AN ABSTRACT OF THE THESIS OF

William Fred Schillinger for the degree of Doctor of Philosophy

in Crop and Soil Science presented on April 6, 1992

Title: Fallow Water Retention and Wheat Growth as Affected by Tillage Method and Surface Soil Compaction

Abstract approved: Redacted for Privacy

Floyd E. Bolton

No-tillage winter wheat (Triticum aestivum L.) grown in a wheat-fallow cropping system has consistently produced lower grain yields than conventionally tilled soils in the semiarid Pacific Northwest. A 2-year study was conducted in a long-term tillage trial at Moro, OR to determine factors responsible for differences in wheat growth and yield as affected by moldboard plow, stubble mulch, and no-tillage fallow method. Soil water, soil mineral N, plant N uptake, soil temperature, above-ground dry matter accumulation, and yield components were measured.

The highest fallow efficiency during both years was achieved by stubble mulch tillage, followed by the plow and no-tillage systems. Accelerated water loss from no-tillage fallow occurred during the hot, dry summer due to uninterrupted capillary flow. The main yield limitations to no-tillage technology in this study were: (1) diminished seedzone water at planting time in the fall which resulted in reduced germination and stand establishment; (2) cooler spring soil temperatures which slowed crop development and dry matter accumulation, and; (3) production of fewer spikes per unit area.

The second objective of this study was to determine if late season seedzone water loss from fallow could be reduced by altering

the physical characteristics of the dust mulch. Loss of seedzone water appears to accelerate in late August and September because of increased diurnal heat flux. Compacting the soil surface with a roller in mid-August increased surface bulk density and volumetric water content to depths as great as 10 cm. Evaporative water loss from compacted plots, however, occurred at a faster rate than from control plots and, by mid-September, there were no differences in seedzone water content among treatments. Increased soil thermal conductivity appeared to be the reason for accelerated water loss in compacted treatments. Although water loss occurred at a faster rate in compacted treatments, compacting fallow soils with a roller immediately prior to fall seeding may increase winter wheat germination, emergence, and stand establishment during years of marginal seedzone water.

Fallow Water Retention and Wheat Growth as Affected by Tillage Method and Surface Soil Compaction

by

William Fred Schillinger

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed April 6, 1992

Commencement June 1992

APPROVED:

Redacted for Privacy

Professor of Crop and Soil Science in charge of major

Redacted for Privacy

Head of Department of Crop and Soil Science

Redacted for Privacy

Dean of Graduate School

Date thesis is presented April 6, 1992

Typed and formated by William F. Schillinger

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Dr. Floyd E. Bolton for his guidance, encouragement, support, and friendship throughout my graduate studies at Oregon State University. A special thanks is extended to Mr. Erling Jacobsen and Mr. Scott Case of the Sherman Experiment Station in Moro for their invaluable assistance in monitoring instruments, performing field operations, and helping in other ways too numerous to mention. I am very grateful to the faculty members who served on my committee; Drs. Don Wysocki, Tom Chastain, Russ Karow, and Doug Johnson. I thank Dr. Paul Rasmussen and Dr. Warren Kronstad for the use of laboratory facilities and equipment. I appreciate Ms. Nan Scott's incredible computer skills and her willingness and patience to teach these skills to others. Dr. Larry Boersma deserves special thanks for his review and comments of Manuscript I. Fellow graduate student John DeNoma's help and expertise in machinery repair, metal fabrication, and "how things get done in the department" has been very useful and is much appreciated. Finally, I am grateful to my wife, Valerie, and my children, Mark and Kathryn, for their love, support, and understanding during these very interesting years in Corvallis.

This thesis is dedicated to the memory of my grandfather, Fred Schillinger, and my father, William Fred Schillinger, Sr. Both were life-long dryland wheat farmers near Odessa, Washington.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

Figure | Page

MANUSCRIPT III (Continued)

LIST OF TABLES

LIST OF APPENDIX FIGURES

LIST OF APPENDIX TABLES

INTRODUCTION

A winter wheat-fallow cropping system is widely practiced by growers in areas of Pacific Northwest receiving less than 380 mm annual precipitation (Leggett and Nelson, 1960). This cropping system consists of a 14-month fallow cycle, which begins after harvest in July or August, and a 10-month crop cycle, which begins at planting in September or October. A portion of the precipitation occurring during the 14-month fallow period is stored in the soil profile for use by the following wheat crop. This practice makes it possible to produce a crop with lower risk of failure whereas, with annual cropping yields are variable and risk of crop failure is much greater.

About 70% of the annual precipitation in the Pacific Northwest occurs during the fall and winter. Maximum efficiency in storing winter precipitation is critical for achieving high yield. There are many factors that affect the amount of water stored in fallow soil over winter and the stored water which can be conserved during the dry summer. These factors include soil infiltration rate, soil depth, soil texture, soil structure, heat flux, and the rate of water movement in the liquid phase and vapor phase (Boersma and Jackson, 1977). These factors are greatly influenced by tillage method.

Additional benefits of fallowing include a longer period for the breakdown of crop residue, which releases nutrients for plant use, and better weed control. However, fallow is not essential for supplying nutrients because fertilizer can be supplied economically (Leggett et al., 1976). The primary objective of fallow is to store water and under certain conditions to control weeds.

A disadvantage to fallowing is the increased problem of wind and water erosion. A principle goal for both soil and water conservation is to maintain a cloddy surface and to preserve as much crop residue as possible on the surface during the fallow period. Water erosion during the winter of the crop year can be greater than in fallow because surface residue is at a minimum, the soil is usually poorly structured, and crop growth has not yet provided effective surface cover. Erosion control is greatly influenced by type of tillage method because it determines the amount of crop residue left on or near the soil surface.

Initial, or primary, tillage is carried out in the early spring as soon as the soil has dried enough for proper equipment operation. Fall tillage is of little benefit in storing winter precipitation unless the soil is frozen for prolonged periods. The standard implements used for primary tillage are the moldboard plow, sweep plow, chisel plow, and disk plow. The moldboard plow inverts and pulverizes the upper soil profile sufficiently to bury surface residues. Once commonly used in the wheat-fallow cropping system, the moldboard plow has largely been replaced by the chisel, sweep, and disk plow. These implements break, lift, cut, or otherwise loosen the surface soil without inversion. Some surface residues are shallowly buried while the remainder remain on the surface to form a stubble mulch. Stubble mulching reduces erosion because the residues increase surface roughness and infiltration. Secondary tillage, generally with a rodweeder, is carried out periodically during the spring and summer to control weeds and to maintain a surface mulch.

Another method which is receiving major attention is no-tillage, where herbicides are used to control weeds and the soil is undisturbed until planting. Soil erosion is greatly reduced with no-tillage compared to other fallow methods. Limited information is available concerning the effects of no-tillage fallow on water conservation and wheat yields in the Pacific Northwest.

Tillage method greatly effects soil biological, chemical, and physical properties. These differences have important implications to the wheat grower in the amount of water stored during fallow, mineralization of organic matter, erosion control, fertilizer placement and recovery, disease and weed control, labor and machinery requirements, wheat growth, and grain yield.

Research for the thesis was conducted at the Sherman Experiment Station, Moro, Oregon. Mean annual 80 year (1910-1990) precipitation at this location is 290 mm. The soil at the experimental site is a Walla Walla silt loam (coarse loamy, mixed, mesic, Typic Haploxeroll) overlying basalt bedrock.

Manuscript I focuses on seedzone water retention during fallow as affected by late season compaction of the surface dust mulch with a roller. Loss of seedzone water appears to accelerate in late August and September because of increased diurnal heat flux. A 2-year experiment was conducted to determine if the rate of water loss during this time period could be reduced by altering the physical characteristics of the dust mulch. The research was important to wheat producers in the semiarid Pacific Northwest because reduction in late season seedzone water loss would likely improve wheat seed germination, emergence, and stand establishment.

Manuscripts II and III of the thesis compare the long-term effects of no-tillage, stubble mulch tillage, and moldboard plow tillage in a wheat-fallow cropping system. A tillage trial was established in 1981 to evaluate the long-term effects of these three fallow management systems on wheat yield. The no-tillage treatment has consistently produced lower grain yields than the other treatments. The objective in Manuscripts II and III was to determine factors responsible for yield differences.

The specific objective of Manuscript II was to determine the rate and extent of fallow season soil water loss in the three tillage systems. Soil water status was measured throughout two 14-month fallow periods. Total soil profile water storage, seedzone water content, and fallow efficiency were evaluated in the three fallow systems.

Manuscript III covers stand establishment, development, and yield components of winter wheat as affected by tillage method. Soil water, soil mineral N, plant N uptake, soil temperature, and dry matter production were measured at several wheat plant development stages during two 10-month cropping cycles. Yield components were measured at time of harvest. Factors responsible for grain yield differences are discussed.

LITERATURE REVIEW

Principles of Water Conservation

Movement of Liquid Water in Soils

Water is the major limiting factor for dryland wheat production in the semiarid Pacific Northwest. Tillage operations are designed to maximize water retention in the soil during the fallow season. Water retention, hydraulic conductivity, and diffusivity of soils as functions of water content play a central role in determining the movement and storage of water in soil (Klute, 1982). Tillage modifies both bulk density and pore size distribution of the soil. These largely determine soil hydraulic properties.

The term hydraulic conductivity describes water movement in both saturated and unsaturated soils. In saturated soils, gravity controls the water potential gradient. In unsaturated soils, matric potential controls the water potential gradient, and water moves in films surrounding the soil particles and capillary pores (Hillel, 1971). The matric potential, or suction, is due to the physical affinity of the water to the soil particle surfaces and capillary pores. When a matric potential exists, water will flow in the pores and creep along the hydration films over the particle surfaces in a tendency to equilibrate the potential (Hillel, 1982). The important problems of water movement during infiltration and of redistribution of water after infiltration has ceased involve unsaturated flow.

The rate of water infiltration into soil is an extremely important factor in soil water recharge. The path of downward movement of water following its application to the soil surface was described by Kramer (1969). He depicted five zones downward in the soil profile as: (1) a saturation zone which reached a maximum depth of 1.5 cm; (2) a transition zone, a region of rapid decrease of water content extending to a depth of about 5 cm; (3) the main transition zone, a region in which only small changes in water content occurred; (4) a wetting zone, a region of fairly rapid change in water content, and; (5) the wetting front, a region of very steep gradient in water content which represents the visible limit of water penetration.

Although liquid water flow is due primarily to gradients caused by differences in water content, it is also caused by thermal gradients, usually hot to cold (Marshall and Holmes, 1988). Jackson et al. (1965) demonstrated temperature induced soil-water movement by enclosing a soil sample of uniform water content inside a sealed cylinder. A thermal gradient across the cylinder caused soil water redistribution. Drying occurred at the warm side while the water content increased on the cool side. Infiltration of water is known to be sensitive to soil temperature as well. Bigger and Taylor (1960) showed that an increase in soil temperature of 20 ^{0}C caused a 20% increase in infiltration rate.

Conservation of Water in Fallow

Efforts to minimize fallow water loss have produced considerable information about the processes of infiltration, evaporation, and the effect of surface residue. Penman (1941), and later Idso et al. (1974), conducted extensive studies on soil water evaporation. Penman showed that movement of free water depends on capillary conductivity and the tension gradient; both of which are functions of water content. Work by Idso et al. under field conditions supported the concept of evaporation occurring in three stages. The first evaporative stage is characterized by a high evaporative rate controlled by atmospheric conditions. Loss occurs at about the same rate as from free water surface. This stage lasts as long as the water flow rate to the surface equals the loss rate by evaporation. The second stage of evaporation begins when soil water cannot be transmitted to the surface fast enough to meet evaporative demand. The surface will then begin to dry. In this stage, soil conditions control the flow of water to the surface. Hydraulic conductivity decreases in drying soil (Marshal and Holmes, 1988). The third stage of evaporation is characterized by a low and relatively constant evaporation rate because water can no longer move to the surface as a liquid. The zone of evaporation is now below the surface and water must move as vapor through the dried layer. Although Idso et al. found all three stages of drying to occur under field conditions, workers sometimes consider the second and third stages as one phase (Papendick and Campbell, 1974).

Retardation of evaporation during the first stage of drying can enhance the process of infiltration and allow more water to migrate downward in the soil profile where it can be conserved and is less likely to be lost by evaporation (Hillel, 1971). Conservation tillage systems, in which plant residues are maintained on or near the soil surface, exert the greatest influence during the first stage of drying. Relatively small amounts of surface residues reduce evaporation by: (1) reflecting sunlight which otherwise would be absorbed as heat; (2) acting as a thermal insulator to limit the flow of heat from the atmosphere to the soil, and; (3) reducing turbulent air exchange by creating a dead air space above the soil surface which reduces the transfer rate of water vapor from the soil to the atmosphere (Lemon, 1956; Papendick and Campbell, 1974).

The effect of surface residue during the second stage of drying is only slight as the reduction in evaporation rate will now depend on decreasing the diffusivity and conductivity of the soil profile with depth (i.e. by thermal and water flow properties of dry soil layer) (Hillel, 1982). Tilling the soil surface to create a loose soil structure causes rapid drying and the development of a soil mulch which increases resistance to upward liquid flow of water. In addition, tillage decreases thermal conductivity of the soil which further reduces the evaporation rate through lowered soil temperatures (Papendick and Campbell, 1974).

Water Retention in the Wheat-Fallow Cropping System

Fallow Water Retention in the Great Plains

In the Great Plains, much of the precipitation occurs during the period of high potential evaporation. Thus, in the Great Plains it is necessary to consider evaporation and infiltration as simultaneous processes when evaluating the effect of tillage on soil water storage. In the Pacific Northwest, which has high winter precipitation and low summer rainfall, infiltration is of little concern during the period of high potential evaporation (Papendick et al., 1973).

The effects of fallow method on soil water and wheat yields has been widely studied in the Great Plains. However, because of the complexity of evaporation and infiltration processes involved in water storage, conclusions often have been contradictory. Tillage comparisons in the wheat-fallow cropping system in the Great Plains indicate that no-tillage fallow either stores more water than stubble mulch fallow (Good and Smika, 1978; Wicks and Smika, 1973; Fenster and Peterson, 1979; Smika, 1990), or that there is little difference in water storage between no-tillage and stubble mulch tillage method (Wiese and Army, 1960; Black and Power, 1965; Tanaka, 1985).

In an early study comparing water storage in no-tillage to stubble mulch tillage in the Great Plains, Army et al., (1961) found that only if rains are frequent can greater quantities of residue on the soil surface be expected to improve water storage by increasing depth of water percolation. They reported that with continued drying, cumulative evaporation from a plow, stubble mulch, and no-tillage plots eventually become equal.

Black and Power (1965) evaluated the effects of mechanical fallow, chemical plus mechanical fallow, and complete chemical fallow methods on fallow water retention in a 4-year study in Montana. They found that complete chemical fallow stored the least water. Water storage was significantly increased when chemical fallow method included a late spring (early June) tillage. One tillage operation performed at this time in conjunction with adequate chemical or mechanical weed control thereafter, was equally effective in water conservation as any combination of single or multiple subtillage operations with or without spray treatment. Black and Power concluded that herbicides could be used in place of one or more mechanical fallow operations at any time except late spring.

Greb et al. (1967) reported net gains in soil water storage during fallow due to increased quantities of wheat straw in a 3-year study conducted at test sites in Nebraska, Colorado, and Montana. The largest net gains in soil water storage as affected by various application rates of straw were made from the mid-April to mid-June period. They found that soil water evaporation losses were reduced in a near linear fashion as the rate of surface straw increased from 0 to 90% soil cover. With only one exception, their data for all years at all locations showed a progressive increase in soil water storage with increasing application rates of straw regardless of the quantity of precipitation occurring during the fallow year.

Bond and Willis (1971) conducted laboratory studies with soil columns wetted to various levels. They reported that water storage could be increased when residue levels were adequate to reduce initial evaporation and thus permit water to penetrate to greater depths. However, large amounts of surface residues were required to obtain water savings over an extended period.

Black and Siddoway (1979) also reported that soil water storage increased in proportion to the quantity of surface residue. Therefore, tillage operations that bury large amounts of crop residue cause a proportional reduction in soil water storage and crop yield.

Tanaka (1985), in Montana, argued that precipitation frequency and distribution are just as important as quantity and position of surface residue in fallow water retention. He suggested that for no-tillage fallow to effectively store more soil water than stubble mulch fallow in the Great Plains, frequent precipitation during low potential evaporation periods is necessary. Citing Caprio et al. (1980), Tanaka stated that, in the northern Great Plains, 36% of total precipitation occurs during a period of low potential evaporation from April through June. It is also during this period that the first tillage operation for stubble mulch fallow occurs; prior to this all fallow ground is treated the same. Therefore, soil water content in chemical and stubble mulch fallow methods are more likely to differ after the first tillage operation and before July 1. After July 1, less precipitation and high potential evaporation would reduce the effectiveness of residue covered no-tillage surfaces. Tanaka suggested that a practical method to reduce soil water loss in no-tillage fallow may be to create a soil mulch with shallow tillage just prior to periods of high potential evaporation. This would reduce evaporative losses by disrupting pore continuity and restrict upward movement of soil water.

Smika (1990) reported overall fallow efficiencies of 40%, 47%, and 49% for plow, stubble mulch, and no-tillage treatments, respectively, in a 12-year experiment in Colorado. Although annual precipitation varied for 264 to 535 mm, there was no consistent relative change in water storage among treatments during dry, average, or wet years.

Fallow Water Retention in the Pacific Northwest

Early investigators, McCall and Hails (1921), and McCall and Wander (1924), wrote that the dry farming experiment stations in the Pacific Northwest had clearly demonstrated the importance of working summer fallow early in the spring. They reported that, although farmers understood the importance of keeping the fallow free from weeds, considerable late plowing was done each year when there is a heavy growth of volunteer wheat and weeds to turn under.

McCall (1925) , conducted a 6-year study on fallow water retention at Lind, WA (240 mm annual precipitation). He found that spring and summer rainfall events in the semiarid Pacific Northwest were seldom of sufficient magnitude to fill and penetrate through the mulch. He concluded that: (1) the soil mulch has an inhibitory effect on water absorption when rains are not of sufficient volume to fully penetrate the mulch; (2) the mulch prevents the loss of water already in the soil by checking evaporation, and; (3) water conservation is dependent on climatic conditions which influence both absorption and retention of soil water.

The slowness with which animal-powered farming operations were conducted in early years meant that large acreages did not get plowed until much later than was ideal. Improvements in agricultural equipment were introduced at various times during the 1920s and early 1930s which had a major impact on dryland farming in the Pacific Northwest. Hill and Jackman (1960) listed major equipment innovations of this era: (1) the introduction of reliable crawler tractors in the 1930s which permitted much better timing of farm operations which could now be conducted under optimum moisture conditions; (2) disk plows were introduced which left most of the stubble exposed at the surface and provided some protection from wind erosion; (3) rod weeders, operating below rather than at the surface, replaced harrows in summer fallow weeding operations, and; (4) the deep furrow grain drill which, by planting seeds deeper, enabled farmers to make more use of subsoil moisture and thereby increased their chances of obtaining successful stands of early fall plantings of winter wheat.

Massee and Siddoway (1970), in a 6-year study in southeast Idaho, found that soil water content at the end of fallow was related to soil water content at the time tillage was initiated in the spring. The largest fallow water losses occurred following springs that had above-average profile water storage. When profile water storage was low, subsequent evaporative losses were also low. Using linear regression analysis to estimate the trend for years, they found that the profile water losses (Y) were related to May profile storage (X) by the equation:

$$Y = 14.4 + 0.90X, \ r^2 = 0.73^{**}$$

The equation indicates that no loss would occur if 15.6 cm of soil water was present in May, but that 90% of any amount greater than 15.6 cm would be lost by fall. A close association between seedzone (7.5 to 15 cm) water content at time of initial tillage and at planting was also found:

$$Y = 3.5 + 0.65X, \ r^2 = 0.67^{**}$$

Finally, the authors reported that soil water content in the fall was not appreciably affected by summer rainfall. Using multiple regression to separate the effects of May soil profile water storage from summer fallow period precipitation on evaporative profile losses provided verification of the effect of precipitation. The r^2 value increased to only 0.77 from a value of 0.73 for May profile water storage alone. This strengthened the contention that quantitative May profile water storage was the main variable associated with summer fallow evaporation losses in the Pacific Northwest.

Papendick et al. (1973) found that the depth of the dry soil mulch affected summer soil temperatures and seedzone water at the end of fallow in a 240 mm rainfall zone at Lind, Washington. Increasing the depth of the tillage mulch from 6 to 11 cm reduced over-summer seedzone drying sufficiently to benefit wheat emergence. Reduction of drying was greatest when the seedzone had good capillary continuity with deeper soil layers. Soil water was more evenly distributed under the shallow mulch, but the deep mulch retained more water in the seedzone. Seedzone water was improved most by shallow initial sweep tillage in combination with rodweeding to sweep tillage depth. Wheat emergence rates were markedly influenced by tillage-induced differences in seedzone water. Emergence 8 days after planting was 18% for the shallow mulch and 57% for the deep mulch. The seeding depth in the deep mulch was at least 5 cm deeper than in the shallow mulched plots. The loose soil in the deep-tilled plots allowed the furrow drill to penetrate deeper and place the seed in wetter soil. Papendick et al. concluded that under dryland conditions in the Pacific Northwest, seedzone water could be best conserved through using a soil mulch of maximum resistance to vapor and liquid water flow, and maximum thermal insulation, overlying a seedzone having good capillary continuity with the deeper soil layers.

In a review article on summer fallow in the Pacific Northwest, Leggett et al. (1976) reported that over-winter fallow efficiencies from 4 locations in eastern Washington and 1 location in northern Idaho ranged from 52% to 73%. They recommended that primary spring tillage be conducted as early as possible because early tilled fallow was always superior for water storage and wheat yield as compared to delayed tillage. They suggested that early tillage was effective in reducing soil water loss by controlling early season weed transpiration and probably by decreased capillary conductivity to the soil evaporating surface.

Allmaras et al. (1977) measured the hydraulic conductivity of a Walla Walla silt loam soil near Pendleton, OR, to determine the effect of chiseling on water retention. Hydraulic conductivity-water content data for the 10 cm, 20 cm, and 30 cm depths showed that chiseling increased the conductivity at lower water contents. At higher water contents, the conductivity of the untilled soil was greater than that of the chiseled soil for the same three depths. Hydraulic conductivity-water content functions were unaffected by chiseling below 40 cm as would be expected since the chiseling depth was 40 cm.

Work conducted by Massee and McKay (1979) in the high snowfall regions of eastern Idaho showed that allowing stubble to stand over-winter after harvest trapped snow and increased soil water. Winter wheat yields were increased by 0.336 Mg ha^{-1} for each additional foot of snow trapped.

Ramig and Ekin (1991) conducted at 6-year study in eastern Oregon to determine when water was stored or lost in the wheat-fallow rotation and to determine the effect of tillage method on water conservation. The study was conducted at two sites, Moro and Pendleton, where annual precipitation averaged 290 mm and 413 mm, respectively. Six treatments were established: (1) spring moldboard plow; (2) fall flail, spring sweep; (3) fall burn, spring sweep; (4) fall disk, spring sweep; (5) fall chisel, spring sweep, and; (6) spring sweep. Rodweeding was performed as needed during the summer to control weeds. At both the low and high precipitation sites, significantly less water was stored when the stubble was burned. There were no significant differences among the other treatments at either location. Water storage during the crop winter was found to be less efficient than during the fallow winter. This was attributed to: (1) fallow tillage which had flattened and buried some of the crop residues, exposing the soil surface to drying winds and soil freezing, and; (2) destruction of macroporosity in the soil surface by tillage which reduced the infiltration rate.

No-tillage Fallow in the Pacific Northwest

Few studies have been conducted in the Pacific Northwest to compare water storage of no-tillage to conventional fallow management practices. In a 4-year study near Pendleton, OR, Oveson and Appleby

(1971) found that no-tillage plots consistently stored less water than plots which received stubble mulch tillage at various times during the spring. During the crop year, grain yields from no-tillage plots were significantly reduced compared to yields from tilled plots. Delaying the first tillage until June decreased water storage in comparison to other tillage treatments.

Lindstrom et al. (1974) compared the effects of fall tillage (moldboard and chisel), spring tillage (sweep and disk), and no-tillage on fallow water storage in a 2-year study at Lind, WA. Method of fall tillage did not influence either net storage or depth distribution of water during a mild winter but markedly increased soil water storage during a cold winter. Increased water storage with fall tillage during the cold winter was attributed to better infiltration during major water runoff on frozen soils. There was visual evidence of considerable runoff from the untilled surface in particular, but minimal runoff from the chiseled surface. Spring tillage method had no influence on over-summer water retention during either year. Seedzone water contents were lowest with no-tillage fallow. No-tillage fallow had insufficient seedzone water for satisfactory emergence of fall sown wheat.

Papendick and Miller (1977) reported that sandy soils have the greatest potential for no-tillage fallow in the Pacific Northwest because the water conserving effect of tillage mulch diminishes with coarser textured soils. With finer textured soils, first-stage drying is longer; and during rainless periods, the soils dry deeper than coarser textured soils because of higher unsaturated conductivities. Sandy soils, they reported, tend to self-mulch and conduct water upward very slowly in the untilled condition.

Schieferstein (1980), a Technical Representative for Shell Chemical Company, reported increased fallow water retention and ensuing increased grain yield from chemical fallow compared to stubble mulch fallow at 9 locations in the Pacific Northwest. Location of the experiments was not reported. Weeds in the chemical fallow were controlled with a herbicide developed by Shell Chemical Company.

Hammel et al., (1981) measured heat and water flow in the upper soil layer with emphasis on effects of stubble mulch tillage and no-tillage on these processes and ultimately the seedzone water content. They then developed a prediction model. Treatments were established in the spring on wheat stubble near Lacrosse, WA (320 mm annual precipitation). Measured water loss rates average 0.16 mm/day for stubble mulch tillage and 0.27 mm/day for no-tillage during a 90 day period in the summer. Evaporative water loss with no-tillage during the 90-day period was 70% higher than for stubble mulch tillage. Water content at time of fall seeding in the no-tillage treatment was too low for successful seed germination and emergence whereas water in the plow tillage treatment was adequate. The simulation model which Hammel et al. developed, using meteorological data and soil properties, was able to predict measured water losses fairly accurately. Simulated evaporation from no-tillage decreased steadily during the summer and approached the rate from stubble mulch tillage at the end of 90 days. The reduction in evaporation rate in time with no-tillage in the simulation model resulted from increased resistance to liquid flow to the surface as the surface layer dried. The lower evaporation rate for stubble mulch in the simulation model resulted from disruption of pore continuity with lower layers. This allowed water lost from the seedzone to be replenished from layers below by flow due to matric potential.

Bolton and Booster (1981) listed the following problems with no-tillage fallow in the Pacific Northwest: (1) the surface 7.5 to 13 cm of soil may be quite hard and dry at planting time; (2) poor seed-soil contact which, coupled with low soil water, can cause delayed and spotty stands; (3) stubble residue may adversely affect equipment operating characteristics, and; (4) phytotoxic substances in the residue material may reduce seedling vigor.

Avcin (1988) measured over-winter water storage and over-summer water loss in a 1-year study of the long-term tillage trial at Moro, OR. The no-tillage treatment conserved 60% of over-winter precipitation compared to 57% and 55% for the plow and stubble mulch treatments, respectively. At the end of fallow period, however, the top 30 cm of the no-tillage treatment had the least water and there were no differences in total profile water among treatments.

Veseth (1988), referring to work by Hammel and Papendick in a 200 mm annual precipitation region in Washington, reported little difference in seedzone water between stubble mulch and no-tillage treatments. Lack of difference between treatments was attributed to the low evaporative loss from the "self mulching" sandy soils.

Tillage Effects on Nutrient Distribution and Fertilizer Efficiency

Residue Placement and Mineralization

Both fallowing and crop residue management have a significant impact on the OM level in a soil. Organic N-containing compounds, the product of microbial decomposition of crop residue, account for over 90% of the total N in most agricultural soils (Haynes, 1986). During decomposition, some of the C and N is immobilized into microbial tissue and part is microbially converted into resistant humic substances, which constitute the bulk of soil OM. Tillage accelerates net mineralization of soil organic N by increasing soil porosity and aeration, and exposing surface residues to the soil microbial biomass. In contrast, no-tillage results in the accumulation of OM in the surface soil (Douglas and Goss, 1982).

Smith and Douglas (1968) buried straw samples from three spring wheat varieties in field plots that had been fertilized with 0, 89, or 268 kg N ha^{-1}. Straw decomposition after three months in the field was not influenced by soil N rate, but straw N percentage increased with each increment of N fertilizer. They found that the straw C percentage remained almost constant, but the C/N ratio narrowed with increasing N and with loss of C. The color of the buried straw did not change with time in the soil, but the straw lost 44% of its original dry weight in three months. Smith and Douglas concluded that wheat straw may remain bright and clean without the browning associated with decomposition until 60 to 90% of the straw has decomposed.

Douglas et al. (1980) evaluated straw composition and placement effects on decomposition at Pendleton, OR. Wheat straw with three different N and S contents was place above, on, and below the soil surface to simulate standing stubble, straw matted on the surface, and straw plowed under. Residue losses were 25, 31, and 85% for placements above, on, and in the soil, respectively, after 26 months exposure. Decomposition rate for the above-surface and on-surface straw was nearly constant with little response to seasonal changes in precipitation, relative humidity, or air temperature. The decomposition rate of buried straw, however, responded to both soil water content and temperature. Net N mineralization for buried straw occurred at rates up to three times higher than that for above-surface and on-surface placement.

