a way to incorporate the ash such that minimal amounts were left in the the upper 20 to 30 cm of the modified profile.

The method of ash application was modified on the Cuda site. The fly ash used was from the BWL, this time the ash was brought directly from the holding bins that collected the electrostatic precipitator ash from the Erickson plant in Lansing, MI. The ash was applied using a spreader designed by Dr. C.M. Hansen, Professor Emeritus, Department of Agricultural Engineering, Michigan State University, and built by BWL personnel. This spreader hitched to the rear of the ash hauling trucks and dispensed an even 5 centimeter layer of ash over the surface of the soil. Applications to treatments requiring more than 5 centimeters of ash were accomplished by subsequent trips across the area.

A third field site (Figure 3) was established in the spring of 1986 at an area located near West Olive, MI. This site, called the Campbell site, consisted of Croswell

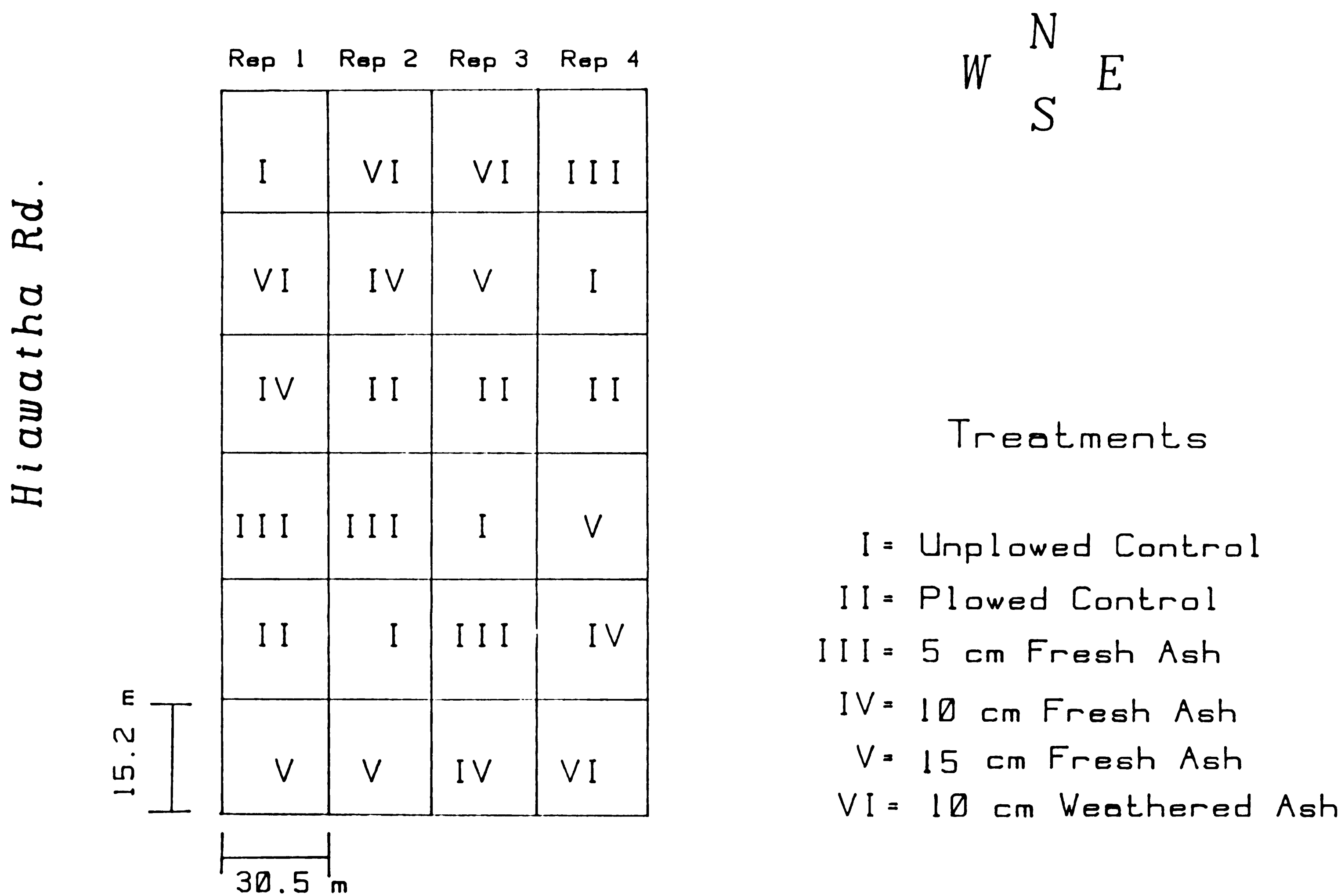


Figure 3. Plot diagram, Campbell site, West Olive MI.

& Au Gres sands (Entic Haplorthod sandy, mixed, mesic), located in T. 6 North, R. 16 West, Section 10, east of Hiawatha road, Ottawa County, MI. This soil was described as being not well suited for crops, having low fertility, as well as low available water holding capacity (Ottawa County Soil Survey, 1972). The experimental design was a split block (two crops), arranged in randomized complete blocks, supporting 4 replications of 6 treatments consisting of: unplowed and plowed control, 5 centimeter fresh ash, 10 centimeter fresh ash, 15 centimeter fresh ash, and 10 centimeter weathered ash. The experimental area was divided into 24 units, each 15.2 m by 30.5 m in size.

The fly ashes used in this field experiment were transported from the Consumers Power Company Cobb generating facility in Muskegon, MI. The spreader used at the Cuda site was again used to apply the ash at the Campbell site. The fresh ash that was applied came from the electrostatic precipitators at the Cobb plant, while the weathered material was excavated from a fly ash sluicing pond located near the plant.

The last field site was established in the spring of 1988 and is called the Bil-Mar Site. This site consists primarily of Rubicon sands (Entic Haplorthods, sandy, mixed, mesic) and is located in T. 6 North, R. 15 West, Section 7, Ottawa County, MI. The soil series is described as having low natural fertility, rapid permeability, and very low water holding capacity. While the soil is not suitable for crop production without irrigation, it is used in a few places for specialty crops where irrigation is used (Ottawa County Soil Survey, 1972).

This site was not designed for replicated experimentation, but rather as a large scale field demonstration area. Nearly 3.2 hectares were modified by an 1815 Mg ha^{-1} fly ash addition. Ash for this site was provided by Consumers Power Company, and was transported from the Cobb generating plant's ash sluicing ponds, near Muskegon, MI.

The fly ash was transported from the ponds to the field site in 50 ton gravel trains. An ash receiving station was set up on the southern end of the field. The trucks dumped the ash in piles, which were then leveled out into loading strips with a road grader. The ash was picked up and applied to the field using a John Deere pan scraper. Application rates averaged 1815 Mg ha^{-1}, a 15 to 20 cm layer was deposited on the soil surface. The fly ash was incorporated with the Towner giant disk plow used previously, pulled by a D-9 Caterpillar tractor from the Campbell generating complex.

Ash incorporation disturbed the soil profile severely enough that it was too loose for conventional planting. A secondary tillage operation, using a Brillion field cultivator, was performed on all sites except the Bil-Mar site, right after incorporation. This was done to consolidate the soil profile and to level the soil surface for better seed-soil contact at planting.

Cropping of the Field Sites

The cropping strategy for these field experiments was to: (1) field test the ability of the soil profile modifications to produce significant increases in crop yields and (2) evaluate any potential plant toxicities which might exist due to the application of fly ashes.

Eaton Rapids

The Miller Trust site, established in 1985, was planted to corn in the 1985 and 1986 growing seasons, and soybeans in 1987. The Cuda site, initiated in 1986, was planted to corn during the 1986, 1987, and 1988 growing seasons. The varieties used were, Voris hybrid (#V2331) in 1985 at the Miller Trust Site, and Pioneer hybrid (#3744) at both sites in 1986, and the Cuda site in 1987 and 1988. Corsoy 79 soybeans were planted on the Miller Trust site in 1987. Corn was planted with a 4-row Buffalo no-till planter, 75 cm row spacing at the rate of 65,700 plants per hectare. Liquid fertilizer, (10-34-0) was banded 5 cm below and 5 cm beside the row, at the rate of 123 kg ha^{-1}. Urea (46-0-0) and potash (0-0-60) were custom blended and broadcast at the rate of 270 kg ha^{-1} and 300 kg ha^{-1}, respectively, at the time of planting. Soybeans were planted with a Tye no-till drill, 20 cm row spacing, at the rate of 100 kg ha^{-1}. Fertilizer (5-20-20) was applied through the drill attachment at the rate of 112 kg ha^{-1}. An additional 67 kg ha^{-1} of potash (0-0-60) was broadcast prior to the time of planting.

Weed control was maintained by a mixture of atrazine and alachlor (Lasso). The herbicides, mixed at the 4.72 L ha^{-1} rates, were used on the corn areas during the 1986 through 1988 growing seasons. Soybean weed control was established through the use of a 3-way mixture of metribuzen (Lexone) 4L 0.88 L ha^{-1}, alachlor (Lasso) 4L 5.8 L ha^{-1}, and glyphosphate (Roundup) 3.5 L ha^{-1} rate. The insecticide Counter (terbufos (S-[[(1,1-dimethylethyl) thio] methyl] 0,0-diethyl phosphorodithioate)) 15 G, was applied at the time of planting to the corn to provide Corn Rootworm (*Diabrotica longincornis*) control.

West Olive

Crops raised on the Campbell site were corn and soybeans, 1986; corn and wheat, 1987; and corn and sorghum sudangrass, 1988. Corn and soybeans were planted on June 10, 1986. Soybeans were planted on adjacent sides of each block, so that the soybeans from the middle two replicates were planted and grown next to soybeans on the outer two replicates. Corsoy 79 soybeans at the rate of 32,100 plants per hectare, with the remainder of the area planted to corn (Pioneer #3744) at the rate of 64,200 plants/hectare. Both the corn and soybeans were planted with a John Deere 7000 minimum tillage planter, 75 cm row spacing. The plots were fertilized with 135 kg ha^{-1} as urea (46-0-0), and 225 kg ha^{-1} as potash (0-0-60). Both the soybeans and the corn had 112 kg ha^{-1} of (0-46-0) banded 5 cm beside and 5 cm below the row at the time of planting.

Herbicides were applied prior to planting on the corn areas and were incorporated in the initial tillage operation. The herbicide used in 1986 was a mixture of atrazine 1.2 L ha^{-1}; cyanazine 2.3 L ha^{-1}, and EPTC R-29148 dietholate 2.4 L ha^{-1}. Soil acidity was reduced by the addition of 6.7 Mg ha^{-1} dolomitic lime.

Wheat was planted on the areas previously planted to soybeans on October 6, 1986. Augusta white winter wheat was planted using a Tye no-till drill, with 17.5 cm row spacing at the rate of 150 kg ha^{-1}. Fertilizer applications of 56 kg ha^{-1} of N as ammonium nitrate (34-0-0) and 100 kg ha^{-1} potash (0-0-60). A second fertilizer application was made in April of 1987 consisting of 45 kg ha^{-1} N as urea (46-0-0) using a Gandy fertilizer spreader.

In the 1987 and 1988 cropping seasons, corn was replanted on the same areas as in 1986 using a Buffalo no-till 4-row planter, 75 cm row spacing, at the rate of 65,700 plants ha^{-1}. The variety used was Pioneer hybrid

#3707. Fertilizer applications of 295 kg ha^{-1} of potash (0-0-60) and 270 kg ha^{-1} of urea (46-0-0) were made in 1987 prior to planting, using a Gandy fertilizer spreader. Preplant fertilizer applications in 1988 were the same as 1987, however, a broadcast fertilizer spreader was used. Liquid (10-34-0) was applied as a starter fertilizer through the planter at the rate of 123 kg ha^{-1}. In addition, nitrogen and potassium were applied in late May (1987) and early June (1988) as a surface side dress application. Fertilizer was applied by hand at the rate of 45 kg ha^{-1} N as urea, and 45 kg ha^{-1} potash. Lime was custom applied at the rate of 6.7 Mg ha^{-1} in 1987 on the area previously planted to corn.

Weed control on corn grown in 1987 was provided by application of a mixture of atrazine 4L 2.3 L ha^{-1}, and alachlor 3.5 L ha^{-1}, sprayed preemergence. A second application of atrazine was made in an effort to control weeds, postemergence, at the rate of 3.5 L ha^{-1} with crop oil concentrate. Herbicide application in 1988 on corn ground consisted of a mixture of 3.5 L ha^{-1} of atrazine and 4.7 L ha^{-1} of alachlor at the time of planting. An application of 3.5 L ha^{-1} of glyphosphate was made to both the corn and the sorghum sudangrass areas.

Sorghum sudangrass was planted on June 8, using a Tye no-till grain drill, 20.3 centimeter row spacing at the rate of 38 kg ha^{-1}. Fertilization was made preplant broadcast at the same rate and time as the corn areas previously described.

Plant Sampling and Measurement

Plants were measured at various growth stages in 1987 and 1988. Corn plant height and leaf growth was monitored in 1988. Plant height was monitored weekly until tasseling (Vt) by measuring the maximum leaf extension of the uppermost three leaves of five plants per plot area. Leaf area was estimated by measuring the length and width of the top three leaves of a corn plant, on the same five plants per plot area. Methods described by McKee (1963) and Daughtry & Hollinger (1984) calculate the area of a corn leaf with the relationship: $A = F * (L * W)$ where 'F' is an empirically derived slope of the function of leaf area and leaf Length (L) * Width (W). Reported values of 'F' range from 0.73 (McKee et al, 1964) to 0.785 (Daughtry et al, 1984). An 'F' value of 0.75 was used to calculate the leaf area on the plants measured in this experiment.

Plant dry matter sampling of the above ground portions of the plants, cut above the brace roots, were taken at various times over the growing season. Plant samples were collected, 5 plants per plot area and dried at 65° C for 4 to 5 days and weighed. Plant heights were also measured on 20 plants per plot area during the 1987 and 1988 growing seasons.

Ear corn was harvested by hand from 12.2 m of row per plot and the ears husked and weighed. In 1986, 12 ears/plot were subsampled, run through a grain sheller, and evaluated for gravimetic moisture content. Grain samples were collected for tissue analysis, and ear corn harvest weights were converted to bushels of #2 shelled corn at 15.5% moisture. In 1987 and 1988, the harvest procedure was the same, however, all of the ears harvested were run through a tractor powered sheller and then evaluated for moisture content. Plant populations were determined for the area harvested.

Corn silage yields, taken in 1986 and 1988, were measured by removing the ears from 12.2 m of row, weighing them, and cutting the corn plant off just above the brace roots. The stalks were then weighed in the field, and 5 stalks/plot were subsampled, chopped using a small flail chopper, for silage analysis and moisture determination. Ears were collected, 10 plot^{-1}, to determine the moisture content for dry matter yields. Wheat was harvested in July of 1987 using a Hege plot combine. A 9.14 m by 9.14 m area near the center of the plot was harvested. Grain was weighed, and a subsample was collected for tissue analysis and gravimetric moisture determination. Yields were corrected to 13.5% moisture.

Soybeans were harvested in October of 1987 using a Hege plot combine. An area 170 meters square was harvested near the center of each plot. Grain was weighed, and a subsample was collected for moisture determination as well as grain tissue analysis. Yields were determined and corrected to 13% moisture.

Sorghum sudangrass was harvested in August of 1988 using a flail chopper (Carter) harvester. A 9.14 m by 9.14 m area was harvested near the center of each plot. All of the vegetative material was removed from the plot, leaving only a 5-7.5 cm portion of the stalk remaining as stubble. The biomass was weighed, a subsample was collected for gravimetric moisture determination and tissue analysis, and yields were reported as Mg of dry matter per hectare.

Methods of Soil Moisture Measurement

Soil moisture measurement can be achieved through several types of analysis. The most common and widely used method to determine the moisture content of a soil is gravimetric analysis. Soil is collected, weighed, oven dried, and reweighed to determine moisture content on a per weight basis. However, soil moisture information is often more useful when it is related on a per volume basis. Volumetric soil moisture contents can be determined directly by collecting a sample of known volume and completing the analysis as above. Soil moistures can be determined gravimetrically, and then converted to volumetric moisture through the relationship:

$$V_w = w(P_b/P_w)$$

where 'V_w' is the volumetric moisture content, 'w' is the gravimetric moisture content, 'P_b' is the bulk density of the soil, and 'P_w' is the density of water (Hillel, 1982).

In addition to direct measurements of soil water content, several indirect methods have been developed. These include electrical resistance measurements, such as gypsum or nylon moisture blocks, and the neutron scattering method. Measurement of soil moisture with a neutron hydroprobe was developed in the 1950's and has gained wide acceptance because it allowed for non-destructive and repeated sampling of the same location (Hillel, 1982). Soil moisture is measured with the neutron probe by the thermalization of emitted fast neutrons. Thermalization occurs when a fast neutron encounters a nuclei of the same order of mass, an inelastic collision takes place, and much of the energy of the neutron is lost. Collisions with higher mass nuclei are elastic, and hence, little energy is lost. The hydrogen nuclei in soil moisture are nearly the same mass as a neutron, and are very effective in slowing down fast neutrons. Slow neutrons are backscattered to the probe and detected by boron-triflouride neutron tubes. The pulses generated are transmitted to a counter and data logger (Partridge, 1967).

The neutron hydroprobe consists of two main parts. It has a probe which contains the source of neutrons, typically of radium-beryllium origin, and an electrical impulse counter, which records the number of pulses of electrical power generated by the reflection of slow neutrons through a collector sensor.

Soil Moisture Measurements

Soil moisture was monitored throughout the growing season at each site. Weekly rainfall amounts were collected on site with a standard rain gauge. Daily precipitation amounts were obtained from recording stations located at Eaton Rapids and Grand Haven, MI. A neutron hydroprobe (Campbell Pacific Nuclear Corporation; Pacheco CA; Model 503 Hydroprobe) was used to monitor the soil water content on all sites, during all growing seasons. Measurements were made at 15, 30, 45, 60, and 75 centimeter depths, measuring the volumetric moisture content from 0 to 30, 15 to 45, 30 to 60, 45 to 76, and 60 to 90 centimeters respectively.

Soil moisture was also monitored gravimetrically at the West Olive site during 1988. A large pit, exposing several bands of fly ash or organic matter (from the topsoil in the plowed control), was opened in an unplowed control, plowed control, and a 15 centimeter fresh fly ash treatment. Material was carefully removed from the profile at 12.5, 37.5, 62.5 and 76 centimeter depths, and placed into sealed aluminum weighing tins. Samples were collected from within and between the ash and organic matter bands at 37.5 and 62.5 centimeters deep. Gravimetric moisture content was determined by weighing the sample and then oven drying the soil at 105° C for 48 hours and re-weighing.

Plant Moisture Stress Measurement

Transpiration is the process in which internal cell water is diffused through the stomata and evaporated into the atmosphere. Stomatal opening and closing is a function of the turgor pressure of the guard cells in the leaf. Essentially, the rate of transpiration is regulated by the supply of energy available to evaporate water, the difference in vapor concentration or pressure between the leaves and air (the driving force), and resistances in the water vapor pathway. Resistances are the leaf-air boundary layer, the cuticle, and the stomata (Kramer, 1983).

Measuring the transpiration of a plant can be accomplished through the use of a leaf porometer. Porometers measure the rate of diffusion of water vapor from the leaf surface and readings are measured as diffusion resistance in s cm^{-1}. Measured resistance is a function of cuticular resistance as well as stomatal resistance. If vapor flow through the cuticle is characteristically low, the measurement is a good approximation of stomatal resistance (Kramer, 1983).

Steady state diffusion porometry involves measuring the transpiration of a leaf at ambient conditions. Steady state diffusion porometers measure the flux of water transpired in the chamber, which is then balanced by the outflow of air, at the balanced humidity.

Plant moisture stress was monitored at various dates during the 1987 and 1988 field seasons at the West Olive site. Transpiration, diffusive resistance, and leaf temperature deviation from ambient conditions were measured using a leaf porometer (Licor Corporation; Lincoln NE; Model LI-1600 Steady State Porometer) on corn leaves during times of drought stress. Photosynthetically active radiation (PAR) levels were monitored at the time of measurement.

<u>Root Length Density Measurement</u>

Root growth and exploration in the ash bands and the surrounding soil in a 15 centimeter fresh and an unplowed control treatment were measured during the 1988 growing season. A single pit was excavated in each plot sampled, and a perpendicular face was created in the profile 37.5 centimeters away from a row of corn plants. Samples were taken at depths from 0 to 7.5, 7.5 to 15, 22.5 to 30, 30 to 37.5, 37.5 to 45, 45 to 52.5, 52.5 to 60, 60 to 67.5, and 67.5 to 75 centimeters deep at spacings from 0 to 12.5, 12.5 to 25, and 25 to 37.5 centimeters on both sides of the row. Flat sheet metal cutters, fashioned from 12 gauge steel, were used to separate a 7.5 cm deep by 12.5 cm wide by 76 cm long soil samples.

Once the sample was isolated from the profile, the material was separated into ash, sand, or an ash-sand mixture components. Samples were separated by carefully removing some of the mixed material, and then by scraping the surface of the ash clean of sand and mixed soil, clipping the roots at the proper boundary. Each material was weighed, and a subsample was taken to determine the gravimetic moisture content. Samples were then stored in a cooler, 5^{o} C, until they were washed using a hydropneumatic elutriator (Smucker, 1982). Roots were stored in a 25% solution of ethyl alcohol in a cooler until analysis could be completed. Root length was determined by Tennent's line intersect method using a 2.5 square centimeter grid (Tennent, 1975). This method is a modification of the method described by Newman (Newman, 1966).

RESULTS AND DISCUSSION

Modified Soil Profile

Soil modified with fly ash by incorporation with a giant disk plow results in a series of bands extending 75 cm in depth below the surface of the soil. The ash bands, which run parallel with each other, are characterized by a curved vertical structure with a horizontal trailing edge at the bottom of the modified zone. These bands extend from 5 to 7.5 cm below the surface of the soil to the depth of incorporation.

The configuration of the ash bands is such that there is not a continuous barrier to impede the downward flow of drainage water. However, the bottom of one band is below the top of the one adjacent to it. This allows a path for the drainage of excess water from an intense thunderstorm, while maintaining increased moisture for crop growth. Leaving large amounts of ash at or near the surface of the modified profile is undesirable, because sand-ash mixtures have been shown to reduce the saturated hydraulic conductivity rate and to promote runoff, rather than infiltration and recharge.

In addition to soil water relation considerations, ash on the surface of the soil can lead to increased dust and reduced emergence in seedlings due to increased concentrations of soluble salts or B.

Evaluation of the soil profile at the West Olive site was undertaken in the spring of 1987. This allowed the disturbed soil to settle and to become fully recharged with moisture from the snow melt and spring rainfall. Observation pits showing an exposed modified profile are shown in Figure 4. A 15 cm fresh ash treatment, showing several exposed fly ash bands and adjacent sands, as well as associated increases in moisture, are illustrated here. The fly ash bands were saturated at this time, and maintained an area of increased soil moisture in the adjacent sand.