Veseth (1985) reported on wheat straw decomposition research conducted by Diane Stott at Pullman, WA. Stott periodically collected and weighed straw samples from no-tillage plots left undisturbed for 11 months after harvest. In March, 6 months after harvest, 36% of the straw had decomposed. Of the remaining straw, 61% was laying on the soil surface and 39% was standing. After 11 months, 74% of the original straw had decomposed. 86% or the remaining undecomposed straw was standing with only 14% lying on the soil surface.

Winter wheat residue loss from no-tillage and stubble mulch systems during fallow in Montana was examined by Tanaka (1986). Stubble mulch fallow plots were tilled with sweeps in late May, followed by 3 rodweeding operations. No-tillage plots were sprayed four times during the fallow period to control weeds. The quantity of surface residue on stubble mulch and no-tillage plots at the end of the 14-month fallow was 28 and 72%, respectively, of the initial residue values. At the end of fallow, 37% of the remaining no-tillage residue was standing and the rest flattened on the surface. Flattened residue contained 1.3 times more N than standing residue. Tanaka hypothesized that the greater N concentration in the flat residue occurred because the upper portion of the plant, which became the flat residue, usually has a higher concentration of N than the lower portion at maturity.

Oveson (1966), Rasmussen et al. (1980), and Rasmussen et al. (1989), reported on long-term residue management effects on OM in a wheat-fallow cropping system at Pendleton, OR. Of the seven residue management treatments initiated in 1931, only the addition of 22.4 Mg manure ha^{-1} $year^{-1}$ to straw residue before incorporation prevented a decline in soil N and C. Addition of legume residue and N fertilizer slowed, but did not stop, the decrease in soil N. Soil N showed a continuous downward trend when straw was burned, either in the fall following the crop or in the spring before plowing. Treatments receiving no fertilizer N had a higher C/N ratio than those receiving fertilizer N. Changes in soil C correlated highly with the amount of organic C supplied in crop residue. Changes in N and C with time were primarily confined to the top 20 cm of soil. Rasmussen et al. (1980) developed regression equations which indicated that about 5 Mg crop residue ha^{-1} $year^{-1}$ were needed to maintain soil OM at current levels. Rasmussen et al. (1989) reported that the top 30 cm of soil before cultivation contained more than 5000 kg N ha^{-1}. In 1931, after about 50 years of cropping, the soil contained 3600 kg N ha^{-1} in the top 30 cm.

Doran (1980) measured soil microbial and biochemical changes in the surface soil of reduced tillage systems at 7 locations throughout the United States. In all locations no-tillage was compared to moldboard plowing. He found that C and N contents of surface soil (0 to 7.5 cm) with no-tillage average 25 and 20% higher, respectively, than for plow tillage. Below 7.5 cm the C and N contents of no-tillage soils were the same or lower than with plow tillage. At the 15 to 30 cm depth, no-tillage soils average 7% less C and N than plow treatments. Maximum aerobic microbial activity with plow tillage extended to a greater depth than with no-tillage. Microbial populations under no-tillage decreased rapidly below 7.5 cm. Doran concluded that there were lower levels of plant available NO_3^- and increased potential for immobilization of surface applied N with no-tillage compared with plow tillage.

Broder et al. (1984) examined the long-term influence of plow, stubble mulch, and no-tillage fallow method on nitrifier and denitrifier microbial populations and available N in a wheat-fallow rotation in Nebraska. During the spring, nitrifier populations in the surface 15 cm of the no-tillage and stubble mulch treatments were up to 56% and 35% lower, respectively, than those in plowed soil. Soil denitrifier populations were highest for no-tillage, followed by stubble mulch and plow tillage. Lower population of nitrifiers and higher population of denitrifiers corresponded to lower NO_3^- levels in no-tillage compared to the other treatments. Broder et al. postulated that differences in soil temperature and water content, as related to changes in surface residue cover, appeared to be major factors for differences in spring nitrifier and denitrifier populations among tillage treatments.

Lamb et al. (1985) studied fallow NO_3^- accumulation as affected by tillage method in a wheat-fallow rotation in Nebraska. Nitrate levels during 13 fallow seasons were measured following establishment of no-tillage, stubble mulch, and plow tillage plots in 1970. Overall, tillage method did not effect the time at which NO_3^- started to accumulate during the fallow period nor the rate of accumulation. The most rapid accumulation of NO_3^- usually began during July of the fallow year for all tillage methods and continued to October. Although tillage method did not affect NO_3^- accumulation, they cautioned that the time at which a soil sample is taken is very important in recommending the amount of fertilizer N needed. A soil sample taken in June would have only 50% of the total NO_3^- accumulated at seeding time. This could cause a larger amount of fertilizer N to be recommended than was needed.

Follett and Peterson (1988) investigated surface soil nutrient distribution in long-term tillage trial in Nebraska. No-tillage, stubble mulch, and plow treatments had been established for 16 years when the study was conducted. Analysis of samples collected from depths of 0 to 5 cm, 5 to 10 cm, and 10 to 20 cm indicated that no-tillage resulted in the maintenance of a greater quantity soil OM compared to plow tillage, especially in the surface 5 cm. Plow tillage had the lowest levels of extractable K, Zn, Cu, and P in the top 10 cm. Extractable nutrients were not affected by tillage below 10 cm.

Fertilizer N Use and Recovery

Nitrogen is a major essential nutrient and is required by plants in substantial quantities. It is a constituent of all proteins, of many metabolic intermediates involved in synthesis and energy transfer, and of nucleic acids. Nitrogen is the most common key limiting factor for crop production when supplies of soil water are adequate (Olson and Kurtz, 1982). Crop residues with a wide C/N ratio, when mixed with soil, immobilize inorganic N from both fertilizer and soil sources, but the interaction between fertilizer N and surface crop residues have not been extensively documented (Fredrickson et al., 1982). Research comparing the effects of tillage method on availability of fertilizer N in the wheat-fallow cropping system have given variable results.

Pumphrey and Rasmussen (1982) reported that reduced tillage systems for winter wheat production in the Pacific Northwest initially require larger rates of N fertilizer than conventional tillage systems. They recommended that, to avoid nutrient deficiencies, up to 20% additional N be applied to each crop for 6 to 8 years after starting reduced tillage. For complete no-tillage systems, they suggested that additional N was not required when fertilizer is banded below the seed. Broadcast application of fertilizer N in no-tillage systems was not recommended as it had shown poor efficiency.

Koehler et al. (1983) conducted a 5-year fertilizer placement study in a 400 mm annual precipitation zone near Davenport, WA. Winter wheat yields averaged 0.27 Mg ha^{-} higher when fertilizer N was banded compared to broadcast in plow and no-tillage systems. Grain yields from plow tillage averaged 0.202 Mg ha^{-} higher than those from no-tillage plots with both band and broadcast fertilizer N application.

Klepper et al. (1983) recommended placement of nutrients below residue accumulation zones for most efficient crop use in conservation tillage systems. They cautioned that the quantity of fertilizer that can be supplied with the seed is limited because excessive fertilizer concentrations with or immediately below the seed may burn roots and delay emergence. Placement of banded N at a distance of 3 to 5 cm below and up to 5 cm to one side was found sufficient in a silt loam soil to efficiently provide nutrients to a seedling and not damage roots.

Bolton (1988) compared the effectiveness of anhydrous ammonia injected into the soil two months prior to seeding and Solution 32 sprayed (at the same rate as the anhydrous ammonia) in a band between seed rows at time of seeding. The experiment was conducted in Moro, OR, on land prepared by stubble mulch tillage method. Bolton reported that the source and method of N application had no significant effect on grain yield.

Varvel et al. (1989) studied N placement effects in three fallow systems in a long-term tillage trial in Nebraska. Dry matter, grain yield, N concentration, N uptake, and fertilizer recovery were all significantly affected by fallow method during the 3-year study. They were greatest for the plow followed by stubble mulch and no-tillage systems, respectively. Nitrogen placement, however, had no effect on any of the variables in any of the tillage systems. Varvel et al. believed that N immobilization was not a factor in explaining yield differences among tillage treatments. They theorized that the cool soil temperatures that predominate in the central Great Plains from fall planting until late spring may not be conducive to N immobilization and that fall precipitation probably moves surface applied fertilizer N into the soil past the zone of OM accumulation where immobilization would occur. Although surface applied N was in contact with OM from time of seeding with no-tillage, soil temperatures were presumed to be too low for much biological activity to occur. Another possible explanation given by the authors was that tillage treatments in the long-term tillage trial had reached a new steady state equilibrium.

In a review article on N utilization with no-tillage, Fox and Bandel (1986) concluded that for nonvolatilizing sources, N fertilizer use efficiency may be higher, lower, or the same as in tilled soils. They reported that N use efficiency was likely to be higher with no-tillage in climates where soil water is limiting, and lower in cool, moist climates with poorly drained soils where large denitrification losses may occur. Nitrogen use efficiency, according to Fox and Bandel, may possibly be lower for several years after converting to no-tillage in semiarid environments but, after a period of time, increased soil organic N content of the untilled soil should result in comparable N availability in tilled and untilled soils. The mineralization rate may be slower in untilled soil but the organic N pool should, at some time, become large enough that the same amount of N is mineralized as in the tilled soils. Consequently, similar N fertilizer efficiency would be attained in untilled and tilled soils.

Germination and Stand Establishment of Winter Wheat

Adequate stand establishment is essential for winter wheat to reach its yield potential. Water for germination must be retained no deeper than 12 to 15 cm below the surface for deep furrow planting (Hammel et al., 1981). Such factors as high surface residues, clodiness, and nonuniform seedzone water distribution combine to cause potential problems with stand establishment in conservation tillage systems (Rickman and Klepper, 1984).

Hanks and Thorp (1956) placed wheat seeds at a uniform planting depth at different water potentials. They found that the rate of emergence decreased as the water content of the soil decreased. Total emergence was also reduced as the water content decreased.

Sunderman (1964) found differences in emergence ability among winter wheat varieties subjected to various depths of planting. He reported a significant correlation between coleoptile length (measured in the laboratory) and percent emergence (measured in the field).

Guls and Allan (1976) measured wheat coleoptile length and emergence rate as effected by soil water potentials ranging from -0.2 MPa to -1.4 MPa. They reported that time to emergence nearly doubled for each decrease of -0.4 MPa. Coleoptile length and root weight were also progressively reduced with decreasing water potential.

A model predicating winter wheat germination and emergence as affected by soil water content, planting depth, and temperature was developed by Lindstrom et al. (1976). They found that germination rate decreased as seedzone water decreased and that wheat would emerge better from soils having low seedzone water content at low temperatures than at higher temperatures. Rate of coleoptile elongation was viewed as the most important factor influencing emergence rate. They developed equations for predicting wheat emergence based on soil water, soil temperature, and planting depth as single factors and as a combination of factors.

Noori et al. (1985) measured the effects of injecting small amounts of water into the seedzone at seeding on germination and stand establishment of winter wheat at Moro, OR. Injection rates were 0, 20, 40, 50, and 60 mL water/m row. Seedzone water potential at time of planting was -1.1, -0.9, and -0.6 MPa, respectively, during the 3-year experiment. All water injection rates gave a greater initial (14 d after planting) and final (early spring) emergence than the 0 mL water/m row treatment. Injecting 20 mL water m/row in a relatively wet (-0.6 MPa) fallow plot had the same effect on germination and emergence as injecting greater amounts of water. In a relatively dry (-0.9 MPa) seedbed, however, there was a large difference in emergence and stand establishment between 20 and 40 mL water/m row. Noori et al. concluded that injecting water with the seed when seeding into dry soil could give significant economic returns.

Papendick and Miller (1977) reported that wheat yields in a 520 cm annual precipitation zone decreased 10% with stubble mulching, compared to moldboard plowing, in both annual cropping and fallow systems. Difficulty with stand establishment, reduced seedling vigor, and heavier infestations of downy brome and wild oats contributed to the lower yields. They theorized that surface residues may reduce wheat yields by releasing phytotoxic decomposition products.

The effects of no-tillage and moldboard plow residue management on growth and development of annually-planted wheat was investigated by Cochran et al. (1982) near Pullman, WA. Treatments included standing stubble, complete residue removal by burning, moving the crop residue away from the seed row, and residue incorporation by moldboard plow. They found that moving the crop residues away from the seed row alleviated the high crown node set which, in turn, reduced visual injury from herbicides. Grain yields among treatments were equal during the 3-year study.

In a 1-year study of the long-term tillage trial at Moro, OR, Avcin (1988) reported that the number of spikes per unit area and grain yield from the no-tillage treatment were significantly lower than that from plow and stubble mulch treatments. Avcin attributed reduced spikes per unit area as the main yield component limitation.

Rasmussen et al. (1989) reported that in long-term tillage experiments conducted at Pendleton, OR from 1934 to 1955, wheat grown on summer-fallowed land yielded 12% higher when plowed than when disked. A similar study, conducted from 1963 to 1987 with semi-dwarf wheat varieties, found that plow treatments outyielded stubble mulch (disk or sweep) by an average of 9%. Rasmussen et al. had no clear reason for the yield differences, but hypothesized that lower grain yield with stubble mulch tillage may be related to slower crop development during early spring.

MANUSCRIPT I

Seedzone Water Retention in a Dust Mulch Fallow as Affected by Late Season Compaction

Seedzone Water Retention in a Dust Mulch Fallow as Affected by Late Season Compaction

ABSTRACT

Loss of seedzone water from fallowed soils in the semiarid wheat (Triticum aestivum L.) production regions of the Pacific Northwest is relatively low during most of the summer but appears to accelerate in late August and September because of increased diurnal heat flux. A 2-year study was conducted to determine if the rate of water loss during this time period could be reduced by altering the physical characteristics of the dust mulch on the soil surface. The effects of compacting the surface dust mulch with a roller on soil bulk density and volumetric water content were investigated at Moro, OR, on a Walla Walla silt loam soil (coarse loamy, mixed, mesic, Typic Haploxeroll). Compacting the soil surface in mid-August increased bulk density in the soil surface and reduced the thickness of the dust mulch layer. Significantly higher volumetric water content in compacted versus control plots was measured to a depth of 10 cm during a 3 d period after the compacting operation. Evaporative water loss from compacted plots, however, occurred at a faster rate than from control plots and, by mid-September, there were no differences in 0 to 30-cm soil water content among treatments. It appears that the thermal conductivity of compacted treatments was higher than for control plots and that the increased vapor pressure gradient was responsible for accelerated water loss from compacted plots between mid-August and mid-September. Although water loss

occurred at a faster rate in compacted treatments, compacting fallow soils with a roller immediately prior to fall seeding may increase winter wheat germination, emergence, and stand establishment during years of marginal seedzone water content.

Additional Index Words: soil water, bulk density, winter wheat, soil compaction, water vapor.

INTRODUCTION

Inadequate seedzone water is a major limitation to establishment of fall-sown wheat in semiarid areas of the Pacific Northwest. Low water potential at time of seeding may result in slow seed imbibition and germination, which influences seedling vigor and can effect yield (Noori et al., 1985). Growers in these low precipitation areas practice a cereal-fallow rotation to conserve water in the root zone during the fallow period for use by the succeeding crop. Spring tillage during the fallow cycle with a sweep cultivator, disk, or moldboard plow, followed by three or more rodweedings to control weeds and form a dust mulch is commonly practiced by growers in this region. Rodweeding creates a low bulk density dust mulch which overlays a firm moist layer at the rodweeding depth (Pikul et al., 1985). The dust mulch conserves soil water during dry periods by slowing or preventing capillary flow to the soil surface where it would be lost to evaporation (Hammel et al., 1981). In addition to restricting the liquid phase flow of water, the finely divided soil aggregates of a surface dust mulch reduce the flow of heat into the soil (Boersma and Jackson, 1977).

During summer, water loss from fallow soil occurs mainly as vapor flow through soil pores across a 5 to 15-cm thick dust mulch. To maintain seedzone water, water lost through vapor flow must be replenished by liquid flow from the moist soil below (Papendick et al., 1973). Rate of seedzone water loss in well mulched fallow is relatively low during most of the summer but seems to accelerate in late August and September (Russelle, 1979). This acceleration of water loss is caused by the increasingly low night temperatures that occur in late summer which rapidly reduce soil surface temperatures while higher temperatures exist at lower depths (Boersma and Jackson, 1977). Under these conditions, the vapor concentration gradient towards the soil surface is quite high and, as water vapor moves from warm to cooler portions of the soil, considerable soil water loss may occur (Hillel, 1982). When the water loss rate through the dust mulch is greater than the replenishment rate from the moist soil below, drying in the seedzone occurs.

Water vapor movement is a process of diffusion and, occasionally, mass flow. Diffusion, however, is generally considered the main mechanism of vapor flow and can be described by the equation:

$$q = -D_v \; f \; a \; \nabla P$$

where D_v is the diffusivity of water vapor in air, f is the air-filled porosity, a is the tortuosity of the flow path, and ∇P is the vapor pressure gradient (Marshall and Holmes, 1988). By compacting the soil surface, the soil air-filled pore volume is decreased which decreases f and causes an increase in the tortuous path length (Hillel, 1982). As the tortuosity factor is the inverse of tortuous path length, the a value also decreases (Russel, 1973). Compaction of the soil surface, however, will also affect soil thermal properties. By decreasing soil porosity, soil thermal conductivity will be increased. Because the influence of temperature on water vapor pressure gradients is quite large, compacting the dust mulch will increase ∇P. Thus, the beneficial effects of reduced pore volume on reducing water vapor flow may be negated by increased heat flow (Papendick, et al., 1973).

The objective of this study was to determine if compacting the surface of a dust mulch during the period of high diurnal heat flux in August and September would reduce seedzone water loss from fallow. This study was prompted by observations that alleys between experimental plots, which receive heavy equipment traffic, often produce better stands than the plots. This experiment tested the hypothesis that compacting the surface of a dust mulch during a period of high diurnal heat flux would result in increased diffusion resistance. The hypothesis was based on the premise that the effects of reduced soil porosity and increased tortuosity might outweigh that of an increased vapor pressure gradient and, if correct, would result in reduced loss of seedzone water.

MATERIALS AND METHODS

The 2 year experiment was conducted during August and September of 1990 and 1991 at Oregon State University's Sherman Experiment Station in Moro, OR on a Walla Walla silt loam soil (coarse loamy, mixed, mesic Typic Haploxeroll). The 80-year mean (1910-1990) annual precipitation for this location is 290 mm. Slopes at the experimental site were < 2%. Experimental design was a randomized block with four replications. Four treatments were established:

1. Plow Control: Moldboard plow (15 cm deep) for initial tillage in March to create a bare soil surface, followed by 3 shallow (5 to 10 cm) rodweedings.
2. Plow Compacted: Same as treatment 1 except that the soil surface was compacted in August.
3. Stubble Mulch Control: Sweep plow (15 cm deep) for initial tillage in March to create a stubble mulch fallow where approximately 70% of the residue remained on the soil surface, followed by 3 shallow (5 to 10 cm) rodweedings.
4. Stubble Mulch Compacted: Same as treatment 3 except that the soil surface was compacted in August.

On 15 August, in both 1990 and 1991, the soil surface of treatments 2 and 4 was compacted by making one pass through each 41 m x 2.44 m plot with a roller attached behind a rodweeder and pulled by a small crawler tractor. The roller was a cylindrical tank filled with water. Total mass was 714 kg and dimensions were, length 182 cm and radius 23 cm. An average of 13.9% of the roller surface area was in contact with the soil, exerting a pressure of 0.019 MPa. Following the rolling operation, bulk density and volumetric water content were determined from both compacted and control treatments at 2 cm increments to a depth of 10 cm using an incremental soil sampler developed by Pikul et al. (1979). The incremental soil sampler is specially designed for sampling in loose dry surface soil. A tractor mounted hydraulic soil probe was used to take core samples for bulk density and volumetric water determination at 5 cm increments from the 10 to 30 cm depth. Between 18-21 September of both 1990 and 1991 soil volumetric water content was again obtained from these depth intervals using the same procedure. Four and eight cores were taken at each depth per treatment in 1990 and 1991, respectively. These cores were used to determine bulk density and volumetric water content. Analysis of variance was conducted for water at each sampling depth as well as for total water in the 30-cm soil profile.

RESULTS

Diurnal temperatures and precipitation from 15 August to 18 September in 1990 and 1991 are shown in Fig. I.1. In 1990, there was 43.7 mm of precipitation, almost three times the 80-year mean, of which more than 80% occurred between 15-30 August. Maximum temperatures and diurnal temperature flux were less than average during this period of unusually high rainfall. In 1991, the opposite extreme occurred; trace amounts of precipitation, high maximum temperatures, and wide diurnal temperature flux.

The increase in soil bulk density in the surface 10 cm resulting from compaction is shown in Fig. I.2. The greatest bulk density difference between compacted and control treatments occurred at 0 to 2 cm and decreased proportionally with soil depth. A higher bulk density layer, apparently due to rodweeding, was measured at 7 cm in both plow and stubble mulch systems in 1990, whereas it was difficult to discern in 1991.

Volumetric water content of compacted and control treatments measured on 15-18 August and 18-21 September in 1990 and 1991 is presented in Fig. I.3 and Fig. I.4, respectively. Soil water (cm) at each sampling depth as well as total water (cm) in the 0 to 30-cm soil profile for each treatment is shown in Tables I.1-4. In 1990, significant differences in mid-August soil water content between control and compacted treatments were observed to a depth of 10 cm in the plow system and to 6 cm in the stubble mulch system, resulting from the increased bulk density and reduced thickness of the dust mulch layer caused by compaction (Tables I.1 and 2). Compaction increased mid-August total water in the top 30 cm of the soil by 0.48 cm in the plow tillage and 0.27 cm in the stubble mulch tillage over control treatments. Because of the precipitation which occurred during the 1990 study period, all treatments held more water at the end of the study period than in mid-August, thus reducing the usefulness of the 1990 data for the purpose of this study.

In 1991, significant increases in mid-August volumetric water content were measured in compacted versus control treatments to a depth of 8 cm in both the plow and stubble mulch systems (Tables I.3 and I.4). Total water (cm) in the 0 to 30 cm depth of compacted plots was increased by 0.25 cm in the plow tillage and 0.27 cm in the stubble mulch tillage over control treatments. Water loss occurred at a much faster rate from compacted than from control plots. The plow compacted treatment lost 0.58 cm of 0 to-30 cm soil water between 15 August and 18 September whereas only 0.35 cm of soil water was lost from the plow control treatment. Similarly, 0.64 cm of 0 to 30-cm soil water in the stubble mulch compacted treatment was lost between 15 August and 18 September, whereas the control treatment lost only 0.29 cm. Water in the moist soil below rodweeding depth in both the compacted plow and stubble mulch systems was slightly greater than that of control treatments in August, but less than that of control treatments in September (Fig. I.4).

The results from this experiment lead us to hypothesize that the thermal conductivity of compacted treatments was higher than control plots and that the increased vapor pressure gradient was responsible for accelerated water loss from compacted plots between mid-August and mid-September. This is opposite to our original thoughts which were that the compaction effects of reduced soil porosity and increased tortuosity might outweigh those of increased thermal conductivity.

CONCLUSIONS

Although water loss occurred at a faster rate from compacted treatments, the initial effect of compaction was to significantly increase the volumetric water content to a soil depth as great as 10 cm. This could have important practical implications for wheat producers in semiarid regions of the Pacific Northwest. Growers often postpone planting winter wheat past the optimum sowing date due to insufficient seedzone water. The seedzone generally extends down to 15 cm. In a relatively dry soil, small increases in water content can produce marked increases in wheat germination and emergence rate

(Hanks and Thorp, 1956). During years of marginal seedzone water, compacting the soil surface immediately before planting may possibly result in enhanced seed germination and emergence. Rate of seedzone water loss after planting on compacted soils could be less than measured in the experiment because diurnal temperature flux is reduced during late September and October. Once wheat seedlings have emerged, the risk of drought injury is reduced since roots penetrate to deeper water and the quantity of precipitation normally increases in early October.

Growers commonly conduct a final rodweeding operation immediately prior to seeding wheat to insure a weed-free seedbed. The roller used in the experiment was pulled behind a rodweeder because, we feel, grower acceptance of new technology is largely contingent on how well the technology fits within their accustomed field practices. A farm-scale roller could be: (1) fabricated at a relatively low cost; (2) easily pulled by conventional tractors, and; (3) hitched behind a rodweeder during the normal weeding operation prior to seeding, therefore requiring no additional field operations by the grower.

Compacting the surface of a dust mulch with a roller is a concept which has some potential for increasing economic returns for growers in the wheat-fallow production regions of the Pacific Northwest, thus further testing of this concept appears warranted. Logical extensions of this research might include the effects of various levels of soil surface compaction by a roller on: (1) soil susceptibility to wind and water erosion, and; (2) the rate of wheat seed germination and emergence, and quality of stand establishment.

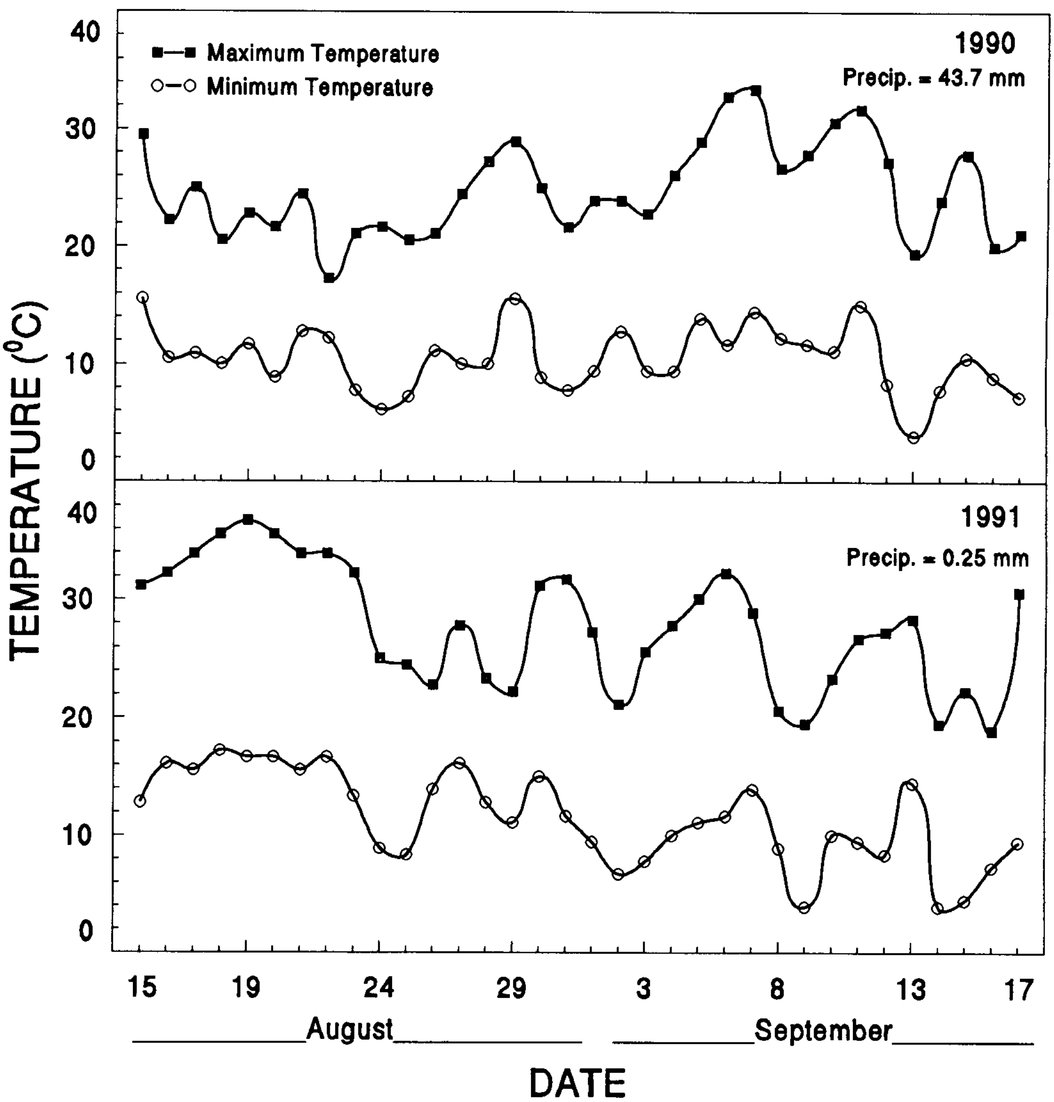


Figure I.1. Maximum and minimum air temperatures between August 15 - September 18 at the Sherman Experiment Station in Moro, Oregon.