Soil Physical Measurements

Soil moisture characterization, air filled porosity, and pore size distribution curves of the Boyer loamy sand, Croswell sand, and fly ash are given in Figures 5 through 7, respectively.

Soil moisture characteristic values (Figure 5) for the West Olive site show a field capacity (6 kPa matric suction) value of 0.075 m^3 m^{-3} soil water for Croswell sand. This indicates a very low water holding capacity and severe limitations for agricultural use. Boyer loamy sand from the Eaton Rapids sites retained 0.26 m^3 m^{-3} soil

Figure 4. Observation pit exposing a 15 cm fresh ash treatment cut perpendicular to the direction of plowing at West Olive in early spring, 1987. (The fly ash is the dark bands which extend to 75 cm below the surface of the soil).

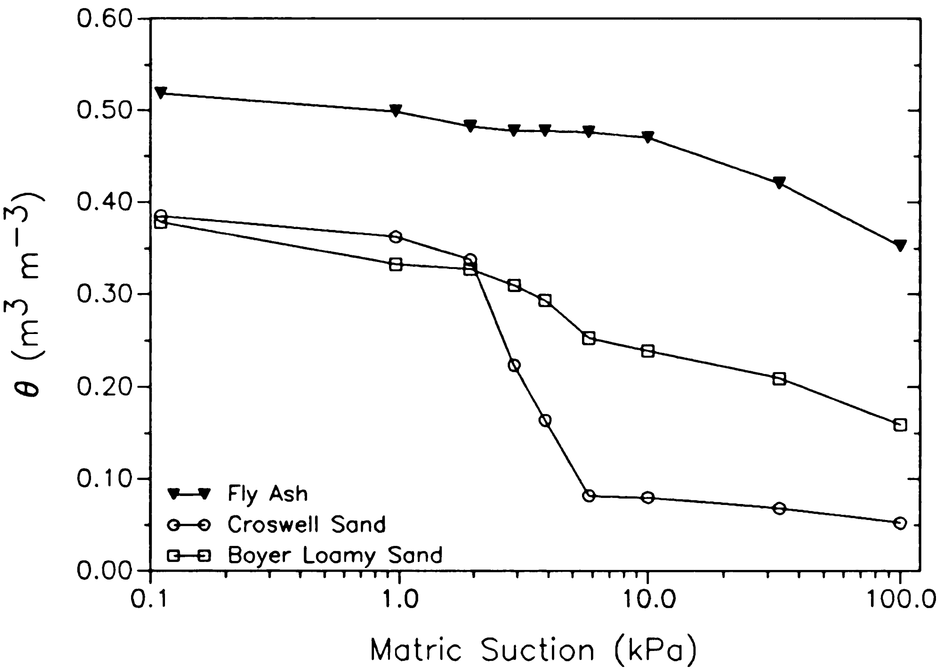


Figure 5. Water retention characteristic curves of Boyer loamy Sand, Croswell sand, and coal fly ash.

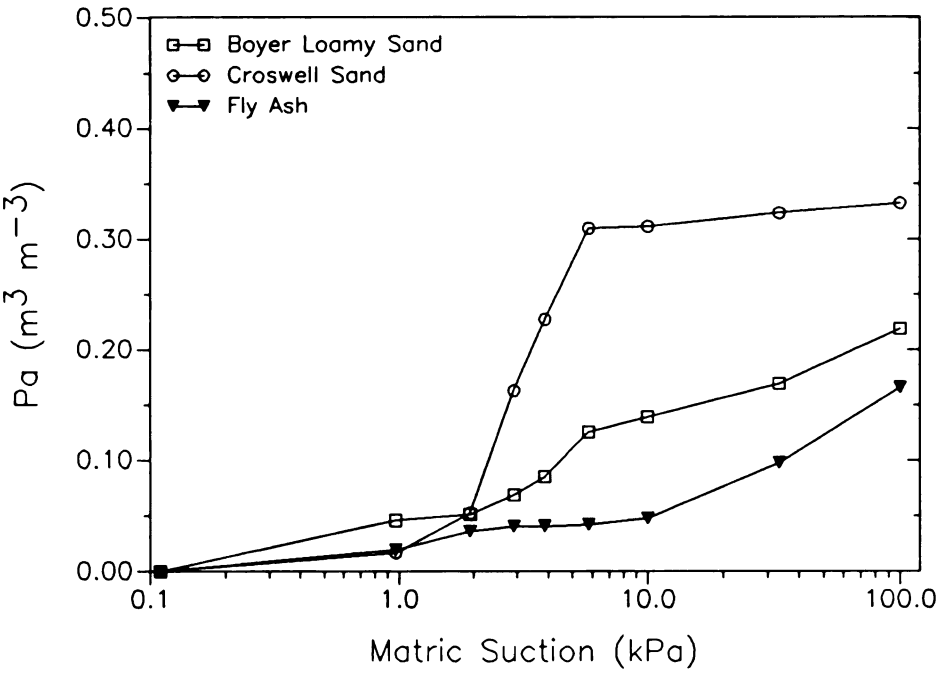


Figure 6. Air Porosities of Boyer Boyer loamy Sand, Croswell sand, and coal fly ash.

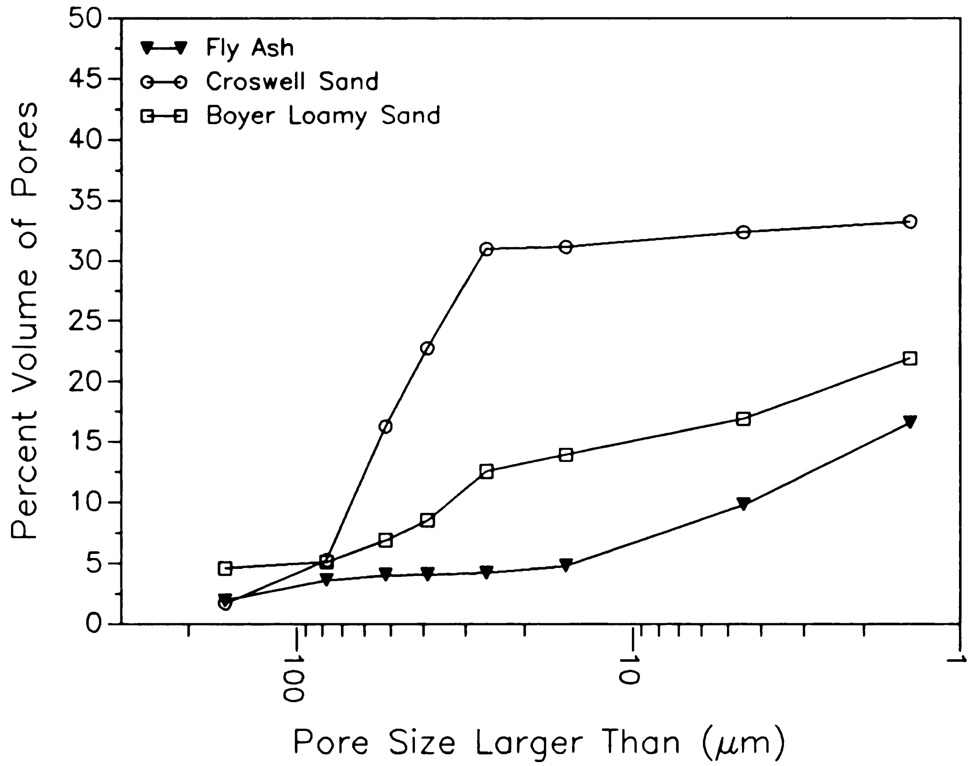


Figure 7. Pore size distribution of Boyer loamy Sand, Croswell sand, and coal fly ash.

water at field capacity, indicating large differences in soil textures between the research locations. Fly ash moisture release characteristics reveal a much greater value, 0.47 $m^3\ m^{-3}$ moisture content, at field capacity. At the 100 kPa matric suction level, volumetric soil water levels for Croswell sand, Boyer loamy sand, and fly ash were at 0.5, 0.16, and 0.35 $m^3\ m^{-3}$, respectively. This shows good separation of the relative availability of the soil water for plant use between the soils and the fly ash additive. In an attempt to ascertain the lower limit of plant available moisture, samples were equilibrated at 1500 kPa matric suction (commonly accepted as the permanent wilting point). The moisture content of the fly ash sample was 0.029 $m^3\ m^{-3}$, indicating that nearly all of the moisture retained by the fly ash incorporated into the soil was available to the plant.

Air porosities for Croswell sand, Boyer loamy sand, and fly ash are shown in Figure 6. These relationships show that the majority of the pore space in the Croswell sand is filled with air at field capacity, while Boyer loamy sand and fly ash are considerably lower, (2.5 and 6.5 times, respectively).

Pore size distribution of the three materials is given in Figure 7. Again, there is a large separation between the Croswell and Boyer soils. Most of the pores ranged between 20-80 um in the Croswell sand. The Boyer loamy sand has a more even distribution, with a larger proportion of the pores 10 um or smaller than the Croswell. The majority of the pores in the fly ash are 10 um or smaller.

Climatological Information

Rainfall patterns for the West Olive site from 1986 to 1988 are given in Figures 8 and 9. Rainfall amounts varied each year. 1986 received the most rainfall, and 1988 the least during the growing season. Cumulative rainfall totals for the May through September growing season peaked 550 mm in 1986, 440 mm during 1987, and reached only 260 mm in 1988. Precipitation exceeded the long term average (1940-1970) recorded for the 5 month growing season , 377 mm, during 1986 and 1987.

Distribution patterns for rainfall varied over the period of the study. At the West Olive site, rainfall was either at or below normal during May and June, and well above normal in September for all three growing seasons. The 1986 season was characterized by above normal rainfall in July and August, and a wet September, when 102 mm of rain fell, accounting for 60% of the seasonal departure. By contrast, 1987 and 1988 were both very dry in May and June, and still below normal in July. The extent of the drought was more severe during 1988. Rainfall was near normal during August in 1987 and 1988, and above normal during September in 1987. Daily precipitation data for

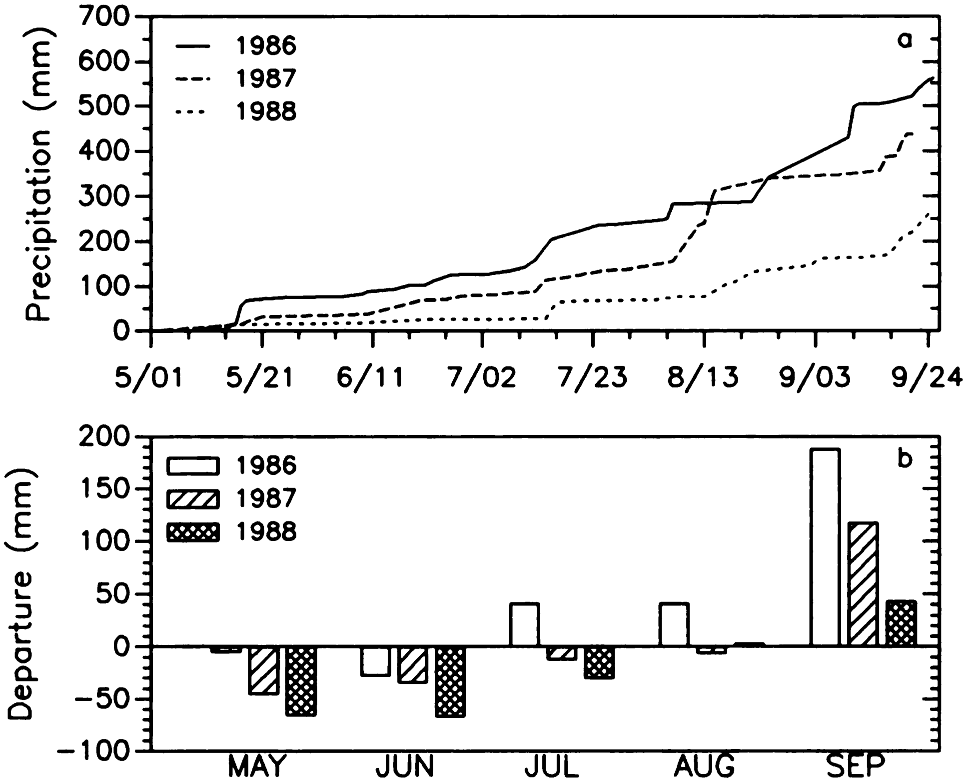


Figure 8. Cumulative precipitation through the growing season (a) and monthly rainfall departures (b) from 1986 through 1988 at the Campbell research site located near West Olive, MI.

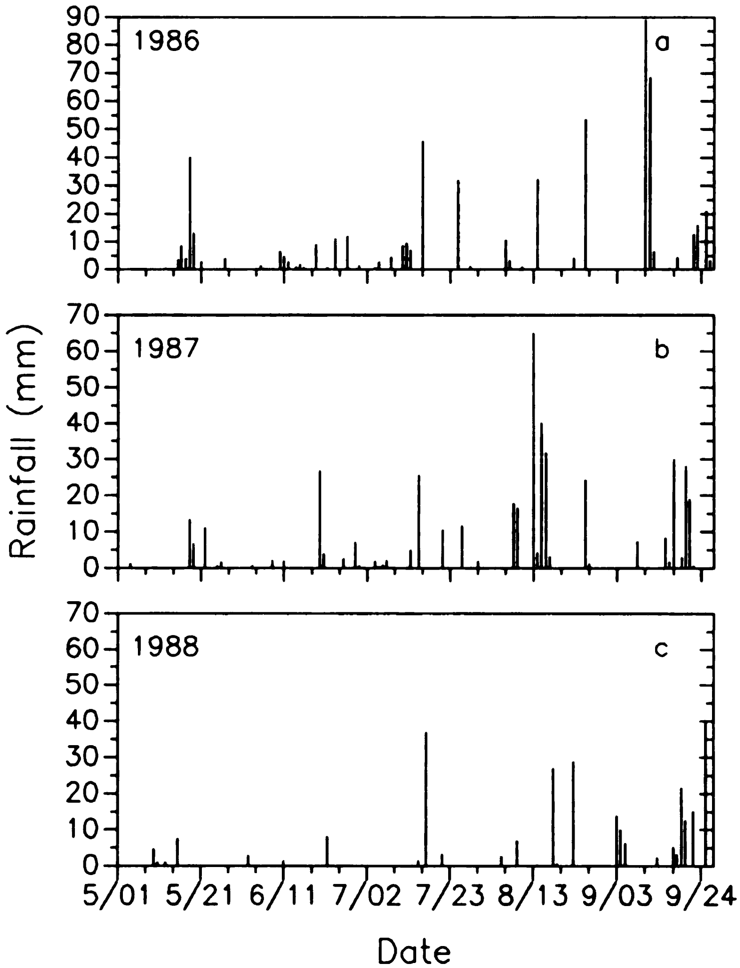


Figure 9. Daily precipitation received during the growing season in 1986 (a), 1987 (b), and 1988 (c) at the Campbell research site located near West Olive, MI.

May to September from 1986 through 1988 is reported in Figure 9(a,b,c). The rainfall distribution information illustrates that the conditions for soil moisture and crop growth were somewhat similar in 1987 and 1988 but were more moist during the 1986 growing season.

Rainfall patterns for the Eaton Rapids research sites from 1985 to 1988 are given in Figures 10 through 13. Yearly rainfall totals were variable, with 1986 receiving the greatest rainfall, and 1988 receiving the lowest during the growing season. Cumulative rainfall for the May through September growing season was 392 mm in 1985, 505 mm in 1986, 450 mm in 1987, and 390 mm in 1988, (Figure 10a and 11a). Precipitation amounts equaled the long term average (1940-1970) recorded for the 5 month growing season , 396 mm, in 1985 and 1988, and exceeded this level during 1986 and 1987, due principally to heavy rainfall in the month of September.

At the Eaton Rapids site, the 1985 season was characterized by a dry May and June, a wet August, and a dry September (Figure 10b). During the next three years, rainfall was either at or below normal during May and June, and at or above normal in August and September for the 1986 through 1988 growing seasons (Figure 12b). The 1986 season was characterized by above normal rainfall in July, and an exceptionally wet September. Like West Olive, 1987 and 1988 were both very dry in May and June,

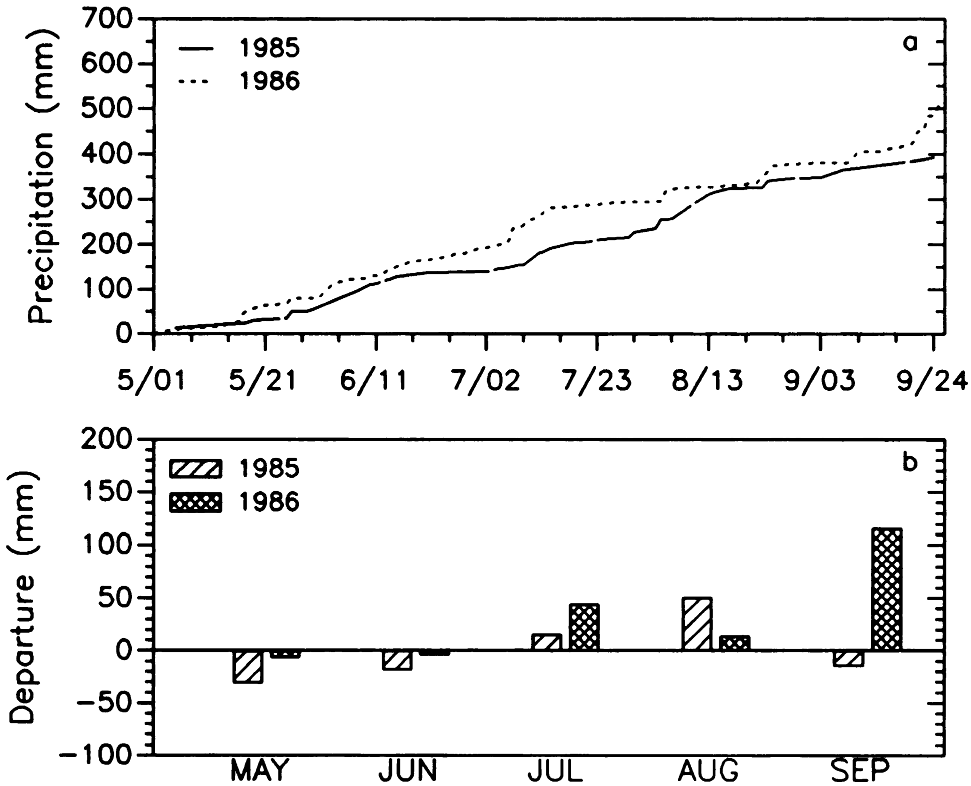


Figure 10. Cumulative precipitation through the growing season (a) and monthly rainfall departures (b) during 1985 and 1986 at the Miller Trust and Cuda research sites located near Eaton Rapids, MI.

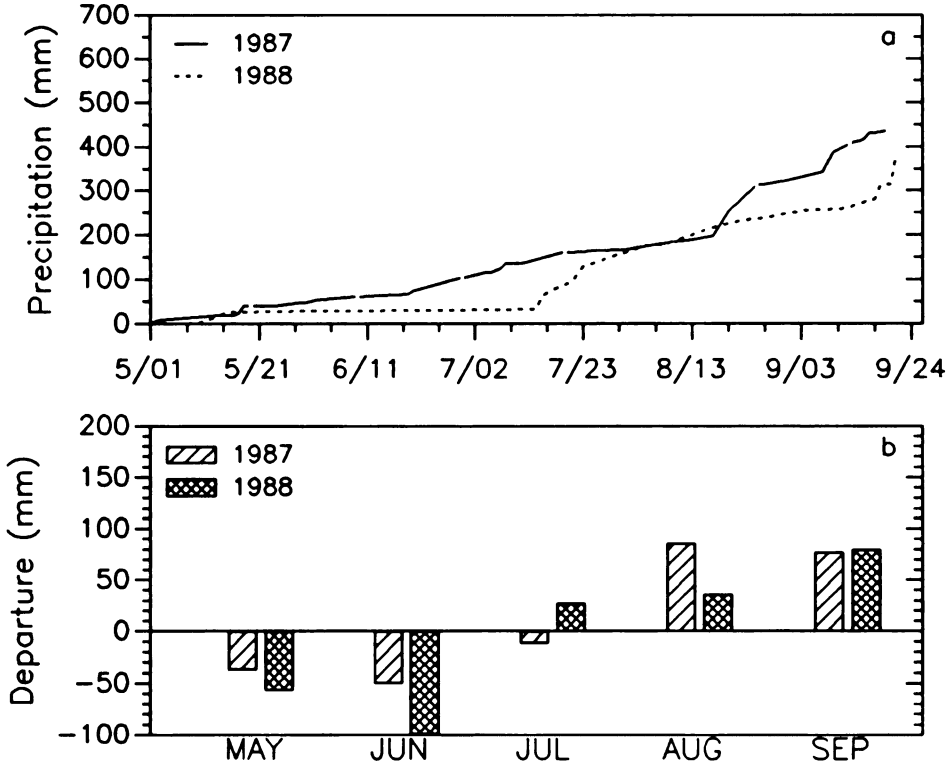
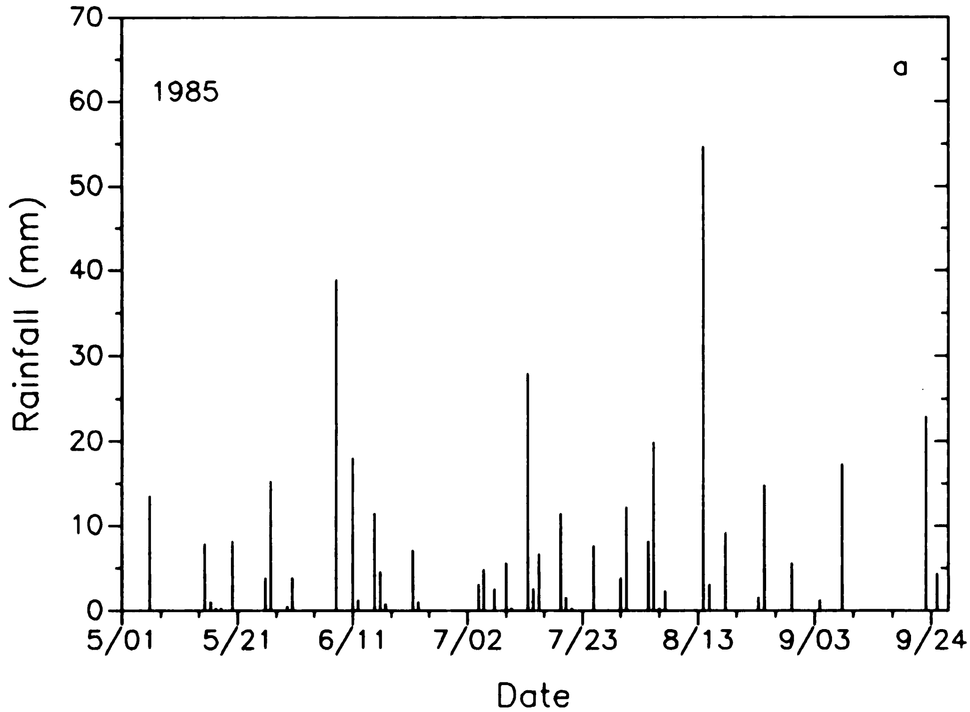


Figure 11. Cumulative precipitation through the growing season (a) and monthly rainfall departures (b) during 1987 and 1988 at the Miller Trust and Cuda research sites located near Eaton Rapids, MI.