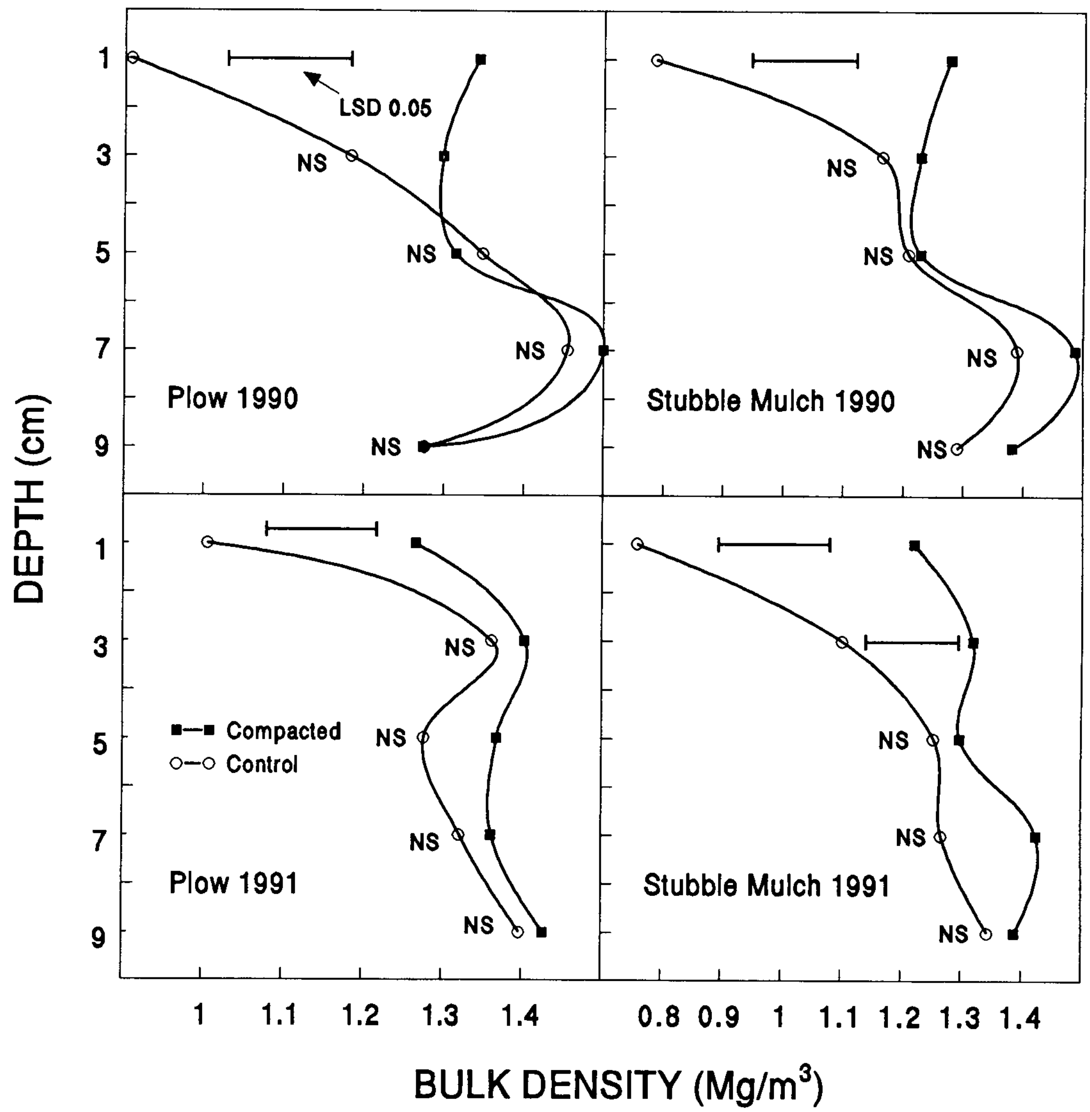


Figure I.2. Soil bulk density in the surface 10 cm of plow and stubble mulch tillage systems as affected by compaction.

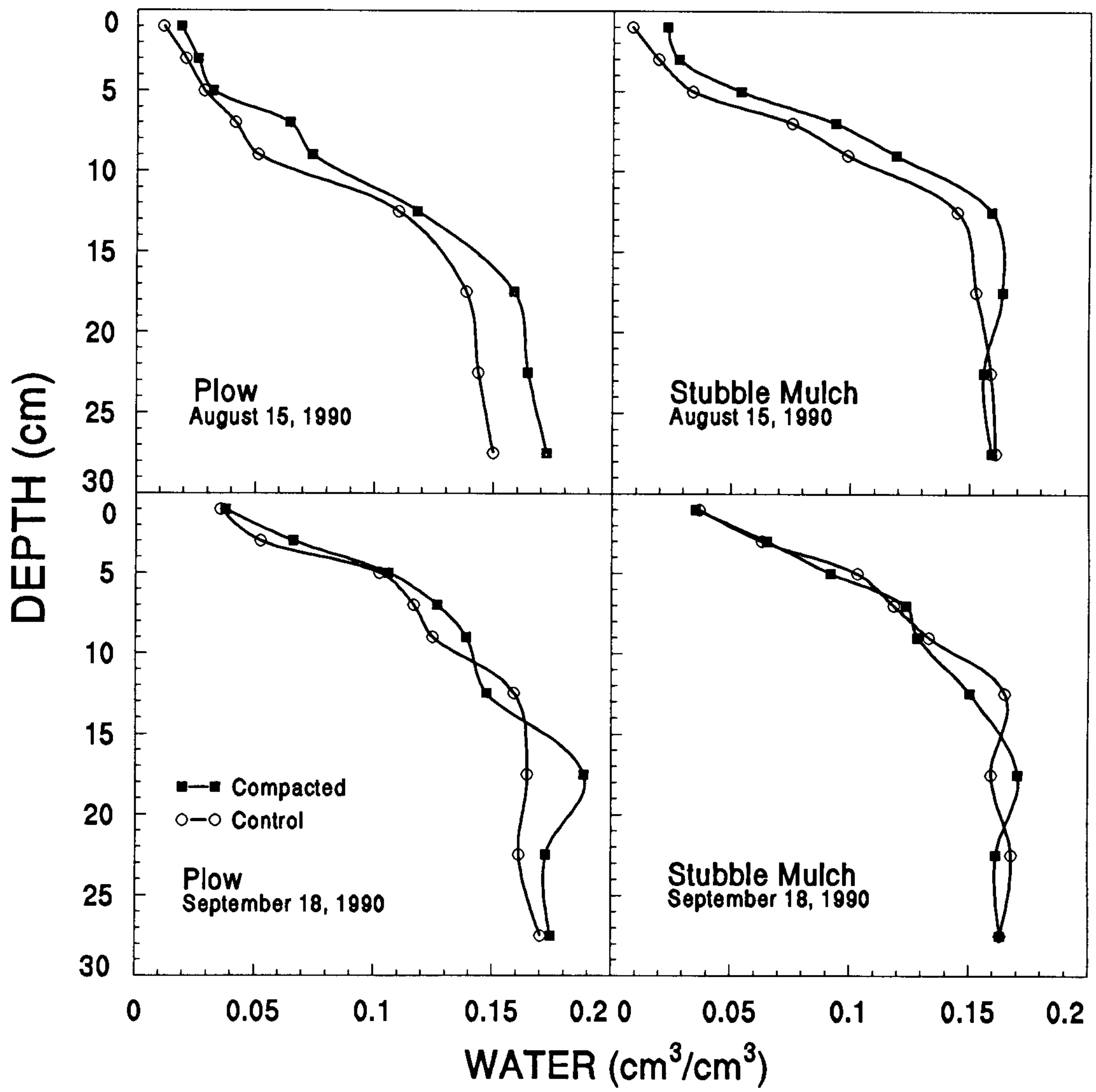


Figure I.3. Soil water in the surface 30 cm of plow and stubble mulch tillage systems as affected by compaction in 1990.

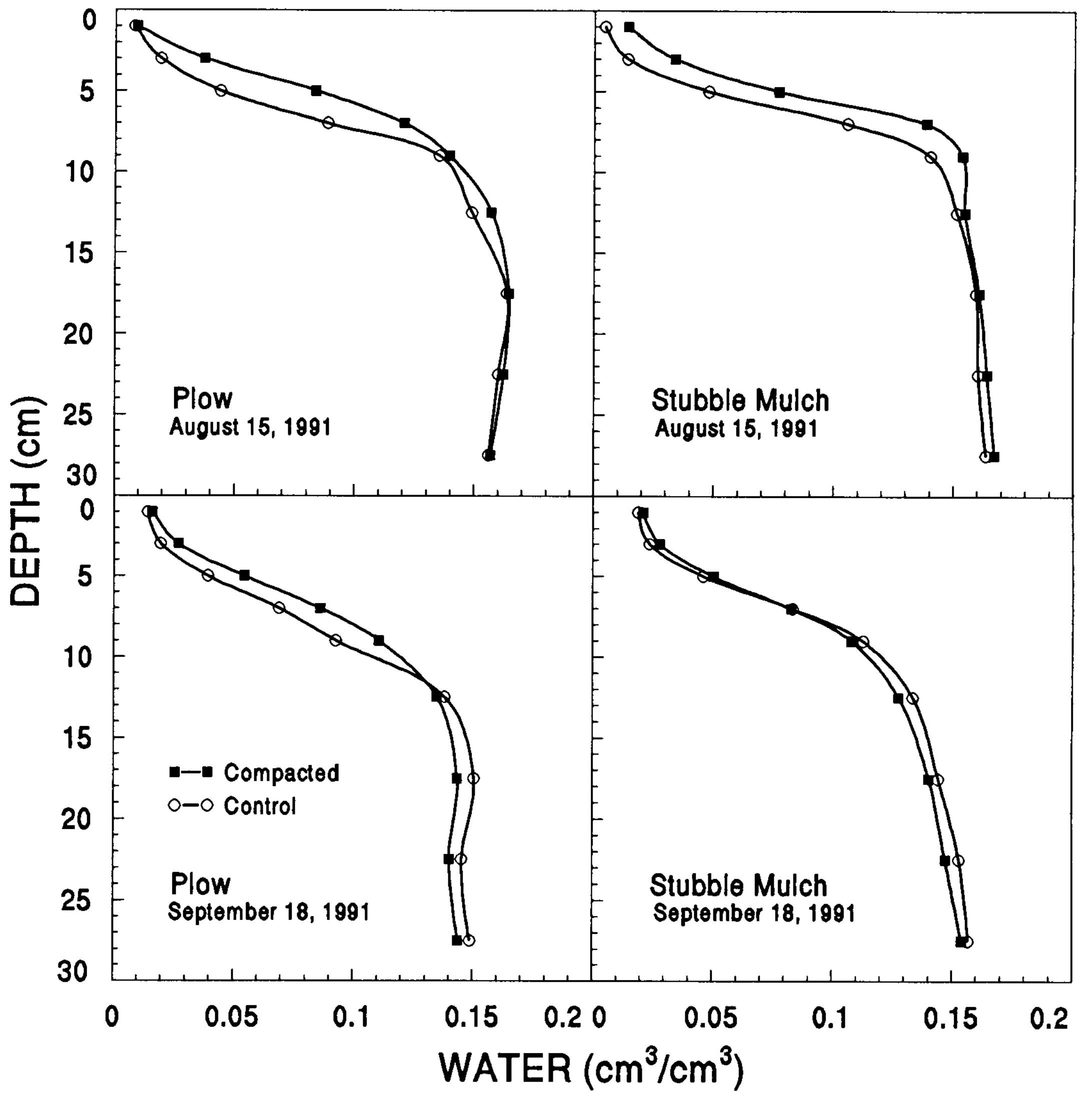


Figure I.4. Soil water in the surface 30 cm of plow and stubble mulch tillage systems as affected by compaction in 1991.

Table I.1. Water (cm) in the top 30 cm of moldboard plow summer fallow as affected by compaction in 1990.

Depth (cm)	Compacted August 15	Control August 15	Compacted Sept. 18	Control Sept. 18	P-Value
0-2	0.0371	0.022	0.0385	0.0533	.0932
2-4	0.0509 a [1]	0.0410 a	0.1326 b	0.1049 b	.0015
4-6	0.0636 a	0.0566 a	0.2122 b	0.2048 b	.0000
6-8	0.1284 a	0.0827 b	0.2532 c	0.2334 c	.0000
8-10	0.1471 a	0.1019 b	0.2778 c	0.2494 c	.0000
10-15	0.5880	0.5490	0.7375	0.7950	.1052
15-20	0.7925	0.6915	0.9415	0.8230	.0586
20-25	0.8220	0.7180	0.8625	0.8060	.1310
25-30	0.8620	0.7490	0.8725	0.8510	.2307
Total	3.4916 ab	3.0121 a	4.3283 b	4.1208 ab	.0000

[1] Within row means followed by the same letter are not significantly different at $P = 0.05$.

Table I.2. Water (cm) in the top 30 cm of stubble mulch summer fallow as affected by compaction in 1990.

Depth (cm)	Compacted August 15	Control August 15	Compacted Sept. 18	Control Sept. 18	P-Value
0-2	0.0456 a [1]	0.0161 b	0.0706 c	0.0735 c	.0000
2-4	0.0549 a	0.0376 a	0.1301 b	0.1263 b	.0000
4-6	0.1072 a	0.0666 b	0.1841 c	0.2062 b	.0000
6-8	0.1864	0.1500	0.2468	0.2368	.0828
8-10	0.2376	0.1969	0.2568	0.2662	.0712
10-15	0.7935	0.7220	0.7510	0.8250	.5165
15-20	0.8180	0.7625	0.8525	0.7965	.1339
20-25	0.7790	0.7945	0.8075	0.8390	.6784
25-30	0.7960	0.8040	0.8155	0.8160	.7707
Total	3.8182 a	3.5502 a	4.1149 b	4.1855 b	.0011

[1] Within row means followed by the same letter are not significantly different at $P = 0.05$.

Table I.3. Water (cm) in the top 30 cm of moldboard plow summer fallow as affected by compaction in 1991.

Depth (cm)	Compacted August 15	Control August 15	Compacted Sept. 18	Control Sept. 18	P-Value
0-2	0.0185 a [1]	0.0160 a	0.0323 b	0.0222 b	.0149
2-4	0.0747 a	0.0383 b	0.0543 ab	0.0395 b	.0000
4-6	0.1673 a	0.0877 b	0.1093 b	0.0790 b	.0003
6-8	0.2408 a	0.1772 b	0.1772 b	0.1383 b	.0141
8-10	0.2790 a	0.2704 a	0.2210 b	0.1852 b	.0021
10-15	0.7850 a	0.7435 a	0.6740 b	0.6900 b	.0001
15-20	0.8220 a	0.8180 a	0.7175 b	0.7520 b	.0019
20-25	0.8105 a	0.8000 a	0.7010 b	0.7270 b	.0001
25-30	0.7850	0.7800	0.7190	0.7435	.0827
Total	3.9828	3.7311	3.4006	3.3767	.0717

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

Table I.4. Water (cm) in the top 30 cm of stubble mulch summer fallow as affected by compaction in 1991.

Depth (cm)	Compacted August 15	Control August 15	Compacted Sept. 18	Control Sept. 18	P-Value
0-2	0.0284 a [1]	0.0086 b	0.0418 c	0.0380 c	.0000
2-4	0.0673 a	0.0278 b	0.0562 ac	0.0475 c	.0030
4-6	0.1537 a	0.0957 b	0.1012 b	0.0926 b	.0083
6-8	0.2772 a	0.2112 b	0.1654 b	0.1667 b	.0044
8-10	0.3068 a	0.2802 a	0.2160 b	0.2254 b	.0003
10-15	0.7720 a	0.7555 a	0.6375 b	0.6675 b	.0000
15-20	0.8030 a	0.7960 a	0.7005 b	0.7205 b	.0000
20-25	0.8205 a	0.8020 a	0.7360 b	0.7645 b	.0001
25-30	0.8355 a	0.8100 a	0.7695 b	0.7835 b	.0022
Total	4.0644	3.7950	3.4241	3.5062	.0751

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

REFERENCES

Boersma, L., and T.L. Jackson. 1977. Fundamentals of water conservation practices used in the summer fallow system of farming. In: Proceedings of An International Symposium on Rainfed Agriculture in Semiarid Regions. April 17-22. pp. 219-245.

Hammel, J.E., R.I. Papendick, and G.S. Campbell. 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. Soil Sci. Soc. Am. J. 45:1016-1022.

Hanks, R.J., and F.C. Thorp. 1956. Seedling emergence of wheat as related to soil moisture content, bulk density, oxygen diffusion rate, and crust strength. Soil Sci. Soc. Amer. Proc. 20:307-310.

Hillel, D. 1982. Introduction to soil physics. Academic Press. New York.

Marshall, .J., and J.W. Holmes. 1988. Soil physics. Cambridge University Press. Cambridge.

Noori, F., F.E. Bolton, and D.N. Moss. 1985. Water injection at seeding of winter wheat. Agron. J. 77:906-908.

Papendick, R.I., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in eastern Washington. Soil Sci. Soc. Am. Proc. 37:307-314.

Pikul, J.L, Jr., R.R. Allmaras, and G.E. Fischbacher. 1979. Incremental soil sampler for use in summer-fallowed soils. Soil Sci. Soc. Am. J. 43:425-427.

Pikul, J.L., Jr., R.R. Allmaras, and S.E. Waldman. 1985. Late season heat flux and water distribution in summer-fallowed Haploxerolls. Soil Sci. Soc. Am. J. 49:1517-1522.

Russel, E.W. 1973. Soil conditions and plant growth. Longman Publishers. New York

Russelle, M.P. 1979. Soil moisture and temperature relationships under fallow in eastern Oregon. M.S. Thesis. Crop Science Department. Oregon State University.

MANUSCRIPT II

Summer Fallow Water Storage of No-tillage Versus Conventional Tillage in the Pacific Northwest

Summer Fallow Water Storage of No-tillage Versus Conventional Tillage in the Pacific Northwest

ABSTRACT

Information comparing fallow soil water storage of no-tillage to conventional tillage methods in the semiarid winter wheat (*Triticum aestivum* L.) production areas of the Pacific Northwest is limited. Soil water storage in a long-term tillage trial comparing no-tillage, moldboard plowing, and stubble mulch tillage was measured during two 14-month fallow periods in a 290 mm annual precipitation area in eastern Oregon. The tillage plots were established in 1981, therefore, soil biological and physical conditions within treatments were assumed near equilibrium. The greatest fallow efficiency during both years was achieved by stubble mulch tillage, followed by plowing and no-tillage. Increased water loss from no-tillage fallow occurred during the hot-dry summer due to uninterrupted capillary flow. Seedzone water content of no-tillage at time of planting in the fall was significantly reduced compared to conventionally tilled plots. Unlike the summer rainfall areas of the semiarid Great Plains, where no-tillage fallow often maximizes water storage, accelerated soil water loss during the summer severely limits the scope of no-tillage technology for summer fallowed soils in the semiarid Pacific Northwest.

Additional Index Words: fallow efficiency, winter wheat, chemical fallow.

INTRODUCTION

Water is a major limiting factor in the winter wheat production areas of the semiarid Pacific Northwest. Tillage operations conducted in the wheat-fallow cropping system in this region are designed to maximize soil water retention during the fallow season. The fallow period begins after harvest (July and August) and continues 14 months until wheat is planted in September and October. Soil water recharge occurs during the fallow winter when temperature and evaporation are low and precipitation is maximum. There has been increasing interest in no-tillage technology because it reduces soil erosion and has potential to reduce labor, fuel, and machinery costs. The effects of no-tillage on fallow water retention in the Pacific Northwest has received little attention and needs further investigation.

The physical processes governing evaporation of water from fallowed soils are well accepted. It is recognized that evaporation occurs in three stages. In the first stage, water loss is relatively high because evaporation occurs at about the same rate as from a free water surface (Marshal and Holmes, 1988). This stage lasts as long as the water flow rate to the surface equals the loss rate by evaporation. Retardation of evaporation during the first stage can enhance the process of redistribution and allow more water to migrate downward in the soil profile where it is conserved longer and is less likely to be lost by evaporation (Hillel, 1971). No-tillage and minimum-tillage systems, in which plant residues are maintained on or near the soil surface, exert the greatest influence during the first stage of drying. Relatively small amounts of surface residues reduce evaporation by: (1) reflecting sunlight which would otherwise be absorbed as heat; (2) acting as a thermal insulator to limit the flow of heat from the atmosphere to the soil, and; (3) reducing turbulent air exchange by creating a dead air space above the soil surface which reduces the transfer rate of water vapor from the soil to the atmosphere (Papendick and Campbell, 1974).

When evaporation rate exceeds flow rate to the surface, the soil surface begins to dry and the second stage of evaporation begins. In the second stage, the water loss rate sharply declines as evaporation is limited by the rate at which the drying soil profile can deliver water to the evaporation site. The effect of surface residue during this stage is slight because evaporation rate now depends on diffusivity and conductivity of the soil with depth (i.e. by thermal and water flow properties of the dry soil layer) (Hillel, 1982). Loosening the soil surface with tillage during this stage of drying disrupts capillary continuity to the surface and hastens the formation of a dry layer which increases resistance to upward liquid flow. In addition, tillage decreases thermal conductivity of the soil which reduces the amount of heat available for evaporation (Papendick and Campbell, 1974). As drying continues, the amount of water moving to the soil surface decreases but the fraction of water moving as vapor increases. When the surface soil has air-dried, the third stage of evaporation begins. This stage is characterized by a low and relatively constant evaporation rate because water can no longer move to the surface as a liquid. The zone of evaporation is now below the surface and water will move only as vapor through the dried surface layer (Idso et al., 1974).

The effects of no-tillage fallow compared to conventional tillage methods on water conservation have been extensively studied in the semiarid Great Plains region. Maintaining crop residues on the soil surface during the fallow period increases water infiltration rate and reduces evaporation, often resulting in increased water storage compared to bare soil. No-tillage fallow often maximizes water storage in the Great Plains region (Fenster and Peterson, 1979; Wicks and Smika, 1973; Smika and Wicks, 1968; Smika, 1990).

In contrast to the Great Plains, where the majority of precipitation occurs during summer months, the semiarid regions of the Pacific Northwest receive about 70% of total precipitation between November and April. Summers are dry. While summer rainfall can significantly contribute to stored soil water in the Great Plains, in the semiarid Pacific Northwest, summer rainfall only temporarily retards evaporation from stored soil water (Leggett et al., 1976). Thus, in the Great Plains, one must consider evaporation and infiltration as concurrent processes when evaluating the effect of tillage on soil water storage whereas in the Pacific Northwest, infiltration is of little concern during periods of high potential evaporation (Papendick et al., 1973). Because of these different precipitation patterns, much of the knowledge generated from tillage research on fallow water retention in the Great Plains is not applicable under Pacific Northwest conditions.

Dryland winter wheat conservation tillage research in the Pacific Northwest has mainly focused on comparisons of moldboard plow versus various minimum-tillage stubble mulch systems. Papendick and Miller (1977) reported that stubble mulching conserves more soil water compared to bare soil. Massee and McKay (1979) reported that while stubble mulching will result in cooler soil and lower initial water evaporation rate, mulched soils may, after sufficient drying time, dry to nearly the same water content as clean fallow. Ramig and Ekin (1991) found no differences in fallow efficiency between plow and stubble mulch tillage systems in a six year study conducted at two locations in eastern Oregon.

Only limited research has been conducted on no-tillage winter wheat production on summer fallowed soils in the Pacific Northwest. Oveson and Appleby (1971) found that total water, both in the seedzone and in the entire 1.8 m profile, was reduced in no-tillage plots compared to conventional spring tilled treatments in a study conducted in a 330 mm annual rainfall area in eastern Oregon. Lindstrom et al. (1974) reported similar results from a study conducted in a 240 mm rainfall zone in eastern Washington where spring tillage was used compared to chemical fallow.

The objectives of this research were to determine rate and extent of soil water loss from no-tillage, stubble mulch, and moldboard plow fallow systems throughout the fallow season.

MATERIALS AND METHODS

Data reported in this study were collected between October 1989 and September 1991 at Oregon State University's Sherman Experiment Station in Moro, OR. The soil at the experimental site is a Walla Walla silt loam (coarse silty, mixed, mesic, Typic Haploxeroll) overlying basalt bedrock. Average annual precipitation for this location is 290 mm. Precipitation during the 1989-90 and 1990-91 14-month fallow periods was 80% (250 mm) and 94% (294 mm) of normal, respectively. The experimental site has received less than average annual precipitation for the past seven years.

The tillage trial was established in 1981 to evaluate the long-term effects of three fallow management treatments on grain yield. Paired adjacent plots of land were used so that data could be collected each year from both crop and fallow phases of the experiment. Treatments have remained on the same plots since 1981, so soil biological and physical conditions within treatments were assumed to be near equilibrium. The treatments were: (1) moldboard plow in late March to create a bare soil surface, followed by 3 to 4 shallow (5 to 10 cm) rodweedings; (2) sweep plow in late March to create a stubble mulch fallow with approximately 70% of the residue remaining of on the soil surface, followed by 3 to 4 shallow (5 to 10 cm) rodweedings, and; (3) chemical fallow, where weeds were controlled with herbicides and the soil was disturbed only at planting by a strip-till planter (Bolton and Booster, 1981). Rodweeding operations and herbicide applications were made only when needed for weed control. Treatments were replicated four times in a randomized block design with individual plots measuring 41 m x 2.44 m.

Soil water data were collected during each of two 14-month fallow periods (August-October 1989-90 and 1990-91). To increase the precision of the experiment, three access tubes were installed in each plot. Soil volumetric water content of the 30 to 150 cm depth was measured in 30 cm increments with a neutron probe. The volumetric water content of the 0 to 30 cm depth was measured gravimetrically, as described by Gardner (1986), in two 15-cm core samples. Neutron probe electrical system problems were encountered during the spring of 1990, which made it necessary to obtain all subsequent soil water values gravimetrically. One core sample per plot was obtained by a tractor mounted hydraulic soil probe. During the 1990-91 fallow season, all 30 to 150-cm water values were obtained using the neutron probe. Thus, four and twelve measurements were obtained at each depth per treatment on every sampling date during the 1989-90 and 1990-91 fallow seasons, respectively. Soil bulk density was measured after primary tillage in March, in June, and in August, from core samples taken from the 0 to 15 cm and 15 to 30 cm soil depths during both fallow seasons.

Data were analyzed using analyses of variance for treatment differences in: (A) water content at each sampling depth; (B) total water in the 150 cm soil profile, and; (C) treatment x soil profile depth interaction. Treatments were considered significantly different if the P-Value was < 0.05. Differences in treatment means were separated using Fisher's Protected Least Significant Difference (FPLSD).

RESULTS AND DISCUSSION

Between Year Over-Winter Fallow Efficiency

Soil water storage and fallow efficiency (FE) during two fallow seasons as affected by tillage system are presented Tables II.1 and II.2. In the 1989-90 fallow cycle, 124 mm of precipitation fell between 1 October and time of first sampling in mid-March. Treatment FE ranged from 73% to 79% (Table II.1). In the 1990-91 fallow cycle, 140 mm of precipitation fell during the same time period and FE ranged from 42% to 57% (Table II.2). The large difference in between year over-winter FE can perhaps be explained by a comparison of the climatic conditions. The most obvious differences between the two winters were temperature and distribution of precipitation. Record setting low temperatures in December 1990 froze the soil at the 10 cm depth for 23 d and at the 30 cm depth for 46 d. Differences in FE between years may possibly be due to reduced infiltration during the extended soil freeze during the 1990-91 cycle, although observed water runoff was minimal.

Table II.3 shows monthly precipitation, percent of monthly precipitation occurring in amounts > 5 mm/d, and average monthly wind speed (km/hr) from October to March during both fallow seasons. In 1989-90, 81% of over-winter precipitation had occurred by the end of

January, compared to only 63% during the same time period in 1990-91. Papendick and Campbell (1974) reported that first stage evaporative losses can be especially high during late winter and early spring when temperature is increasing. Precipitation falling during late winter and early spring will therefore likely be evaporated to a greater extent than precipitation occurring during early to mid-winter.

Average wind speeds during January and February 1990 were high, but did not appear to have much effect on over-winter FE, perhaps because February 1990 precipitation was very low.

Although unclear, it is most likely that the differences in over-winter FE between the two years can be attributed to distribution of over-winter precipitation. FE was low during 1990-91 possibly because 37% of over-winter precipitation occurred after January when it was less effectively stored than that precipitation occurring earlier.

Table II.1. Water (cm) and fallow efficiency (FE) in 150 cm soil profile as affected by tillage system during the 1989-90 fallow season.

	Tillage Treatment						
	Plow		Stubble Mulch		No-tillage		
Date	Water[1]	FE	Water	FE	Water	FE	P-Value
10-6-89	12.51 a	—	12.16 b	—	11.73 c	—	.0240
3-20-90	21.84 ab	73	22.23 a	79	21.36 b	75	.0004
5-15-90	20.78 ab	51	21.23 a	56	19.68 b	49	.0475
6-03-90	21.02	43	22.66	53	21.52	49	.2266
7-19-90	20.53 a	38	21.66 b	45	17.78 c	29	.0001
9-15-90	20.36 a	31	21.51 b	37	18.56 c	29	.0198

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

FE = Fallow Efficiency % = (Net gain soil water, cm / Fallow precipitation, cm) X 100.

Table II.2. Water (cm) and fallow efficiency (FE) in 150 cm soil profile as affected by tillage system during the 1990-91 fallow season.

	Tillage Treatment						
	Plow		Stubble Mulch		No-tillage		
Date	Water[1]	FE	Water	FE	Water	FE	P-Value
7-17-90	11.53 a	—	11.66 a	—	12.89 b	—	.0003
3-20-91	19.15 a	44	21.53 b	57	20.14 c	42	.0003
4-25-91	16.83 a	28	18.81 b	37	17.86 c	26	.0000
5-18-91	17.20 a	27	18.98 b	34	19.02 b	29	.0000
6-06-91	16.70 a	24	18.19 b	30	18.04 b	23	.0002
7-24-91	16.68 a	20	18.07 b	25	16.67 a	15	.0000
8-16-91	16.37 a	19	17.46 b	22	16.47 a	14	.0000
9-20-91	15.75 a	16	16.92 b	20	15.81 a	11	.0000

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

FE = Fallow Efficiency % = (Net gain soil water, cm / Fallow precipitation, cm) X 100.

Table II.3. Monthly precipitation, percentage of monthly precipitation occurring in events of more than 5 mm, and average monthly wind speed, for October through March during two fallow seasons.

	1989-90			1990-91		
Month	Precip. (mm)	Precip. > 5 mm/d	Wind km/hr	Precip. (mm)	Precip. > 5 mm/d	Wind km/hr
Oct.	15.0	0%	5.80	32.3	84%	5.96
Nov.	24.4	66%	7.24	15.5	51%	7.73
Dec.	12.2	62%	4.19	18.8	39%	5.47
Jan.	48.5	60%	9.26	22.1	80%	4.67
Feb.	4.3	0%	8.85	15.2	42%	4.83
Mar.	19.3	0%	6.12	36.3	61%	6.44

Tillage Effects

Soil water storage during two fallow seasons as affected by tillage system are presented in Figs. II.1 and II.2 and Tables II.1 and II.2. During both years, initial soil water was low at time of harvest (beginning of fallow). Differences among treatments at the beginning of fallow were small. By early spring, prior to primary tillage, differences were more evident. Over-winter FE was highest for the stubble mulch treatment during both years of the study. There was little difference in over-winter FE between plow and no-tillage during either year. Although the amount of current year crop residue (residue from the most recent crop) was similar for plow and stubble mulch treatments during both fallow seasons, residual soil surface residue (undecomposed from previous crop years) in the stubble mulch system was apparently responsible for reducing heat flow and turbulent air exchange, thus diminishing first stage evaporation and increasing over-winter FE compared to the plow system. The similarity in over-winter FE between the plow and no-tillage treatments was most adequately explained by greater quantities of current season residue in the plow treatment balancing the effect of more residual surface residue, but less current season residue, in the no-tillage system. It was also possible that a tillage pan in plow treatment restricted water infiltration to some degree, thereby increasing the amount of water retained near the surface where it was more subject to evaporation.

Following primary tillage of the plow and stubble mulch treatments in late March, capillary continuity with the deeper soil was broken which hastened the first stage of drying. Vapor flow replaces liquid flow as the primary fraction of water moving to the soil surface at this stage, and the dry surface layer now controls the evaporation rate while the residue effect is secondary. Differences in over-winter seedzone water accumulation between stubble mulch and plow treatments gradually diminished during the spring and summer until, at the end of fallow in both years, there were no differences in 0 to 30-cm water (Fig. II.1 and Fig. II.2). Total profile water and FE, however, were significantly higher in stubble mulch than in the plow treatment at the end of both fallow seasons. This indicates that the larger quantity of water which migrated into the lower soil profile due to the extended first stage drying in the stubble mulch treatment was effectively stored throughout the fallow season.

The no-tillage system lost both seedzone and total profile water at an increased rate during the hot, dry summer months. Short-term retention of spring season precipitation was highest for no-tillage following primary tillage of the plow and stubble mulch treatments in late March (Fig. II.1 and Fig. II.2). Surface residues, however, are less important than tillage for water conservation as the frequency of rainfall decreases. Loss of water from the no-tillage treatment was hastened during both summers by soil capillary continuity whereas the continuity of the capillary channels in conducting water from the subsoil to the soil surface were effectively broken in the plow and stubble mulch treatments (Fig. II.1 and Fig. II.2). No-tillage had the lowest FE during both years (Table II.1 and Table II.2).

Heavy rainfall occurring in late August minimized treatment differences in 0 to 30-cm water at the end of the fallow period in 1990 (Fig. II.3). Diminished seedzone water in the no-tillage treatment was readily apparent in 1991. Insufficient seedzone water is a major limitation to establishment of fall-sown wheat in the semiarid Pacific Northwest. Small increases in seedzone water content can produce a marked increase in wheat germination and emergence. Low FE and accelerated seedzone water loss would appear to limit the potential for no-tillage technology on summer fallowed soils in the semiarid Pacific Northwest.

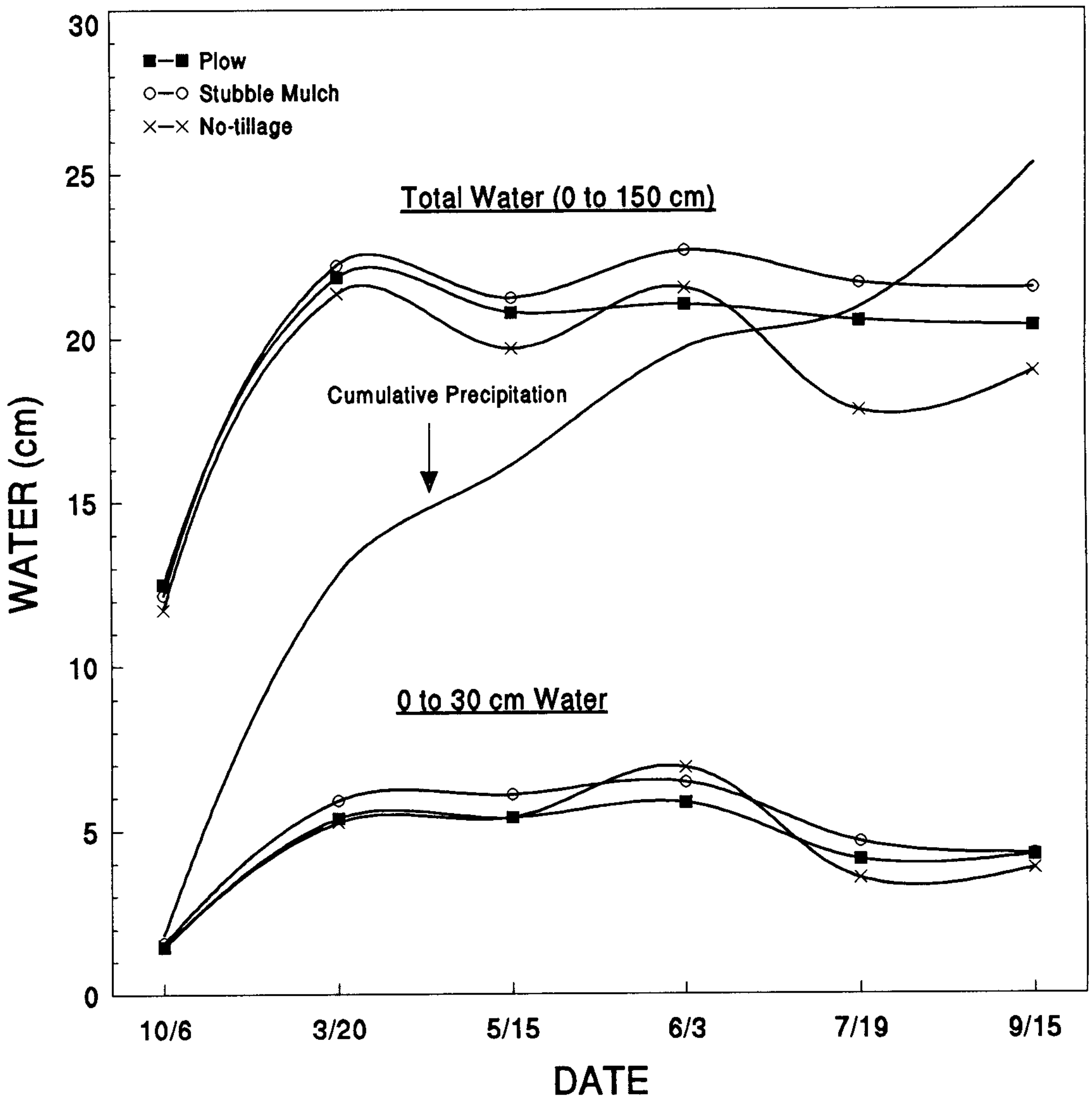


Figure II.1. Soil water (cm) as affected by tillage method during the 1989-90 fallow season.

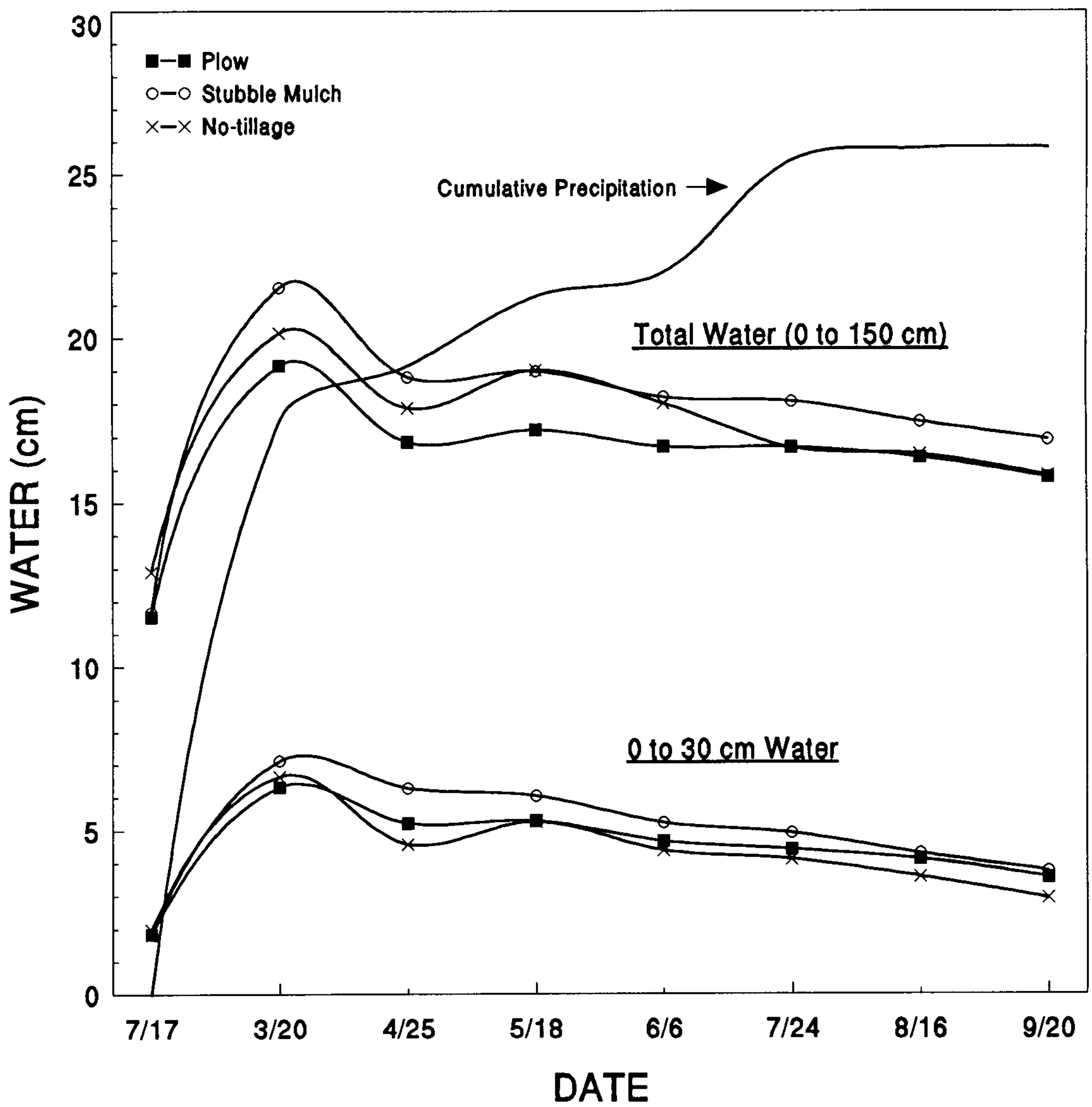


Figure II.2. Soil water (cm) as affected by tillage method during the 1990-91 fallow season.

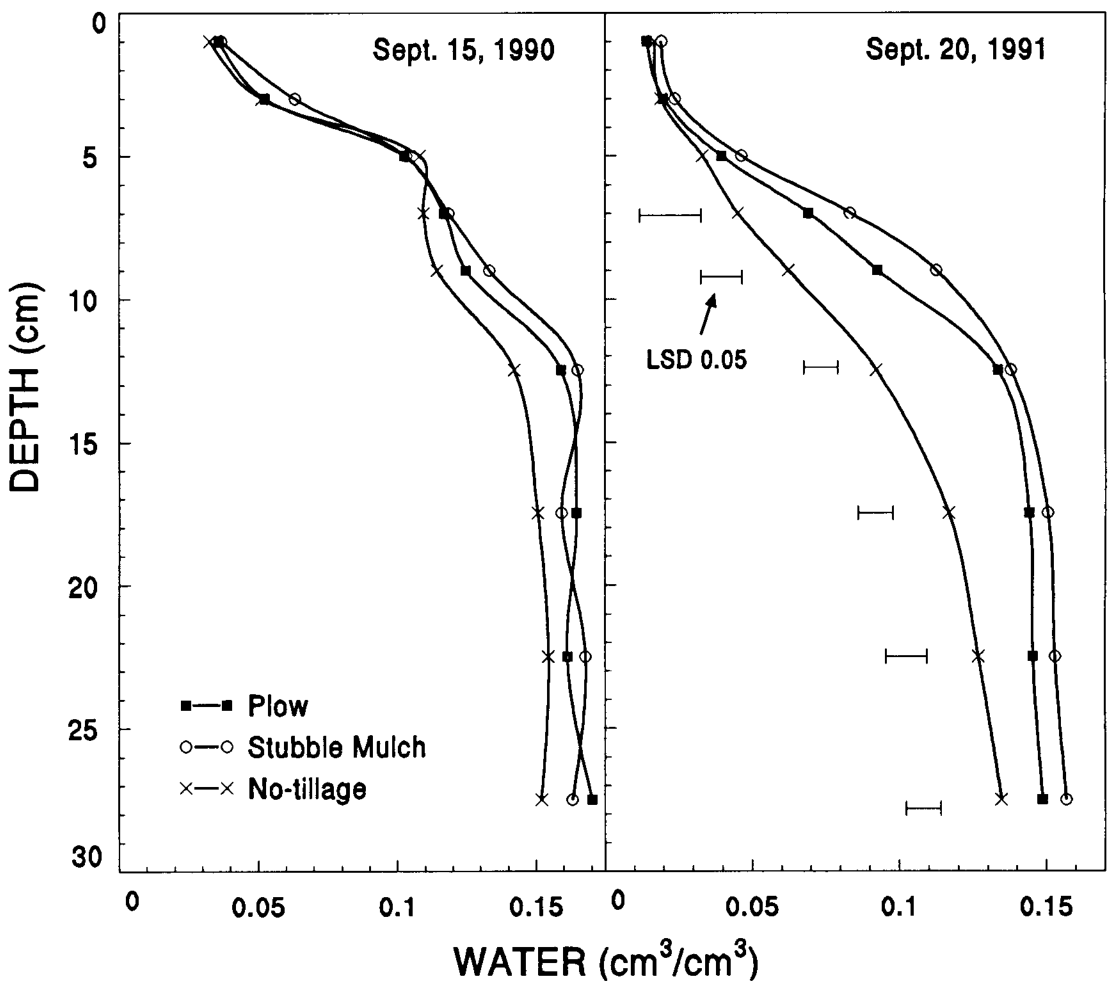


Figure II.3. 0 to 30-cm soil water as affected by tillage system at the end of the 1989-90 and 1990-91 fallow seasons.

REFERENCES

Bolton, F.E. and D.E. Booster. 1981. Strip-till planting in dryland cereal production. Transactions of the ASAE 24(1):59-62.

Fenster, C.R. and G.A. Peterson. 1979. Effects of no-tillage compared to conventional tillage in a wheat-fallow system. Nebraska Agric. Exp. Stn. Res. Bull. 289.

Gardner, W.H. 1986. Water content. In: Methods of soil analysis; Part 1 - Physical and mineralogical methods. American Society of Agronomy Monograph No. 9. Madison, Wisconsin.

Hillel, D. 1971. Soil and water: physical principles and processes. Academic Press. New York.

Hillel, D. 1982. Introduction to soil physics. Academic Press. New York.

Idso, S.B., R.J. Reginato, R.D. Jackson, B.A. Kimball, and F.S. Nakayama. 1974. The three stages of drying of a field soil. SSSA Proc. 38:831-837.

Leggett, G.E., R.E. Ramig, L.C. Johnson, and T.W. Massee. 1976. Summer fallow in the Northwest. In: Summer fallow in the United States 6:110-135. USDA Special Publication.

Lindstrom, M.J., F.E. Koehler, and R.I. Papendick. 1974. Tillage effects on fallow water storage in the Eastern Washington dryland region. Agron. J. 66:312-316.

Marshall, T.J. and J.W. Holmes. 1988. Soil Physics. Cambridge University Press. Cambridge.

Massee T. and H. McKay. 1979. Improving dryland wheat production in eastern Idaho with tillage and cropping methods. University of Idaho Agricultural Experiment Station Bulletin No. 581.

Oveson, M.M. and A.P. Appleby. 1971. Influence of tillage management in a stubble mulch fallow-winter wheat rotation with herbicide weed control. Agron. J. 63:19-20.

Papendick, R.I. and G.S. Campbell. 1974. Wheat-fallow agriculture: why, how, when? In: 2nd regional wheat workshop. Ankara, Turkey.

Papendick, R.I., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in Eastern Washington. Soil Sci. Soc. Amer. Proc. 37:307-314.

Papendick, R.I. and D.E. Miller. 1977. Conservation tillage in the Pacific Northwest. J. Soil Water Cons. Jan.-Feb. 49-56.

Ramig, R.E. and L.G. Ekin. 1991. When do we store water with fallow? 1991 Columbia Basin Agric. Res., Oregon Agric Expt. Stn. Special Report 860. pp. 56-60.

Smika, D.E. 1990. Fallow management practices for wheat production in the central Great Plains. Agron. J. 82:319-323.

Smika, D.E. and G.A. Wicks. 1968. Soil water storage during fallow in the Central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Amer. Proc. 32:591-595.

Wicks, G.A. and D.E. Smika. 1973. Chemical fallow in a winter wheat-fallow rotation. Weed Science 21 (2) 97-102.

MANUSCRIPT III

Development and Yield Components of Dryland Winter Wheat as Affected by Tillage Method

Development and Yield Components of Dryland Winter Wheat as Affected by Tillage Method

ABSTRACT

No-tillage winter wheat (Triticum aestivum L.) grown under a wheat-fallow rotation has consistently produced lower grain yields than conventionally tilled soils in the semi-arid Pacific Northwest. A 2-year study was conducted in a long-term tillage trial at Moro, OR to determine factors responsible for differences in wheat growth and yield as affected by moldboard plow tillage, stubble mulch tillage, and no-tillage. The tillage plots were established in 1981. Soil biological and physical conditions within treatments were assumed to be near equilibrium. Soil water, soil mineral N, plant N, soil temperature, and above-ground dry matter (DM) production were measured at seeding and at several plant development stages. During both years, reduced seedzone water at seeding adversely affected germination and stand establishment in the no-tillage treatment. The moldboard plow treatment attained vigorous fall stands and had the most rapid accumulation of DM. This resulted in early depletion of available soil water and some reduction in grain yield due to post-anthesis water stress. Germination, stand establishment, and DM production in the stubble mulch treatment were reduced compared to the plow treatment, but slower rate of water use resulted in less post-anthesis water stress and slightly higher grain yield than the plow treatment. Early spring 5-cm soil temperatures were highest for the plow, averaging about 0.5 ^{0}C and 3.0 ^{0}C warmer than the stubble

mulch and no-tillage treatments, respectively. Available soil water was depleted in the plow and stubble mulch treatments at time of harvest, whereas the no-tillage treatment did not utilize all available water in either year. This experiment suggests that the main yield limitations for no-tillage technology in the wheat-fallow production regions of the Pacific Northwest may be: (1) diminished seedzone water at time of planting which results in reduced germination and stand establishment; (2) cooler spring soil temperatures which slows crop development and DM accumulation and; (3) production of fewer spikes per unit area.

Additional Index Words: conservation tillage, no-tillage, Pacific Northwest.

INTRODUCTION

Winter wheat production in the semiarid Pacific Northwest is limited primarily by water and nitrogen, both of which are affected by tillage practices. When water is limiting, germination, plant stand establishment, plant growth, and crop yield are all related quantitatively to the water supply. Leggett (1959) reported that approximately 100 mm of soil water was required to grow a wheat crop to the point where grain production begins.

Water commonly becomes limiting to the wheat plant in the semiarid Pacific Northwest at anthesis. Environmental conditions before anthesis influence both number and size of spikes in wheat, and thus determine the potential number of grains. Conditions at anthesis and a few days thereafter determine how many grains are set. Water stress at this stage will reduce the number of kernels because of dehydration of pollen grains. Pollen grain germination and pollen tube growth down the style into ovary and ovule are also affected (Arnon, 1972). Wardlaw (1971) reported that water deficit during the first 7 days following anthesis severely reduced net photosynthesis in the flag leaf and spike of wheat and that grain weight per spike was significantly reduced. Arnon (1972) reported that when water supply is adequate, spike number per unit area had the greatest effect on grain yield, whereas under water stress, grain number per spike, and occasionally 1000-grain weight affected grain yield as much as spike number per unit area.

Water retention during the fallow period is of critical importance for subsequent wheat growth. Studies conducted in the semiarid Great Plains have shown that no-tillage fallow often maximizes water storage compared to conventional tillage (Fenster and Peterson, 1979; Wicks and Smika, 1973; Smika, 1990). In the Pacific Northwest, where the majority of precipitation occurs in the winter, there is growing evidence that no-tillage fallow stores less total profile water and seedzone water compared to conventionally tilled soils (Oveson and Appleby, 1971; Lindstrom et al. 1974).

Nitrogen cycling, metabolism, and availability to plants are greatly influenced by degree and type of tillage. Tillage, depending on type and degree, incorporates some portion of the crop residue beneath the soil surface which accelerates mineralization of organic

N. In contrast, no-tillage results in the accumulation of residues in surface soil. These residues, which have a high C:N ratio, can immobilize mineral N in the soil surface. Indications of N deficiency or wheat yield limitations have led several workers to conclude that higher rates of fertilizer N are required for no-tillage than for conventionally tilled soils (Doran, 1980; Smith and Howard, 1980; Fredrickson et al., 1982). There is evidence, however, that the N requirement for wheat is nearly the same in no-tillage and conventional tillage provided N fertilizers are placed below the residue layer in no-tillage to avoid microbial immobilization of fertilizer N (Rasmussen, 1983; Rasmussen et al., 1983).

Plant growth is directly related to nutrient and water availability. The rate of development for wheat is directly related to accumulated heat units. For cereals, the temperature at the growing point of the plant is the temperature of interest for predicting plant development (Rickman and Klepper, 1983). The growing point is in the meristem within the crown. Soils under no-tillage management have been reported to have lower daily maximum temperatures than tilled soil (Wall and Stobbe, 1984). Smika and Ellis (1971) reported that wheat plants grown on slowly-warmed soil developed fewer tillers and spikes per plant than did plants grown in soil warmed more rapidly during the spring. Wilkins et al. (1988) reported that increased standing residue changed the plant environment by lowering soil temperature and decreasing photosynthetically-active radiation to the extent that growth of winter wheat was depressed. The objective of this study was to identify factors responsible for grain yield differences as affected by tillage method in a wheat-fallow rotation in eastern Oregon.

MATERIALS AND METHODS

Data reported in this study were collected between October 1989 and September 1991 from the long-term tillage plots at Oregon State University's Sherman Experiment Station at Moro, OR. The tillage plots were established in 1981, therefore, soil biological and physical conditions within treatments were assumed to be near equilibrium. Information on soil type, precipitation, and tillage treatments are given in Manuscript II. Each treatment was replicated four times in a randomized block design with individual plots measuring 41 m x 2.44 m. All data were analyzed by analysis of variance (ANOVA). Treatments were considered significantly different if the P-Value was < 0.05. Differences in treatment means were separated using Fisher's Protected Least Significant Difference (FPLSD).

Fertilization and Seeding

In August 1989, anhydrous ammonia (82% N as NH_3) was injected into the fallowed plow and stubble mulch treatments at a rate of 56 kg N ha^{-1}. The no-tillage treatment was fertilized at the same rate at time of seeding with surface applied Solution 32 mixed with 1.1 kg ha^{-1} atrazine for downy brome (Bromus tectorum) control. Winter wheat (cv. Malcolm) was seeded in 40-cm rows at a rate of 56 kg ha^{-1} on 6 October in all treatments. Deep furrow drills were used to seed the plow and stubble mulch treatments. A strip-till planter was used on the no-tillage treatment. The strip-till planter simultaneously sprays fertilizer N and herbicide uniformly on surface, tills a strip which disturbs about 25% of the soil surface, and plants seed in the tilled strip (Bolton and Booster, 1981).

In 1990, 78 kg N ha^{-1} as Solution 32 mixed with 1.1 kg ha^{-1} atrazine was surface applied to all treatments on 19 September. Plots were seeded on 20 September. All other procedures remained the same as in 1989.

Soil Water Content

Data on soil water status were collected during two 10-month cropping periods. Three neutron probe access tubes were installed to a depth of 150 cm in each plot one d after seeding. Soil volumetric water content of the 30 to 150 cm depth was measured in 30 cm increments with a neutron probe. Volumetric water content of the 0 to 30 cm depth was measured gravimetrically, as described by Gardner (1986), in two 15-cm core samples. Soil water was measured at time of fall planting, and at Feekes Growth Stages (FS) 4 (lengthening of leaf sheath); 5 (leaf sheaths strongly erected); 7 (second node visible); 10 (boot); 10.5 (anthesis) and; 11.4 (ripe for cutting) (Large, 1954). The neutron probe experienced electrical problems during the spring of 1990 which necessitated that all subsequent 1989-90 soil water measurements be obtained gravimetrically, using one core sample per plot obtained by a tractor mounted soil probe. In the 1990-91 cropping period, all 30 to 150 cm water measurements were made using the neutron probe. Thus, three times as many soil water values were obtained in 1990-91 than in 1989-90. This increased the precision of the experiment in 1990-91 compared to 1989-90. Plant leaf temperature, an indicator of water stress, was determined at anthesis during both years with an infrared thermometer.

Soil Nitrogen and Plant Nitrogen Uptake

Soil samples for NO_3^- and NH_4^+ determination were taken at seeding and at FS 4, 5, 7, 10, 10.5, and 11.4. Samples were obtained one d after planting in 1989 (following fertilizer application) and one d before planting (before fertilizer application) in 1990. Samples were divided into 0 to 7.5, 7.5 to 15, 30 to 60, 60 to 90, 90 to 120, and 120 to 150 cm increments. Three 150-cm core samples were taken from each plot, from which one composite sample for each sampling depth was made. All samples were air-dried, ground, and analyzed for 1 M KCL-extractable NH_4^+ and NO_3^- with an Alpkem RFA 300 autoanalyzer.

Plant samples were collected at FS 4, 5, 7, 10, 10.5, and 11.4. In the 1989-90 season, random samples were cut at the soil surface from internal plot rows. Destructive sampling was limited to minimize the effect on plot grain yield. Collection of samples of sufficient size for DM determination was not possible. In the 1990-91 season, duplicate plots were planted to allow for DM determination in randomly selected 1 m row sections at each FS. In 1989-90, leaf and stem portions of plant tissue were divided for separate N analysis. Whole plant samples were used for N analysis in 1990-91. Samples were oven dried at 60 ^{0}C for 48 h, weighed for DM determination, and then ground to pass through a 0.5 mm screen. A LECO CHN-600 carbon-hydrogen-nitrogen analyzer was used for determination of total N (%). Plant N uptake (kg N ha^{-1}) was calculated as the product of [plant tissue N(%) x DM (Mg ha^{-1}) x 1000].

Soil Temperature

Thermistors were inserted at a depth of 5 cm in the seeded furrow of all tillage treatments 2 d after planting during the second year of the study. Soil temperatures were recorded twice daily on an automatic data logger at 03:00 and 15:00 hours. It was assumed that these times would approximate daily minimum and maximum air temperatures. Other climatic data were acquired from the records of a standard U.S. Weather Bureau shelter located less than 1 km from the experimental site.