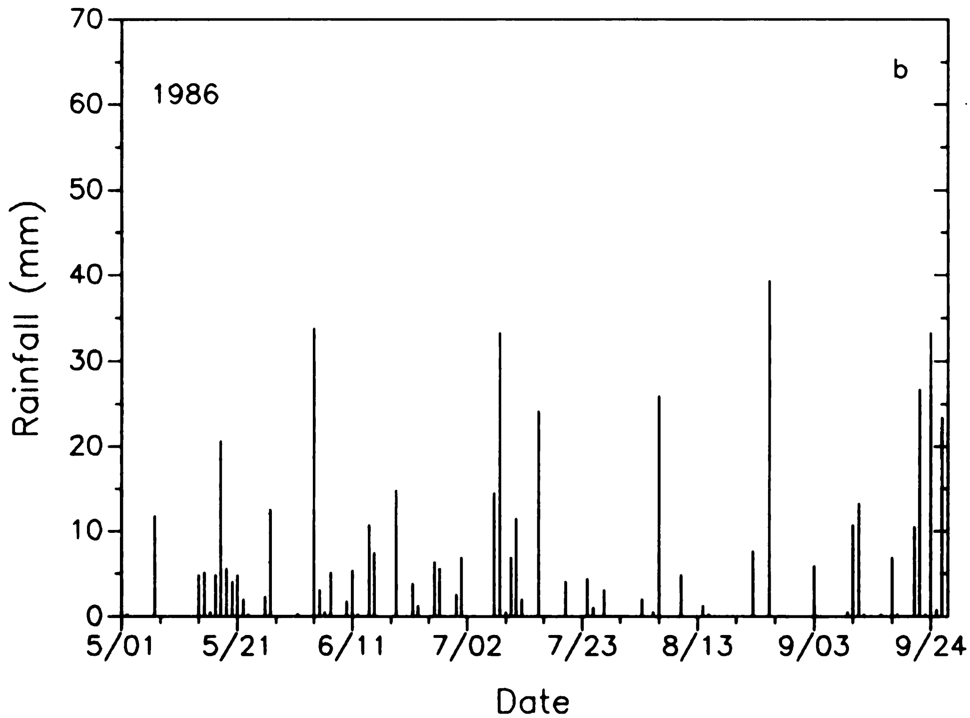


Figure 12. Daily precipitation received during the growing season in 1985 (a) and 1986 (b) at the Miller Trust and Cuda research sites, located near Eaton Rapids, MI.

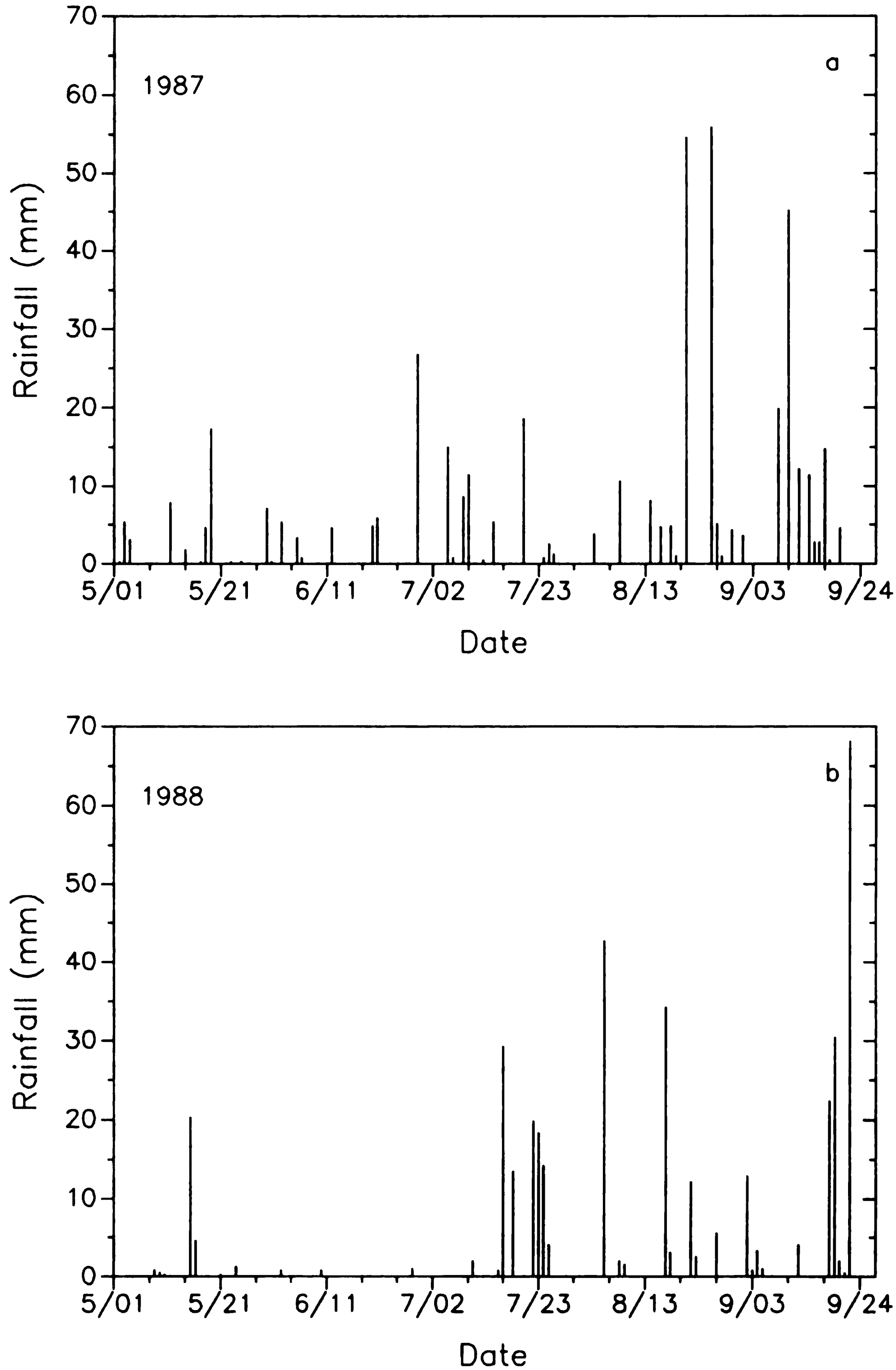


Figure 13. Daily precipitation received during the growing season in 1987 (a) and 1988 (b) at the Miller Trust and Cuda research sites, located near Eaton Rapids, MI.

with the most severe drought conditions occurring during the 1988 growing season. Precipitation was only slightly below normal in 1987 and somewhat above normal in 1988 during the month of July.

Daily precipitation data for May to September from 1986 through 1988 is reported in Figure 13(a,b,c). The rainfall patterns at the Eaton Rapids sites suggest that soil moisture conditions for crop growth and production varied over the four year study and were frequently unlike the precipitation amounts received at the West Olive site.

<u>Soil Moisture</u>

Moisture content was measured for the ash, sand, and incorporated A horizon components of the 15 cm fresh ash, unplowed control, and plowed control treatments at the 37.5 cm (Figure 14a) and 62.5 cm (Figure 14b) depths at West Olive during 1988. Soil moisture increases, within the the fly ash band, in comparison to moisture levels of the incorporated A horizon (O.M. band) of the plowed control, and sands of the unplowed control were substantial. The fly ash in the bands of the treated soils contained moisture levels which ranged from 400% more water in late July, to 150% more moisture by early September than the sand of the unplowed contol treatment. Although some increase in moisture content was shown during late July in the banded A horizon of the plowed control treatment compared to the sands sampled from the

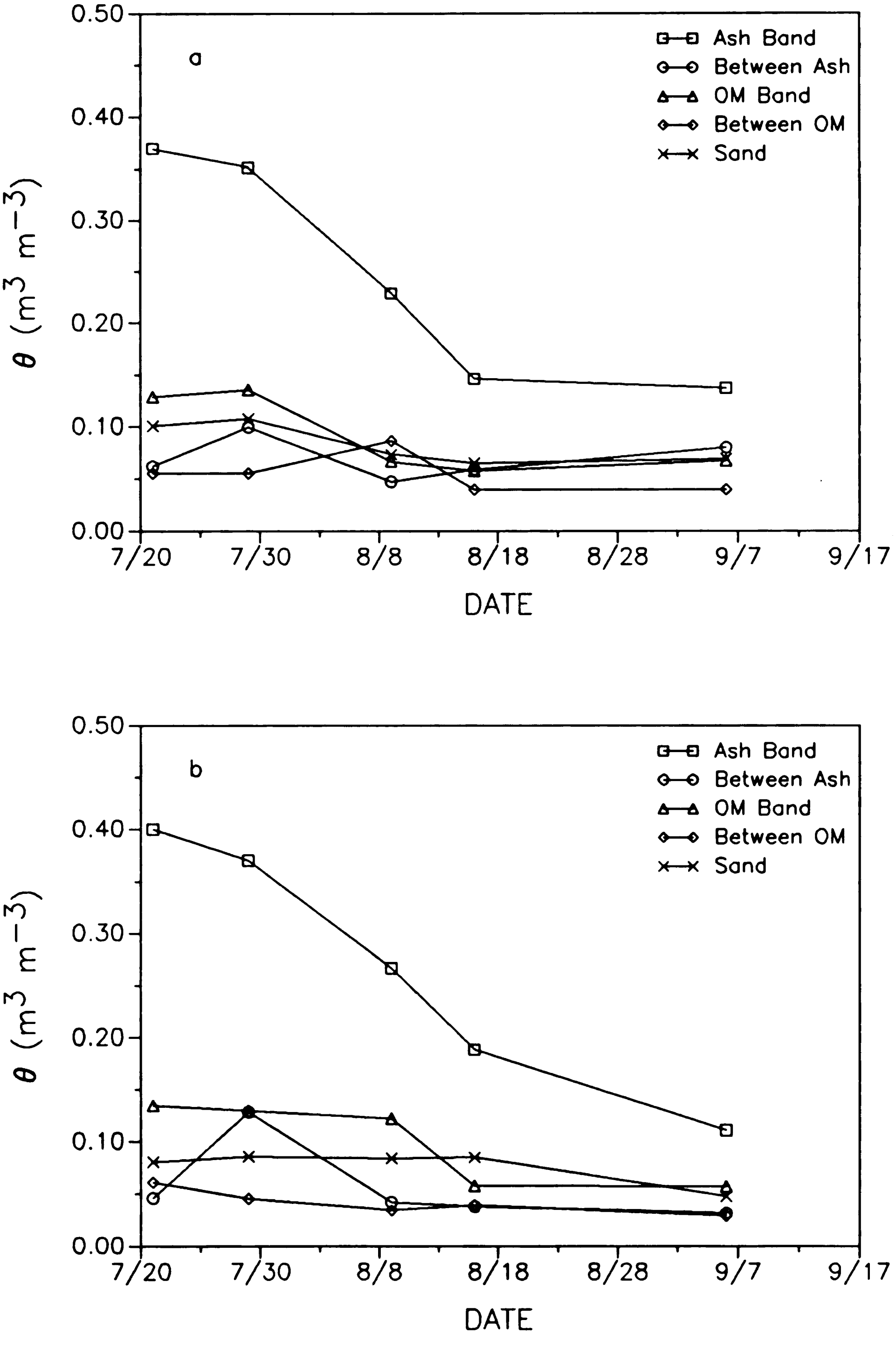


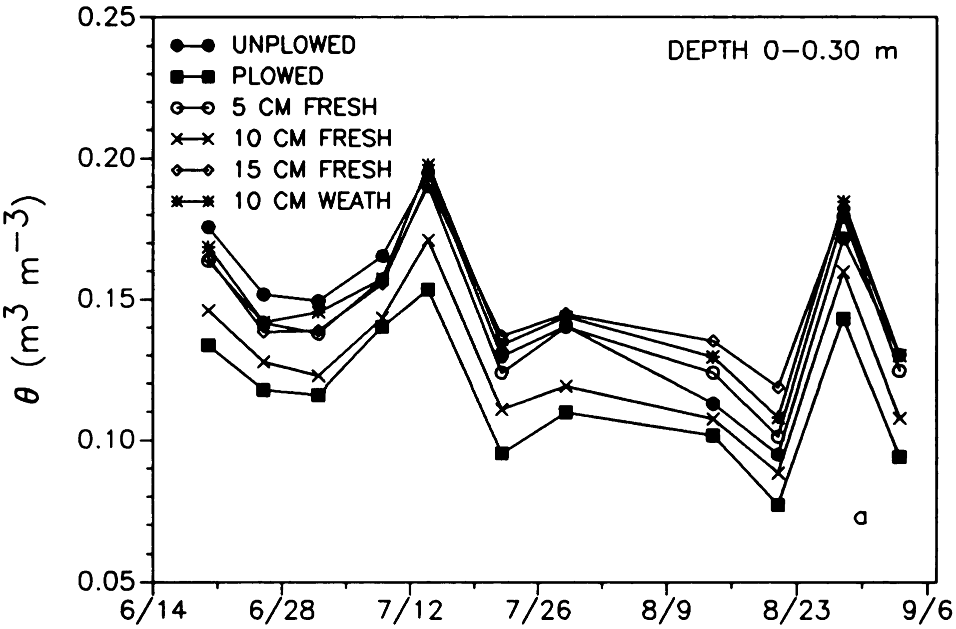
Figure 14. Moisture content of fly ash and sand between fly ash bands (15 cm fresh ash), topsoil O.M. bands and sand between bands (plowed control), and sand (unplowed control) at 37.5 cm (a) and 62.5 cm (b) depth at the Campbell research site, West Olive MI.

unplowed control, these increases were very small compared to those of the ash bands. Moisture content of soil between the ash bands and the incorporated A horizon of the plowed control treatment showed no increases compared to the unplowed control treatment.

While moisture increases within the ash band are dramatic, the 15 cm ash application rate represents a 25% addition to the solum by volume. This moderates the amount of water available for plant use throughout the profile by a factor of 4.

The decline of moisture in the ash bands over the course of 1988 can be attributed to plant water use during the extreme drought conditions throughout the summer. There was inadequate rainfall to recharge soil moisture until late in the growing season. In addition, significantly increased plant vegetative growth was recorded on the 15 cm fresh ash treatment. Since evapotranspiration would be increased with greater plant growth, much of the soil moisture contained within the ash band was utilized to support the significantly increased vegetative growth and yields on these treatments.

Volumetric soil moisture content values of fly ash modified Croswell sand at various depths, as measured by a neutron hydroprobe, are reported in Figures 15-17 for the 1986 growing season. Although fly ash incorporation took place just before planting in June, the abundant rainfall



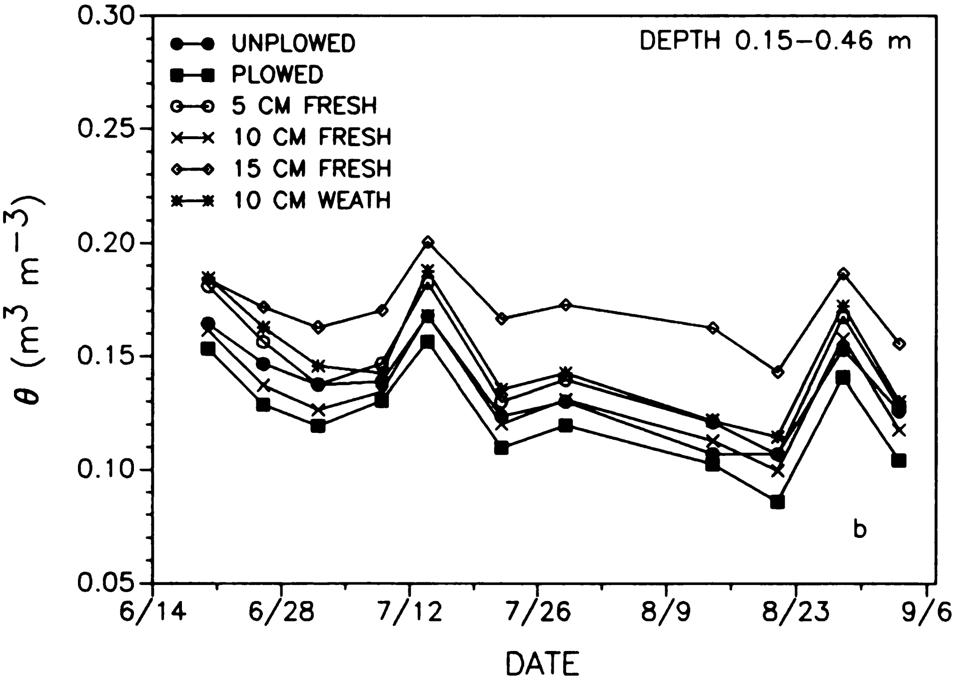


Figure 15. Water content of fly ash modified Croswell sand at the 0-0.30 m (a) and 0.15-0.46 m (b) depths in plots planted to corn during 1986 at the Campbell research site, West Olive MI.

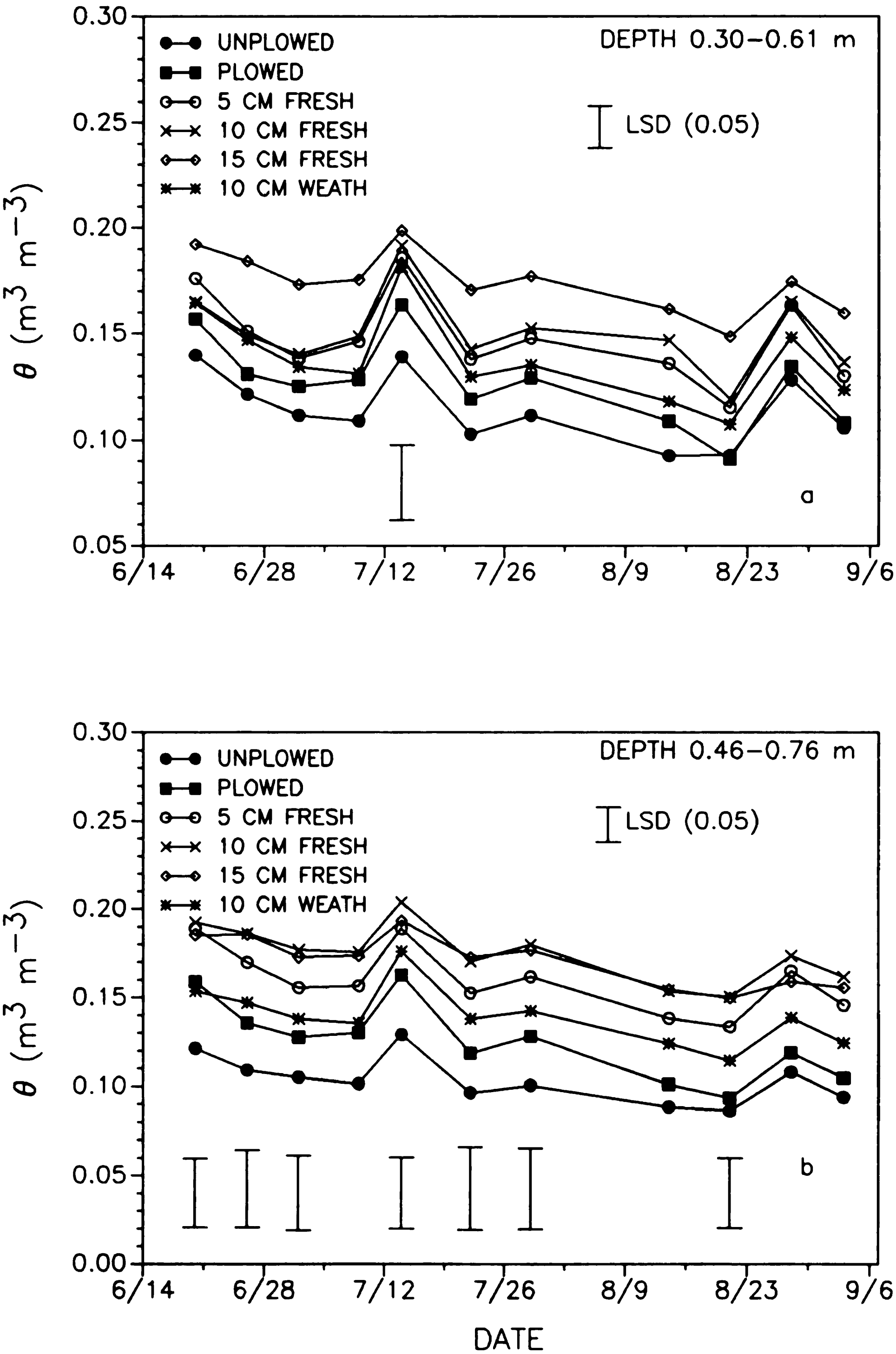


Figure 16. Water content of fly ash modified Croswell sand at the 0.30-0.61 m (a) and 0.46-0.76 m (b) depths in plots planted to corn during 1986 at the Campbell research site, West Olive MI.

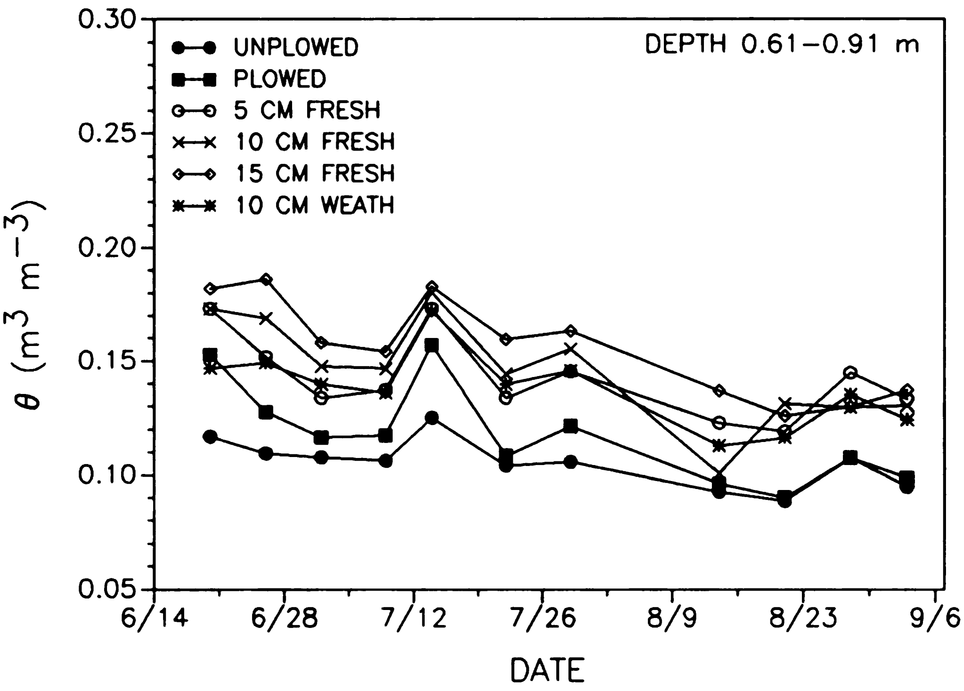


Figure 17. Water content of fly ash modified Croswell sand at the 0.61-0.91 m depth in plots planted to corn during 1986.

received during 1986 at West Olive allowed the ash bands to become moist, and differences in soil moisture between treatments were found. While high variability in measurements exist due to access tube placement in proximity to the ash band at any measured depth, some statistically significant differences between treatments were found, particularly at the lower depths measured.

The trend of increased soil moisture with increasing rates of ash application was apparent for all depths except the 0.0 to 0.30 m interval. The 15 cm ash treatment showed a statistically significant increase in soil moisture over either control treatment on July 15 at this depth (Figure 15a). Soil moisture content values showed good separation at the 0.46 to 0.76 m depth (Figure 16b) with all ash treatments consistently recording increased soil moisture values over either control treatment on all sampling dates except the first. The 15 cm fresh ash treatment was significantly higher in soil moisture content than either control treatment on June 21, July 3, July 22, July 29, and August 21 of 1986. Soil volumetric moisture contents for the 0.61 to 0.91 m depth, shown in Figure 17, showed no statistically significant differences between treatments.

Volumetric soil moisture measurement of ash modified Croswell sand at various depths, as measured by a neutron hydroprobe during 1987, are reported in Figures 18-20.

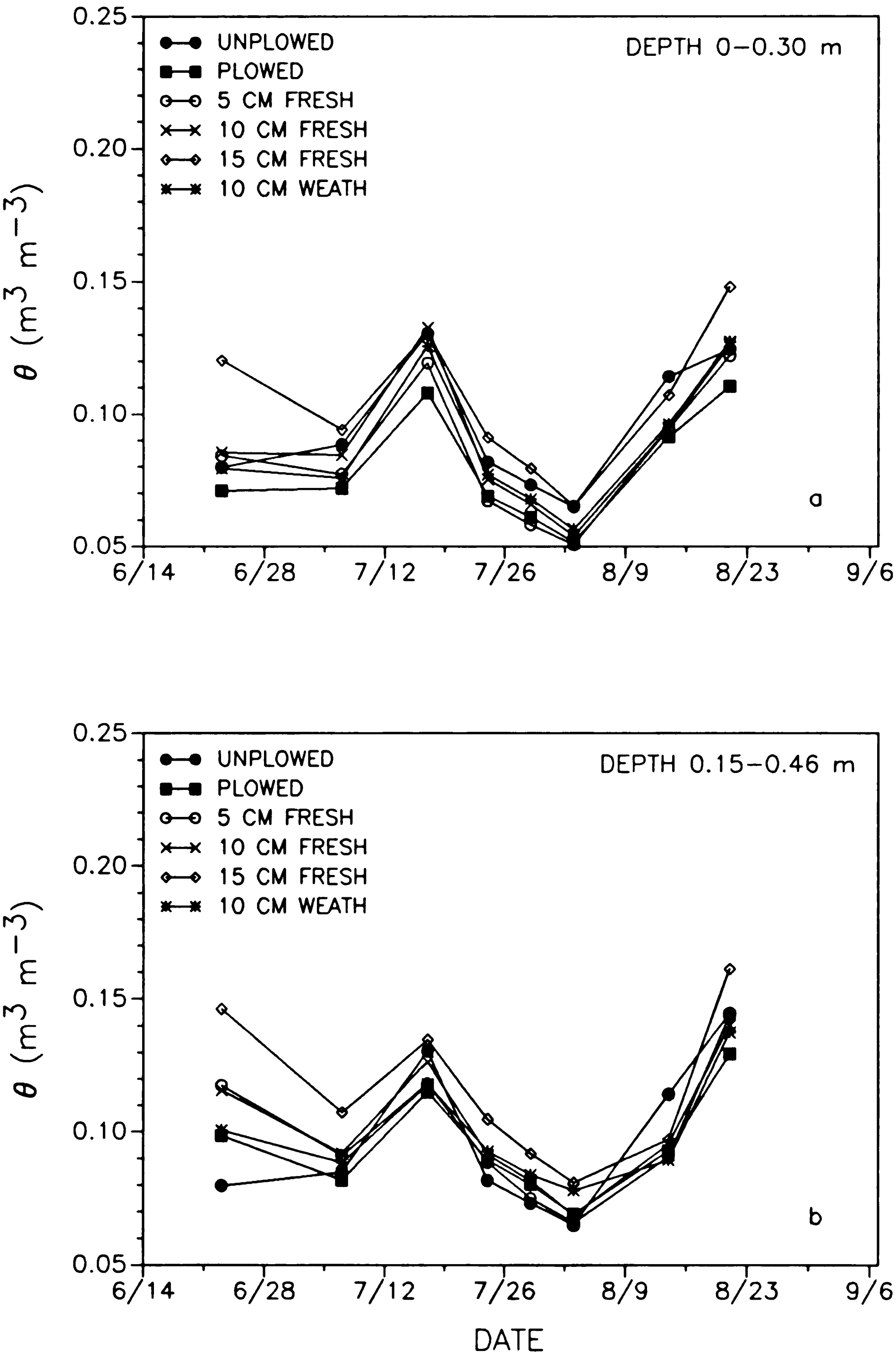


Figure 18. Water content of fly ash modified Croswell sand at the 0-0.30 m (a) and 0.15-0.46 m (b) depths in plots planted to corn during 1987 at the Campbell research site, West Olive MI.

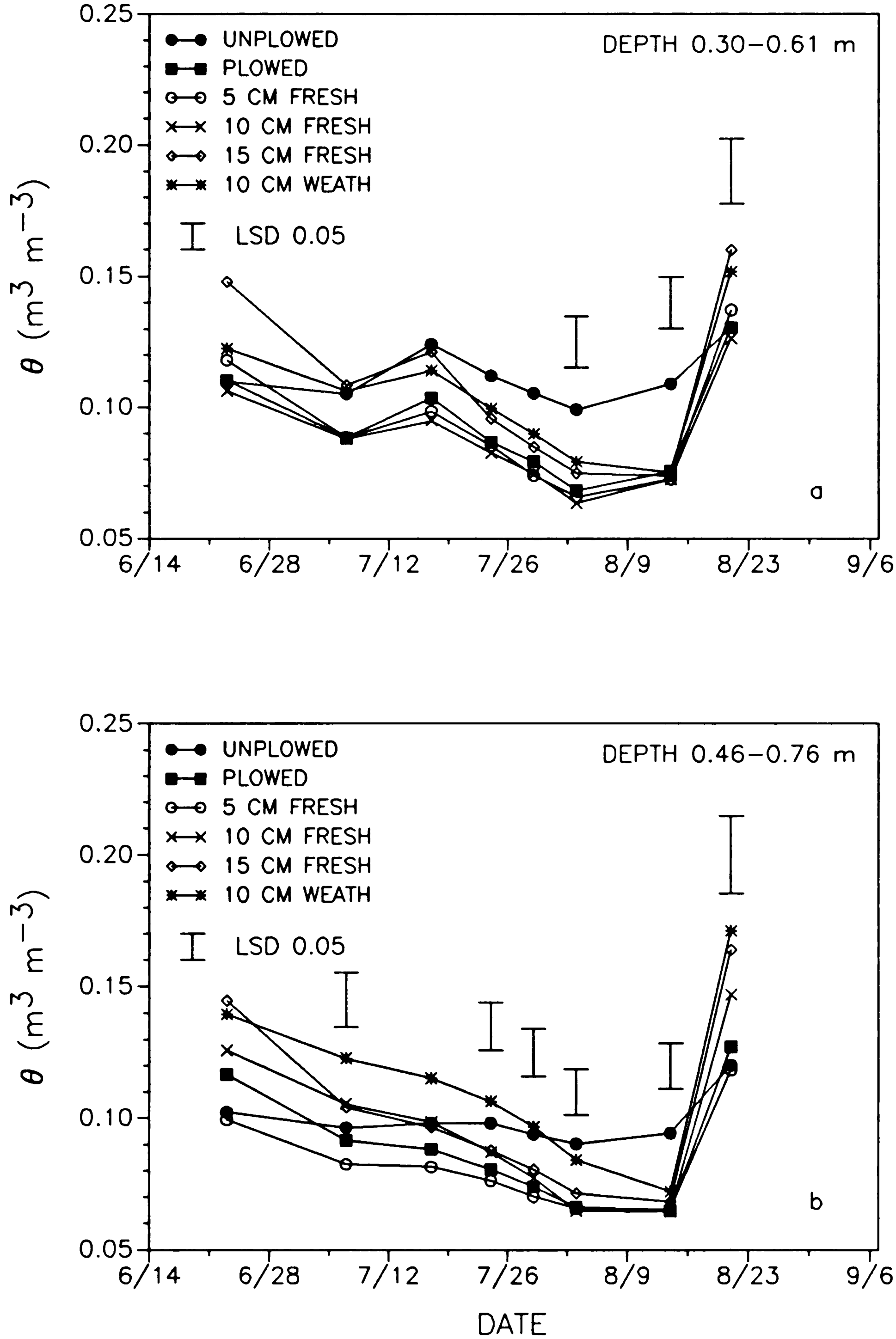


Figure 19. Water content of fly ash modified Croswell sand at the 0.30-0.61 m (a) and 0.46-0.76 m (b) depths in plots planted to corn during 1987 at the Campbell research site, West Olive MI.

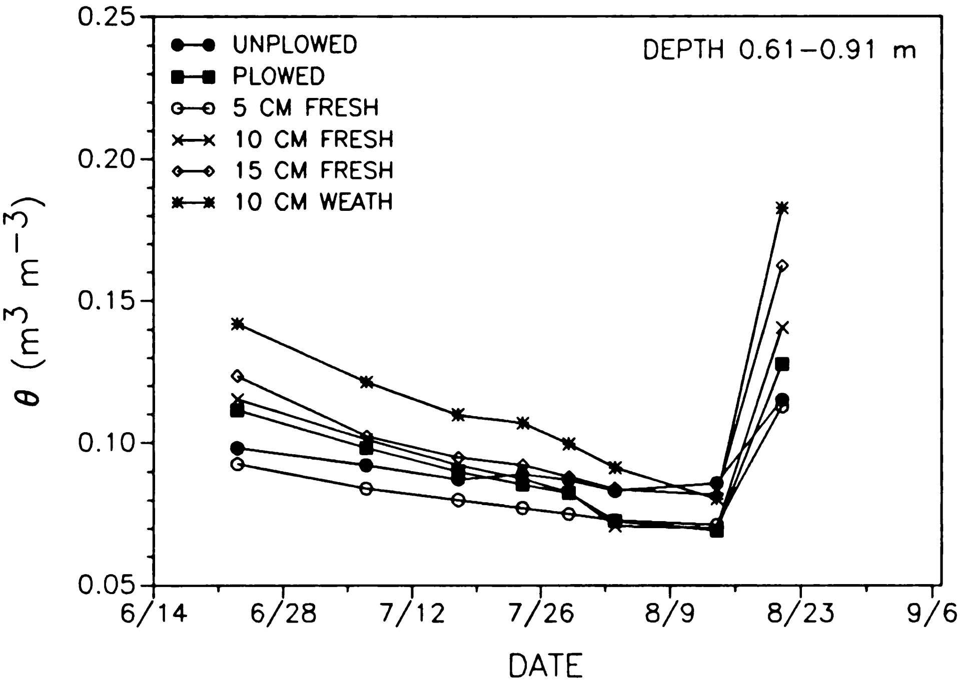


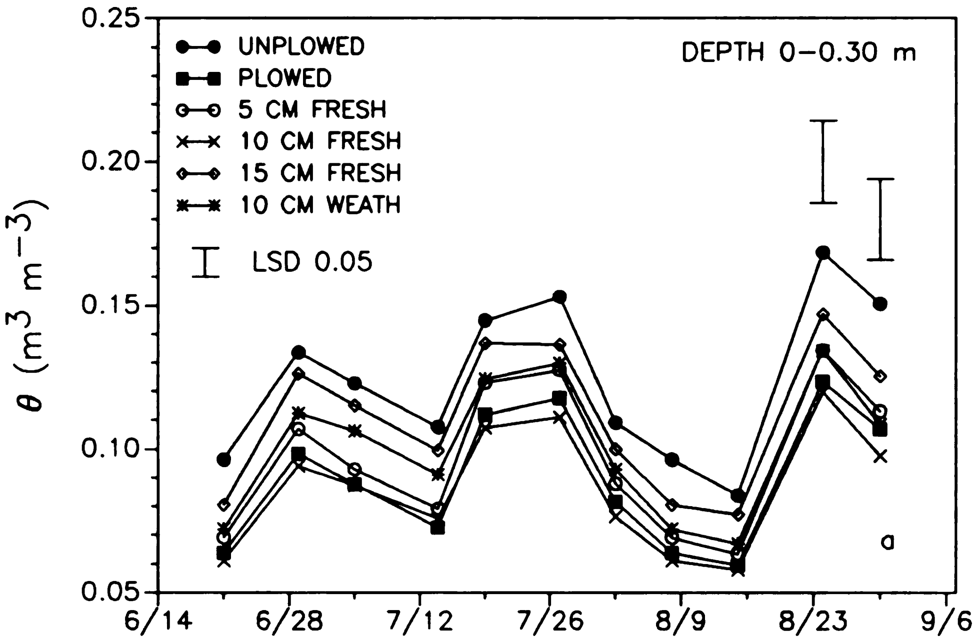
Figure 20. Water content of fly ash modified Croswell sand at the 0.61-0.91 m depth in plots planted to corn during 1987.

The soil moisture measurements reflect the much drier weather conditions in the 1987 growing season. Soil moisture levels of all treatments were reduced by 0.04 m^3 m^{-3} for the driest period of 1987, late July to early August, compared to the same period during 1986. The only exception to this trend was the unplowed control, which recorded comparatively higher soil moisture content at the 0.30 to 0.61 m depth and below. This can be explained by the reduced size of the plants growing on the unplowed control treatments, which removed less water from the soil than more vigorous plants growing on the other treatments. The timing of this drought stress became important because it occurred during tasseling and early grain fill, the most critical stage of plant development which effects corn yield.

Soil moisture measured at the 0 to 0.30 m depth (Figure 18a) again tends to show inconsistent soil moisture differences compared to levels of ash application. No statistically significant differences were found at the 0.15 to 0.46 m interval, (Figure 18b). Significant increases in soil moisture content were recorded on the unplowed control treatment at the 0.30 to 0.61 m soil depth (Figure 19a) from mid-June to mid-August, with statistically significant increases over all treatments on August 3 and 13. Rainfall recovered the soil moisture in the 10 cm weathered and 15 cm fresh ash treatments on the

August 22 sampling date, showing significantly higher moisture contents than either control treatment. Soil moisture content values at the 0.46 to 0.76 m depth (Figure 19b) showed a statistically significant increase in moisture on the 10 cm weathered ash treatment over either control treatment on July 6. Significantly higher moisture was reported in the unplowed control treatment compared to all other treatments on August 13, and significantly higher moisture content for the 15 cm fresh and 10 cm weathered ash treatments compared to either control treatment on August 22. No statistically significant differences were found at the 0.61 to 0.91 m depth interval (Figure 20).

Volumetric moisture content measurement of Croswell sands at the West Olive site during the 1988 growing season are reported in Figures 21-23. The soil moisture content reflected the extent of the drought conditions over much of the growing season. Soil moisture levels on all treatments recorded much lower values than those of the more normal 1986 season. One particular rainfall event, which occurred on July 15 and can be seen in the 0 to 0.30 and 0.15 to 0.46 m depth soil moisture measurements (Figure 21), was instrumental in sustaining the plants on the drier treatments. Plant growth on the unplowed control treatment was severely reduced compared to the other treatments which may explain the higher soil



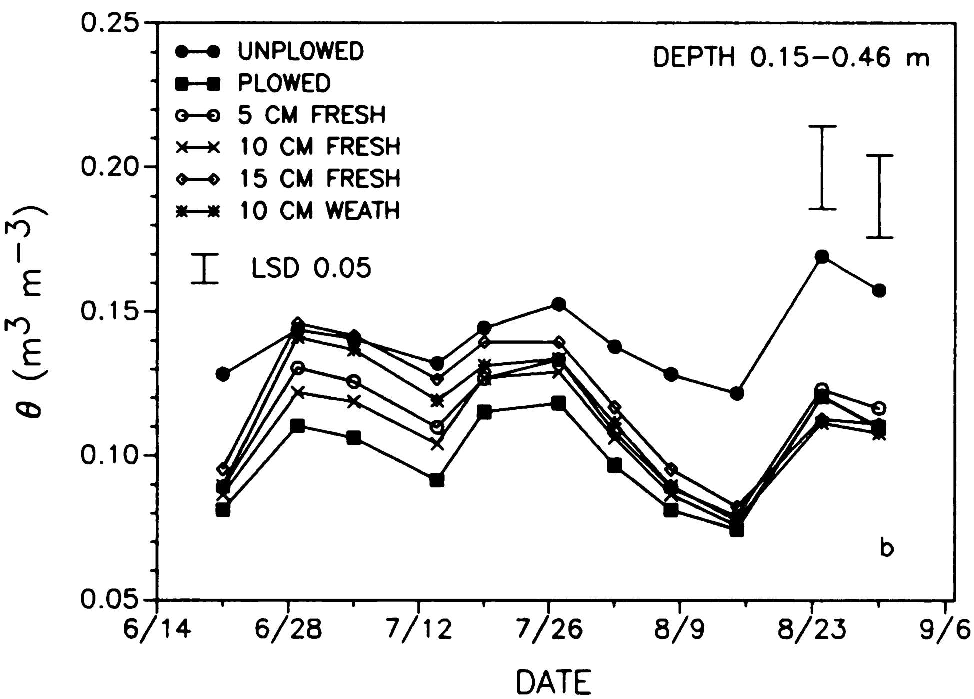


Figure 21. Water content of fly ash modified Croswell sand at the 0-0.30 m (a) and 0.15-0.46 m (b) depths in plots planted to corn during 1988 at the Campbell research site, West Olive MI.

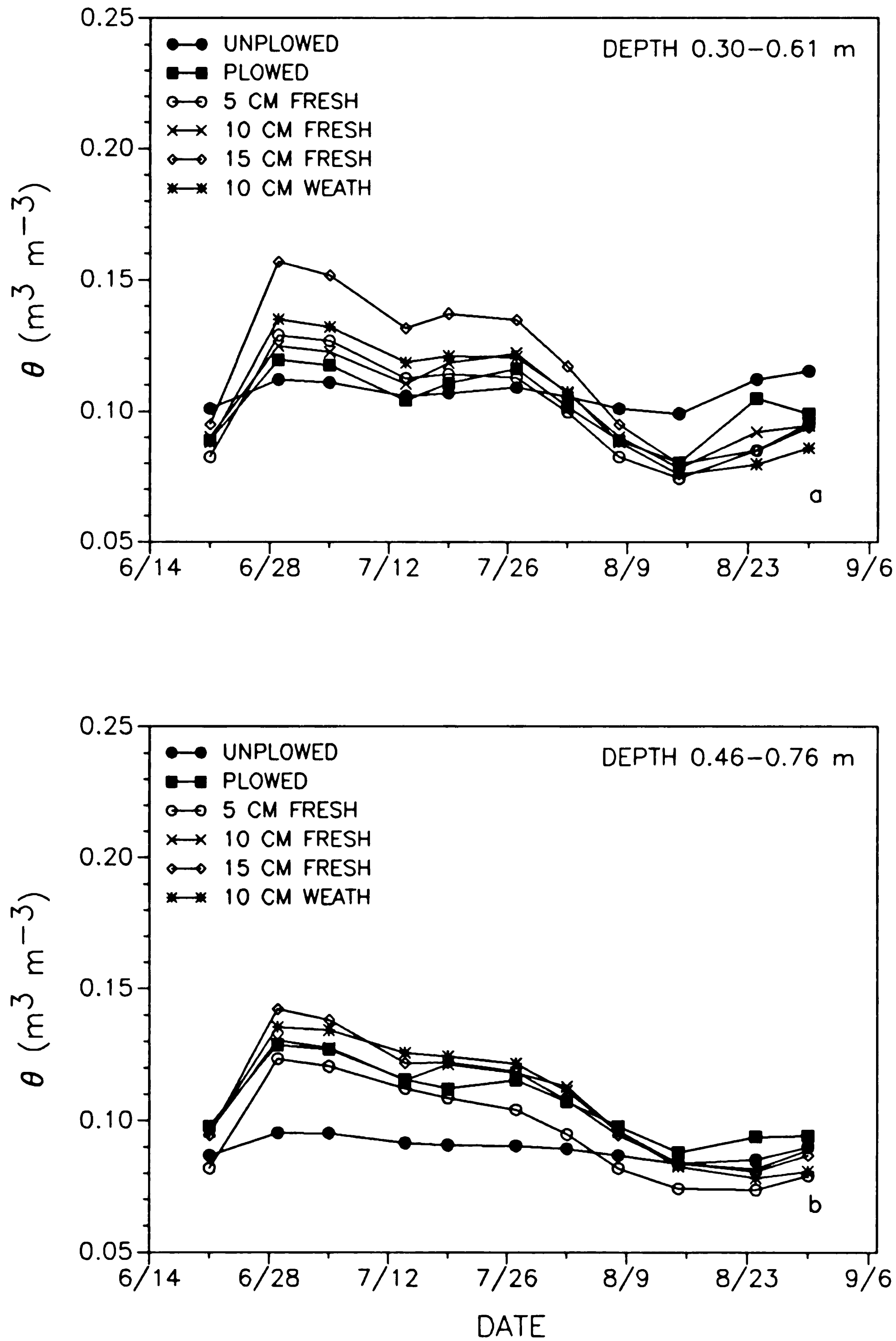


Figure 22. Water content of fly ash modified Croswell sand at the 0.30-0.61 m (a) and 0.46-0.76 m (b) depths in plots planted to corn during 1988 at the Campbell research site, West Olive MI.

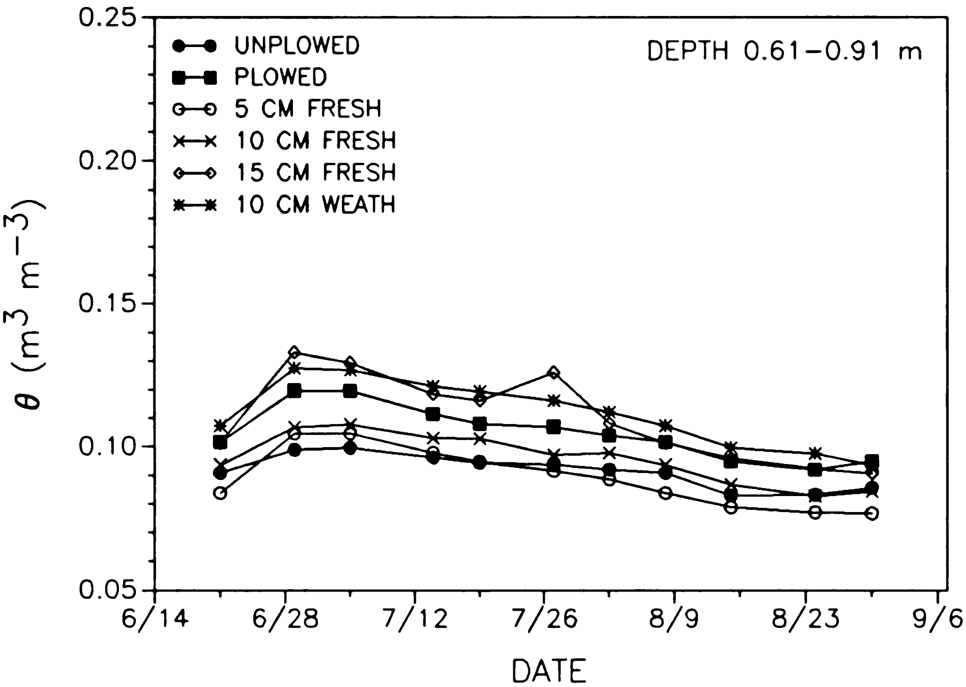


Figure 23. Water content of fly ash modified Croswell sand at the 0.61-0.91 m depth in plots planted to corn during 1988.

moisture content of this treatment in the upper levels of the soil toward the end of the season.