RESULTS AND DISCUSSION

Surface Soil Nutrient Distribution

The long-term effects of no-tillage resulted in higher levels of surface soil extractable P, mineralizable N, exchangeable K, and organic carbon (Fig. III.1). Accumulation of organic carbon at the soil surface in the no-tillage treatment appears to be largely responsible for differences in extractable soil nutrients. With no-tillage, much of the P and K brought up by the roots and recycled

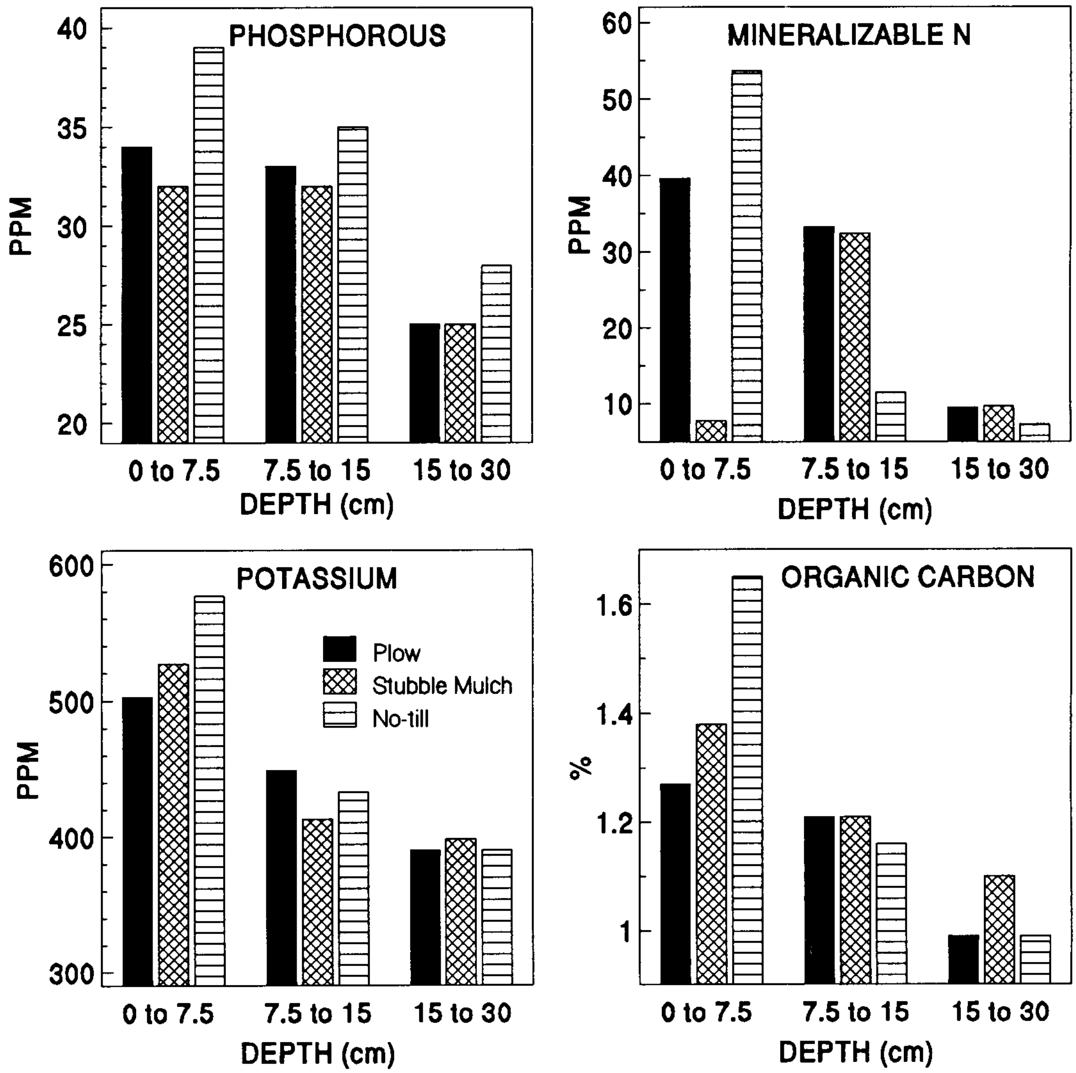


Fig. III.1. Extractable P, mineralizable N, exchangeable K, and organic carbon in the surface soil as affected by tillage method.

into the crop residue tends to become concentrated in the soil surface. In general, no-tillage resulted in increased nutrient concentrations in the surface 0 to 7.5 cm and a rapid decrease with depth. The plow and stubble mulch tillage resulted in more homogeneous soil fertility status in the surface 30 cm. These findings are consistent with those found in the literature (Eckert, 1985; Follett and Peterson, 1988). There were no differences among treatments in surface soil pH (not shown). These results show that changes in soil surface nutrient status can be expected with no-tillage technology.

1989-90 Crop Season

Soil water, soil mineral N, and plant N uptake as affected by tillage system throughout the 1989-90 growing season are presented in Fig III.2. Soil N (NO_3^- + NH_4^+) in the plow treatment at time of planting was nearly 250 kg ha^{-1}, greatly exceeding that found in the other treatments (Fig. III.2C). The reason for these differences is not clear, but an error in the calibration and/or operation of the anhydrous NH_3 applicator seems likely. The no-tillage treatment had 50% and 66% less mineral N in the surface 15 cm at time of planting than the stubble mulch and plow treatments, respectively. The no-tillage treatment was fertilized with surface applied Solution 32 at time of seeding (2 d before soil samples were taken), whereas the other treatments received sub-surface injection of anhydrous ammonia during the summer. The low mineral N content in the surface of the no-tillage treatment soon after fertilizer N application is indicative of short-term immobilization of much of the surface applied fertilizer N by microorganisms due to larger quantities of surface residue in the no-tillage treatment.

Soil mineral N in the plow treatment remained significantly higher than in no-tillage plots until FS 7, and stubble mulch plots through FS 10.5 (Fig. III.2C). Nitrate was depleted in the stubble mulch treatment by FS 7 and in the plow and no-tillage treatments by FS 10 (Fig. III.3). Downy brome infestation was responsible for early N depletion in the stubble mulch treatment. Soil N at FS 10, 10.5 and 11.4 was almost entirely in the form of NH_4^+. Total soil mineral N increased between FS 7 and FS 10 in all treatments, indicating that mineralization of organic N exceeded plant uptake of N after FS 7.

The stubble mulch treatment had significantly more soil water than the other treatments at time of planting, but the opposite was the case by FS 5 (Fig. III.2D). Available soil water was nearly depleted by FS 10 in the stubble mulch treatment, whereas the plow and no-tillage treatments still had available soil water reserves. By FS 11.4, available water was depleted in both stubble mulch and plow treatments whereas the no-tillage treatment still had available water remaining in the lower soil profile. The early depletion of soil water in the stubble mulch treatment can mainly be attributed to heavy downy brome infestation. Downy brome, a winter annual which completes its life cycle by late spring, is an especially troublesome weed for winter wheat producers in the Pacific Northwest. Downy brome infestation in the stubble mulch was significantly higher than the other treatments (Table III.1). The effect of downy brome infestation on grain yield among treatments is seen in the high coefficient of determination (r^2= .72) (Table III.2). Poor stand establishment in the no-tillage treatment, evidenced by reduced number of tillers and spikes per meter row (Table III.1), was the probable reason for lesser exploitation of soil water.

Although DM at each FS was not measured during the 1989-90 crop season, total DM for stubble mulch at FS 11.4 was only 58% of the plow treatment. Grain protein, number of tillers, and spikes per m row were also significantly reduced in the stubble mulch treatment compared to plow (Table III.1). Figure III.2A and III.2B further reflect the diminished plant N status in the stubble mulch treatment at each growth stage due to downy brome.

Table III.1. Yield Components and crop characteristics of Malcolm winter wheat grown under three tillage systems in 1989-90.

	Tillage Method					
COMPONENT/CHARACTERISTIC	PLOW	SM	NT	SIG.	SE	LSD
Grain yield (Mg ha^{-1})	3.707	2.206	2.643	NS	0.44	
Kernels $spike^{-1}$	26.74	17.56	27.26	NS	3.29	
1000 grain wt. (g)	38.75	44.10	44.00	NS	1.83	
Grain protein (%)	11.74	8.81	9.70	**	0.10	1.23
Tillers per plant	6.6	4.7	5.25	**	0.31	1.07
Spikes/meter row	145	118	93	**	6.33	21.9
Total DM (Mg ha^{-1})	13.38	7.80	8.42	**	0.30	0.10
Harvest index (%)[t]	27.7	28.27	31.37	NS	1.91	
Plant height (cm)	80	79.5	80.5	NS	0.99	
Downy brome DM (Mg ha^{-1})	0.71	1.29	0.81	*	0.22	0.31

NS = not significant
** = significant at 1% level
 * = significant at 5% level
[t] Harvest index = grain yield/total above-ground dry matter

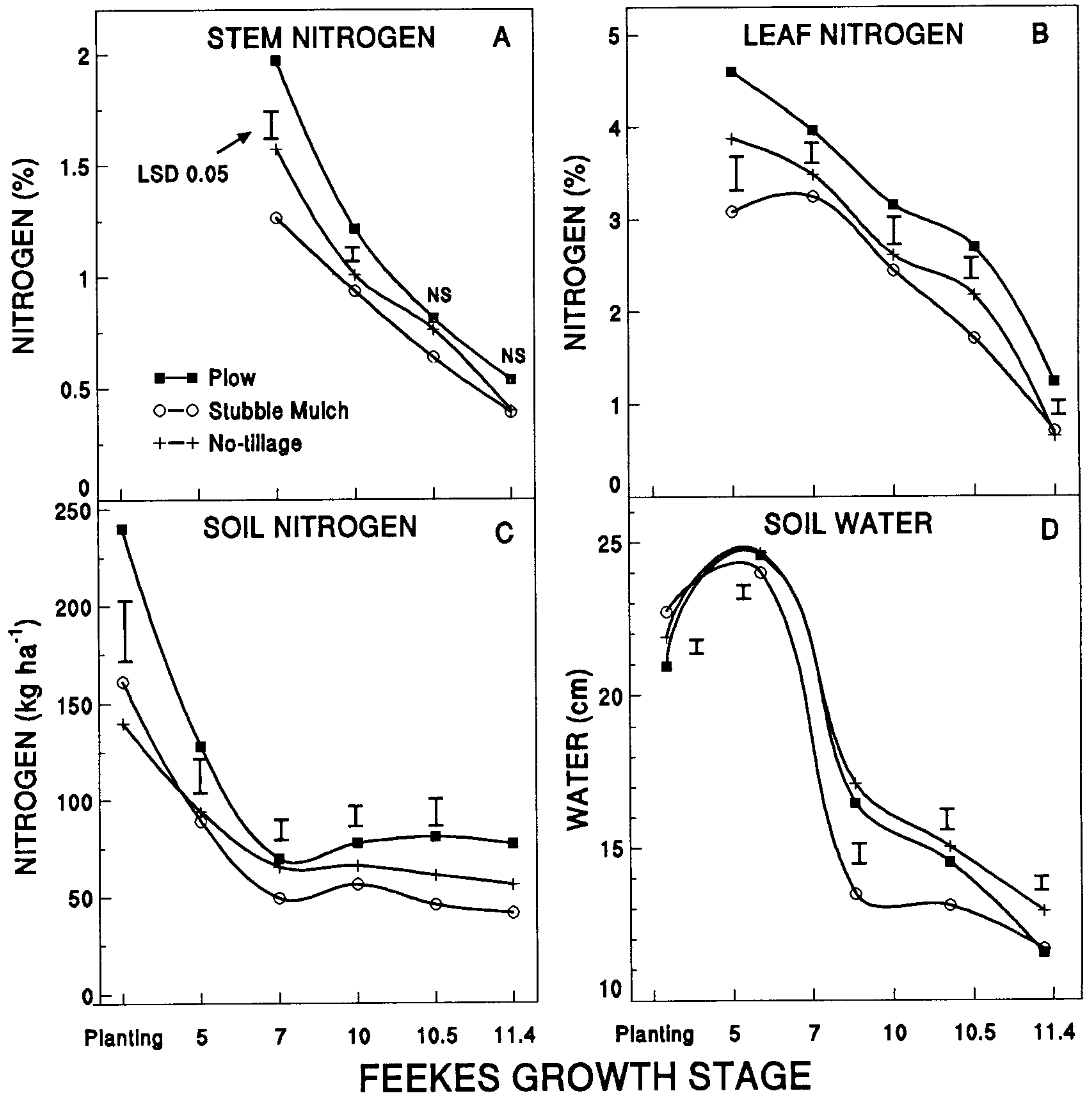


Fig. III.2. Stem nitrogen, leaf nitrogen, mineral nitrogen in 150 cm of soil, and water in 150 cm of soil as affected by tillage system at several growth stages during 1989-90.

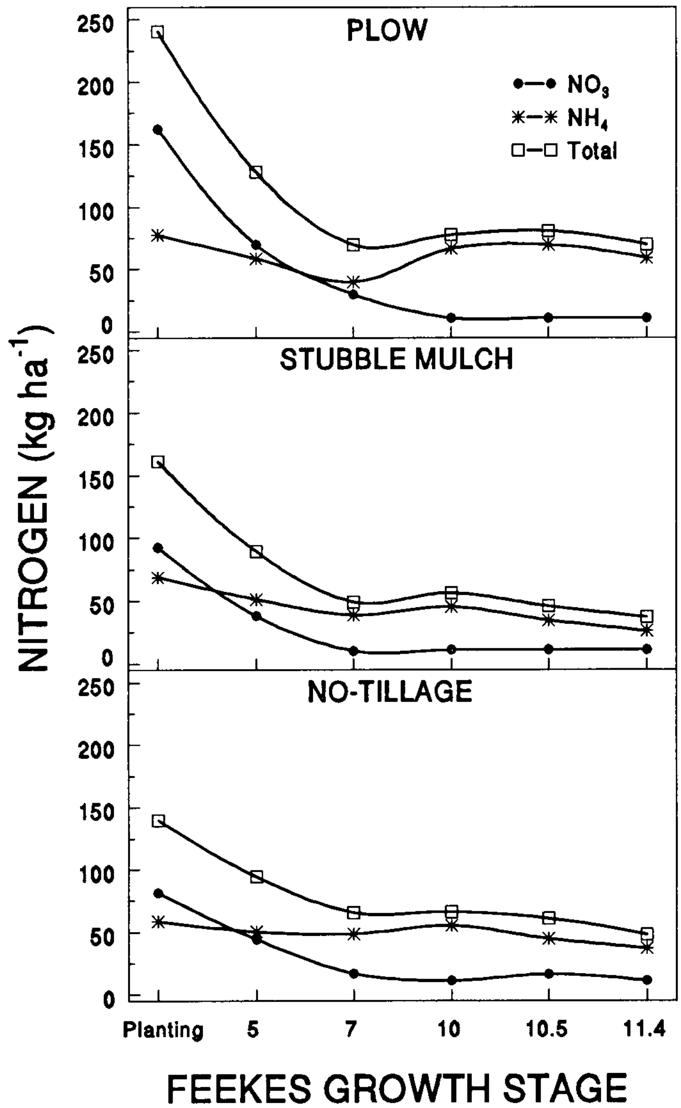


Fig. III.3. Mineral nitrogen in 150 cm of soil as affected by tillage system at several growth stages during 1989-90.

Table III.2. Coefficients of determination for regression models to describe the relationship of yield components and crop characteristics to grain yield in 1989-90 and 1990-91.

	1989-90		1990-91	
Variable	r^2	P-Value	r^2	P-Value
Dry matter	.76	.0002	.58	.0038
1000 grain weight	.06	.3722	.08	.3565
Spikes per m row	.32	.0568	.61	.0026
Kernels per spike	.36	.0386	.13	.2498
Downy brome DM	.72	.0005	---	---
FS 2 Plant stand	---	---	.38	.0315

1990-91 Crop Season

Early Development

Soil mineral N, analyzed from samples obtained before fertilizer N application, was significantly higher in no-tillage than in the other treatments (Fig III.4C). Differences were most pronounced in the surface 15 cm. This indicates that greater fallow season N mineralization occurred in the no-tillage treatment due to larger quantities of surface residue.

Total soil water as well as seedzone water at time of planting was greatest for stubble mulch, followed by the plow and no-tillage treatments (Fig. III.4D). Germination and stand establishment were greatest in the plow treatment, followed by stubble mulch and no-tillage. This is reflected by highly significant ($P = .0315$) differences in plants per m row measured at FS 2 (Table III.2). Better seed-soil contact, more uniform seedbed conditions, and better grain drill performance are probable explanations why, despite less seedzone water, stand establishment in the plow treatment exceeded that in the stubble mulch treatment.

Maximum soil temperature at 5 cm initially was lower under no-tillage than in the other treatments. By the 6th week after planting, however, stubble mulch had the lowest soil temperature and the no-tillage and plow treatments were about equal (Fig. III.5A). The no-tillage treatment had poorer plant stand establishment than the other treatments, therefore plant shading was reduced. Soil temperatures at 5 cm were equal in the plow and no-tillage treatments by the 6th week after seeding perhaps because plant shading in the plow treatment offset the effect of more surface residue, but little plant shading, in the no-tillage treatment.

Another explanation for shifts in relative soil temperature among treatments with time could be erosion of soil from furrow ridges into the furrows. Depth of thermistors initially placed 5 cm below the soil surface 2 d after planting were remeasured at FS 2. Depth to the 5-cm thermistor had increased by 2.7, 2.0, and 0.7 cm for plow, stubble mulch, and no-tillage treatments, respectively. Soil deposited into the furrow of the no-tillage treatment was significantly reduced compared to other treatments ($P = .0044$). The greater quantity of soil deposited into the furrow in plow and stubble mulch treatments may explain the decrease in 5-cm soil temperature over time in relation to the no-tillage treatment.

Spring Development

Thermistors were reset in all treatments under the seeded furrow on 20 March (FS 4). Some thermistors in the no-tillage treatment were moved to bordering furrows where the plant stand was more representative of the plot average. During the 5 wk period when plants were in FS 4 to FS 7, maximum soil temperature in the no-tillage treatment averaged about 3 ^{0}C and 2.5 ^{0}C cooler than in the plow and stubble mulch treatments, respectively (Fig. III.5B). Because of poor plant stands, no-tillage had significantly more 0 to 15-cm soil water than the other treatments between FS 4 and FS 7. The energy required to warm a wet soil is much greater than that of a dry soil. This is the most important factor affecting soil temperature (Thomas, 1986). It seems likely that the effects of surface residue and water combined to keep no-tillage soil temperatures cooler than the other treatments. This effect would be especially notable during early spring following winter precipitation and when there is limited plant canopy.

By FS 4 distinct differences among treatments were apparent. The crop sown in the plow treatment accumulated more DM (Fig. III.4B), depleted more soil water (Fig. III.4D), had the lowest concentration of plant tissue N (Fig. III.4A), and had the highest uptake of plant N (Fig. III.6B).

Between FS 4 and FS 10, a general linear decrease in soil water (Fig. III.4D) and plant N concentration (Fig. III.4A) among treatments can be seen. The plow treatment depleted soil N at a slightly faster rate than the stubble mulch and no-tillage treatments between FS 4 and FS 7 (Fig. III.4C). Plant N uptake was essentially completed in the plow and stubble mulch treatments by FS 7, whereas in the no-tillage treatment plant N uptake continued until FS 10 (Fig. III.6B). Cooler soil temperatures slowed spring growth and development in the no-tillage treatment and, combined with plentiful soil water and soil N, contributed to extended plant N uptake in the no-tillage treatment. A flush of N mineralization between FS 7 and FS 10, similar to that noted during the 1989-90 crop season, is clearly seen in the plow treatment, but is less apparent in the other treatments (Fig. III.6A, III.6C, and III.6D). Between FS 7 and FS 10 there was a rapid accumulation of DM with corresponding rapid depletion of soil water. The surface soil was dried and then rewetted by several precipitation events during this time period. Cycles of surface wetting and drying generally cause flushes in N mineralization. Increasing soil temperature during the spring enhances the effect of wetting on N mineralization (Agarwal et al., 1971a). Recently mineralized N accumulated in the soil of the plow and stubble mulch treatments because plant N uptake was completed by FS 7.

By FS 10.5, visual signs of water stress (flag leaf rolling) was observed in the stubble mulch treatment and was more pronounced in the plow treatment, whereas no water stress was apparent in no-tillage plots. Leaf temperature was significantly lower ($P = .0097$) in no-tillage plots than in the other treatments. This corresponds to significantly higher soil water content in no-tillage plots compared to the other treatments at FS 10.5.

<u>Yield Components and Crop Characteristics</u>

Late development of many of the reproductive tillers in the no-tillage treatment contributed to reduced grain weight, kernels per spike, harvest index, and grain yield, compared to the plow and stubble mulch treatments (Table III.3). Grain protein in the no-tillage treatment was significantly higher than in the other treatments because more soil N was present than needed for growth. Grain protein provides some indication of the nitrogen fertility of the growing crop and/or water stress as the grain was maturing. Grain protein $< 9\%$ indicates that the wheat plant may not have had adequate nitrogen. Grain Protein $> 11.5\%$ is associated with either: (1) more than adequate N for optimum growth, or; (2) water stress during the later stages of growth (Pumphrey and Rasmussen, 1982).

Excessive vegetative development in the plow treatment led to more rapid depletion of soil water and the plants were unable to form satisfactory spikes or to fill grain adequately, compared to the stubble mulch treatment. This is evidenced by greater dry matter production and reduced kernels per spike, harvest index, grain weight, and grain yield. Coefficients of determination for regression models describing the relationship of yield components and crop characteristics to grain yield are shown in Table III.2. Spikes per m row ($r^2 = .61$) was the yield component most closely correlated with grain yield. Dry matter production ($r^2 = .58$) was the measured crop characteristic most closely correlated with grain yield.

CONCLUSIONS

This study shows that seedzone water at planting, plant stand establishment, early spring soil temperature, DM production, number of productive tillers, and grain yield were reduced in no-tillage compared to conventional tillage practices.

It is hypothesized that the main factor responsible for reduced germination and plant stand establishment in the no-tillage treatment was diminished seedzone water at planting. In a relatively dry seedbed, a small increase in soil water content can produce a marked increase in wheat germination and emergence rate (Hanks and Thorp, 1956). Higher quantities of surface residue in the no-tillage treatment and, to a lesser extent, in the stubble mulch treatment, likely contributed to reduced germination and stand establishment compared to plow tillage because of poorer seed-soil contact.

The wheat plant has a considerable capacity to increase the number of tillers per plant, when sufficient space is available to the individual plant (Arnon, 1972). Although tillering did compensate for reduced stand establishment in the no-tillage treatment to some extent in 1990-91, number of spikes was significantly reduced compared to the other treatments during both years. High positive correlations have consistently been obtained showing wheat grain yield dependent primarily on number of spikes per unit area (Langer, 1980). Although the correlation between spikes per unit area and grain yield was reduced somewhat during the year of heavy downy brome infestation, it was the most significant of the yield components during the second year of the study, when weeds were not a factor.

Lower late winter and early spring soil temperature with no-tillage contributed to slower crop development and DM accumulation compared to the other treatments. There was a highly significant relationship between DM production and grain yield during both years. This further emphasizes the importance of stand establishment and successful early tiller production on grain yield under dryland conditions.

This study provided evidence of greater fallow season surface soil N mineralization, as well as immobilization of surface applied N fertilizer, in the no-tillage treatment. Treatment differences in soil mineral N and plant N uptake measured in the spring, however, could not be attributed to N immobilization. Immobilization of surface applied fertilizer N due to surface residue in the no-tillage treatment appeared to be short-term, and therefore unlikely to have affected mineral N availability in the spring.

No-tillage soil management is being accepted as an alternative system of crop production in many parts of the world. This acceptance is primarily due to reduced soil erosion and farm energy use. Grain yield reductions associated with no-tillage, however, limit its potential for the wheat-fallow cropping system in the Pacific Northwest.

Table III.3. Yield components and crop characteristics of Malcolm winter wheat grown under three tillage systems in 1990-91.

	Tillage Method					
COMPONENT/CHARACTERISTIC	PLOW	SM	NT	SIG.	SE	LSD
Grain yield (Mg ha^{-1})	3.186	3.429	1.595	*	0.32	1.109
Kernels per spike	23.54	26.18	22.90	NS	2.27	
1000 grain wt. (g)	40.95	42.56	39.98	NS	0.85	
Grain protein (%)	9.39	9.28	11.97	**	0.08	0.27
Spikes/meter row	134.8	129.3	75.5	*	12.2	42.1
Total DM (Mg ha^{-1})	11.17	10.73	8.20	NS	1.09	
Harvest index (%)[t]	28.52	31.96	19.44	**	7.30	8.46
Plant height (cm)	80.6	82.0	81.0	NS	0.96	
Plants m row at FS 2	14.7	12.0	6.5	**	0.53	2.31
Tillers per plant	5.70	5.25	8.25	**	0.13	1.26

NS = not significant
** = significant at 1% level
* = significant at 5% level
[t] HI = grain yield/total above-ground dry matter

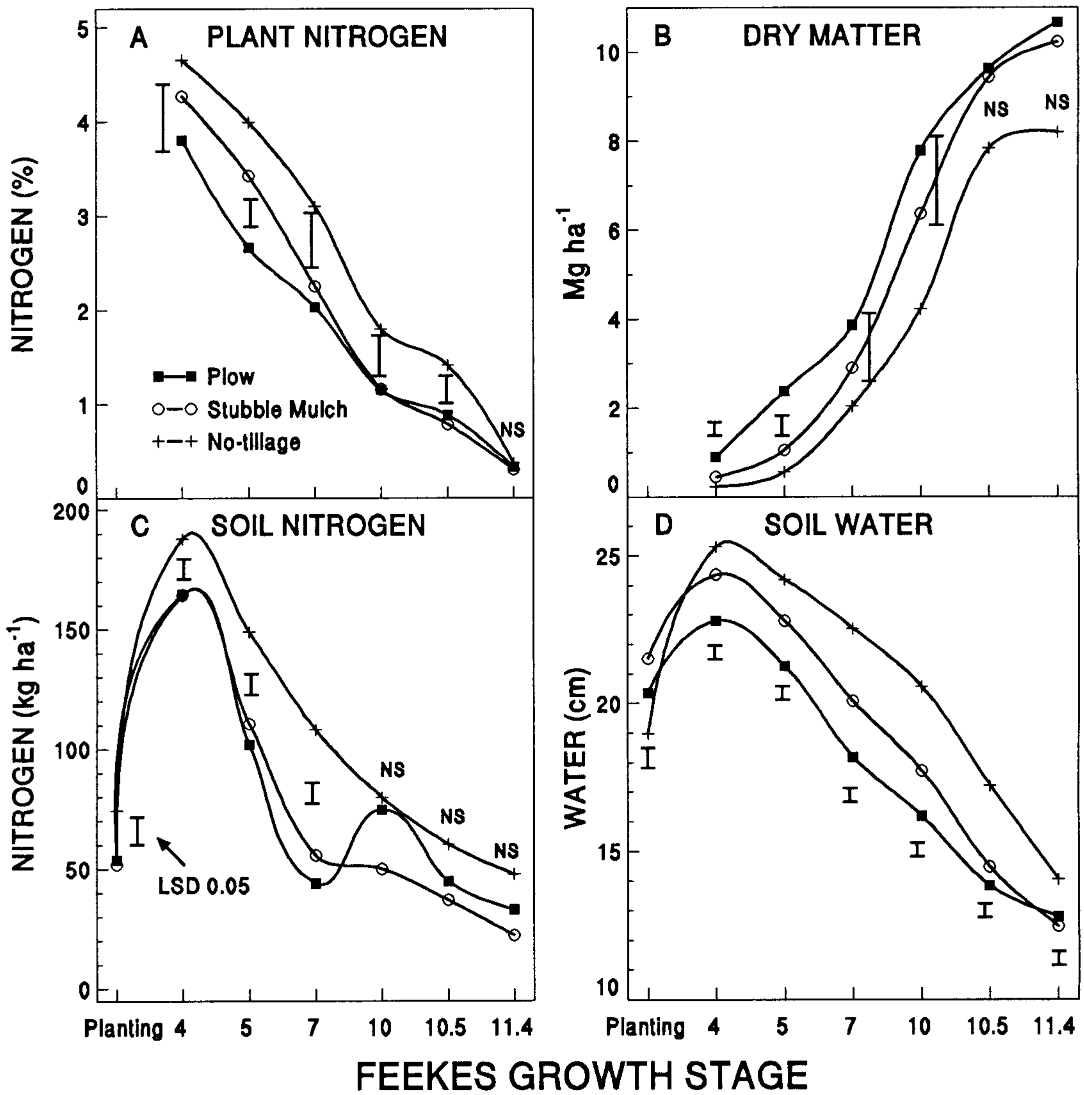


Fig. III.4. Plant nitrogen, dry matter production, mineral nitrogen in 150 cm of soil, and water in 150 cm of soil as affected by tillage system at several growth stages during 1990-91.