Soil moisture levels for the 0 to 0.30 m depth, given in Figure 21a, show a good deal of separation between treatments compared to the 1986 and 1987 growing seasons. The unplowed control treatment is consistently higher in soil moisture content throughout the growing season, followed by the 15 cm fresh ash treatment, with the plowed control and the 10 cm fresh ash treatment being the lowest. The unplowed control and 15 cm fresh ash treatments were significantly higher in soil moisture than the plowed control and the 10 cm fresh ash treatments on August 24, and the unplowed control was significantly above the same treatments on the last date sampled. Soil moisture levels measured at the 0.15 to 0.46 m depth (Figure 21b) show the same general moisture trends as those of the layer above. All ash treatments showed improved soil moisture as compared to the plowed control treatment, except on August 24. Samples at this depth show a greater separation than all other treatments from the moisture levels of the unplowed control at the end of the season. These are significant during the last two dates sampled.

Moisture content at the 0.30 to 0.61 m depth (Figure 22a) showed the best improvement of soil moisture holding capacity in response to fly ash addition. The highest moisture levels were recorded on the 15 cm fresh ash treatment until August 9, with the lowest moistures on either the control treatments or the 5 cm fresh ash addition. This moisture holding enhancement trend, although not statistically significant, demonstrates the ability of ash modified soils to retain more soil moisture at levels of up to 0.04 $m^3\ m^{-3}$ and maintain this advantage while supporting significantly greater plant growth. Soil moisture contents were improved through the critical corn growth stage of tasseling, completed in early August, under conditions with no significant rainfall during the first two months of the growing season.

Moisture measurements taken at the depth 0.46 to 0.76 m (Figure 22b) show the same general trend for moisture levels. However, the plowed control treatment consistently showed higher moisture levels than either the unplowed control treatment or the 5 cm fresh ash treatment. Separation between the rest of the ash treatments and the plowed control became minimal after July 27. Soil moisture levels were only marginally greater for the plowed control over all treatments on the last two sampling dates.

Volumetric soil moisture data for 0.61 to 0.91 m, given in Figure 23, reflect the same general patterns as the soil sampled in the layers above. The 10 cm weathered and the 15 cm fresh ash treatments are consistently higher than the plowed control through August 1. The plowed control is consistently higher in soil moisture than either the 5 or 10 cm fresh ash treatments or the unplowed control treatment. No statistically significant differences between treatments were measured at this depth.

Plant Growth and Development

The growth and development of corn plants was monitored during the 1987 and 1988 growing seasons at both the Eaton Rapids Cuda and West Olive research sites.

Corn plant heights measured during the 1987 growing season on July 29 and 30, at West Olive and Eaton Rapids, respectively, are reported in Table 1. The plants were measured at tasseling (Vt). Measurements showed a rate response pattern, where the unplowed and plowed control treatments demonstrated significantly reduced plant heights compared to the 15 cm fresh ash treatments at both locations. At West Olive, plant height was significantly increased on the 10 cm weathered and the 15 cm fresh ash treatments compared to the 5 and 10 cm fresh ash treatments. The plowed control treatment posted a significant increase in plant height over the unplowed control at both locations. Plant height on the 15 cm ash treatment in comparison to the plowed and unplowed controls increased by 77% and 26%, respectively, at West Olive and 32% and 16% respectively, at Eaton Rapids.

Table 1. Corn vegetative growth as measured by plant height at West Olive and Eaton Rapids on July 29 and 30, 1987, respectively.

Treatment	Height (cm)	
	W. Olive	E. Rapids
Unplowed Control	122±15	176±5
Plowed Control	171±18	201±8
5 cm Fresh Ash	180±18	212±8
10 cm Fresh Ash	192±9	216±5
15 cm Fresh Ash	216±9	233±6
10 cm Weathered Ash	201±12	---
LSD (0.05)	18	16

Plant growth rates for corn at the Eaton Rapids Cuda site are reported in Figures 24(a,b) and 25. Weekly leaf extension measurements were made from June 28, when the plants were approximately at the fifth leaf stage (V5), through August 5 when the plants had completed tasseling (Vt). The resulting corn plant growth curves formed a rate response pattern with consistently lower vegetative growth on control treatments than on ash treatments. The 15 cm fresh ash treatment had the largest vegetative growth, with statistically significant increases over either control treatment on all dates except the last.

Plant growth rates at the West Olive site are reported in Figures 26(a,b) and 27. Plant growth patterns reveal the same trends in response to fly ash additions as the Eaton Rapids site during 1988. Although significant increases in plant height were not found until the July 13 sampling date, separation between treatments began in early July, with the 10 cm weathered and 15 cm fresh ash treatments consistently showing greater plant growth compared to either of the control treatments. The plowed control treatment retained a growth advantage over the unplowed control throughout most of the growing season. In addition to weekly monitoring of the growth of five individual plants during the 1988 growing season, plant heights and dry matter measurements were taken to determine differences in vegetative growth among

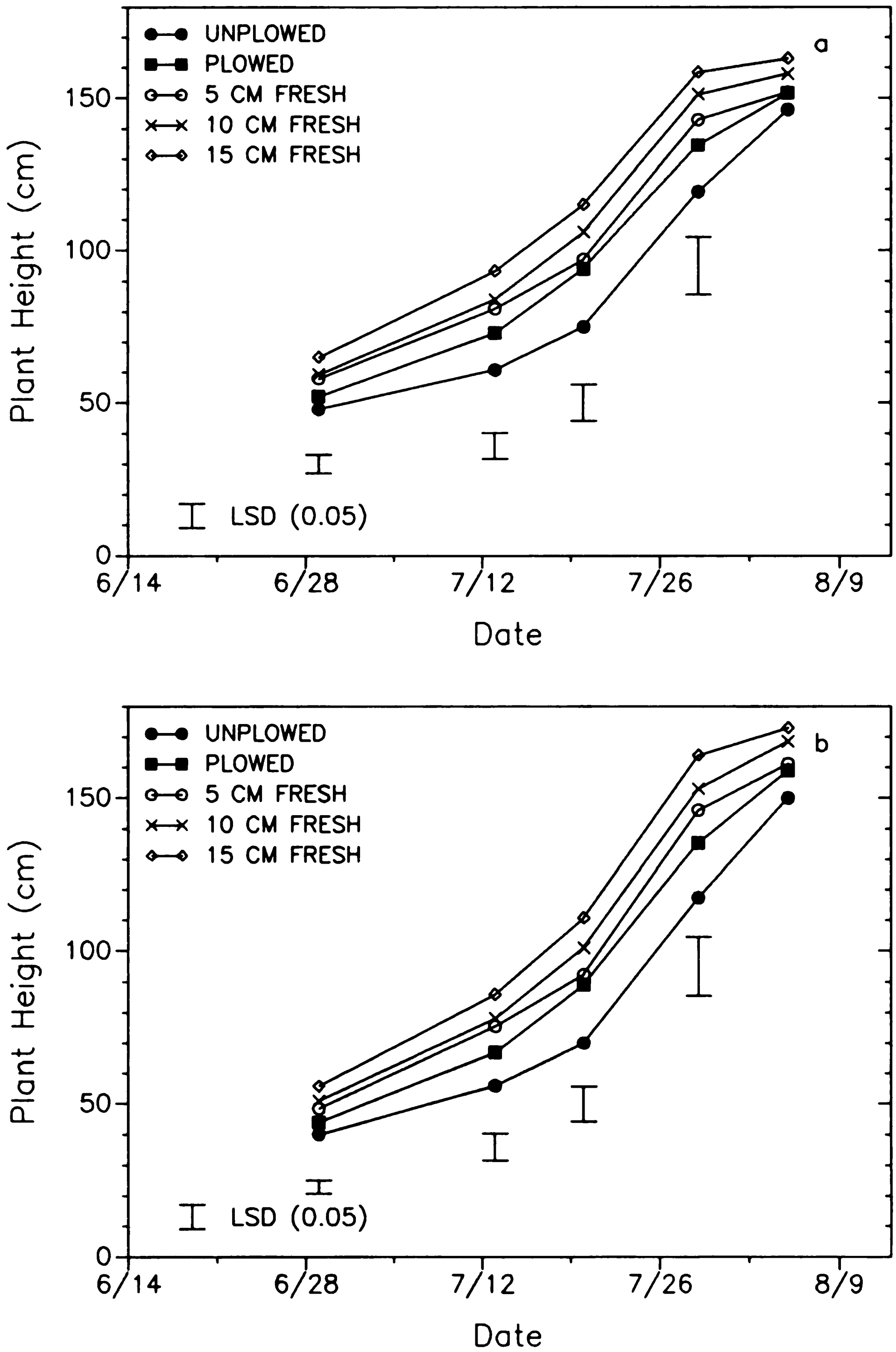


Figure 24. Plant height measurements taken from the third uppermost (a) and second uppermost (b) corn leaves during the 1988 growing season at the Cuda research site, Eaton Rapids MI.

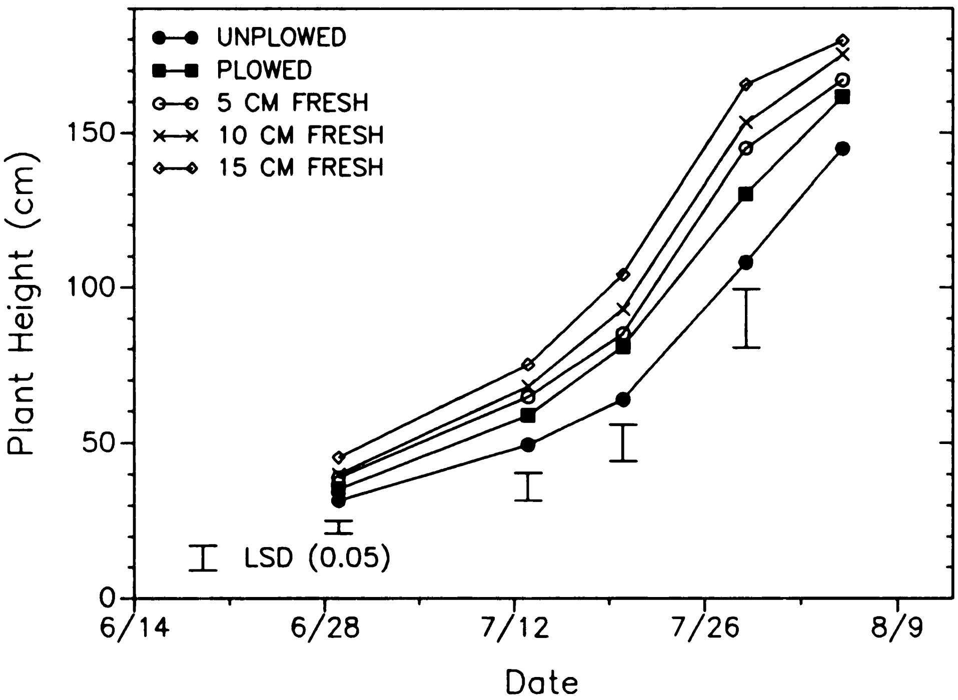


Figure 25. Plant height measurements taken from the uppermost corn leaf during the 1988 growing season at the Cuda research site, Eaton Rapids MI.

treatments.

Corn plant heights measured during 1988 at West Olive are reported in Table 2. Vegetative growth measurements were taken on June 22 and July 19. The July 22 sampling date showed no significant differences between treatments.

The July 19th sampling recorded significantly increased vegetative growth on the 15 cm fresh ash treatment over all treatments except 10 cm weathered ash. This represents a 1.5 fold increase in plant height on the 15 cm fresh ash treatments compared to the unplowed control. Once again, the unplowed control treatments showed significantly reduced corn plant height compared to the plowed control and all of the ash incorporation treatments.

Vegetative growth of corn at Eaton Rapids during 1988 reveals rate response growth patterns with significant increases in plant height early in the growing season. Plant height measurements, taken on June 21, July 18, and August 17 are reported in Table 3. Plant heights show significantly increased plant growth on the 10 and 15 cm fresh ash treatments on the June 21 sampling date. The July 18th measurement showed significantly increased plant height on all ash treatments compared to the controls, and a significant increase on the 15 cm fresh treatment over the 5 cm fresh ash amendment. This represents a 1.5 and 1.4 fold increase in plant height on the 15 cm fresh ash

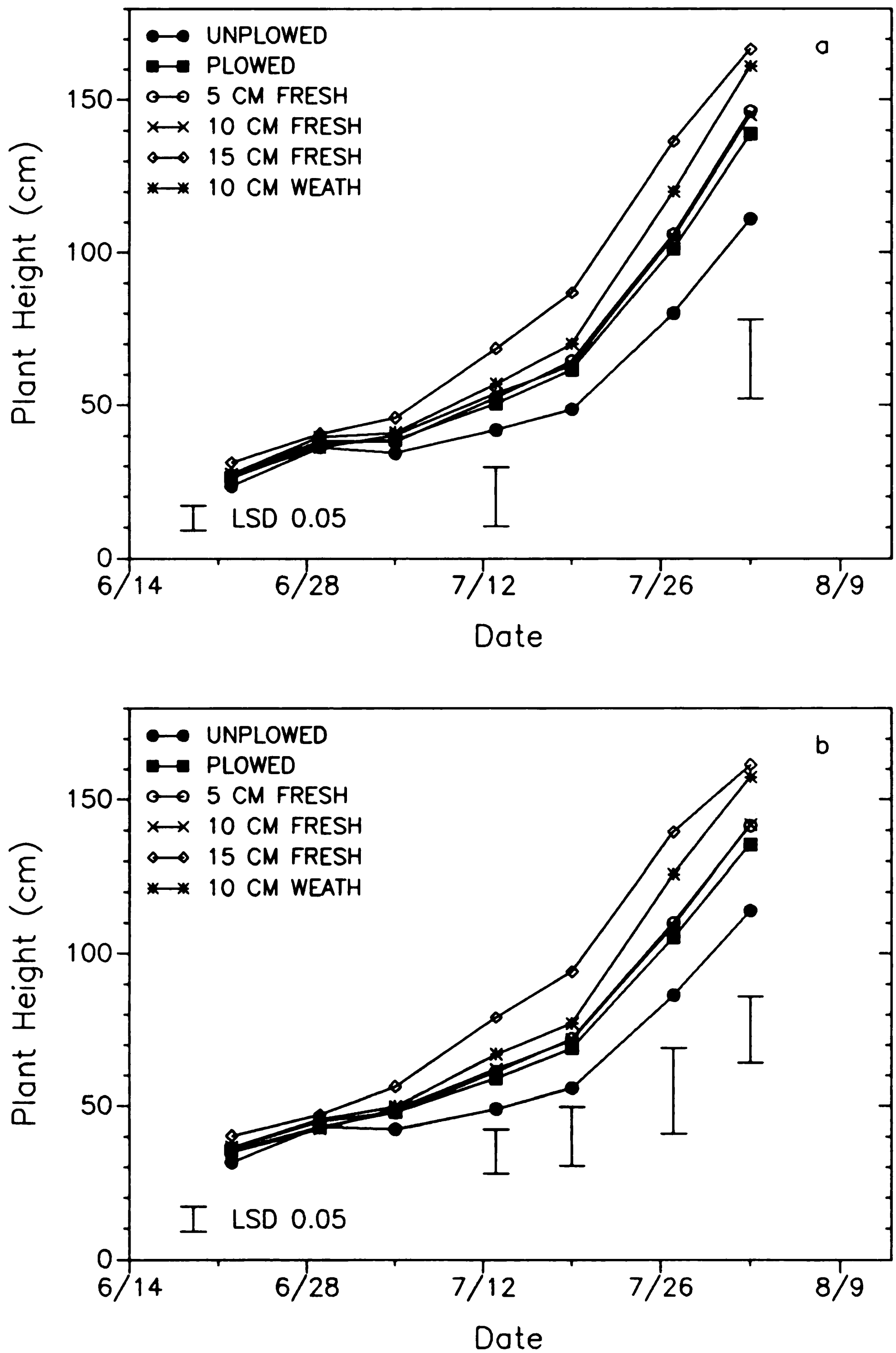


Figure 26. Plant height measurements taken from the third uppermost (a) and second uppermost (b) corn leaves during the 1988 growing season at the Campbell research site, West Olive MI.

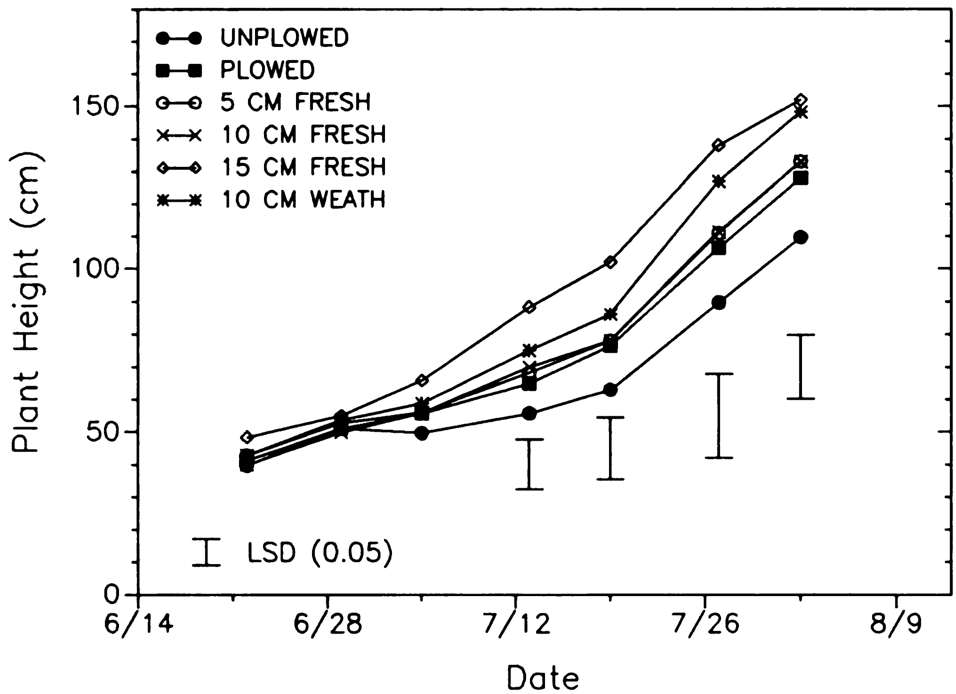


Figure 27. Plant height measurements taken from the uppermost corn leaf during the 1988 growing season at the Campbell research site, West Olive MI.

Table 2. Corn vegetative growth as measured by plant height at West Olive during the 1988 growing season.

Treatment	Height (cm)	
	6/22	7/19
Unplowed Control	18±2	24±5
Plowed Control	21±4	31±5
5 cm Fresh Ash	19±2	31±4
10 cm Fresh Ash	19±2	32±3
15 cm Fresh Ash	24±3	39±4
10 cm Weathered Ash	20±2	34±2
LSD (0.05)	NS	5

treatment compared to the unplowed and plowed control, respectively.

The final measurement, taken on August 17, shows that the differences in plant height between treatments were not statistically significant. This is probably due to the fact that adequate rainfall was received at this site from the latter part of July through September. The difference in height between the shortest treatment, the unplowed control, and the tallest, the 15 cm fresh ash, was only 11 cm.

Plant vegetative growth measured by plant height showed consistant increases on the ash amended soils compared to control treatments. Plant height differences between treatments showed good separation during the growing season but tended to drop below the levels of significance by the final dates sampled. This may have been a function of delayed vegetative growth on the control treatments due to early drought stress conditions.

Plant growth was also monitored by measuring the area of the three uppermost leaves during the early part of the growing season. Figures 28(a,b) and 29 report leaf areas calculated from measurements taken on June 29, July 13, and July 20 during 1988 at the Eaton Rapids Cuda research site.

On the first two measurement dates, leaf area followed a rate response pattern for each leaf measured. The

Table 3. Corn vegetative growth as measured by plant height at the Eaton Rapids Cuda site during the 1988 growing season.

Treatment	Height (cm)		
	6/21	7/18	8/17
Unplowed Control	23±.9	68±4	189±6
Plowed Control	24±6	74±15	185±12
5 cm Fresh Ash	26±2	90±10	190±4
10 cm Fresh Ash	30±.7	98±5	190±6
15 cm Fresh Ash	32±2	105±4	200±13
LSD (0.05)	4	11	NS

smallest leaf area was recorded on the control treatments and the largest on the 15 cm ash treatment. The July 20 measurement shows the unplowed control treatment exceeding the 5 cm ash treatment for all three leaves. The 15 cm ash treatment recorded significantly greater leaf area than either control treatment for the first two sampling dates but was only significantly different from the unplowed control on July 20.

Leaf area measurements taken at West Olive, illustrated in Figures 30(a,b) and 31, show the same rate response pattern to fly ash additions as the Eaton Rapids site. The largest leaf area was measured on the 15 cm fresh ash treatment, with both the unplowed and plowed controls measuring the least. The largest increase in leaf area in response to fly ash incorporation was measured on the third uppermost corn leaf, with less separation between treatments found for the top two leaves measured. The 5 cm fresh fly ash treatment showed little or no increase in leaf area over either of the control treatments. The 10 cm fresh and 10 cm weathered ash treatments showed similar responses, with the third uppermost leaf showing a slight increase for the weathered ash over the fresh.