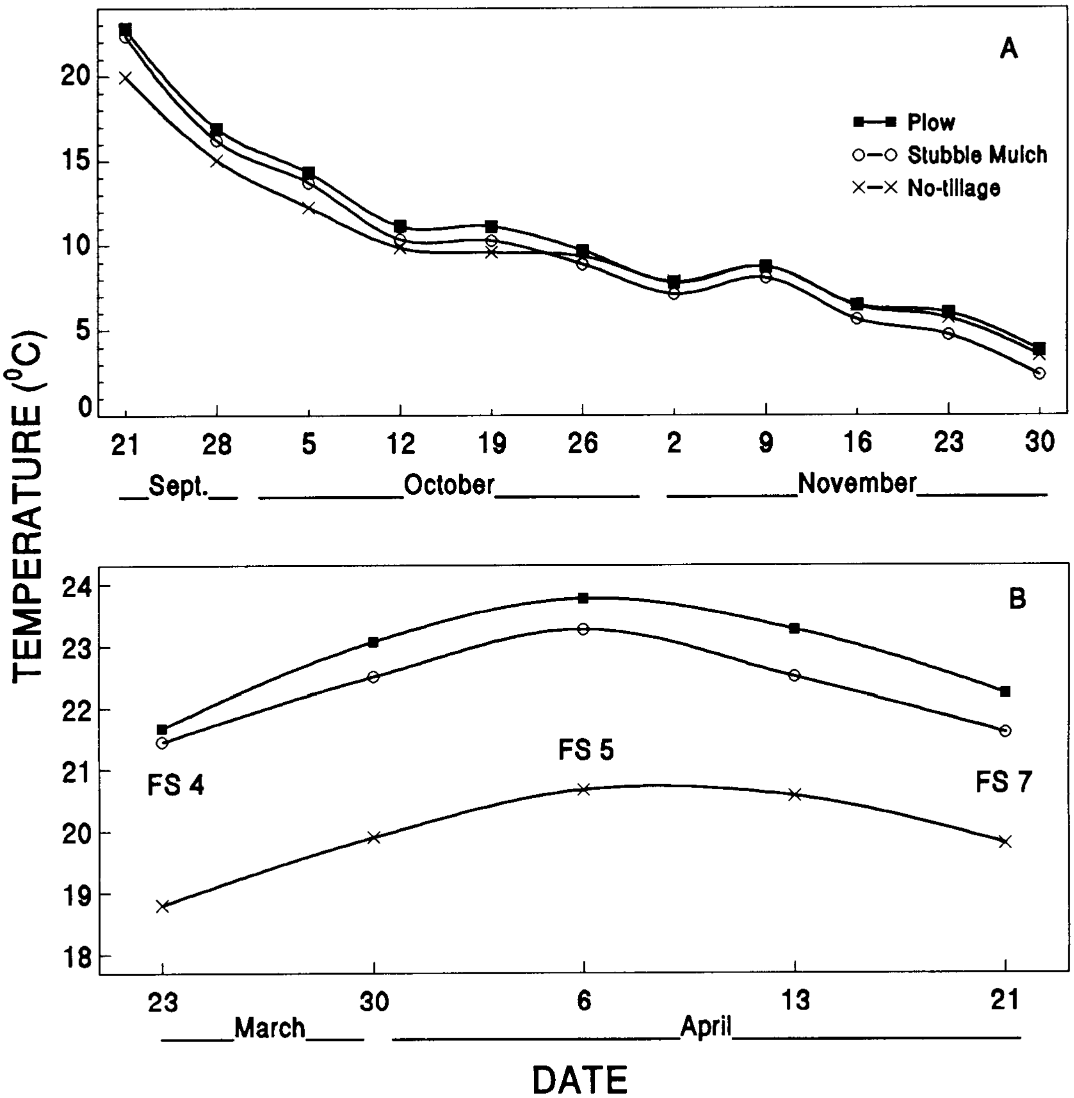


Fig. III.5. Maximum 5 cm soil temperatures as affected by tillage system during 1990-91.

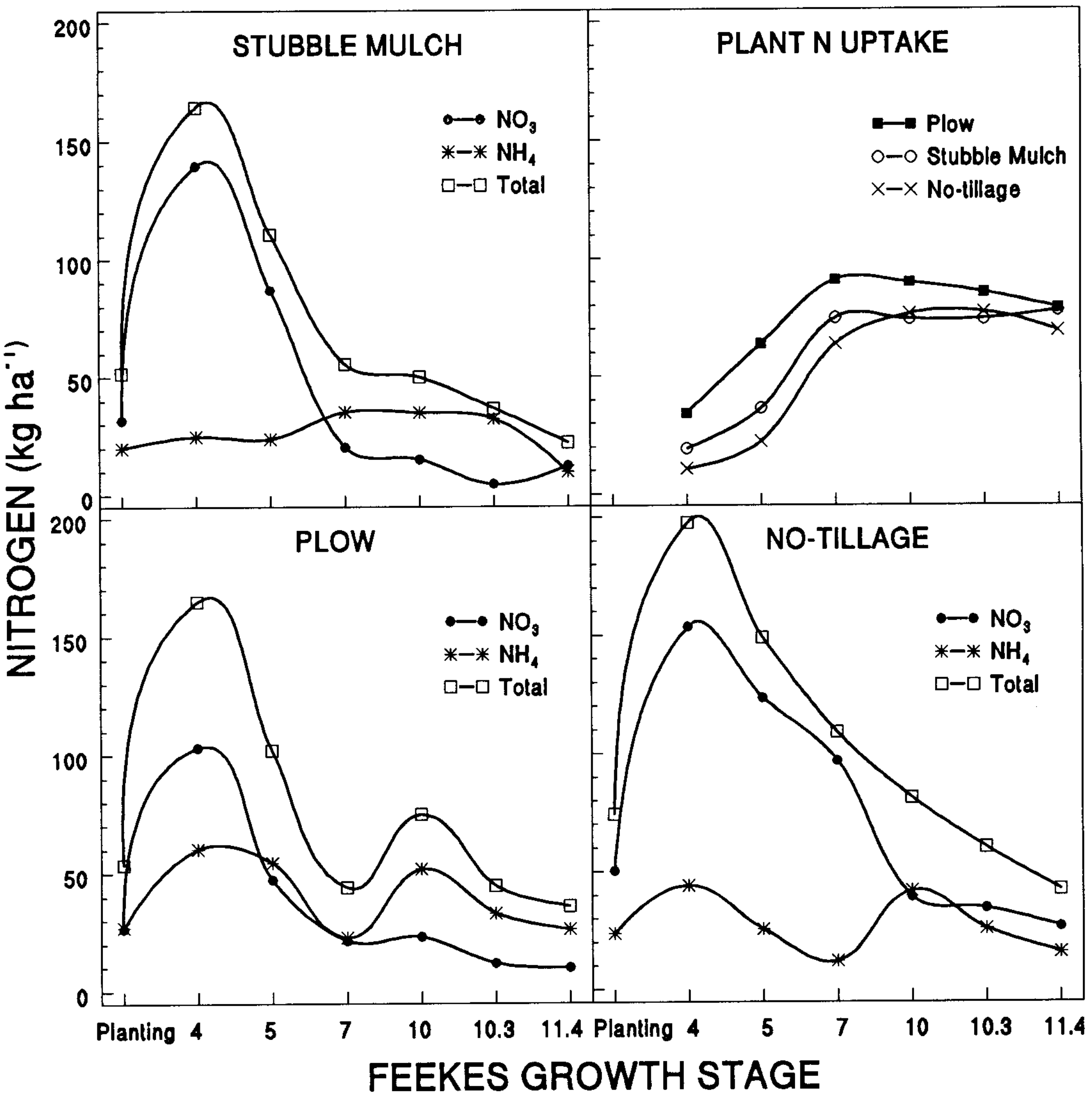


Fig. III.6. Mineral nitrogen in 150 cm of soil and plant nitrogen uptake as affected by tillage system at several growth stages during 1990-91.

REFERENCES

Agarwal, A.S., B.R. Singh, and Y. Kanehiro. 1971a. Soil nitrogen and carbon mineralization as affected by drying-re-wetting cycles. Soil Sci. Soc. Am. Proc. 35:96-100.

Arnon, I. 1972. Crop production in dry regions. Leonard Hill, London.

Bolton, F.E. and D.E. Booster. 1981. Strip-till planting in dryland cereal production. Transactions of the ASAE 24(1):59-62.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765-771.

Eckert, D.J. 1985. Effect of reduced tillage on the distribution of soil pH and nutrients in soil profiles. J. Fert. Issues 2:86-90.

Fenster, C.R. and G.A. Peterson. 1979. Effects of no-tillage compared to conventional tillage in a wheat-fallow rotation. Nebraska Agric. Stn. Bull. 289.

Follett, R.F. and G.A. Peterson. 1988. Surface soil nutrient distribution as affected by wheat-fallow tillage systems. Soil Sci. Soc. Am. J. 52:141-147.

Fredrickson, J.K., F.E. Koehler, and H.H. Cheng. 1982. Availability of ^{15}N-labelled nitrogen in fertilizer and in wheat straw to wheat in tilled and no-till soil. Soil Sci. Soc. Am. J. 46:1212-1222.

Gardner, W.H. 1986. Water content. In: Methods of soil analysis: Part 1 - Physical and mineralogical methods. American Society of Agronomy Monograph No. 9. Madison, Wisconsin.

Hanks, R.J., and F.C. Thorp. 1956. Seedling emergence of wheat as related to soil moisture content, bulk density, oxygen diffusion rate, and crust strength. Soil Sci. Soc. Amer. Proc. 20:307-310.

Langer, R.H.M. 1980. Growth of the grass plant in relation to seed production . In: Herbage seed production. Proc. New Zealand Grassland Association Conf. Canterbury, New Zealand. Nov. 13-15, 1979.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

Leggett, G.E. 1959. Relationships between wheat yield, available moisture and available nitrogen in Eastern Washington dry land areas. Wash. Agr. Exp. Stat. Bull. 609:1-16.

Lindstrom, M.J., F.E. Koehler, and R.I. Papendick. 1974. Tillage effects on fallow water storage in the eastern Washington dryland region. Agron. J. 66:312-316.

Oveson, M.M. and A.P. Appleby. 1971. Influence of tillage management in a stubble mulch fallow-winter wheat rotation with herbicide weed control. Agron. J. 63:19-20.

Pumphrey, F.V. and P.E. Rasmussen. 1982. Winter wheat fertilization in the northeast intermountain region of Oregon. Oregon State Univ. Agric. Exp. Stat. Circ. No. 691.

Rasmussen, P.E. 1983. Winter wheat response to nitrogen fertilizer in no-till annual cropping and conventional tillage wheat-fallow rotation. Columbia Basin Agric. Research Special Report 680.

Rasmussen, P.E., R.E. Ramig, and D.E. Wilkins. 1983. Wheat and barley fertilizer response in conservation tillage systems. Proceedings, 34th Fertilizer Conference of the Northwest, Portland, Oregon, July 12-13, 1983.

Rickman, R.W. and B.L. Klepper. 1983. Using air temperature to anticipate wheat crop development. Oregon Agric. Exp. Stn. Special Report 680.

Smika, D.E. and R. Ellis. 1971. Soil temperature and wheat straw mulch effects on wheat plant development and nutrient content. Agron. J. 63:388-391.

Smika, D.E. 1990. Fallow management practices for wheat production in the central Great Plains. Agron. J. 82:319-323.

Smith, K.A. and R.S. Howard. 1980. Field studies of nitrogen uptake using ^{15}N-tracer methods. J. Sci. Food Agric. 31:839-840.

Thomas, G.W. 1986. Mineral nutrition and fertilizer placement. In: No-tillage and surface tillage agriculture. John Wiley & Sons, New York.

Wall, D.A. and E.H. Stobbe. 1984. The effect of tillage on soil temperature and corn growth in Manitoba. Can. J. Plant Sci. 64:59-67.

Wardlaw, I.F. 1971. The early stages of grain development in wheat: Response to water stress in a single variety. Aust. J. Biol. Sci. 24:1047-1055.

Wicks, G.A. and D.E. Smika. 1973. Chemical fallow in a winter wheat-fallow rotation. Weed Science 21 (2) 97-102.

Wilkins, D.E., B.L. Klepper, and P.E. Rasmussen. 1988. Management of grain stubble for conservation tillage systems. Soil Tillage Res. 12:25-35.

BIBLIOGRAPHY

Agarwal, A.S., B.R. Singh, and Y. Kanehiro. 1971a. Soil nitrogen and carbon mineralization as affected by drying-re-wetting cycles. Soil Sci. Soc. Am. Proc. 35:96-100.

Allmaras, R.R., R.W. Rickman, L.G. Ekin, and B.A. Kimball. 1977. Chiseling influences on soil hydraulic properties. Soil Sci. Soc. Am. J. 41:796-803.

Army, T.J., A.F. Wiese, and R.J. Hanks. 1961. Effect of tillage and chemical weed control practices on soil moisture losses during the fallow period. Soil Sci. Soc. Amer. Proc. 25:410-413.

Arnon, I. 1972. Crop production in dry regions. Leonard Hill, London.

Avcin, A. 1988. Effects of tillage systems on nitrate-nitrogen accumulation and soil structure. M.S. Thesis. Crop Science Department. Oregon State University.

Bigger, J.W., and S.A. Taylor. 1960. Some aspects of the kinetics of moisture flow into unsaturated soils. Soil Sci. Soc. Amer. Proc. 24:81-85.

Black, A.L. and J.F. Power. 1965. Effect of chemical and mechanical fallow methods on moisture storage, wheat yields, and soil erodibility. Soil Sci. Soc. Am. Proc. 29:465-468.

Black, A.L., and F.H. Siddoway. 1979. Influence of tillage and wheat straw residue management on soil properties in the Great Plains. J. Soil and Water Cons. 33:220-223.

Boersma, L., and T.L. Jackson. 1977. Fundamentals of water conservation practices used in the summer fallow system of farming. In: Proceedings of An International Symposium on Rainfed Agriculture in Semi-Arid Regions. April 17-22. pp. 219-245.

Bolton, F.E. 1988. Source and method of nitrogen fertilizer and herbicide applications in winter wheat, Moro 1987. In: Oregon State University Agric. Exp. Stat. Special Report 827, pp.35-36.

Bolton, F.E. and D.E. Booster. 1981. Strip-till planting in dryland cereal production. Transactions of the ASAE 24(1):59-62.

Bond, J.J. and W.O. Willis. 1971. Soil water evaporation: Long-term drying as influenced by surface residue and evaporation potential. Soil Sci. Soc. Am. Proc. 35:984-987.

Broder, M.W., J.W. Doran, G.A. Peterson, and C.R. Fenster. 1984. Fallow tillage influence on spring populations of soil nitrifiers, denitrifiers, and available nitrogen. Soil Sci. Soc. Am. J. 48:1060-1067.

Caprio, J.M., R.D. Snyder, and G.K. Grunwald. 1980. Precipitation probabilities in Montana. Montana Agric. Exp. Stn. Bull. 712.

Cochran, V.L., L.F. Elliott, and R.I. Papendick. 1982. Effect of crop residue management and tillage on water use efficiency and yield of winter wheat. Agron. J. 74:929-932.

Douglas, C.L., Jr., R.R. Allmaras, P.E. Rasmussen, R.E. Ramig, and N.C. Roager, Jr. 1980. Wheat straw composition and placement effects on decomposition in dryland agriculture of the Pacific Northwest. Soil Sci. Soc. Am. J. 44:833-837.

Douglas, J.T. and M.J. Goss. 1982. Stability of organic matter content of surface soil aggregates under different methods of cultivation and in grassland. Soil Tillage Res. 2:155-175.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765-771.

Eckert, D.J. 1985. Effect of reduced tillage on the distribution of soil pH and nutrients in soil profiles. J. Fert. Issues 2:86-90.

Fenster, C.R. and G.A. Peterson. 1979. Effects of no-tillage compared to conventional tillage in a wheat-fallow rotation. Nebraska Agric. Stn. Bull. 289.

Follett, R.F. and G.A. Peterson. 1988. Surface soil nutrient distribution as affected by wheat-fallow tillage systems. Soil Sci. Soc. Am. J. 52:141-147.

Fox, R.H. and V.A. Bandel. 1986. Nitrogen utilization with no-tillage. In: No-Tillage and Surface-Tillage Agriculture, pp. 117-148. John Wiley & Sons. New York.

Fredrickson, J.K., F.E. Koehler, and H.H. Cheng. 1982. Availability of ^{15}N-labelled nitrogen in fertilizer and in wheat straw to wheat in tilled and no-till soil. Soil Sci. Soc. Am. J. 46:1212-1222.

Gardner, W.H. 1986. Water content. In: Methods of soil analysis: Part 1 - Physical and mineralogical methods. American Society of Agronomy Monograph No. 9. Madison, Wisconsin.

Good, L.G., and D.E. Smika. 1978. Chemical fallow for soil and water conservation in the Great Plains. J. Soil Water Conserv. 33:89-90.

Greb, B.W., D.E. Smika, and A.L. Black. 1967. Effect of straw mulch rates on soil water storage during summer fallow in the Great Plains. Soil Sci. Soc. Amer. Proc. 31:556-559.

Guls, A. and R.E. Allan. 1976. Stand establishment of wheat lines under different levels of water potential. Crop Sci. 16:611-615.

Hammel, J.E., R.I. Papendick, and G.S. Campbell. 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. Soil Sci. Soc. Am. J. 45:1016-1022.

Hanks, R.J., and F.C. Thorp. 1956. Seedling emergence of wheat as related to soil moisture content, bulk density, oxygen diffusion rate, and crust strength. Soil Sci. Soc. Amer. Proc. 20:307-310.

Haynes, R.J. 1986. The decomposition process: Mineralization, immobilization, humus formation, and degradation. In: Mineral Nitrogen in the Plant-Soil System. Academic Press

Hill, D.D. and E.R. Jackman. 1960. They broke the trail. Oregon Wheat Commission, Pendleton, Oregon.

Hillel, D. 1971. Soil and water: physical principles and processes. Academic Press. New York.

Hillel, D. 1982. Introduction to soil physics. Academic Press. New York.

Idso, S.B., R.J. Reginato, R.D. Jackson, B.A. Kimball, and F.S. Nakayama. 1974. The three stages of drying of a field soil. SSSA Proc. 38:831-837.

Jackson, R.D., D.A. Rose, and H.L. Penman. 1965. Circulation of water in soil under a temperature gradient. Nature 205:314-316.

Klepper, B.L., P.E. Rasmussen, and R.W. Rickman. 1983. Fertilizer placement for cereal root access. J. Soil and Water Conservation 38:250-252.

Klute, A. 1982. Tillage effects on the hydraulic properties of soil: a review. In: Predicting Tillage Effects on Soil Physical Properties and Processes. ASA Special Pub. No. 44.

Koehler, F.E., G.M. Hyde, and J. Hammel. 1983. Optimum methods of fertilizer application for minimum till and no-till in eastern Washington and northern Idaho. In: Proceedings of 34th Annual Northwest Fertilizer Conference, pp. 43-48. Portland, Oregon, July 11-14, 1983.

Kramer, P.J. 1969. Plant and Soil Water Relationships. McGraw Hill, New York.

Lamb, J.A., G.A. Peterson, and C.R. Fenster. 1985. Fallow nitrate accumulation in a wheat-fallow rotation as affected by tillage system. Soil Sci. Soc. Am. J. 49:1441-1446.

Langer, R.H.M. 1980. Growth of the grass plant in relation to seed production . In: Herbage seed production. Proc. New Zealand Grassland Association Conf. Canterbury, New Zealand. Nov. 13-15, 1979.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

Leggett, G.E. 1959. Relationships between wheat yield, available moisture and available nitrogen in Eastern Washington dry land areas. Wash. Agr. Exp. Stat. Bull. 609:1-16.

Leggett, G.E. and W.L. Nelson. 1960. Wheat production as influenced by cropping sequence and nitrogen fertilization in the 10 to 15 inch rainfall area of eastern Washington. Wash. Agric. Exp. Stat. Bull. 608.

Leggett, G.E., R.E. Ramig, L.C. Johnson, and T.W. Massee. 1976. Summer fallow in the Northwest. In Summer fallow in the United States 6:110-135. USDA Special Publication.

Lemon, E.R. 1956. The potentialities for decreasing soil moisture evaporation loss. SSSA Proc. 20:120-125.

Lindstrom, M.J., F.E. Koehler, and R.I. Papendick. 1974. Tillage effects on fallow water storage in the eastern Washington dryland region. Agron. J. 66:312-316.

Lindstrom, M.J., R.I. Papendick, and F.E. Koehler. 1976. A model to predict winter wheat emergence as affected by soil temperature, water potential, and depth of planting. Agron. J. 68:137-141.

Marshall, J., and J.W. Holmes. 1988. Soil physics. Cambridge University Press. Cambridge.

Massee T. and H. McKay. 1979. Improving dryland wheat production in eastern Idaho with tillage and cropping methods. University of Idaho Agricultural Experiment Station Bulletin No. 581.

Massee, T.W. and F.H. Siddoway. 1970. Summer fallow soil water losses on intermountain dryland and its effect on cropping winter wheat. Agron. J. 62:722-725.

McCall, M.A. 1925. The soil mulch in the absorption and retention of moisture. J. Agric. Res. 30:819-831.

McCall, M.A. and H.F. Hails. 1921. Investigations in dry farm tillage. Wash. Agr. Expt. Sta. Bull. 164.

McCall, M.A. and H.M. Wander. 1924. The principles of summer fallow tillage. Wash. Agr. Expt. Sta. Bul. 183.

Noori, F., F.E. Bolton, and D.N. Moss. 1985. Water injection at seeding of winter wheat. Agron. J. 77:906-908.

Olson, R.A. and L.T. Kurtz. 1982. Crop nitrogen requirements, utilization, and fertilization. In: Nitrogen in Agricultural Soils, pp.567-604. Am. Soc. Agron., Madison, Wisconsin.

Oveson, M.M. 1966. Conservation of soil nitrogen in a wheat summer fallow farming practice. Agron. J. 58:444-447.

Oveson, M.M. and A.P. Appleby. 1971. Influence of tillage management in a stubble mulch fallow-winter wheat rotation with herbicide weed control. Agron. J. 63:19-20.

Papendick, R.I., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in eastern Washington. Soil Sci. Soc. Am. Proc. 37:307-314.

Papendick, R.I. and G.S. Campbell. 1974. Wheat-fallow agriculture: why, how, when? In: 2nd regional wheat workshop. Ankara, Turkey.

Papendick, R.I. and D.E. Miller. 1977. Conservation tillage in the Pacific Northwest. J. Soil Water Cons. Jan.-Feb. 49-56.

Penman, H.L. 1941. Laboratory experiments on evaporation from fallow soil. J. Agric. Sci. 31:454.

Pikul, J.L, Jr., R.R. Allmaras, and G.E. Fischbacher. 1979. Incremental soil sampler for use in summer-fallowed soils. Soil Sci. Soc. Am. J. 43:425-427.

Pikul, J.L., Jr., R.R. Allmaras, and S.E. Waldman. 1985. Late season heat flux and water distribution in summer-fallowed Haploxerolls. Soil Sci. Soc. Am. J. 49:1517-1522.

Pumphrey, F.V. and P.E. Rasmussen. 1982. Winter wheat fertilization in the northeast intermountain region of Oregon. Oregon State Univ. Agric. Exp. Stat. Circ. No. 691.

Ramig, R.E. and L.G. Ekin. 1991. When do we store water with fallow? 1991 Columbia Basin Agric. Res., Oregon Agric Expt. Stn. Special Report 860. pp. 56-60.

Rasmussen, P.E. 1983. Winter wheat response to nitrogen fertilizer in no-till annual cropping and conventional tillage wheat-fallow rotation. Columbia Basin Agric. Research Special Report 680.

Rasmussen, P.E., R.R. Allmaras, C.R. Rohde, and N.C. Roager, Jr. 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. Soil Sci. Soc. Am. J. 44:596-600.

Rasmussen, P.E., R.E. Ramig, and D.E. Wilkins. 1983. Wheat and barley fertilizer response in conservation tillage systems. Proceedings, 34th Fertilizer Conference of the Northwest, Portland, Oregon, July 12-13, 1983.

Rasmussen, P.E., H.P. Collins, and R.W. Smiley. 1989. Long-term management effects on soil productivity and crop yield in semi-arid regions of eastern Oregon. Columbia Basin Agric. Research Center Station Bull. 675.

Rickman, R.W. and B.L. Klepper. 1983. Using air temperature to anticipate wheat crop development. Oregon Agric. Exp. Stn. Special Report 680.

Rickman, R.W. and B.L. Klepper. 1984. Tiller, leaf and root appearance in winter wheat: Unstressed and stressed development patterns. In: Oregon State University Agric. Exp. Stat. Special Report 713, pp. 17-23.

Russel, E.W. 1973. Soil conditions and plant growth. Longman Publishers. New York

Russelle, M.P. 1979. Soil moisture and temperature relationships under fallow in eastern Oregon. M.S. Thesis. Crop Science Department. Oregon State University.

Schieferstein, R.H. 1980. Innovative fallow systems for dryland wheat. Weeds Today. Early Spring pp. 11-12.

Smika, D.E. and G.A. Wicks. 1968. Soil water storage during fallow in the Central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Amer. Proc. 32:591-595.

Smika, D.E. and R. Ellis. 1971. Soil temperature and wheat straw mulch effects on wheat plant development and nutrient content. Agron. J. 63:388-391.

Smika, D.E. 1990. Fallow management practices for wheat production in the central Great Plains. Agron. J. 82:319-323.

Smith, J.H. and C.L. Douglas. 1968. Influence of residual nitrogen on wheat straw decomposition in the field. Soil Sci. 106 (6) 456-459.

Smith, K.A. and R.S. Howard. 1980. Field studies of nitrogen uptake using ^{15}N-tracer methods. J. Sci. Food Agric. 31:839-840.

Sunderman, D.W. 1964. Seedling emergence of winter wheat and its association with depth of sowing, coleoptile length under various conditions, and plant height. Agron. J. 56:23-26.

Tanaka, D.L. 1985. Chemical and stubble-mulch fallow influences on seasonal soil water contents. Soil Sci. Soc. Am. J. 49:728-733.

Tanaka, D.L. 1986. Wheat residue loss for chemical and stubble-mulch fallow. Soil Sci. Soc. Am. J. 50:434-440.

Thomas, G.W. 1986. Mineral nutrition and fertilizer placement. In: No-tillage and surface tillage agriculture. John Wiley & Sons, New York.

Varvel, G.E., J.L. Havlin, and T.A. Peterson. 1989. Nitrogen placement evaluation for winter wheat in three fallow tillage systems. Soil Sci. Soc. Am. J. 53:288-292.

Veseth, R. 1985. Winter wheat straw decomposition rate. STEEP Extension Conservation Farming Update. Chapter 2, Residue Management, No. 2. PNW Conservation Tillage Handbook Series.

Veseth, R. 1988. Maintaining surface residue on summer fallow. STEEP Extension Conservation Farming Update. Chapter 3, Residue Management, No. 11. PNW Conservation Tillage Handbook Series.

Wall, D.A. and E.H. Stobbe. 1984. The effect of tillage on soil temperature and corn growth in Manitoba. Can. J. Plant Sci. 64:59-67.

Wardlaw, I.F. 1971. The early stages of grain development in wheat: Response to water stress in a single variety. Aust. J. Biol. Sci. 24:1047-1055.

Wiese, A.F. and T.J. Army. 1960. Effect of chemical fallow on soil moisture storage. Agron. J. 52:612-613.

Wicks, G.A. and D.E. Smika. 1973. Chemical fallow in a winter wheat-fallow rotation. Weed Science 21 (2) 97-102.

Wilkins, D.E., B.L. Klepper, and P.E. Rasmussen. 1988. Management of grain stubble for conservation tillage systems. Soil Tillage Res. 12:25-35.

APPENDIX

Appendix Table 1. Fallow soil water (cm) on each sampling date during the 1989-90 fallow season.

October 6, 1989

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	0.578	0.615	0.609	.6515
15-30	0.897	0.968	0.899	.2967
30-60	2.374	2.272	2.277	.3243
60-90	2.323	2.338	2.275	.6797
90-120	2.473	2.327	2.327	.0647
120-150	3.861	3.642	3.345	.2450
Total	12.506 a [1]	12.162 b	11.732 c	.0240
				T*D [2] .0512

March 20, 1990

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.611 a	2.935 b	2.491 a	.0002
15-30	2.752 a	2.973 b	2.748 a	.0031
30-60	4.625	4.821	4.601	.3022
60-90	3.007	3.023	3.042	.6577
90-120	3.715	3.606	3.689	.2044
120-150	5.129	4.920	4.785	.0585
Total	21.839 ab	22.228 a	21.356 b	.0004
FE [3]	73	79	75	T*D .0000

April 7, 1990[4]

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.518 a	2.905 b	2.298 c	.0000
15-30	2.613 a	2.817 b	2.545 a	.0007
Total	5.131 a	5.722 b	4.843 a	.0097

April 30, 1990[4]

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.743 a	3.093 b	3.006 b	.0000
15-30	2.637 a	2.871 b	2.676 a	.0260
Total	5.380 a	5.964 b	5.682 ab	.0223

[1] Within a row means followed by the same letter are not significantly different at P = 0.05.

[2] Tillage * Depth interaction

[3] FE = Fallow Efficiency % = (Net gain soil water, cm / fallow precipitation, cm) X 100

[4] 30 to 150 cm values not reported because of neutron probe malfunction.

Appendix Table 1 (continued).

May 15, 1990

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.617 a	3.079 b	2.658 a	.0034
15-30	2.758	3.004	2.733	.2128
30-60	4.425	5.181	4.422	.3888
60-90	2.649	2.728	2.470	.7331
90-120	3.597	3.216	3.243	.3328
120-150	4.743	4.020	4.152	.0910
Total	20.784 ab	21.228 a	19.678 b	.0475
FE	51	56	49	T*D .0419

June 3, 1990

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.874 a	3.354 b	3.658 c	.0004
15-30	2.962	3.106	3.250	.4173
30-60	4.527	4.839	4.620	.6371
60-90	2.578	3.009	2.944	.5203
90-120	3.330	3.783	3.159	.4256
120-150	4.749 a	4.566 a	3.891 b	.0170
Total	21.020	22.657	21.522	.2266
FE	43	53	49	T*D .0022

July 19, 1990

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.602 a	2.217 b	1.507 a	.0196
15-30	2.499 a	2.422 a	2.017 b	.0504
30-60	4.467	4.683	4.152	.1252
60-90	2.845	3.417	3.096	.4881
90-120	3.783	3.717	3.069	.2186
120-150	5.334	5.224	3.942	.6541
Total	20.530 a	21.676 b	17.783 c	.0001
FE	38	45	29	T*D .0000

Appendix Table 1 (continued).