Leaf area was increased for plants grown on the ash amended soils compared to values measured for plants grown on either control treatment. Increases of leaf area with inceases in moisture content of the soil is consistant

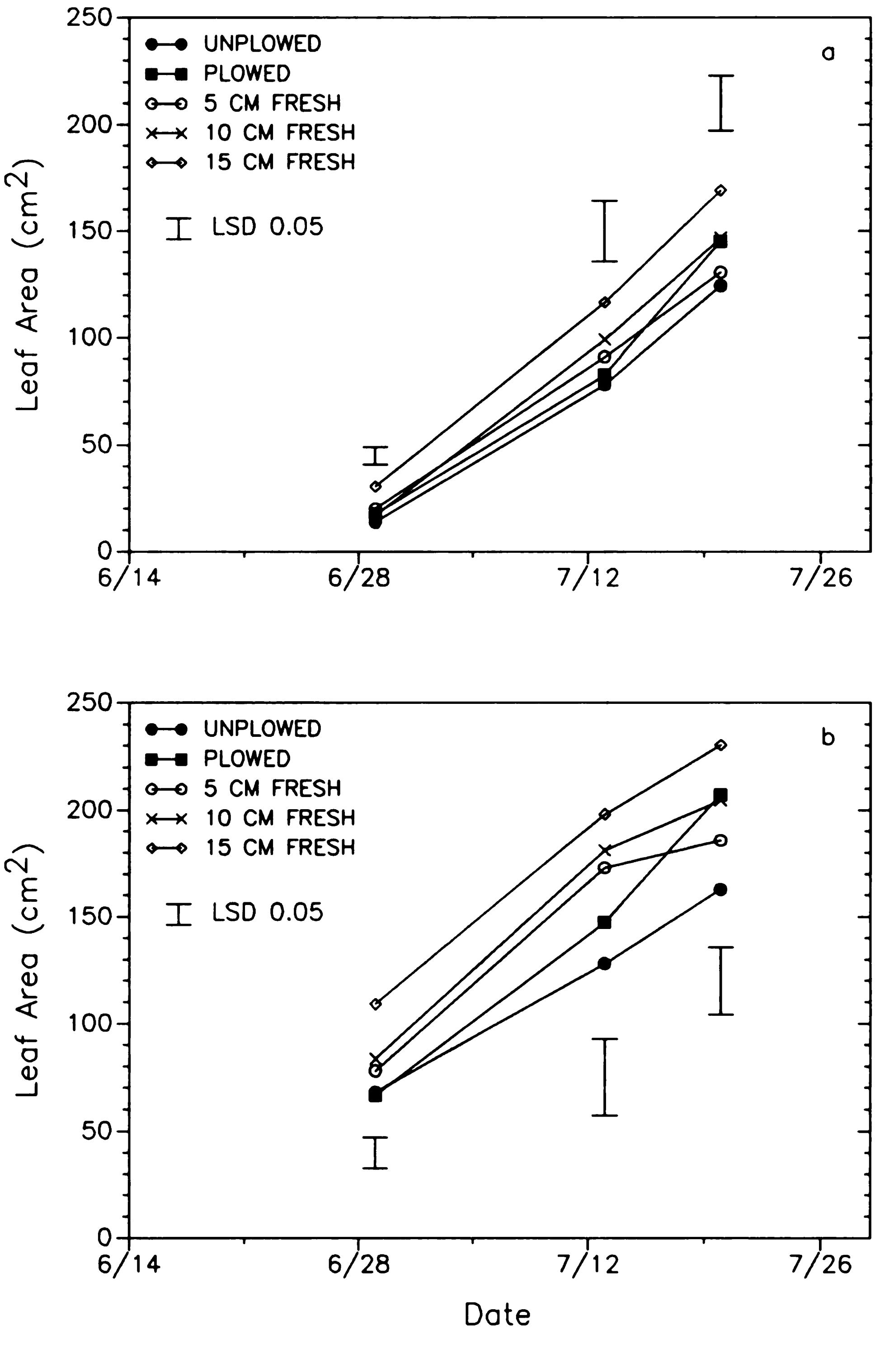


Figure 28. Leaf area measurements taken on the uppermost (a) and second uppermost (b) corn leaves during the 1988 growing season at the Cuda research site, Eaton Rapids MI.

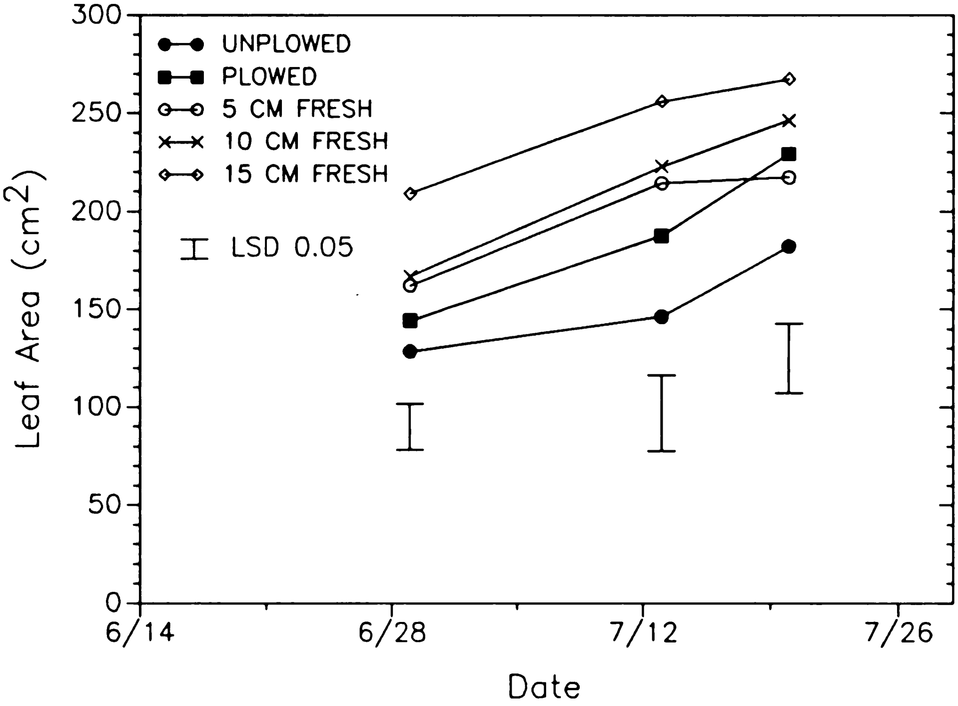


Figure 29. Leaf area measurement of the third uppermost corn leaf during the 1988 growing season at the Cuda research site, Eaton Rapids MI.

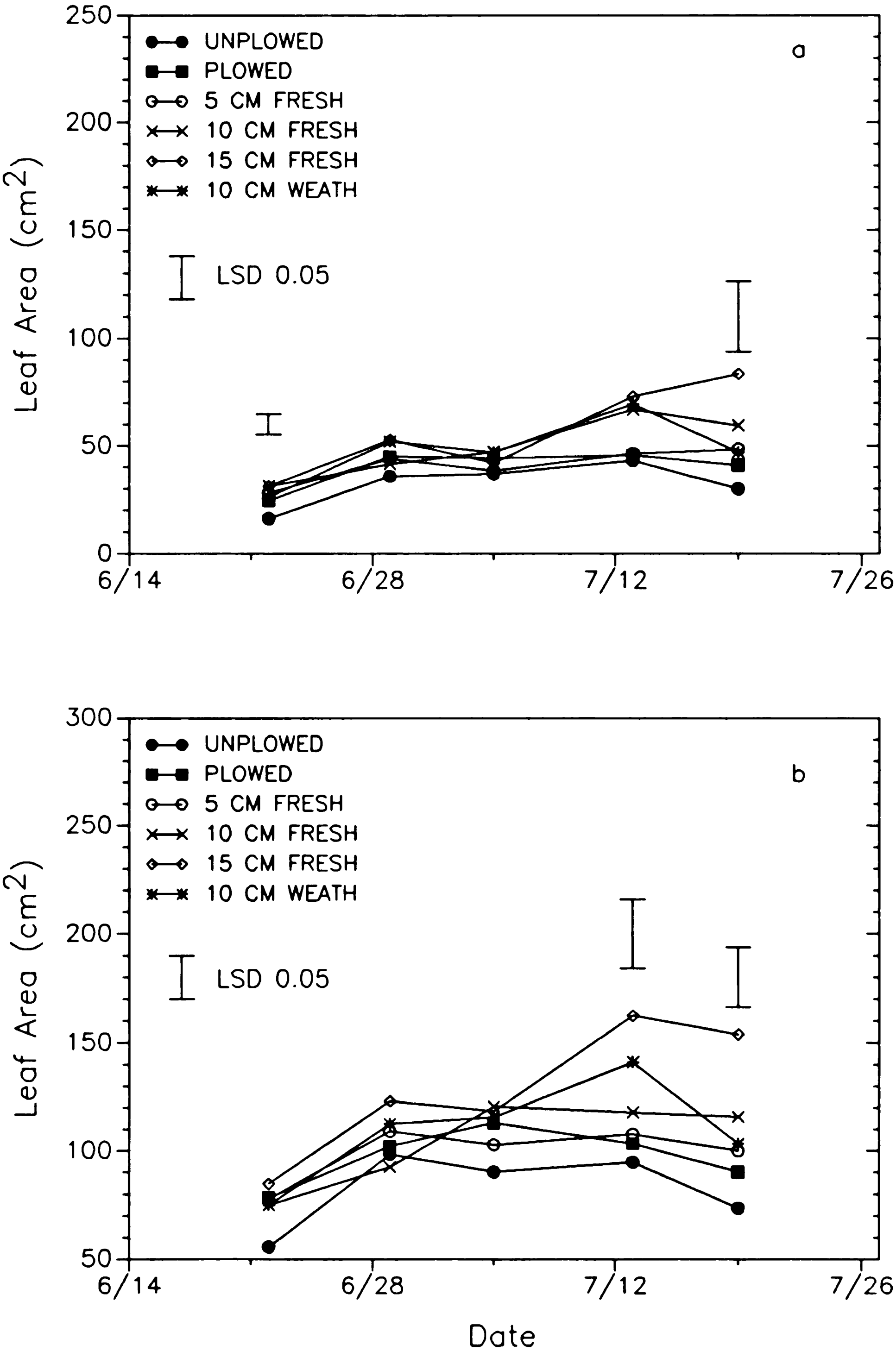


Figure 30. Leaf area measurements taken on the uppermost (a) and second uppermost (b) corn leaves during the 1988 growing season at the Campbell research site, West Olive MI.

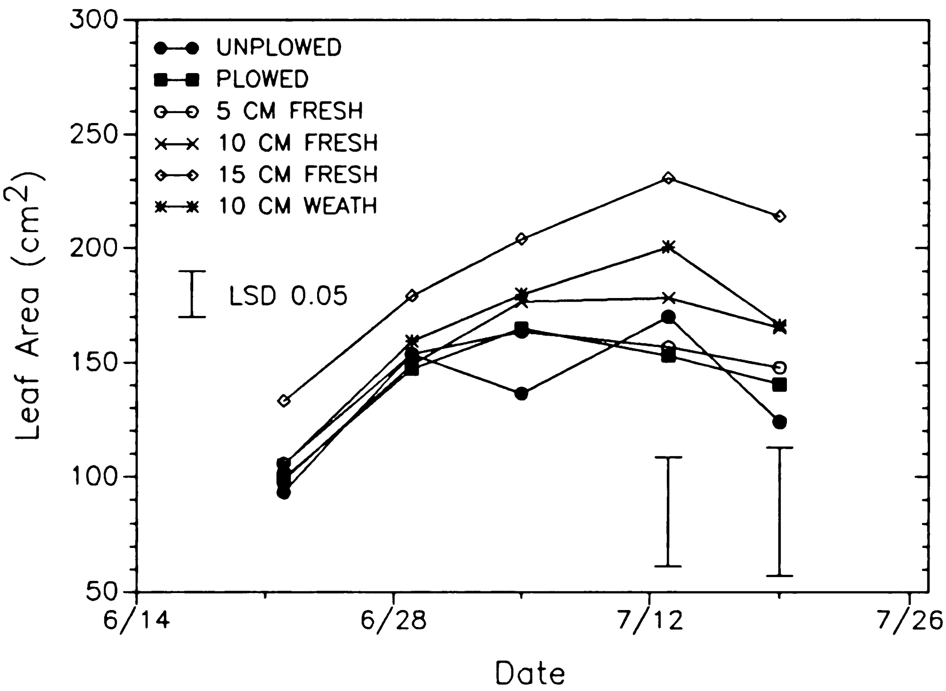


Figure 31. Leaf area measurement of the third uppermost corn leaf during the 1988 growing season at the Campbell research site, West Olive MI.

with leaf area response to drought stress reported by Denmead and Shaw (1960).

Plant vegetative growth differences between treatments were also monitored by the measurement of dry matter content of the above ground portion of the corn plant. Dry matter contents for West Olive during 1988 are reported in Table 4. On the July 19 sampling date, plant dry matter content was significantly increased for all treatments over the unplowed control treatment except the 5 cm fresh ash. The 15 cm fresh ash treatment dry matter content was significantly greater than the dry matter accumulation for all other treatments, showing a 4.5 and 2 fold increase over the unplowed and plowed control treatments, respectively. The August 10 sampling showed the 10 cm weathered ash with the greatest dry matter accumulation per plant, and the unplowed control the lowest. All treatments showed significantly greater dry matter values compared to the unplowed control.

Corn dry matter content at the Eaton Rapids site tend to follow a rate response relationship early in the 1988 growing season. The results of dry matter sampling, taken on June 21, July 18, and August 17, are reported in Table 5. The June 21 dry matter values range from a low of 2.3 g plant^{-1} on the unplowed control to a high of 4.8 g plant^{-1} on the 10 cm fresh ash treatment, with the 15 cm fresh treatment recording a value of 4.7 g plant^{-1}. The

Table 4. Corn vegetative growth as measured by plant dry matter content at West Olive during the 1988 growing season.

Treatment	Dry Matter Weight (g/plant)	
	7/19	8/10
Unplowed Control	5.4±2.6	39.9±3.1
Plowed Control	12.1±4.6	63.8±20.4
5 cm Fresh Ash	10.1±3.0	60.7±14.4
10 cm Fresh Ash	12.7±2.4	70.0±13.9
15 cm Fresh Ash	24.8±4.5	71.8±15.8
10 cm Weathered Ash	14.5±2.7	76.7±20.7
LSD (0.05)	5.4	22.3

Table 5. Corn vegetative growth as measured by plant dry matter content at the Eaton Rapids Cuda site during the 1988 growing season.

Treatment	Dry Matter (g/plant)		
	6/21	7/18	8/17
Unplowed Control	2.3±0.2	8.6±2.4	56.1±3.5
Plowed Control	2.6±0.4	11.2±5.8	62.9±17.8
5 cm Fresh Ash	3.2±0.7	15.8±4.0	61.0±12.1
10 cm Fresh Ash	4.8±1.3	20.7±2.3	67.9±12.3
15 cm Fresh Ash	4.7±1.1	28.2±4.5	75.3±9.6
LSD (0.05)	1.4	5.4	NS

July 18 sampling ranged from 8.6 g plant^{-1} on the unplowed control to 28.2 g plant^{-1} on the 15 cm fresh ash treatment. Although not statistically significant, corn dry matter content of the sampling made on August 17 shows the same general pattern.

Corn Yield Component Measurements

The final measurement of plant height and dry matter content was taken on the same plants monitored for plant growth and leaf area during 1988. Final plant height and dry matter content of these plants are reported in Table 6 for West Olive and Table 7 for the Eaton Rapids Cuda Site.

At West Olive, plant height follows the same pattern as the growth rates. The unplowed control treatment had significantly reduced plant height, 126 cm, compared to all other treatments (Table 6). The 15 cm fresh ash treatment, at 182 cm, recorded significantly greater plant height than either control treatment. The stalk dry weight of corn at West Olive follows the same general pattern, except the unplowed control had a greater average stalk weight per plant than the 5 cm fresh ash treatment. Stalk dry weight comparisons were not significantly different.

Ear dry weight measurements showed a rate response pattern. The highest weights were recorded on the 10 cm weathered ash treatment, 103 g plant^{-1}, followed by the 15 cm fresh ash treatment, 102 g plant^{-1}, in comparison to 30 g plant^{-1} measured on the unplowed control and 70 g plant^{-1} on the plowed control treatments. The unplowed control had significantly lower dry matter ear weight compared to all other treatments, and the 10 cm weathered and the 15 cm fresh ash treatment are significantly higher in ear dry matter content than the plowed control and the 5 cm fresh ash treatments. All ash treatments produced significantly more rows of kernels on corn ears compared to the unplowed control. The reduction in the number of rows of kernels is similar to the results reported by Claassen and Shaw (1970b) in response to drought stress at the time of silking (Claassen and Shaw, 1970b). Increased moisture available for plant use in the ash treatments reduced corn plant moisture stress at this critical period of development.

West Olive ear length measurements showed the same general trend as those of plant height. All treatments showed significant increases in cob length compared to the unplowed control. Ear length was nearly doubled on the 10 and 15 cm ash treatments at West Olive during 1988 compared to the unplowed control. These measurements agree with ear length data reported by Denmead and Shaw (1960), in response to plant moisture stress compared to control treatments.

The number of kernels per row showed the same trend as the ear length measurements. All treatments recorded

Table 6. Corn plant yield component lengths and dry weights from the West Olive research site during the 1988 growing season.

Treatment	Stalk		Ear			
	Weight	Height	Wt.	Rows	Length	Length
	gm/plant[++]	cm	gm/plant[++]	no. of rows[+]	cm	no. of kernels
Unplowed Control	65.7	126	29.3	8	8.9	11
Plowed Control	73.4	155	70.7	10	15.0	23
5 cm Fresh Ash	66.4	160	72.4	11	15.3	22
10 cm Fresh Ash	76.4	159	80.4	12	16.3	26
15 cm Fresh Ash	90.9	182	102.0	11	17.1	29
10 cm Weathered Ash	82.1	176	103.8	12	18.2	33
LSD (0.05)	NS	26	27.1	2	3.3	8

[+] Rows of kernels is expressed as an average number of rows, the number of rows of kernels will be even for any given ear.

[++] Ear and stalk weights expressed as dry weights.

Table 7. Corn plant yield component lengths and dry weights from the Eaton Rapids research site during the 1988 growing season.

Treatment	Stalk		Ear			
	Weight	Height	Wt.	Rows	Length	Length
	gm/plant++	cm	gm/plant++	no. of+ rows	cm	no. of kernels
Unplowed Control	73.1	164	88.9	11	14.5	30
Plowed Control	81.5	184	107.9	12	15.5	32
5 cm Fresh Ash	75.5	186	101.6	12	14.8	30
10 cm Fresh Ash	90.0	194	115.3	12	15.8	32
15 cm Fresh Ash	87.1	200	119.0	13	16.2	33
LSD (0.05)	NS	18	NS	NS	NS	NS

+ Rows of kernels is expressed as an average number of rows, the number of rows of kernels will be even for any given ear.

++ Ear and stalk weights expressed as dry weights.

significantly greater kernel count per row compared to the unplowed control treatment. The 10 cm weathered ash treatment had significantly higher kernel count than either control or the 5 cm fresh ash treatments as well. Kernel number has been shown by many authors to be affected by drought stress.

The Eaton Rapids final plant height, stalk and ear dry matter content measurements, reported in Table 7, though not statistically significant, follow the same general trends as those at West Olive.

<u>Corn Grain Yields and Plant Populations</u>

Fly ash incorporation on Croswell sands at the West Olive research site increased corn grain yields on modified soil compared to the control treatments during each year of the three year field study. Corn grain yields, reported in Table 8, showed that the yield levels of the 15 cm fresh ash treatments were significantly higher than those of the unplowed control. However, the yield increases for all ash treatments were not consistent with the amount of ash incorporated. In 1986, yield depression was recorded on the 10 cm fresh ash treatment, below the yield levels of both the plowed control and the 5 cm fresh ash addition.

Corn yields were exceptionally low during 1986. Ash application and incorporation at the West Olive site was delayed until late May, which forced corn planting into

Table 8. Corn grain yields from the Campbell research site, West Olive, MI, from 1986 through 1988.

Treatment	Yield (Mg ha^{-1})		
	1986	1987	1988
Control			
Unplowed	1.20$\pm$.20	1.30$\pm$.10	0.50$\pm$.20
Plowed	1.50$\pm$.30	3.29$\pm$1.25	1.90$\pm$.95
Ash additions			
5 cm Fresh Ash	1.70$\pm$.30	2.79$\pm$1.04	1.90$\pm$.60
10 cm Fresh Ash	1.45$\pm$.24	3.49$\pm$.54	2.70$\pm$.65
15 cm Fresh Ash	1.80$\pm$.35	4.19$\pm$.95	3.34$\pm$.80
10 cm Weath Ash	1.70$\pm$.45	4.48$\pm$1.0	3.54$\pm$1.05
LSD (0.05)	0.45	1.25	1.15

the first week in June. Also, the ash application process thoroughly disrupted the soil profile, creating excessively loose soil, a less than ideal seed bed. Another possible factor contributing to reduced yields is a lack of adequate soil fertility due to redistribution of the topsoil through the profile. Natural fertility of this soil was low, since the site was cleared of trees just prior to ash application and had not been used agriculturally prior to this experiment.

Another factor possibly contributing to lower yields during 1986 could be related to the water retentive capacity of freshly incorporated ash. Maximum benefit from increased soil moisture retention would be expected on ash modified soils which had been subjected to heavy fall rains and the saturated conditions of early spring. This would allow the ash bands to become fully saturated. Application and incorporation of ash immediately prior to planting is reliant upon substantial rainfall to provide the same moisture holding capacity as that of a pre-established barrier.

Corn yields were again significantly increased by all treatments in comparison to the yield levels of the unplowed control treatments during 1987. Although some increases in yield were recorded for the ash treatments over the level of the plowed control, these were non-significant. Overall yields improved very well in comparison to those recorded during the initial year of the study.

The 1988 field season showed a rate response relationship for treatment yield on fresh ash applications with significant yield increases on all treatments compared to the unplowed control. The plowed control and 5 cm fresh ash treatment yielded the same, with the highest yield of corn grain measured for the 10 cm weathered ash, closely followed by the 15 cm fresh ash treatment. Yield was significantly increased on the 15 cm fresh and 10 cm weathered treatments compared to all other treatments except the 10 cm fresh ash treatment.

Corn grain yield response during 1988 is of particular interest, because of the severe drought conditions which existed through this season. Rainfall patterns added only 75 mm of precipitation over a period from May 1 through July 31, including a single storm in mid July which added over half of this total. This season provided an excellent opportunity to evaluate the effectiveness of the ash modification procedure in periods of prolonged drought stress. Sizable economic increases in corn grain yields were produced on the high ash incorporated treatments in comparison to either control treatment.

There seemed to be a trend for the 10 cm weathered treatments to yield higher than either the 10 cm or the 15 cm fresh ash treatments (Table 8). Corn grain yields were higher in both 1987 and 1988 on the 10 cm weathered ash treatment compared to the 10 cm and 15 cm fresh ash treatments (as well as wheat and sorghum sudangrass yields). While these increases are not statistically significant, they are consistent. Possible explanations could stem from decreases in soluble salt concentrations in the weathered fly ash in comparison to the freshly precipitated ashes. Aside from salinity, higher concentrations of several soluble constituent ions of coal fly ash, such as B and Mo, may have been partially leached from the weathered fly ashes. This could create a situation where a mild toxicity in the fresh ashes may slightly reduce the plant's ability to fully utilize the increased moisture available in the 15 cm fresh ash treatment. It should be pointed out, however, that fresh ash applications, particularly at the higher rates of incorporation, have consistently produced increased corn yields over those of either control treatment during the three years of this field study.

Corn plant population data from 1986 through 1988 from West Olive is reported in Table 9. Although plant populations varied each year, there were no significant differences between treatments during any year of the 3 year study. Since there were no consistent reductions in plant population for any treatment, yield variations were not affected by reduced stand counts.

Table 9. Corn plant populations taken at the Campbell site, West Olive, MI, from 1986 through 1988.

Treatment	Population (10^3 plants ha^{-1})		
	1986	1987	1988
Control			
Unplowed	45.1±1.2	60.7±4.9	61.1±5.1
Plowed	42.6±1.6	58.8±5.7	61.7±3.5
Ash additions			
5 cm Fresh Ash	40.5±3.9	56.3±.10	56.5±11.7
10 cm Fresh Ash	43.4±3.0	61.5±4.2	58.3±5.6
15 cm Fresh Ash	43.8±2.3	58.8±5.2	59.9±4.6
10 cm Weath Ash	44.2±6.7	58.3±1.7	64.2±4.5
LSD (0.05)	NS	NS	NS

Corn was raised at Eaton Rapids in 1985 and 1986 at the Miller Trust site, and from 1986 to 1988 at the Cuda site. Corn grain yields monitored at the Miller Trust site are reported in Table 10. Corn yields showed no particular increase with ash application rate, and in fact, a decrease in yields was shown on the unplowed control, 7.5 cm fresh and 10 cm fresh ash treatments compared to the plowed control and the 5 cm fresh ash applications.

Similar to West Olive, the ash incorporation process continued until the end of May, which delayed corn planting until early June, a less than ideal situation. Again, as at West Olive, the crop was planted in a freshly disturbed, non-moisture equilibrated, soil profile. Due to dry conditions in the spring of 1985, irrigation water was applied soon after planting in an effort to provide enough moisture for wetting the ash in the modified profile. However, this irrigation appeared insufficient to have any beneficial effect.

The 1986 corn grain yields at the Miller Trust site showed improvement from the 1985 yield data. Corn grain yields ranged from 4.49 Mg ha^{-1} on the unplowed control to 6.33 Mg ha^{-1} on the 15 cm fresh ash treatment. Statistically significant increases in corn grain yield were recorded by all ash treatments compared to those of the unplowed control. The yield increase on the 15 cm fresh ash treatment was more than 40%, and 25% higher than

Table 10. Corn grain yields from the Miller Trust and Cuda research sites, located near Eaton Rapids, MI, from 1985 through 1988.

Treatment	Miller site		Cuda site		
	1985	1986	1986	1987	1988
	Yield (Mg ha^{-1})				
Control					
Unplowed	3.34±.30	4.49±.905	4.84±.30	1.75±.30	3.39±.85
Plowed	5.29±.25	4.94±1.05	6.63±.95	2.59±.90	3.94±.75
Ash additions					
5 cm Fresh Ash	4.99±.15	5.74±.90	6.73±1.09	2.59±.35	4.09±1.00
7.5 cm Fresh Ash	3.74±.25	5.94±.65	----	----	----
10 cm Fresh Ash	3.34±.70	6.33±.55	6.68±.70	2.49±.20	4.49±.55
15 cm Fresh Ash+	----	----	6.58±.45	3.24±.09	4.84±.35
LSD (0.05)	0.70	1.25	1.00	0.80	NS

+One replication of this treatment was atypical and was excluded from treatment mean calculations and treated as missing data in statisical analysis.

the unplowed control.

The 1986 corn grain yields at the Cuda site showed no clear trend in treatment response, except for the significant increase in yields on all treatments compared to the unplowed control (Table 10).

Corn grain yields at the Cuda site during 1987 show more separation of the 15 cm ash treatment from the other treatments than in the previous season. Yields ranged from 1.8 Mg ha^{-1} on the unplowed control to 3.2 Mg ha^{-1} on the 15 cm fresh ash treatment. The unplowed control treatment recorded significantly lower yields compared to all other treatments.

Although the 1988 yields were not significantly different from one another, the yield trends indicate a positive rate response to fly ash application. Yields ranged from 3.4 Mg ha^{-1} for the unplowed control to 4.8 Mg ha^{-1} for the 15 cm fresh ash treatment. Fly ash modification on the 15 cm fresh ash treatments enhanced corn grain yield by over 40% compared to the unplowed control treatment, and by more than 20% over those of the plowed controls.

Corn plant populations for the Eaton Rapids field studies are reported in Table 11. Like West Olive, no significant differences between treatments were found on either site, during any year.

Table 11. Corn plant populations from the Miller Trust and Cuda research sites, located near Eaton Rapids, MI, from 1985 through 1988.

Treatment	Miller site		Cuda site		
	1985	1986	1986	1987	1988
	10^3 plants ha^{-1}				
Control					
Unplowed	46.4±3.0	48.7±1.6	47.8±5.0	53.6±4.4	55.3±3.4
Plowed	39.3±3.2	47.6±2.8	50.3±5.8	51.8±2.0	54.7±6.5
Ash additions					
5 cm Fresh Ash	40.5±4.3	54.9±5.4	46.2±0.9	56.4±2.0	65.0±3.3
7.5 cm Fresh Ash	38.7±7.9	51.9±7.8	----	----	----
10 cm Fresh Ash	36.2±10.0	54.0±3.6	50.6±4.1	53.8±4.4	61.1±2.0
15 cm Fresh Ash+	----	----	51.3±5.1	60.4±4.7	61.8±3.4
LSD (0.05)	NS	NS	NS	NS	NS

+One replication of this treatment was atypical and was excluded from treatment mean calculations and treated as missing data in statisical analysis.

Corn Silage Yields

Corn silage yield data, for 1986 and 1988 at West Olive are reported in Tables 12 and 13. No significant differences were found between treatments for any corn silage measurement taken during 1986.

Corn silage yields during 1988 (Table 13) responded positively to increasing levels of fly ash incorporation. Ear dry weights on the fresh ash addition treatments followed a rate response pattern, with the highest ear weight recorded on the 10 cm weathered ash treatment. Ear weights on the 15 cm fresh and 10 cm weathered treatments were significantly increased over those of both control treatments and the 5 cm fresh ash treatment. Ear dry weights on the 15 cm fresh and 10 cm weathered treatments were enhanced over 6 fold from those of the unplowed control treatments and 1.5 fold compared to the plowed control treatments.

Stalk dry weights ranged from 2.2 Mg ha^{-1} on the unplowed control to 3.9 mg ha^{-1} on the 15 cm fresh ash treatments. Significantly higher stalk dry weights were recorded on the 15 cm fresh ash treatments compared to all treatments except the 10 cm weathered ash. Increases in stalk dry weight on the 15 cm fresh ash treatment compared to the unplowed and plowed controls represent a 70% and 40% improvement, respectively, in stalk dry matter yield. Total silage yield values ranged from 3.2 Mg ha^{-1} for the

Table 12. Corn silage yields harvested from the West Olive research site in fall, 1986.

Treatment	Silage[+] Ear wt.	Stalk wt.	Total wt.
	-----	$Mg\ ha^{-1}$	-----
Unplowed Control	3.24	1.85	5.09
Plowed Control	2.81	2.09	4.90
5 cm Fresh Ash	2.65	2.04	4.69
10 cm Fresh Ash	2.65	2.11	4.76
15 cm Fresh Ash	3.42	2.51	5.93
10 cm Weathered Ash	3.09	2.49	5.58
LSD (0.05)	NS	NS	NS

[+] Ear, stalk, and total harvest weights expressed as dry weights.

Table 13. Corn silage yields harvested from the West Olive research site in fall, 1988.

Treatment	Silage[+]		
	Ear wt.	Stalk wt.	Total wt.
	- - - - -	$Mg\ ha^{-1}$	- - - - -
Unplowed Control	0.93	2.23	3.16
Plowed Control	3.25	2.70	5.95
5 cm Fresh Ash	3.28	2.54	5.82
10 cm Fresh Ash	4.46	2.96	7.42
15 cm Fresh Ash	5.68	3.87	9.55
10 cm Weathered Ash	5.71	3.23	8.94
LSD (0.05)	1.48	0.76	2.06

[+] Ear, stalk, and total harvest weights expressed as dry weights.

unplowed control to 9.6 Mg ha^{-1} for the 15 cm fresh ash treatment.

Total silage yields were significantly higher on the 10 cm weathered and the 15 cm fresh ash treatments compared to all other treatments except the 10 cm fresh ash. Total silage yield enhancement on the 15 cm fresh ash treatment compared to the unplowed and plowed control treatments represent over a 3 and 1.5 fold increase, respectively, during 1988.

At the Eaton Rapids Cuda site, ear dry weight, stalk weight, and total silage yields in 1988 were not significantly different between treatments. However, silage yield components do follow a rate response pattern, with the unplowed control treatment consistently yielding the least, and the 15 cm fresh ash treatment the highest, yields.

Wheat Yields at the West Olive Site

Yield data for winter wheat grown during 1986-87 is reported in Table 15. Wheat grain yields were statistically significant and ranged from a low of 0.67 Mg ha^{-1} on the unplowed control treatment to 1.55 Mg ha^{-1} on the 10 cm weathered ash treatment. Although these yields were low, there is a positive treatment effect of increased wheat yield in response to increasing ash incorporation rates. Wheat yields were higher on the 15 cm fresh and 10 cm weathered ash treatments compared to

Table 14. Corn silage yields harvested from the Cuda research site, located near Eaton Rapids, MI, during 1988.

Treatment	Silage[+]		
	Ear wt.	Stalk wt.	Total wt.
	- - - - -	Mg ha^{-1}	- - - - -
Unplowed Control	3.76	2.09	5.85
Plowed Control	4.21	2.03	6.24
5 cm Fresh Ash	4.39	2.35	6.74
10 cm Fresh Ash	4.78	2.55	7.33
15 cm Fresh Ash	5.19	2.54	7.73
LSD (0.05)	NS	NS	NS

[+] Ear, stalk, and total harvest weights expressed as dry weights.

Table 15. Wheat yields at the West Olive site harvested on July 18, 1987.

Treatment	Yield
	$Mg\ ha^{-1}$
Unplowed Control	0.67±0.20
Plowed Control	0.81±0.27
5 cm Fresh Ash	0.81±0.26
10 cm Fresh Ash	1.21±0.34
15 cm Fresh Ash	1.28±0.14
10 cm Weathered Ash	1.55±0.27
LSD (0.05)	0.40

either control treatments and the 5 cm fresh ash treatment. Yield increases on the 10 cm weathered ash compared to the control treatments represent a 2 fold increase. Wheat yields may have been affected by low plant populations due to poor seeding conditions and harsh winter conditions. The wheat was planted in early October during 1986, with apparent adequate growth for overwintering. Evaluation in the spring revealed substantial winter injury, possibly a combined effect of an unusual lack of snowfall and dry surface soil conditions in the Croswell sand.

Soybean Yield at Eaton Rapids Miller Trust Site

Soybean yield differences between treatments were not statistically significant (Table 16). Yield levels did not appear to correlate to ash application rates, with no consistent yield trends visible. The soybean stand in this experiment was very inconsistent, partially due to dry soil conditions at the time of planting. The no-till planter used was unable to adequately penetrate the dry soil surface. Consequently, a substantial portion of the seed was left uncovered or only partially covered, creating a poor stand. Areas harvested were selected from regions in the plots where the soybean population was the highest, however yields still remained low. Ash application rates did not have a detrimental effect on bean yields compared to control treatments where no ash

Table 16. Soybean yields at the Miller Trust site, Eaton Rapids, harvested on October 18, 1987.

Treatment	Yield
	Mg ha^{-1}
Unplowed Control	0.67±0.14
Plowed Control	0.88±0.14
5 cm Fresh Ash	0.67±0.14
7.5 cm Fresh Ash	0.88±0.34
10 cm Fresh Ash	0.94±0.67
LSD (0.05)	NS

was applied.

Sorghum Sudangrass Yield at West Olive

Yield differences in 1988 (Table 17) were statistically significant and followed a rate response relationship for the fresh ash additions. The lowest yields were reported on the unplowed control treatment at 0.9 Mg ha^{-1} and the highest yields on the 10 cm weathered ash addition at 2.1 Mg ha^{-1}. The unplowed control treatment yields were significantly lower than all other treatments. The 10 cm weathered ash treatment yields were significantly higher than the plowed control. Yield enhancement on the 10 cm weathered and 15 cm fresh ash additions represent a 2 fold increase over the yield levels of the unplowed control, and a 27% increase in dry matter production compared to the plowed control treatment.

Bil-Mar Field Demonstration Area

Corn plant growth and dry matter content, measured at tasseling, is given in Table 18. Data from the Bil-Mar farm site, which was a demonstration area rather than a replicated experiment, is given as averages of 4 individual samples per treatment. The site was irrigated at least once a week (when needed) throughout the season by Bil-Mar farm personnel. Average corn plant height was over 40 cm greater on plants raised on the ash modified Rubicon sand as compared to the adjacent control area. Dry matter measurements showed an increase of 46 grams

Table 17. Sorghum sudangrass yields at the West Olive site harvested on August 24, 1988.

Treatment	Yield+
	Mg ha^{-1}
Unplowed Control	0.94±0.23
Plowed Control	1.57±0.27
5 cm Fresh Ash	1.88±0.28
10 cm Fresh Ash	1.90±0.72
15 cm Fresh Ash	2.00±0.16
10 cm Weathered Ash	2.13±0.34
LSD (0.05)	0.53

+ Sorghum sudangrass yield as Mg per hectare dry matter.

$plant^{-1}$ on ash modified soil compared to those of the control areas. This represents a 1.5 fold increase in plant dry matter production and a 1.2 fold increase in plant height on the ash modified soils.

Corn grain and silage yields, reported in Table 19, indicate similar positive plant responses to fly ash modification of Rubicon sands. Corn grain yields were improved dramatically on the ash treated soils, over 2.5 fold, as compared to the untreated control. Corn silage yields were also substantially enhanced with fly ash addition. The ear weight component was enhanced over 2 fold, while the stalk weights were only increased by 15% on the ash treated soils compared to the untreated control areas.

The Bil-Mar demonstration area yield data during the 1988 growing season suggests that there may be potential for improving crop yield performance through fly ash modification when supplemental moisture is applied by irrigation. In years of adequate rainfall, ash modification benefits would be expected to be lower than during years with extended periods of drought. Under irrigation, however, the quantity of water needed to relieve drought stress conditions may be substantially reduced by the modification of the coarse textured soil profiles with coal fly ash. While 1988 was exceptionally dry, which seriously affected the yield of the irrigated

Table 18. Corn vegetative growth at tasseling, (Vt), as measured by plant height and dry matter content at the Bil-Mar farms research site on July 27, 1988.

Treatment[&]	Height	Dry Matter Weight
	cm	g plant^{-1}
Unplowed Control	178±20	88±16
Ash Treatment	221±9	134±25

[&] Values reported are averages of 4 separate measurements taken within treatment areas.

Table 19. Corn silage and grain yields from the Bill-Mar farms research site in fall, 1988.

Treatment [&]	Grain[+]	Silage[++]		
		Ear wt.	Stalk wt.	Total wt.
	Mg ha^{-1}			
Unplowed Control	3.95	3.33	7.08	10.41
Ash Treatment	9.92	8.42	8.18	16.60

[+] Grain yield as Megagrams of #2 yellow corn at 15.5% moisture.

[++] Ear, stalk, and total harvest weights expressed as dry weights.

[&] Values reported are averages of 4 separate measurements taken within treatment areas.

control area, yield levels on the fly ash amended soils under the same irrigation schedule showed impressive increases.

Plant Moisture Stress Measurements

Plant moisture stress was measured over the 1987 and 1988 growing seasons at the West Olive research site. Leaf porometer measurements were taken on both the abaxial (lower) and adaxial (upper) surfaces of the corn leaf by sampling 4 to 5 leaves (both surfaces) from each treatment, then moving to the next treatment to be sampled. Means and standard deviations were calculated upon completion of one cycle of all three treatments. Photosynthetically active radiation (PAR) values measured during 1988 for the upper leaf surface were duplicated in the data tables of both leaf surfaces to serve as a reference of the sunlight intensity at the time of measurement.

The principle measurement of interest in this study was the rate of transpiration. This was to serve as an indicator of differences in plant moisture content between treatments, measured under visible drought stress conditions. The measurement of leaf temperature departure from ambient conditions was also used to compare the extent of drought stress.

Transpiration rates measured from the abaxial leaf surface of corn at the West Olive site during 1987 are reported in Figures 32, 33, and 34. The data from July 29, 1987 (Figure 32) illustrate that plants grown on the 15 cm fresh ash treatments were able to maintain substantially higher transpiration rates during the warmest portion of the day, while the unplowed or plowed control treatments were not able to transpire as rapidly. Measurements taken on July 31, 1987 (Figure 33) shows that transpiration rates are generally higher on the 15 cm fresh ash treatments than on either of the control treatments. Measurements on August 2, 1987 (Figure 34) showed a similar pattern of increased transpiration on the 15 cm fresh ash treatments compared to either control treatment for all sampling intervals except the 1430 hour reading. Rainfall had been inadequate between July 20 to August 20. This period of drought stress was particularly important, because it occurred during the critical period within two weeks of tasseling.

Plant moisture stress measurements made during 1988 are listed in Tables 20 and 21 for the lower and the upper leaf surface, respectively. Although there is variability between plants and sampling times, plants grown on the 15 cm fresh ash treatment show a 2 to 3 fold increase in transpiration over those of the plowed control, and an even greater increase over the transpiration rates of the unplowed control plants. This trend holds true for all sampling dates during the 1988 growing season.

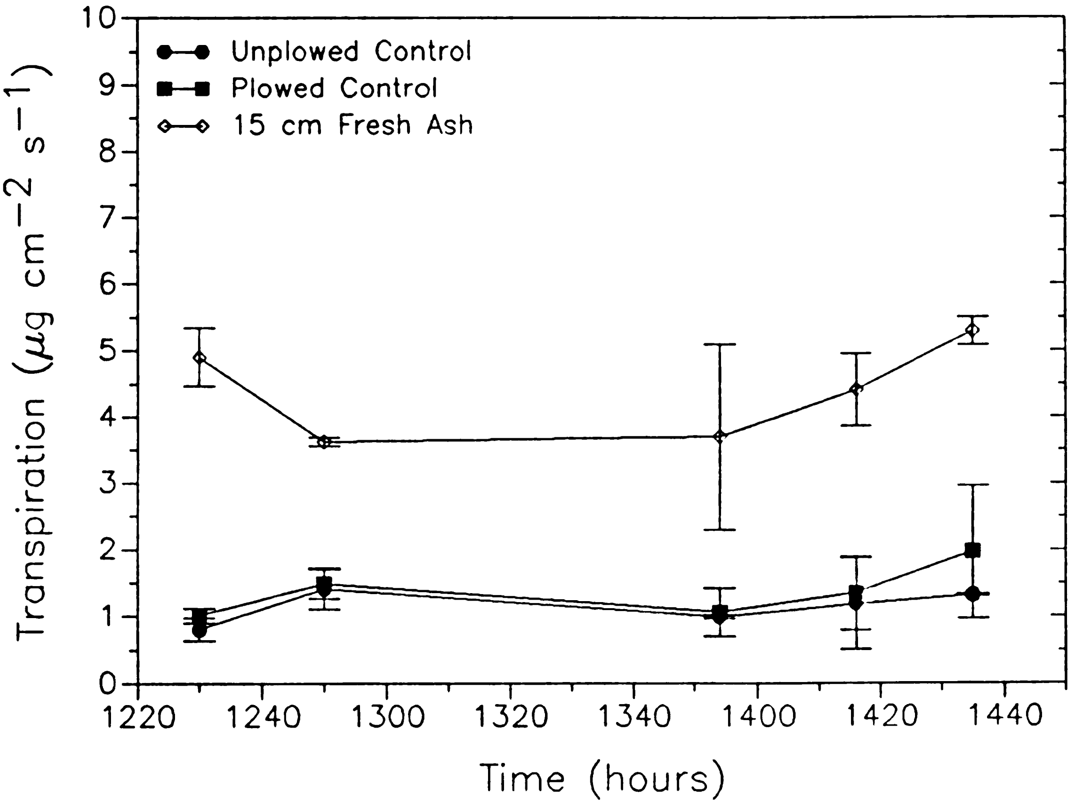


Figure 32. Transpiration rate measured on the lower surface of corn leaves on July 29, 1987 at the Campbell research site, West Olive MI.

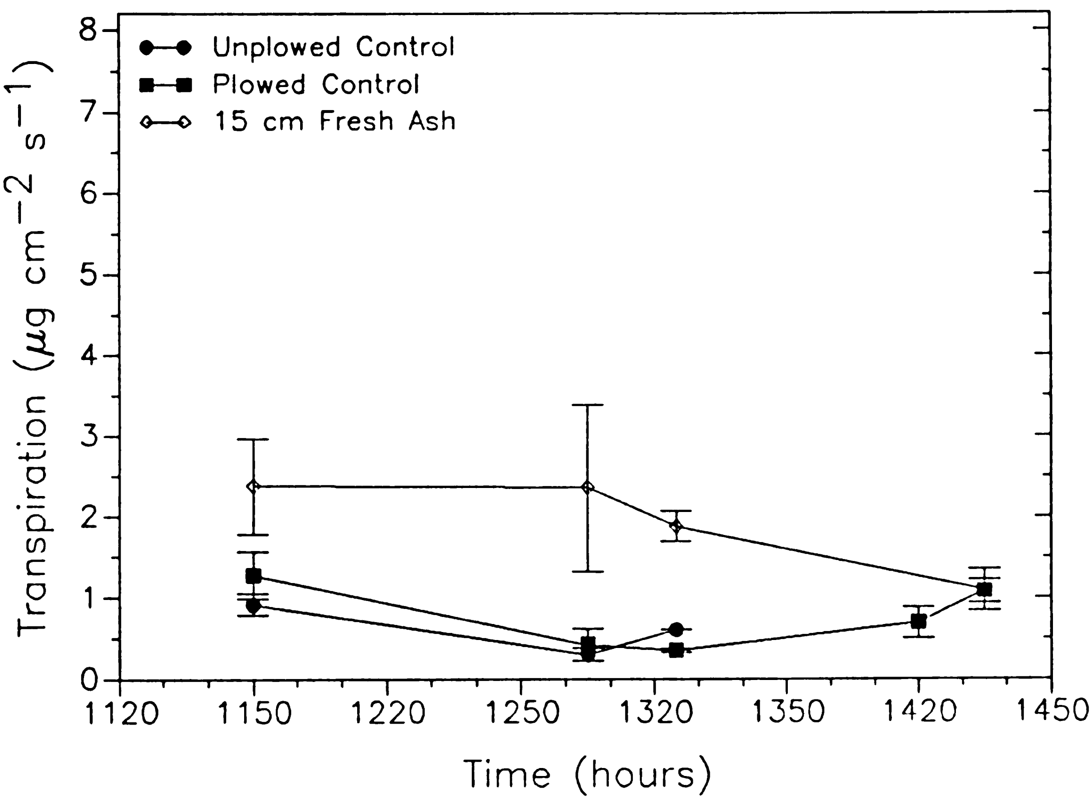


Figure 33. Transpiration rate measured on the lower surface of corn leaves on July 31, 1987 at the Campbell research site, West Olive MI.