September 15, 1990

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.755	1.830	1.539	.3449
15-30	2.479	2.451	2.286	.4521
30-60	4.200	4.404	4.107	.7696
60-90	3.270	3.504	3.564	.8599
90-120	3.738	4.191	3.927	.7983
120-150	4.923 a	5.127 a	3.564 b	.0507
Total	20.365 a	21.507 b	18.987 c	.0198
FE	31	37	29	T*D .1604

Appendix Table 2. Fallow soil water (cm) on each sampling date during the 1990-91 fallow season.

July 17, 1990

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	0.640	0.657	0.724	.7698
15-30	1.191	1.195	1.257	.4025
30-60	2.515	2.534	2.695	.2337
60-90	2.365	2.450	2.536	.3484
90-120	2.254	2.362	2.552	.0955
120-150	2.556	2.464	3.129	.0507
Total	11.527 a[1]	11.662 a	12.893 b	.0003
				T*D[2] .3855

March 20, 1991

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	3.336 a	3.882 b	3.487 a	.0007
15-30	2.982 a	3.240 b	3.153 ab	.0210
30-60	4.344	4.644	4.233	.3630
60-90	2.448	2.969	2.554	.6090
90-120	2.617	3.009	2.800	.2833
120-150	3.420	3.789	3.918	.1201
Total	19.147 a	21.533 b	20.145 c	.0003
FE[3]	44	57	42	T*D .7495

April 25, 1991

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.536 a	3.184 b	2.064 c	.0000
15-30	2.680 a	3.102 b	2.509 c	.0000
30-60	3.732 a	4.239 b	3.801 a	.0039
60-90	2.347	2.555	2.671	.1120
90-120	2.383 a	2.456 a	2.956 b	.0016
120-150	3.153 a	3.270 a	3.861 b	.0113
Total	16.831 a	18.806 b	17.862 c	.0000
FE	28	37	26	T*D .0000

[1] Within a row means followed by the same letter are not significantly different at P = 0.05.

[2] Tillage * Depth interaction

[3] FE = Fallow Efficiency % = (Net gain soil water, cm / fallow precipitation, cm) X 100

Appendix Table 2 (continued).

May 18, 1991

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.625 a	3.142 b	2.823 a	.0002
15-30	2.664 a	2.905 b	2.433 c	.0000
30-60	3.867 a	4.296 b	3.735 a	.0022
60-90	2.365 a	2.844 b	2.979 b	.0476
90-120	2.436 a	2.495 a	3.060 b	.0010
120-150	3.243 a	3.303 a	3.987 b	.0094
Total	17.200 a	18.985 b	19.017 b	.0000
FE	27	34	29	T*D .0000

June 6, 1991

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.053 a	2.421 b	1.978 a	.0000
15-30	2.610 a	2.812 b	2.401 c	.0000
30-60	3.855 a	4.236 b	3.675 a	.0015
60-90	2.414 a	2.831 b	2.774 b	.0244
90-120	2.492 a	2.531 a	3.099 b	.0009
120-150	3.273 a	3.363 a	4.077 b	.0087
Total	16.697 a	18.194 b	18.040 b	.0002
FE	24	30	23	T*D .0000

July 24, 1991

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.839 a	2.250 b	1.699 a	.0000
15-30	2.574 a	2.662 a	2.409 b	.0000
30-60	3.894 a	4.029 a	3.507 b	.0008
60-90	2.554 a	3.105 b	2.439 a	.0000
90-120	2.479 a	2.594 a	2.846 b	.0098
120-150	3.339	3.429	3.768	.1276
Total	16.679 a	18.069 b	16.668 a	.0000
FE	20	25	15	T*D .0000

Appendix Table 2 (continued).

August 16, 1991

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.722 a	1.827 a	1.379 b	.0008
15-30	2.391 a	2.463 a	2.196 b	.0002
30-60	3.822 a	3.933 a	3.453 b	.0000
60-90	2.600 a	3.159 b	2.681 a	.0000
90-120	2.494 a	2.622 a	2.936 b	.0032
120-150	3.345	3.453	3.822	.0989
Total	16.374 a	17.457 b	16.467 a	.0000
FE	19	22	14	T*D .0000

September 20, 1991

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.399 a	1.542 b	0.954 c	.0000
15-30	2.161 a	2.211 a	1.965 b	.0000
30-60	3.621 a	3.774 a	3.381 b	.0004
60-90	2.635 a	3.180 b	2.732 a	.0000
90-120	2.526 a	2.693 a	2.990 b	.0064
120-150	3.411	3.519	3.792	.1830
Total	15.753 a	16.919 b	15.814 a	.0000
FE	16	20	11	T*D .0000

Appendix Table 3. Soil NO_3^- and NH_4^+ (kg ha^{-1}) at several plant growth stages during 1989-90.

October 6, 1989 (Planting)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	88.92 a [1]	61.91 b	33.18 c	.0000	35.96 a	21.18 b	9.05	.0011
15-30	13.68 a	7.06 b	5.29 b	.0343	4.63	4.41	4.63	.6350
30-60	8.38	4.85	7.06	.1730	7.94	10.59	9.71	.1345
60-90	31.77 a	7.50 b	11.47 b	.0120	13.24	10.59	11.03	.5600
90-120	6.18	7.94	10.59	.1870	7.94	11.91	11.91	.3430
120-150	13.68 a	3.09 b	13.68 a	.0480	7.94	10.15	12.35	.0980
Total	162.61 a	92.35 b	81.27 b	.0000	77.65 a	68.83 ab	58.68 b	.0420

April 9, 1990 (Feekes 5)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	5.18	2.83	8.66	.0698	6.78	5.46	8.49	.2840
15-30	17.43	8.28	8.12	.0720	5.79	4.69	4.96	.3465
30-60	21.18 a	6.93 b	7.06 b	.0019	14.34	10.04	9.60	.1464
60-90	10.70	5.68	7.06	.1723	11.36	12.80	10.92	.4587
90-120	9.60	7.06	7.83	.3927	10.70	10.59	9.05	.5399
120-150	5.52	7.17	5.39	.3526	9.49	7.61	7.17	.4903
Total	69.61 a	37.95 b	44.12 b	.0000	58.46	51.19	50.19	.2093

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

Appendix Table 3 (continued).

April 29, 1990 (Feekes 7)

Depth (cm)	NO_3 Plow	NO_3 Stubble Mulch	NO_3 No-tillage	NO_3 P-Value	NH_4 Plow	NH_4 Stubble Mulch	NH_4 No-tillage	NH_4 P-Value
0-15	2.43 a	0.79 a	7.32 b	.0369	4.85	4.80	9.05	.0986
15-30	3.03 a	1.10 b	1.31 b	.0147	4.52	3.86	4.30	.7182
30-60	11.69 a	2.21 b	1.91 b	.0586	8.38	7.94	9.71	.3966
60-90	5.07 a	2.21 b	2.11 b	.0096	8.71	8.71	9.38	.8387
90-120	5.29 a	2.21 b	2.33 b	.0098	7.39	7.61	8.60	.4300
120-150	2.31 a	1.86 b	1.93 b	.0220	5.96	5.85	7.50	.0709
Total	29.82 a	10.38 b	16.91 b	.0383	39.81 a	38.77 a	48.54 b	.0024

May 14, 1990 (Feekes 10)

Depth (cm)	NO_3 Plow	NO_3 Stubble Mulch	NO_3 No-tillage	NO_3 P-Value	NH_4 Plow	NH_4 Stubble Mulch	NH_4 No-tillage	NH_4 P-Value
0-15	1.10	1.10	1.10	.9999	6.84	5.02	6.73	.3971
15-30	1.10	1.10	1.10	.9999	5.46	3.75	5.29	.2827
30-60	2.20	2.20	2.20	.9999	13.24	8.47	11.36	.4776
60-90	2.20	2.20	2.20	.9999	11.58	9.27	10.92	.1303
90-120	2.20	2.20	2.20	.9999	10.70	8.05	10.70	.1289
120-150	2.20	2.20	2.20	.9999	18.75	10.70	10.04	.4099
Total	11.00	11.00	11.00	.9999	66.57 a	45.26 b	55.04 c	.0183

Appendix Table 3 (continued).

June 2, 1990 (Feekes 10.5)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.10 a	1.10 a	5.42 b	.0250	8.99	2.92	11.97	.1678
15-30	1.10	1.10	1.10	.9999	7.89 a	3.64 b	6.67 a	.0151
30-60	2.20	2.20	2.20	.9999	13.35 a	7.61 b	8.27 b	.0551
60-90	2.20	2.20	2.20	.9999	16.88 a	7.17 b	7.50 b	.0182
90-120	2.20	2.20	2.20	.9999	11.69 a	7.50 b	8.93 b	.0065
120-150	2.20	2.20	2.20	.9999	10.92	5.74	6.62	.2036
Total	11.00 a	11.00 a	15.42 b	.0054	69.72 a	34.58 b	49.96 c	.0000

Appendix Table 4. Malcolm wheat leaf and stem nitrogen (%) at various growth stages during the 1989-90.

	LEAF				STEM			
Feekes Stage	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
5	4.60 a[1]	3.08 b	3.87 ab	.0249	—	—	—	—
7	3.96 a	3.24 b	3.48 b	.0232	1.97 a	1.26 b	1.57 b	.0101
10	3.15 a	2.44 b	2.61 b	.0338	1.21 a	0.93 b	1.01 b	.0146
10.3	2.70 a	1.71 b	2.18 c	.0007	0.81	0.63	0.76	.0649
11.4	1.23 a	0.70 b	0.65 b	.0001	0.53	0.39	0.40	.0963

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

Appendix Table 5. Crop soil water (cm) on several sampling dates during the 1989-90 growing season.

October 8, 1989 (Planting)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.533 ab[1]	1.965 a	1.252 b	.0360
15-30	2.349	2.173	1.902	.2004
30-60	4.365	4.545	4.275	.4193
60-90	4.038	4.440	4.245	.1963
90-120	4.098 a	4.458 ab	4.809 b	.0077
120-150	4.551 a	5.157 ab	5.406 b	.0131
Total	20.934 a	22.738 b	21.889 c	.0008
			T * D[2]	.0000

November 1, 1989

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.855	1.947	1.876	.4137
15-30	2.158	2.107	2.035	.1870
30-60	4.296	4.413	4.326	.6858
60-90	4.002	4.377	4.278	.2218
90-120	4.071 a	4.641 b	4.761 b	.0240
120-150	4.503 a	5.076 ab	5.415 b	.0073
Total	20.885 a	22.561 b	22.691 b	.0016
			T * D	.0276

March 21, 1990 (Feekes 4)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.251 a	1.909 b	2.653 c	.0000
15-30	2.637 a	2.091 b	2.658 a	.0000
30-60	5.149 a	4.981 b	4.931 b	.0185
60-90	4.809	4.906	4.738	.3939
90-120	4.742 a	4.960 b	4.696 a	.0201
120-150	4.990	5.166	4.998	.2913
Total	24.578 a	24.013 b	24.674 a	.0000
			T * D	.0000

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

[2] Tillage * Depth interaction

Appendix Table 5 (continued).

April 7, 1990 (Feekes 5)[3]

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.890 a	1.378 b	1.897 a	.0000
15-30	2.295 a	1.698 b	2.241 a	.0000
Total	4.185 a	3.076 b	4.138 a	.0120

April 29, 1990 (Feekes 7)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.670	2.487	2.638	.2273
15-30	1.689 a	1.446 b	1.645 a	.0000
Total	4.359 a	3.933 b	4.283 a	.0016

May 14, 1990 (Feekes 10)

Depth (cm)	Plow	Stubble Mulch	No-tillage		P-Value
0-15	1.242 a	0.991 b	1.134 a		.0070
15-30	1.620 a	1.386 b	1.642 a		.0357
30-60	3.222 a	2.594 b	3.123 a		.0105
60-90	3.009 a	2.439 b	3.177 b		.0383
90-120	3.444 a	2.582 b	3.510 a		.0411
120-150	3.915 a	3.480 b	4.503 c		.0024
Total	16.452 a	13.472 b	17.089 a		.0000
				T * D	.5587

June 2, 1990 (Feekes 10.5)

Depth (cm)	Plow	Stubble Mulch	No-tillage		P-Value
0-15	1.681	1.164	1.558		.1132
15-30	1.191	1.052	1.223		.1525
30-60	2.860	2.654	2.961		.0632
60-90	2.632 a	2.412 a	2.953 b		.0123
90-120	2.794 ab	2.503 a	2.890 b		.0406
120-150	3.357	3.294	3.435		.8056
Total	14.515 a	13.079 b	15.020 a		.0009
				T * D	.6307

[3] 30 to 150 cm values not reported because of neutron probe malfunction.

Appendix Table 5 (continued).

July 17, 1990 (Feekes 11.4)				
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	0.646	0.657	0.724	.7698
15-30	1.191	1.195	1.257	.4025
30-60	2.515	2.534	2.695	.2337
60-90	2.365	2.450	2.536	.3484
90-120	2.254	2.362	2.552	.0955
120-150	2.556 a	2.464 a	3.129 b	.0507
Total	11.527 a	11.662 a	12.893 b	.0003
			T * D	.3855

Appendix Table 6. Malcolm wheat plant nitrogen (%) at several growth stages in 1990-91.

Feekes Stage	Plow	Stubble Mulch	No-tillage	P-Value
4	3.80 a[1]	4.27 ab	4.65 b	.0219
5	2.67 a	3.42 b	3.99 c	.0005
7	2.03 a	2.26 ab	3.10 b	.0461
10	1.15	1.16	1.80	.0734
10.3	0.88 a	0.78 a	1.41 b	.0107
11.4	0.33	0.30	0.36	.4185

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

Appendix Table 7. Soil NO_3^- and NH_4^+ (kg ha^{-1}) at several plant growth stages during 1990-91.

September 20, 1990 (Planting)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	9.81	15.61	23.56	.0647	3.86	2.06	3.44	.1377
15-30	5.83 a	5.24	8.05	.3744	3.58	1.73	1.90	.0631
30-60	8.49	5.22	9.10	.5505	5.83 a [1]	4.77 b	4.25 b	.0520
60-90	1.07	1.93	3.81	.2885	5.52	4.10	5.03	.4275
90-120	0.08	0.90	2.04	.0607	5.06	3.22	4.09	.2953
120-150	1.33 a	2.88 b	3.81 b	.0098	3.22 a	4.09 ab	5.06 b	.0039
Total	26.61 a	31.78 ab	50.37 b	.0593	27.07 a	19.97 b	23.77 ab	.0138

March 18 1991 (Feekes 4)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	29.10	29.65	32.79	.9434	36.38 a	10.75 b	13.85 b	.0150
15-30	13.60 a	19.23 a	41.28 b	.0089	2.60 a	1.71 b	3.47 a	.0300
30-60	40.11	47.22	48.94	.8026	5.21	3.88	6.76	.0937
60-90	12.07	17.63	16.61	.3213	5.72	4.23	7.43	.3525
90-120	3.45	21.16	7.72	.4885	5.13 a	1.82 b	4.82 a	.0466
120-150	4.68	4.46	6.04	.7343	5.21	2.49	7.83	.1077
Total	103.01	139.35	153.38	.0729	60.25 a	24.88 b	44.16 c	.0055

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

Appendix Table 7 (continued).

April 10, 1991 (Feekes 5)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	13.45	13.28	20.34	.4499	25.44 a	5.14 b	5.24 b	.0057
15-30	4.94 a	13.70 ab	22.50 b	.0117	4.10 a	2.18 b	2.65 b	.0203
30-60	16.19	36.13	48.58	.0636	7.63 a	4.89 b	4.70 b	.0146
60-90	6.57	12.15	15.31	.2723	7.42	6.23	6.27	.5073
90-120	2.90	7.06	7.60	.1555	5.58	3.64	4.84	.4098
120-150	3.22 a	4.56 a	9.07 b	.0553	4.37	1.74	1.79	.4784
Total	47.27 a	86.88 ab	123.40 b	.0377	54.54 a	23.82 b	25.49 b	.0021

April 25, 1991 (Feekes 7)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	5.52	2.89	13.45	.0655	9.98	8.61	4.17	.1472
15-30	1.97 a	1.53 a	14.49 b	.0043	0.98 a	4.10 b	0.84 a	.0003
30-60	4.58 a	5.11 a	37.16 b	.0028	3.14 a	7.66 b	2.56 a	.0001
60-90	2.03 a	4.08 a	17.38 b	.0008	3.50	7.88	2.15	.0732
90-120	2.70 a	2.61 a	7.74 b	.0057	3.14	4.34	1.91	.6130
120-150	4.61	4.02	6.55	.1345	1.92	2.74	0.35	.7612
Total	21.41 a	20.24 a	96.77 b	.0004	22.66 ab	35.33 b	11.98 a	.0279

Appendix Table 7 (continued).

May 18, 1991 (Feekes 10)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	7.80	6.55	15.25	.3523	17.52 a	7.86 b	7.24 b	.0071
15-30	1.17	1.27	3.22	.0722	3.39	2.36	4.54	.2754
30-60	3.31	2.18	6.28	.2939	7.98	5.29	8.32	.3380
60-90	1.33	1.63	4.90	.0600	7.40 ab	5.65 a	10.27 b	.0542
90-120	1.58 a	1.22 a	4.59 b	.0078	6.83	5.68	9.69	.4758
120-150	7.72	2.21	4.94	.2015	8.60	8.14	1.90	.4533
Total	22.91	15.06	39.18	.0691	51.72	34.98	41.96	.1270

June 6, 1991 (Feekes 10.5)

	NO_3				NH_4			
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value	Plow	Stubble Mulch	No-tillage	P-Value
0-15	6.06	3.47	9.58	.1498	14.09	9.81	6.21	.5469
15-30	1.11	0.36	1.57	.1105	2.47	2.18	2.40	.9487
30-60	1.72 ab	0.24 a	2.10 b	.0552	5.71	6.91	4.25	.3159
60-90	1.12 a	0.16 b	2.89 c	.0347	5.91	5.37	4.59	.8187
90-120	0.88	0.09	3.26	.1258	2.72	5.12	2.61	.2779
120-150	0.90 a	0.15 a	15.14 b	.0500	2.05	2.86	5.63	.5673
Total	11.79 a	4.47 a	34.54 b	.0401	32.95	32.25	25.69	.4976

Appendix Table 8. Crop soil water (cm) on several sampling dates during the 1990-91 growing season.

September 15, 1990 (Planting)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.755	1.830	1.539	.3449
15-30	2.479	2.451	2.286	.4521
30-60	4.200	4.404	4.107	.7696
60-90	3.270	3.504	3.564	.8599
90-120	3.738	4.191	3.927	.7983
120-150	4.923 a[1]	5.127 a	3.564 b	.0507
Total	20.365 a	21.507 b	18.987 c	.0198
			T * D[2]	.1604

March 20, 1991 (Feekes 4)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.760 a	3.220 b	3.210 b	.0000
15-30	2.892 a	3.330 b	3.328 b	.0000
30-60	5.385	5.283	5.619	.3069
60-90	3.999 a	4.389 ab	5.301 b	.0272
90-120	3.276	3.606	3.378	.1495
120-150	4.473	4.530	4.464	.9753
Total	22.785 a	24.358 b	25.300 c	.0008
			T * D	.1362

April 10, 1991 (Feekes 5)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	2.182 a	2.647 b	3.012 c	.0000
15-30	2.364 a	2.844 b	3.120 c	.0000
30-60	4.656 a	4.674 a	5.271 b	.0342
60-90	3.801 a	4.176 a	5.157 b	.0208
90-120	3.489 ab	3.852 a	3.375 b	.0432
120-150	4.761	4.593	4.260	.2613
Total	21.253 a	22.786 b	24.195 c	.0000
			T * D	.0007

[1] Within row means followed by the same letter are not significantly different at P = 0.05.

[2] Tillage * Depth interaction

Appendix Table 8 (continued).

April 25, 1991 (Feekes 7)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.368 a	1.678 b	2.250 c	.0000
15-30	1.728 a	2.146 b	2.665 c	.0000
30-60	3.564 a	3.870 a	4.836 b	.0001
60-90	3.372 a	3.834 b	4.992 c	.0022
90-120	3.408 a	3.897 b	3.441 a	.0319
120-150	4.731	4.647	4.342	.3602
Total	18.171 a	20.072 b	22.526 c	.0000
			T * D	.0001

May 16, 1991 (Feekes 10)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.666 a	2.032 b	2.382 c	.0000
15-30	1.468 a	1.725 a	2.229 b	.0000
30-60	2.845 a	2.905 a	3.924 b	.0001
60-90	2.928 a	2.932 a	4.365 b	.0000
90-120	2.930 a	3.516 b	3.369 b	.0344
120-150	4.344	4.599	4.290	.6052
Total	16.181 a	17.709 b	20.559 c	.0000
			T * D	.0033

June 6, 1991 (Feekes 10.5)

Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	1.250 a	1.441 a	1.803 b	.0001
15-30	1.275 a	1.375 a	1.692 b	.0001
30-60	2.640 a	2.542 a	3.192 b	.0005
60-90	2.519 a	2.510 a	3.432 b	.0000
90-120	2.548 a	2.776 ab	3.108 b	.0510
120-150	3.603	3.831	3.981	.5423
Total	13.835 a	14.475 b	17.208 c	.0000
			T * D	.4288

July 25, 1991 (Feekes 11.4)

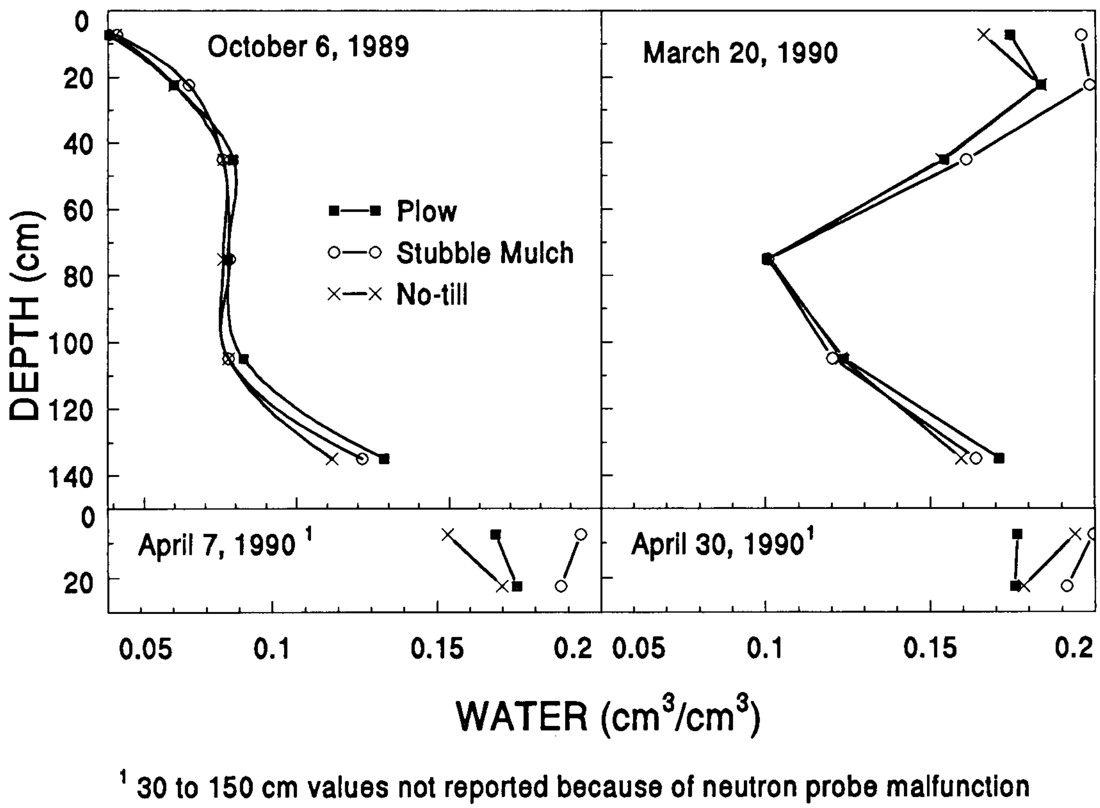
Depth (cm)	Plow	Stubble Mulch	No-tillage	P-Value
0-15	0.778 a	0.772 a	1.011 b	.0006
15-30	1.165 a	1.247 a	1.636 b	.0000
30-60	2.564 a	2.437 b	2.597 a	.0086
60-90	2.473 a	2.413 a	2.734 b	.0010
90-120	2.490	2.446	2.623	.5211
120-150	3.318	3.132	3.441	.6197
Total	12.788 a	12.447 a	14.042 b	.0000
			T * D	.0150

Appendix Table 9. Analysis of soil samples taken on October 7, 1989.

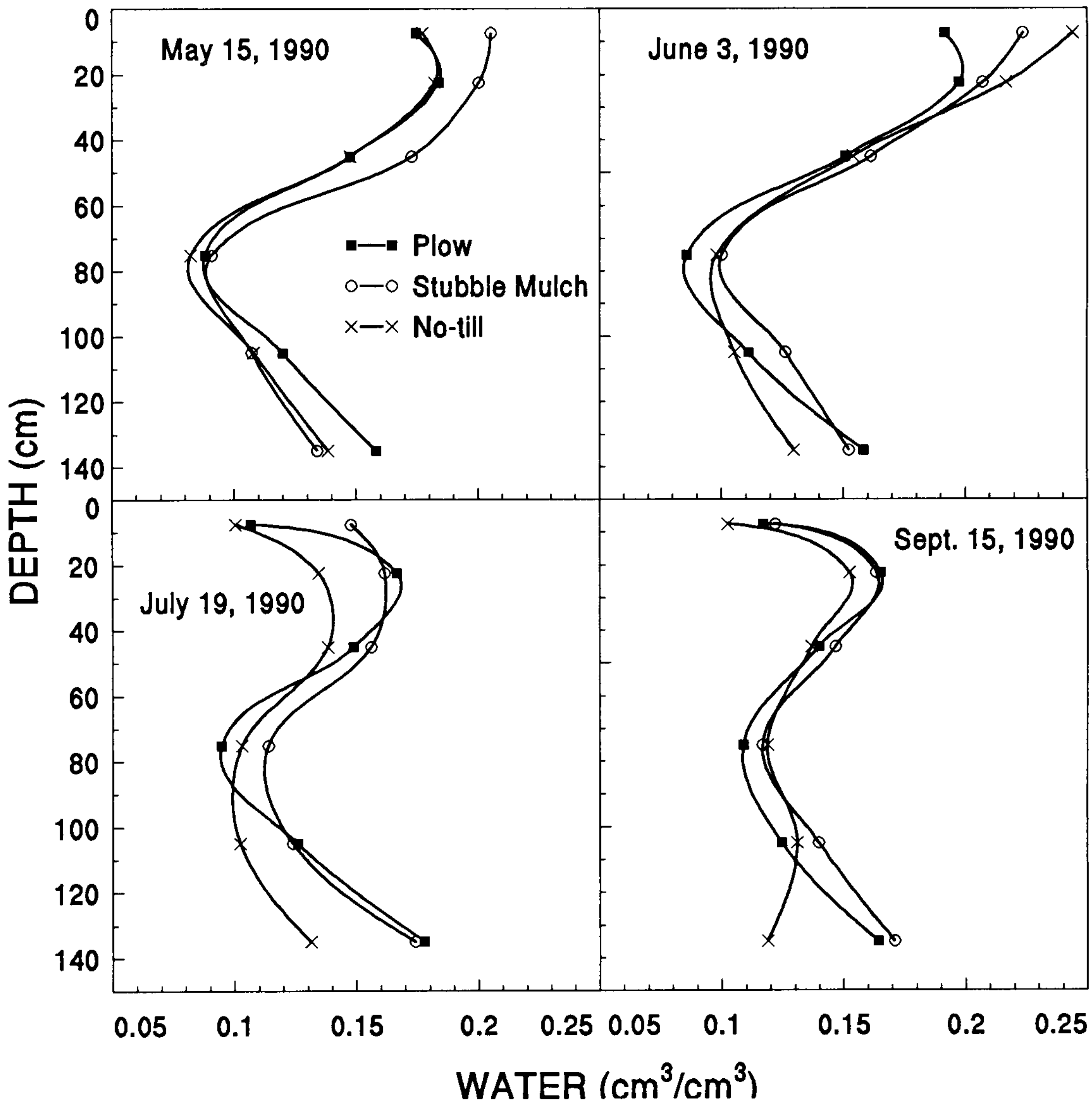
ANALYSIS	SOIL PROFILE DEPTH (cm)	TILLAGE SYSTEM		
		Plow	Stubble Mulch	No-till
pH	0 to 7.5	6.4	6.3	6.4
	7.5 to 15	6.8	6.4	6.5
	15 to 30	7.1	7.4	6.9
	30 to 60	7.6	8.2	7.4
	60 to 90	7.9	8.5	8.5
	90 to 120	8.6	8.7	8.6
	120 to 150	8.9	9.1	8.9
Phosphorous (ppm)	0 to 7.5	34	32	39
	7.5 to 15	33	32	35
	15 to 30	25	25	28
	30 to 60	—	19	—
	60 to 90	—	14	—
	90 to 120	—	9	—
	120 to 150	—	7	—
Potassium (ppm)	0 to 7.5	503	527	577
	7.5 to 15	449	413	433
	15 to 30	390	398	390
	30 to 60	—	277	—
	60 to 90	—	215	—
	90 to 120	—	203	—
	120 to 150	—	137	—
Calcium (meq./100 g)	0 to 7.5	7.9	6.4	6.2
	7.5 to 15	8.7	6.9	6.5
	15 to 30	8.0	9.3	7.7
	30 to 60	—	17.0	—
	60 to 90	—	29.7	—
	90 to 120	—	30.8	—
	120 to 150	—	30.3	—
Magnesium (meq./100 g)	0 to 7.5	2.5	2.3	2.6
	7.5 to 15	2.4	2.4	2.6
	15 to 30	2.9	3.0	3.1
	30 to 60	—	3.5	—
	60 to 90	—	4.1	—
	90 to 120	—	6.9	—
	120 to 150	—	8.3	—

Appendix Table 9 (continued).