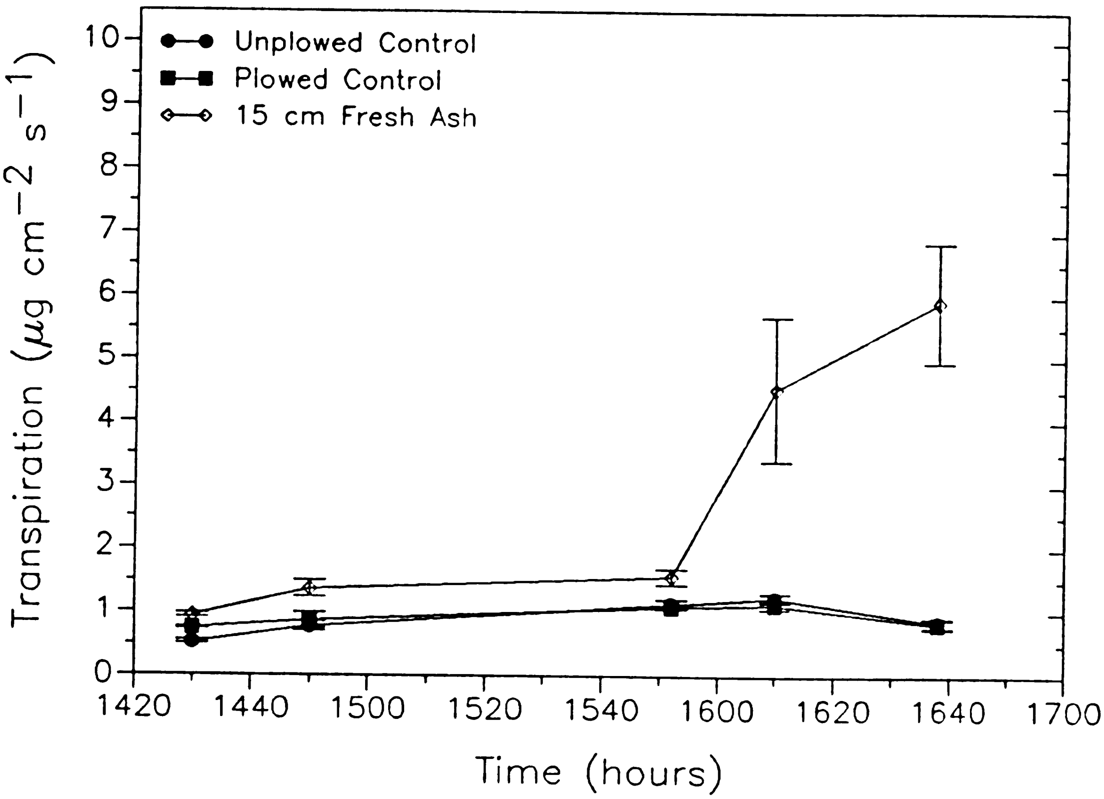


Figure 34. Transpiration rate measured on the lower surface of corn leaves on August 2, 1987 at the Campbell research site, West Olive MI.

Diffusive resistance values measured on both the upper and lower corn leaf surfaces were consistently lower on the 15 cm fresh ash treatment than on either of the control treatments. Diffusive resistance values for lower leaf surfaces showed between a 3 to 4 fold decrease on the 15 cm ash treatment compared to either control treatment. The upper leaf surface recorded a 2 to 3 fold reduction in diffusive resistance as compared to the plowed control, and a 5 to 10 fold advantage over the levels of the unplowed control treatments.

Leaf temperatures on the lower surface of the leaf ranged from 0.08 to 0.27 ^{o}C cooler on the 15 cm fresh ash treatment compared to those of the plowed control treatment and 0.13 to 0.30 ^{o}C cooler than the unplowed control treatment leaf temperatures.

Plant stress measurements reveal the same general pattern for the upper pattern corn leaf surface Transpiration rates ranged from 2 to 4 times greater on the 15 cm ash treatments compared to the plowed control treatments, and from 3 to 12 times higher than the unplowed control transpiration rates.

Increased transpiration, reduced diffusive resistance, and lower leaf temperatures above ambient on the 15 cm fresh ash treatments all show that these plants are consistently under less drought stress than plants grown on the control treatments. Stomates of plants grown on

Table 20. Leaf porometer values measured for the lower leaf surface of corn at the West Olive site during the 1988 growing season.

Treatment	Date	Time	Transpiration	Diffusive Resistance	Leaf Temperature from Ambient	PAR+
			ug cm^{-2} s^{-1}	s cm^{-1}	^oC	uE m^{-2} sec^{-1}
Fresh Ash (15 cm)						
	705	1405	9.90±1.41	2.60±0.49	0.43±.09	1616±19
		1438	11.10±1.23	2.40±0.31	0.63±.05	1630±43
		1508	12.03±0.43	2.20±0.49	0.67±.24	1563±33
	713	1424	8.59±0.92	2.04±0.18	0.55±.05	1720±110
		1515	7.93±0.85	2.08±0.25	0.54±.05	1632±178
	714	1708	12.29±1.04	1.97±0.19	0.15±.05	1445±190
Plowed Control						
	705	1405	2.70±1.14	11.13±3.64	0.60±.07	1673±45
		1438	4.59±1.44	6.68±2.41	0.83±.05	1580±51
		1508	3.62±0.86	8.71±2.61	0.70±.001	1576±25
	713	1424	2.76±0.62	6.44±1.59	0.48±.04	882±109
		1515	3.02±1.09	7.51±3.51	0.80±.09	1710±60
	714	1708	2.84±0.44	9.40±1.93	0.42±.04	1364±103
Unplowed Control						
	705	1405	2.72±0.74	10.88±3.71	0.70±.000	1620±57
		1438	0.42±0.19	84.66±35.97	0.80±.000	1583±79
		1508	1.41±0.64	27.76±12.38	0.70±.000	1516±46
	713	1424	1.84±0.83	12.61±7.16	0.80±.09	1538±143
		1515	1.01±0.16	20.48±3.72	0.96±.05	1656±92
	714	1708	1.86±0.99	18.52±14.07	0.55±.09	1300±127

+ PAR = Photosynthetically Active Radiation.

Table 21. Leaf porometer values measured for the upper leaf surface of corn at the West Olive site during the 1988 growing season.

Treatment	Date	Time	Transpiration	Diffusive Resistance	Leaf Temperature from Ambient	PAR[+]
			$ug\ cm^{-2}\ s^{-1}$	$s\ cm^{-1}$	^oC	$uE\ m^{-2}\ sec^{-1}$
Fresh Ash (15 cm)						
	705	1405	7.22±0.44	3.36±0.17	0.25±.05	1616±19
		1438	5.79±1.15	4.92±1.31	0.47±.05	1630±43
		1508	6.34±2.48	4.95±1.89	0.23±.05	1563±33
	713	1424	5.01±0.44	3.50±0.25	0.35±.05	1720±110
		1515	4.44±0.68	3.84±0.63	0.36±.05	1632±178
	714	1708	6.46±0.61	3.82±0.45	-0.03±.08	1445±190
Plowed Control						
	705	1405	2.25±1.30	17.60±10.3	0.45±.05	1673±45
		1438	1.10±0.79	49.86±40.4	0.61±.07	1580±51
		1508	2.18±0.63	15.03±5.41	0.60±.05	1576±25
	713	1424	3.27±0.84	5.41±1.54	0.43±.04	882±109
		1515	1.39±0.51	17.18±6.10	0.56±.08	1710±60
	714	1708	1.79±0.32	14.72±1.91	0.24±.08	1364±103
Unplowed Control						
	705	1405	1.36±0.57	24.33±11.61	0.57±.09	1620±57
		1438	0.36±0.19	97.86±36.97	0.66±.05	1583±79
		1508	2.31±0.65	13.54±3.37	0.53±.05	1516±46
	713	1424	1.66±0.40	11.20±2.11	0.48±.05	1538±143
		1515	1.39±0.51	16.96±5.96	0.66±.05	1656±92
	714	1708	1.30±0.42	22.98±9.34	0.25±.11	1300±127

[+] PAR = Photosynthetically Active Radiation the 15 cm fresh ash treatment are functioning normally. The more drought stressed plants measured on the control treatments were less capable of transpiring water to reduce the heat load of the plant. These measurements provide evidence that the increased moisture held in the ash modified soil could be utilized to reduce the level of plant drought stress.

Root Length Density Measurement Comparisons

Total root length density (RLD) measurements of corn plants grown in 1988 on the 15 cm fresh ash and the unplowed control treatments are reported in Table 22. The RLD was extraordinarily enhanced by the ash amendment, particularly at the lower depths sampled. Root growth was increased by as much as 10 fold at depths from 45 to 60 cm. Root length density values were enhanced on the 15 cm fresh ash treatment sampled to depths below the zone of ash incorporation. Values were approximately equal in the upper 15 cm, but decreased rapidly at depths below 22.5 cm on the unplowed control treatment.

Root growth increase, in response to fly ash incorporation, shows the corn plant's ability to explore the ash bands, utilizing the increased soil moisture for plant growth and development. One possible explanation for the magnitude of the increase in RLD on the 15 cm fresh ash treatment is the difference in growth and yield of the above ground portion of the plants. The total dry

Table 22. Corn root length density measurements of an unplowed control and a 15 cm fresh ash treatment at the West Olive research site on September 5, 1988.

Upper Value .... 15 cm fresh ash   Lower Value .... unplowed control

Depth (cm)	Distance from Plant (cm) Units = cm cm^{-3}					
	25-37.5 W	12.5-25 W	0-12.5 W	0-12.5 E	12.5-25 E	25-37.5 E
0-7.5	.165	.510	.367	.335	.363	.056
	.133	.449	.521	.338	.508	.936
7.5-15.0	.313	.714	.237	.256	.551	.902
	.483	.097	.236	.287	.328	.441
15.0-22.5	.742	.433	.316	.503	.292	1.440
	.082	.122	.040	.126	.061	.057
22.5-30.0	.952	.671	.626	.787	.366	1.481
	.069	.063	.031	.092	.147	.039
30.0-37.5	.593	.656	.525	.611	.653	.492
	.089	.053	.063	.080	.047	.041
37.5-45.0	.552	.884	1.760	.751	.898	.939
	.051	.052	.042	.044	.024	.040
45.0-52.5	.430	.724	1.003	.454	.284	.739
	.037	.032	.052	.031	.024	.022
52.5-60.0	.466	.831	1.050	1.161	.659	.761
	.052	.011	.031	.034	.023	.021
60.0-67.5	.139	.069	.094	.048	.011	.018
	.021	.031	.020	.017	.015	.009

matter production on the 15 cm fresh ash treatments, as measured by corn silage dry matter yields, represents a greater than 2.5 fold increase over that of the unplowed control treatment. Plant vegetative growth rates monitored through tasseling, (Vt), indicate impaired growth on the unplowed control treatments compared to those of the 15 cm fresh ash. Plant moisture stress measurement also indicated that transpiration rates were consistently higher, and that leaf temperature above ambient conditions, were consistently lower, for plants grown on the 15 cm fresh ash modified soil in compared to plants grown on the unplowed control treatment.

Root growth measured by RLD for the individual ash and sand components of the 15 cm fresh ash treatment are given in Table 23. Samples reported in this table were taken from 22.5 cm to 60 cm deep, where accurate separations of the ash and sand components could be made. The RLD values were generally higher in the ash band samples compared to those of the sand between bands. Higher ash fraction RLD values occurred on 21 of the possible 29 comparisons (one 22.7 to 30.0 cm sample contained no ash, marked N/A). The average combined RLD for all depths and distances from the plant was 0.35 cm cm^{-3} in the ash fraction and 0.21 cm cm^{-3} in the sand fraction, showing a preferential disposition for growth in the ash. While some ash samples showed large increases in RLD compared to the sand fraction at

Table 23. Corn root length density values measured in the ash and sand fractions of a 15 cm fresh ash treatment at West Olive on September 5, 1988.

Upper Value .... Ash fraction   Lower Value .... Sand fraction

Depth (cm)	Distance from Plant (cm) Units = $cm\ cm^{-3}$					
	25-37.5 W	12.5-25 W	0-12.5 W	0-12.5 E	12.5-25 E	25-37.5 E
22.5-30.0	.164	.344	.246	.454	N/A+	1.206
	.473	.226	.216	.064	.131	.048
30.0-37.5	.177	.488	.239	.354	.260	.188
	.234	.165	.104	.147	.168	.190
37.5-45.0	.179	.500	1.371	.194	.298	.390
	.242	.149	.215	.146	.296	.154
45.0-52.5	.175	.419	.178	.204	.164	.329
	.141	.206	.686	.139	.120	.181
52.5-60.0	.096	.525	.453	.200	.141	.204
	.120	.134	.285	.533	.246	.246

N/A+ = no separable ash band was present in this sample.

Note: Measurements of Root Length Density (RLD) were taken from 0 to 67.5 cm deep. RLD values for the layers sampled at depths between 0 to 22.5 and 60 to 67.5 cm were ommitted because they did not contain separable ash fractions.

the same layer and others only small increases, roots were able to fully penetrate and explore the ash bands in a modified profile.

SUMMARY AND CONCLUSIONS

The moisture release curves of the Croswell sand, Boyer loamy sand, and fly ash show an increase in soil moisture for the fly ash at the 100 kPa matric suction level by a factor of three over the Croswell sand and two over the Boyer loamy sands. Since the fly ash has a 1500 kPa matric suction moisture content of 0.02 $m^3\ m^{-3}$, a large portion of this moisture is plant available. If fly ash can be incorporated into the soil profile in a concentrated band, the moisture release characteristics of this band should more closely resemble pure fly ash rather than a mixture of ash and soil.

Once the ash has been incorporated into the soil profile, it should act similarly to other soils which contain layer(s) of different textures. Textural differences in layered soils lead to modified water infiltration rates as compared to uniform soil profile. Miller and Gardener (1962), when looking at the effects of thin layers of different texture sandwiched within an otherwise uniform profile, reported that while matric suction and hydraulic head in any conducting soil must be continuous throughout the profile, abrupt discontinuities in wetness and conductivity may occur at the interlayer boundaries.

Typically, research involving soil moisture infiltration through two distinct texture layers deals with horizontal layer configurations. When coarse textured soils with greater saturated hydraulic conductivity overlie a less conductive, finer textured layer, the overall infiltration rate of the profile becomes that of the least conductive layer. If the infiltration rate through the coarse textured upper layer is large enough, a perched layer of free water may form above the boundary. However, when a finer textured upper layer overlies a coarse textured horizon, subsequent movement of soil moisture into the lower layer is dependent upon the existance of enough positive head to allow water to penetrate the larger pore sizes of the soil below.

While the fly ash incorporation procedure does not produce a continuous horizontal layer in the soil, it does create a similar situation where two distinctly different textures are encountered in downward flow. A perched water table would not be expected to develop in ash modified soils due to drainage potential between ash bands.

Infiltration and recharge of soil moisture into the ash band is most likely to occur during times when the soil is very wet or saturated. In Michigan, these conditions generally occur after snow-melt and during heavy spring rains. As the soil drains and dries, especially on very coarse textured soils such as Croswell sand, the large difference in pore sizes between the fly ash and the sand will cause a disruption of water flow out of the ash band. This break in continuity allows the fly ash to maintain a reservoir of soil moisture which can be readily used by plants.

The banded configuration of ash in the soil would be expected to be efficient in increasing available soil moisture. However, to receive maximum benefit, plant roots must be able to penetrate and explore the ash layer. Soluble salt concentrations, and potentially high levels of boron, were thought to be possible deterrents for root growth within the ash band. Root sampling has shown, however, that corn plant roots are able to grow within this material.

Soil moisture measurements have shown increased moisture content with fly ash modification of the profile. Gravimetric measurement has shown that even during 1988, the driest year of the three year study, fly ash band materials contained vastly more water than either the organic topsoil band in the plowed control or the unplowed control. The moisture content of the soil between the ash bands showed no increase as compared to the control treatments. Volumetric moisture determination using a neutron hydroprobe showed consistent results during the 1986 season, but found less differences between treatments during the drier years of 1987 and 1988. Typically, either the 0.15-0.46 m or the 0.30-0.61 m depth showed an increase in soil moisture for the high ash application rates as compared to the other treatments.

One possible explanation for the less definite measurement as compared to the results from the gravimetric sampling is the lack of resolution with the neutron probe. Measurement is made of a spherical shaped region around the probe, integrating soil moisture over the entire area measured. Hillel (1982) suggests one of the key drawbacks to use of the neutron scattering method is a low degree of spatial resolution. Since the access tubes are placed in the soil at random, the depth at which an individual tube may encounter a fly ash band is unknown. Cassel and Nelson (1985) describes the spatial variability associated with tillage as a function of vertical and lateral changes in soil texture, structure, and organic matter which change soil physical properties in relation to bulk density and mechanical impedance measurement. The same problems with spatial variability would be expected to exist with the incorporation of ash in bands throughout the soil profile.

Corn vegetative growth was substantially increased at the higher levels of fly ash incorporation. The largest seperation between treatments were recorded during the middle of the growing season. Corn leaf area measurement revealed beneficial increases on fly ash modified soils, particularly at the Eaton Rapids site, where measurements showed consistent increase in the area of all three leaves on the 15 cm fresh ash treatment. The West Olive site measurements recorded good increases in leaf area on the third uppermost leaf, but showed less separation for the two uppermost leaves on during the three earliest dates sampled.

Corn grain and silage yields have shown consistent, as well as statistically significant, increases on high ash modified treatments over those of the controls. Corn yields were enhanced by ash application in all years following the first year of ash application, and only showed reduced yields in response to ash application during 1985, the first growing season after ash application at the Miller Trust site. This may have been caused by such factors as lack of rainfall to fully moisten the modified profile before the time of planting and ash remaining on the soil surface reducing germination and seedling growth. Substantial increases in corn grain and silage yield recorded at the West Olive location during the extremely dry year of 1988 were particularly impressive. Although not statistically significant, the 1988 yield trends of corn grain at the Eaton Rapids site, which received adequate rainfall in the late July through September period showed good increases over the control treatments.

Some enhancements in yields were recorded by the plowed control treatments over those of the unplowed control throughout the period of the three year study. This suggests that a beneficial tillage effect created by deep plowing Croswell sand and Boyer loamy sand exists, and apparently can persist for a good deal of time. One possible explanation could be that the loosening effect of the deep tillage is persisting longer than anticipated. Increases in crop yields could not be explained by increased moisture retention of the banded A horizon in the plowed control treatment.

Another consistent trend involving corn grain yields, and essentially all yields recorded except those for corn silage at the West Olive site, is the enhancement of yields on the 10 cm weathered ash treatment over the levels of the 15 cm fresh ash. This trend occurred in spite of an increased soil moisture advantage on the 15 cm fresh ash treatments. A possible explanation for this may be that the fresh ashes contain higher soluble salt or B concentrations, which could reduce plant growth, than the weathered material. Adriano et al (1980) reported that the weathering of fly ash in storage lagoons can stabilize pH as well as precipitate soluble minerals which can minimize impact of ash application to soils on plant growth.

Ordinarily, the nutrient blamed for crop growth and yield reduction in fly ash amended soils is B. While most coal fly ashes are high in B content, it would be expected to be partially removed from the ash by decant waters during the sluicing process. Although a negative effect due to a high B concentration may somewhat reduce the efficiency of the plant to extract the increased soil moisture on the 15 cm fresh ash treatment, yields were only marginally, and never statistically, lower than the 10 cm weathered ash treatments. The ability of the corn roots to penetrate and explore the ash bands, on an equal or slightly preferential basis than the surrounding sand, indicates that a toxicity affecting plant growth is not a problem for corn.

Irrigated corn yields at the Bil-Mar Farms research site show potential for increasing water use efficiency in corn production on ash modified soils. While this site was a large scale demonstration area and not a replicated experiment, a greater than 2 fold increase in average corn grain yield for the ash treated soils compared to the unmodified controls illustrate the possible benefits.

Wheat at West Olive (1987), soybeans at Eaton Rapids (1987),and sorghum sudangrass at West Olive (1988), were used to compare the effects of fly ash incorporation on crops other than corn. Wheat and sorghum sudangrass both showed statistically significant increases with ash application over control treatments. Soybeans, planted during a dry period in the spring of 1987, lacked an adequate stand for a good evaluation. However, soybean yields were not reduced by increasing levels of ash incorporation.

Plant moisture stress in corn was evaluated primarily by transpiration rate measurements taken during periods of visible drought symptoms. Consistently higher transpiration values were found on the 15 cm fresh ash treatment than on either control treatment during 1988. Leaf porometer measurements revealed consistently lower diffusive resistance values on the the 15 cm fresh ash treatments than on either of the controls. The average leaf temperature deviation from ambient conditions was also lower on the high ash amendments compared to either control treatment. The increase in transpiration rate, along with the associated drop in diffusive resistance, provides evidence that the increased soil moisture on the 15 cm fresh ash treatments was utilized by the plants to combat the effects of drought.

This is particularly impressive when comparing the plant heights and dry matter weights between treatments during mid-July when transpiration was measured. Plant height of the 15 cm fresh ash treatments were 15 cm greater than the unplowed and 8 cm larger than the plowed control treatments. Dry matter content on the 15 cm fresh ash treatment was double that of the plowed control, and increased 4 fold over the content of the unplowed control treatment. Both the plant height and dry weight measurements were increased significantly over either control treatment.

And, finally, the RLD information illustrated that corn roots were capable of penetrating and exploring the ash bands completely. The concentration of roots within the ash fraction was greater than those found in the sandy material between the bands. This measurement showed that the fly ash bands within the soil, which were expected to be higher in soluble salt and Boron content, did not create an environment restrictive to root growth. Since the band configuration provides improved soil moisture holding capacity, and is the natural result of incorporation with a giant disk plow, root exploration of the fly ash material is essential for maximum benefit.

Fly ash incorporation into coarse textured soils to improve the water holding capacity had previously shown some success. Although the concept has been tried with large percentage additions of fly ash to soils (Salter et al, 1971; Chang et al, 1977), these incorporations were designed to be a homogeneous mixture with the soil. Even with available water holding capacity increased by as much as 93% at high rates of ash incorporation (up to 753 t ha^{-1}), Salter reported little positive effect on the yields of the crops tested. Chang reported that while ash applications above 25% did increase soil moisture retention at 20 centibars, the availability for plant uptake of this increased soil moisture between 10 and 80 centibars was minimal. The increased availability of soil moisture for the system described in this paper was dependent upon the integrity of the ash band. This process has been successful in physically improving moisture retention and increasing plant productivity of ash modified coarse textured soils.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Coal fly ash can be incorporated into a sand soil with giant disk plow, creating a series of parallel bands in the soil profile.

2. These bands are capable of holding increased moisture compared to the surrounding soil.

3. Corn plant roots are capable of fully exploring the fly ash band within the soil.

4. Corn drought stress, as measured by transpiration rate, diffusive resistance, and leaf temperature above ambient conditions was reduced on Croswell sand modified by the 15 cm ash incorporation rate.

5. Corn plants were able to utilize this increased soil moisture, producing increased vegetative growth and higher yields.

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