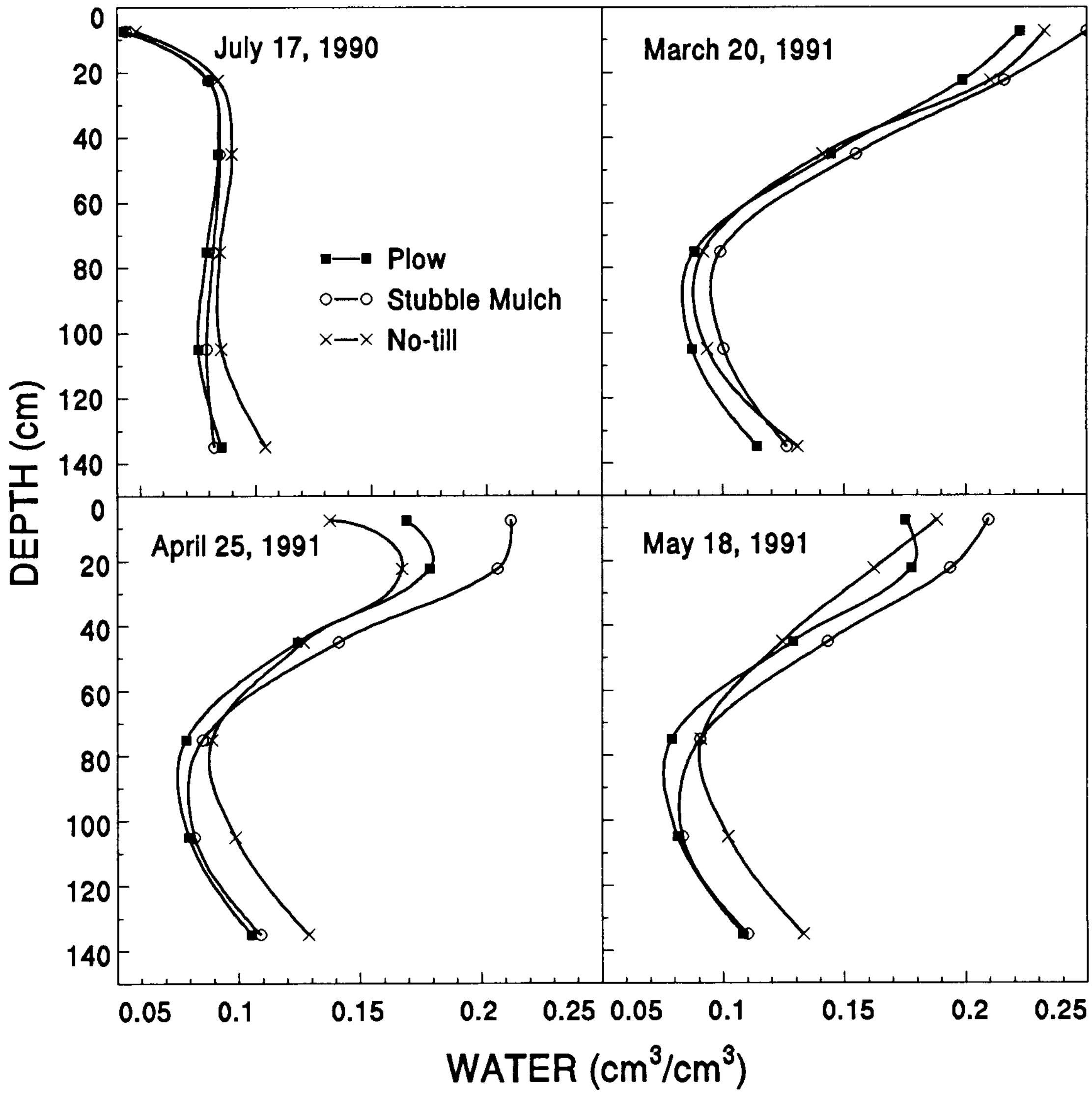
ANALYSIS	SOIL PROFILE DEPTH (cm)	TILLAGE SYSTEM		
		Plow	Stubble Mulch	No-till
Organic Matter (%)	0 to 7.5	1.27	1.38	1.65
	7.5 to 15	1.21	1.21	1.16
	15 to 30	0.99	1.10	0.99
	30 to 60	—	0.94	—
	60 to 90	—	0.77	—
	90 to 120	—	0.39	—
	120 to 150	—	0.33	—
Mineralizable N (ppm)	0 to 7.5	39.6	7.8	53.7
	7.5 to 15	33.2	32.4	11.4
	15 to 30	9.5	9.6	7.3
CEC (meq./100 g)	0 to 7.5	11.8	11.5	11.5
	7.5 to 15	12.1	11.5	11.2
	15 to 30	12.7	13.3	12.8
	30 to 60	—	13.2	—
	60 to 90	—	12.3	—
	90 to 120	—	11.8	—
	120 to 150	—	12.1	—
Soluble Salts (mm/hos/cm)	0 to 7.5	1.20	1.00	0.60
	7.5 to 15	1.10	0.55	0.25
	15 to 30	0.30	0.45	0.20
	30 to 60	0.20	0.35	0.20
	60 to 90	0.25	0.35	0.40
	90 to 120	0.35	0.40	0.40
	120 to 150	0.65	0.60	0.60



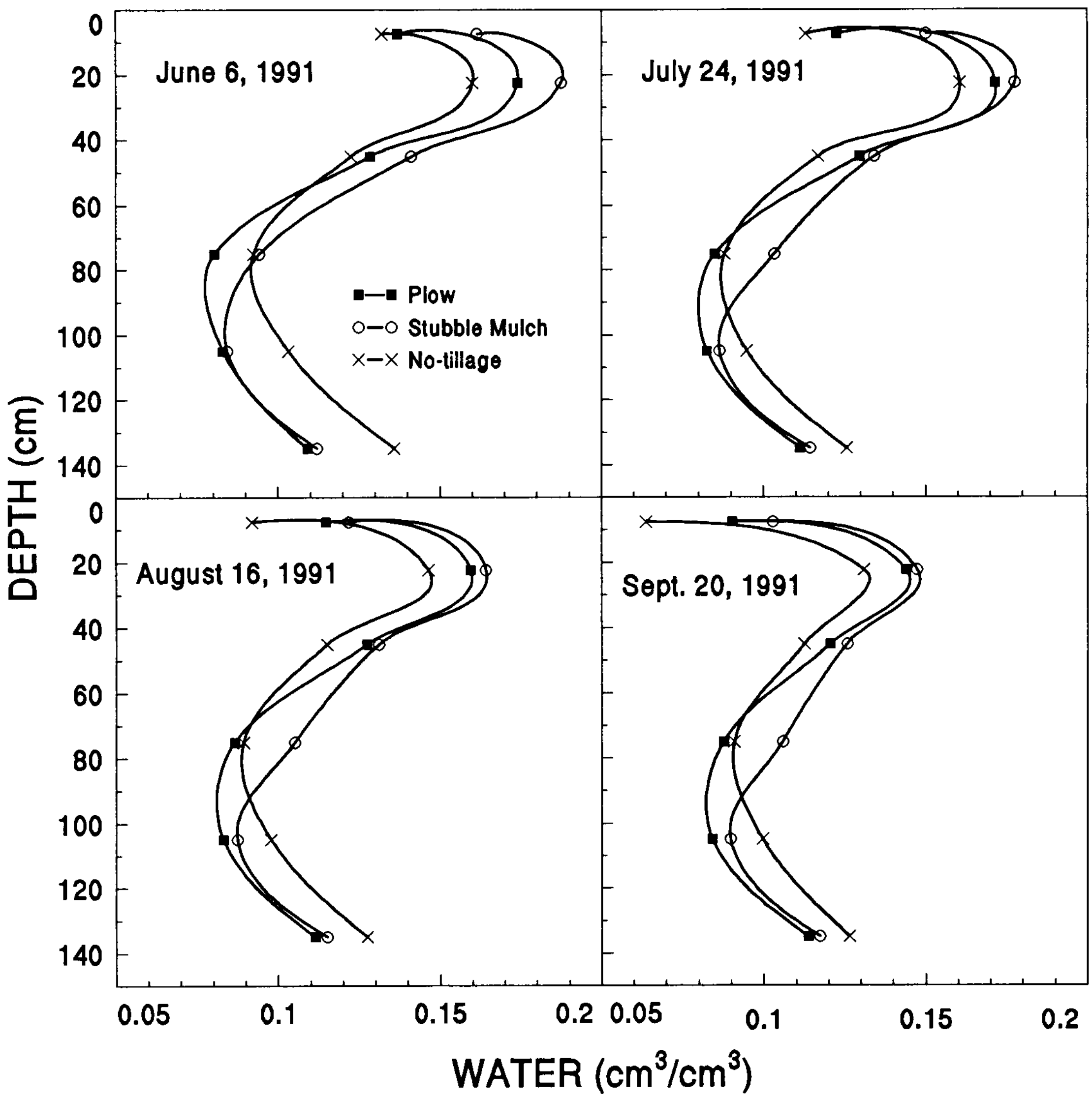
Appendix Figure 1. Soil water on four early sampling dates during the 1989-90 fallow season.



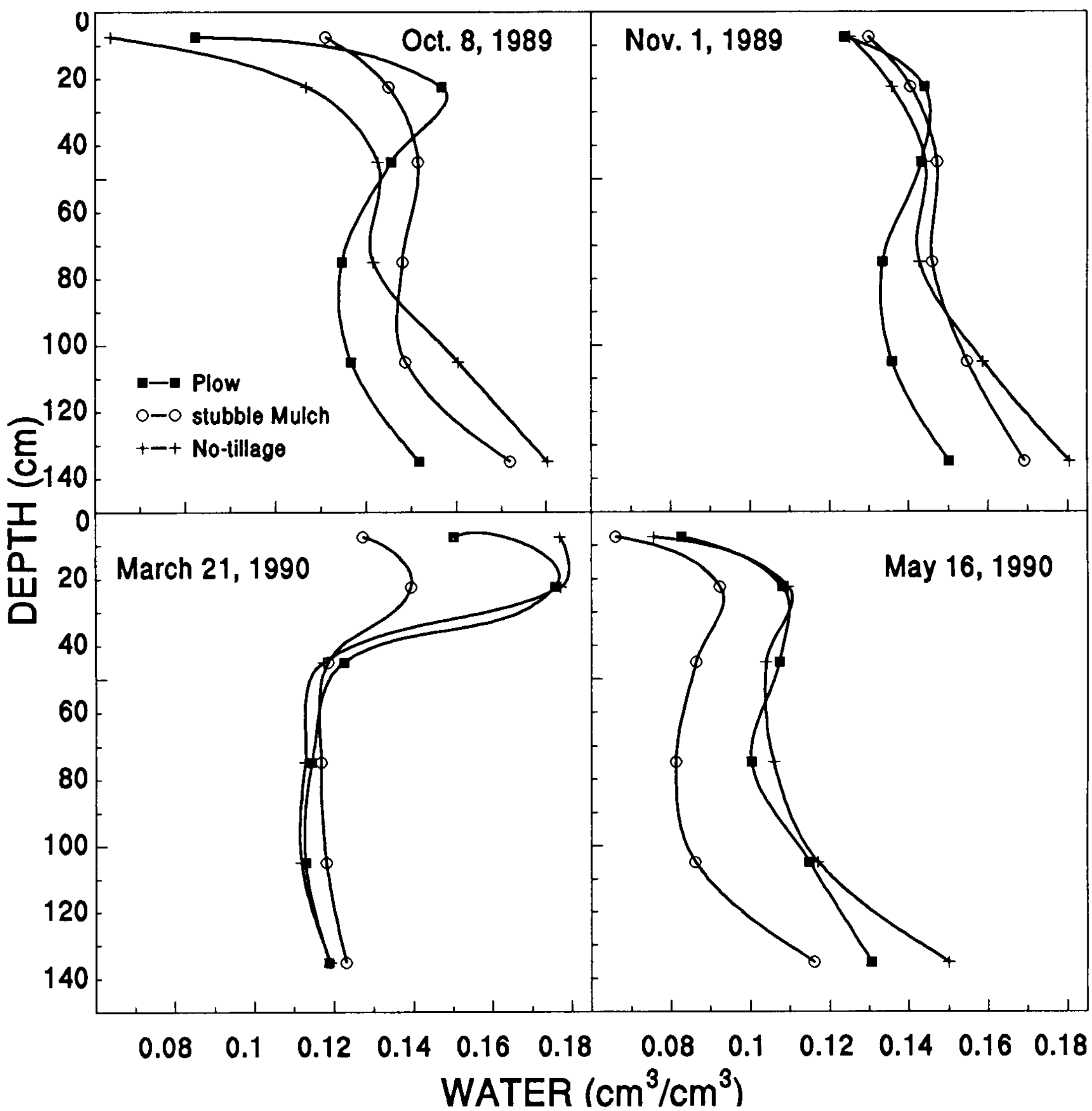
Appendix Figure 2. Soil water on four late sampling dates during the 1989-90 fallow season.



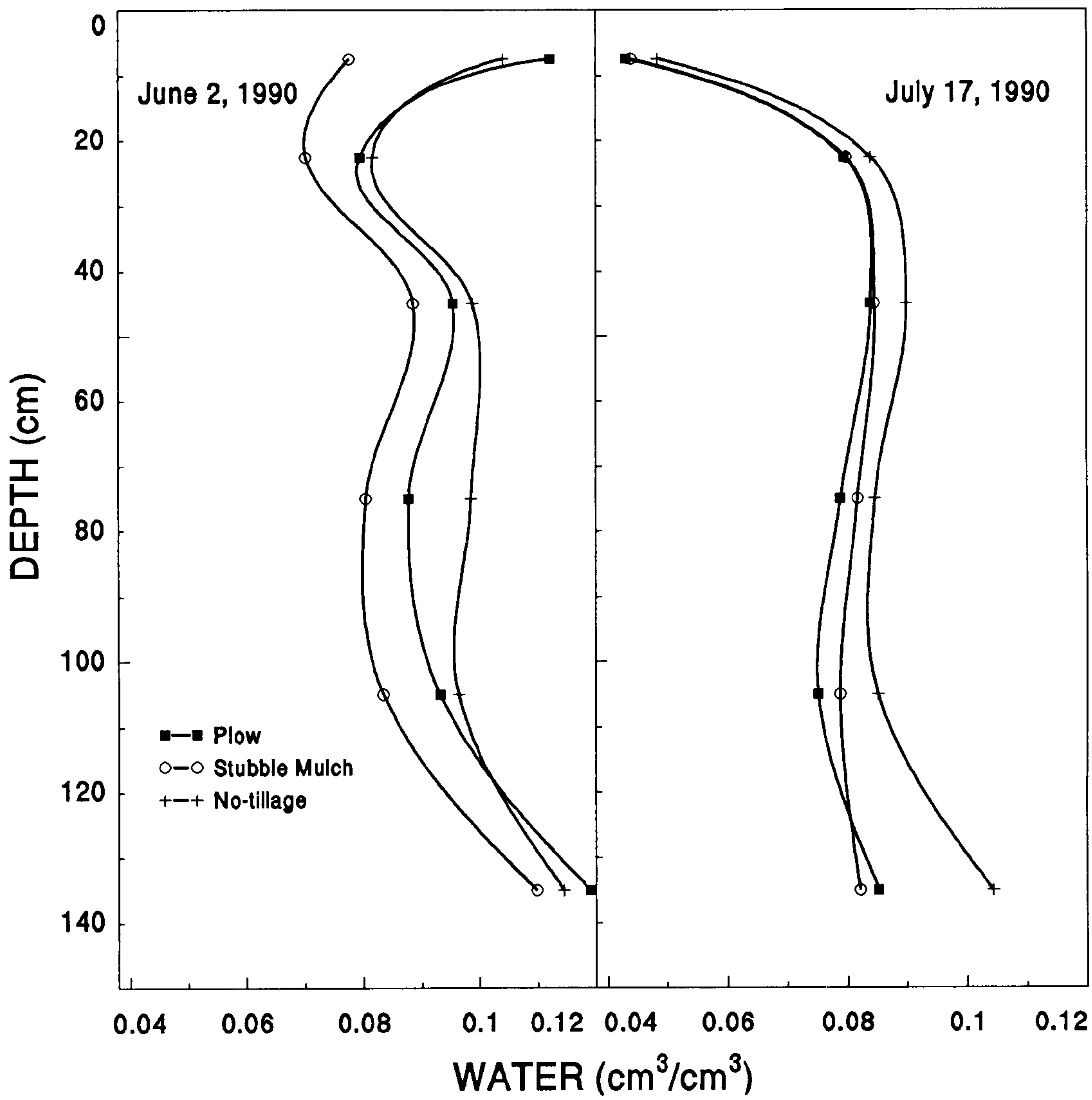
Appendix Figure 3. Soil water on four early sampling dates during the 1990-91 fallow season.



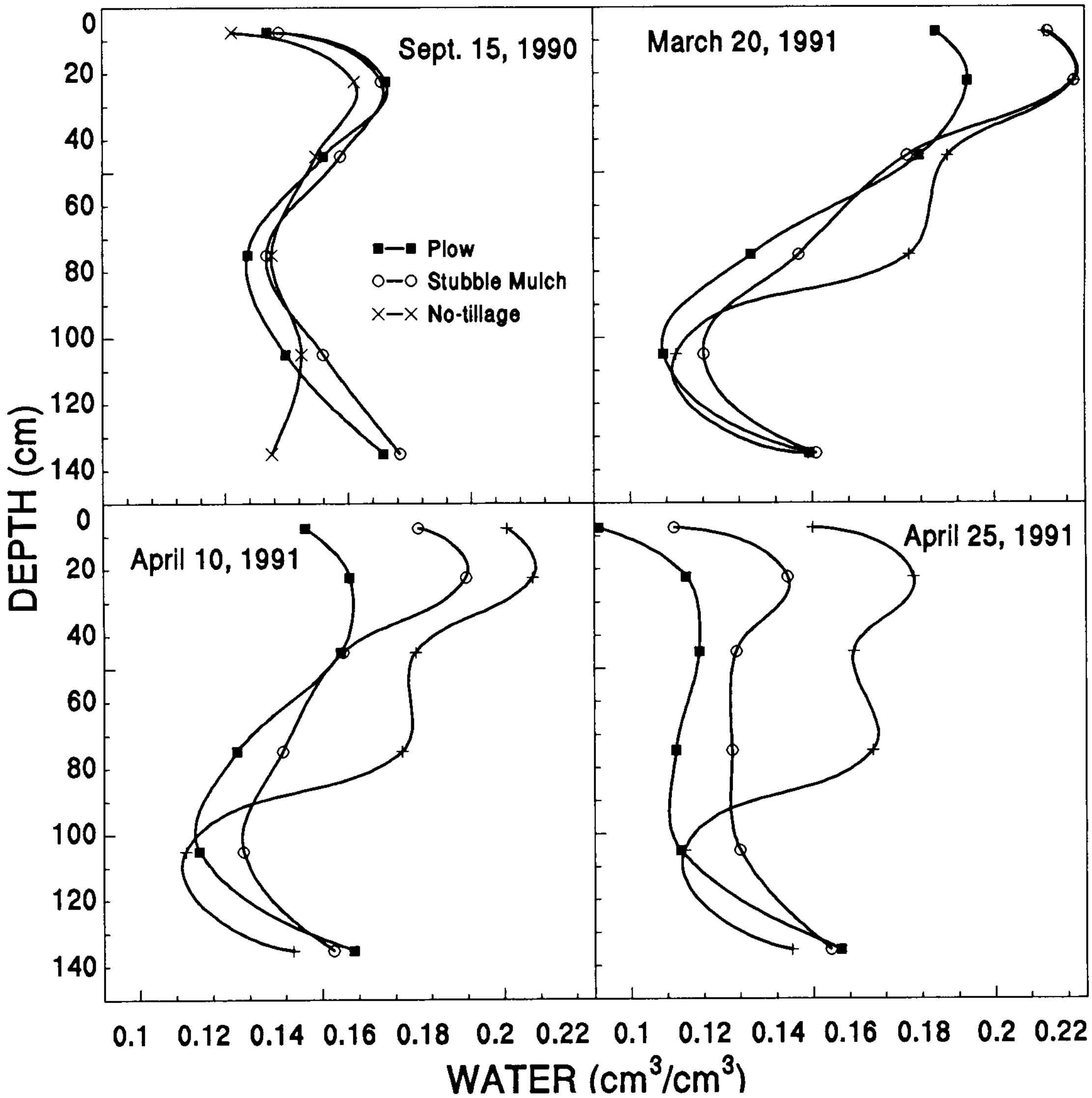
Appendix Figure 4. Soil water on four late sampling dates during the 1990-91 fallow season.



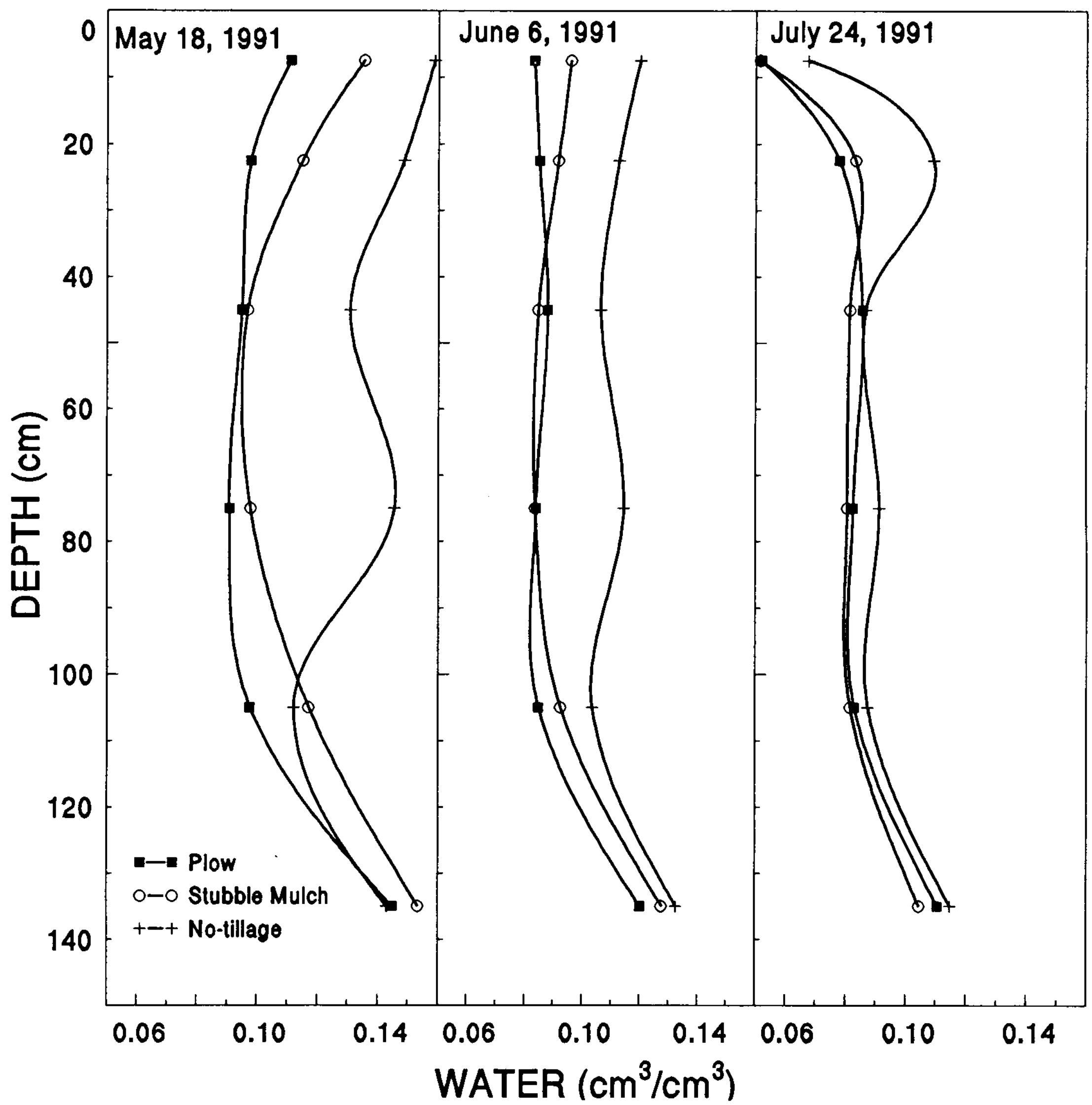
Appendix Figure 5. Soil profile water at several wheat growth stages during 1989-90 as affected by tillage method.



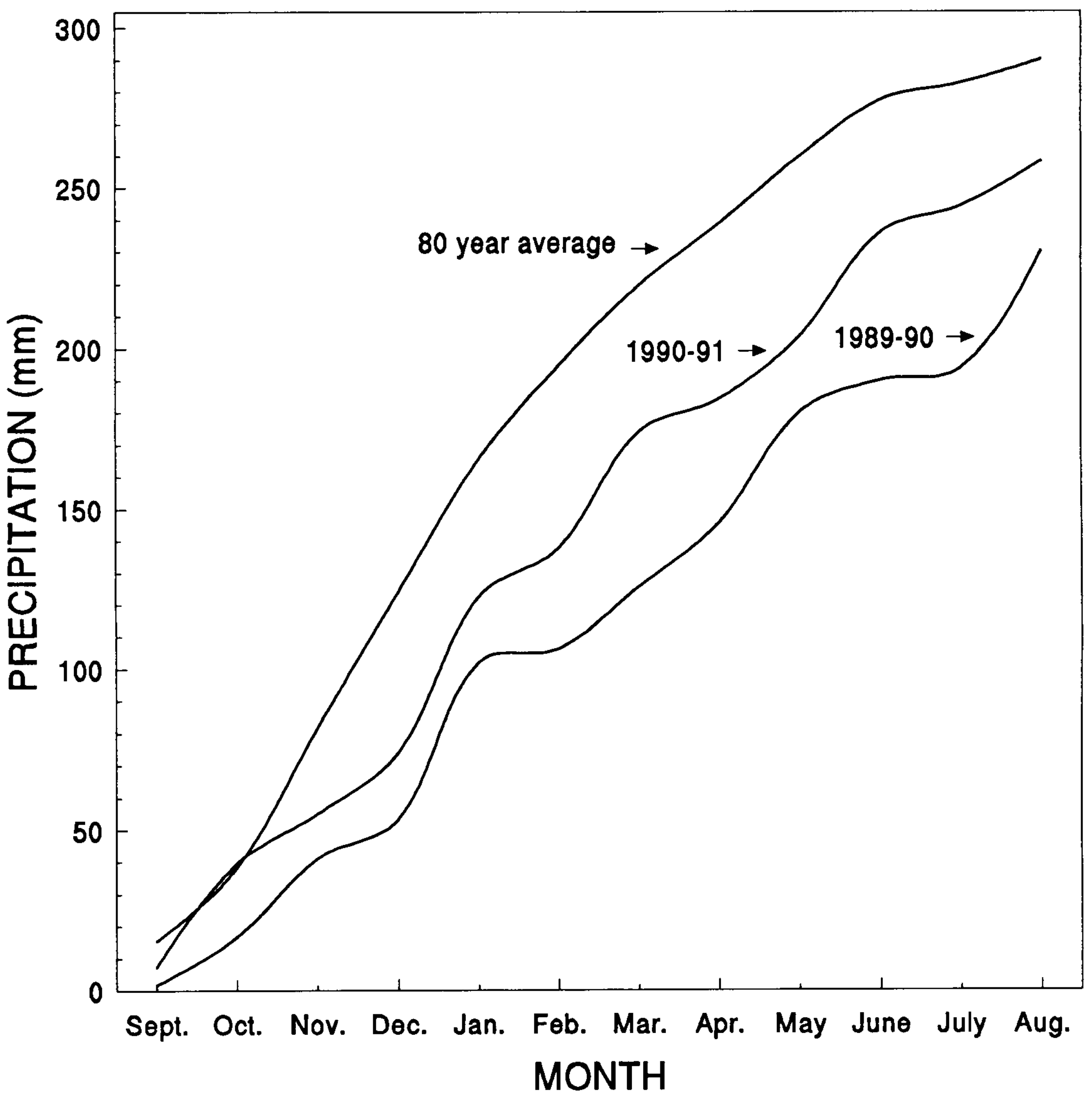
Appendix Figure 5 (continued).



Appendix Figure 6. Soil profile water at several wheat growth stages during 1990-91 as affected by tillage method.



Appendix Figure 6 (continued).



Appendix Figure 7. Annual precipitation at Moro, Oregon.