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Title: SOIL MOISTURE STORAGE, DISTRIBUTION, AND USE BY WINTER WHEAT IN A 250-350 MM PRECIPITATION ZONE OF EASTERN OREGON

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The semi-arid dryland wheat-producing areas of the Pacific Northwest are characterized by cool, moist winters and dry, hot summers. The amount of annual precipitation is generally quite variable and inadequate for annual cropping. Where soil depth is adequate, the predominant loessal soils generally supply sufficient moisture for small grain production through the practice of summer fallowing. Though inefficient in moisture storage, fallowing reduces the risk of crop failure by storing a portion of the precipitation received during the 14-month fallow period for later use during a 10-month winter-grain growing season.

Nitrogen fertilizer rates must be balanced with available moisture supply for maximum yields and desired protein contents. In order to develop predictive moisture availability equations, five fallow-crop precipitation patterns characteristic of the 250-350 mm precipitation zone of eastern Oregon were simulated in the field on a commercial dryland farm near Moro, Oregon, beginning in 1977; two 24-month fallow-crop cycles were completed during a three-year

period. Moisture measurements made to a minimum depth of 270 cm at different times during both the fallow and crop periods have provided useful agronomic information.

The soil moisture content continued to decline through upward movement from the beginning of the fallow period to the period of winter precipitation; vertical movement depended on the tension gradient.

The greatest efficiency in moisture storage occurred during the first winter storage period when the fallow soil was generally dry; cumulative storage efficiency was highest on the plots which had received the least precipitation.

The greatest rate of measured moisture loss occurred immediately after the fallow winter storage period. Soil moisture continued to decline during the remainder of the fallow period, especially in the 0-90 cm soil profile, but at a much lower rate due primarily to the development of a soil mulch through spring tillage.

On the average, there would have been no moisture storage advantage to fallowing when the level of net storage in the spring of the fallow period was 194 mm or greater in the 0-270 cm soil profile ($r^2 = 0.94$).

After the crop winter storage period, comparison of precipitation treatments that eventually would have equal amounts of cumulative precipitation indicated that a greater amount of stored moisture was stored in the plots which had the wetter fallow period, and in these plots more moisture was stored in the 90-180 cm soil profile than in plots with a drier fallow period. The plots with the wetter fallow also showed more soil moisture removal by the crop than plots with a drier fallow.

A significant increase in grain yield, water-use-efficiency, and soil moisture extraction occurred as nitrogen fertilizer rates increased from zero; increases in soil moisture extraction due to fertilizer were most pronounced in the 90-180 cm soil profile.

Linear regression analyses showed the relationship between the maximum grain yield (kg/ha) in each main plot, and the sum (mm) of the precipitation (P) and moisture depletion from the 0-180 cm soil profile (SM) between early spring of the crop period and harvest to be defined by the following equation:

$$Y = 21.1\ (SM + P - 62); \quad r^2 = 0.80$$

Soil moisture held between 1/3 and 15 bars tension was not uniformly depleted to the 15-bar level throughout the root zone, but rather the amount extracted tended to decrease with increasing soil depth.

Extractable moisture, defined as the difference between the highest measured volumetric soil moisture content in early spring of the crop period and the soil moisture content at harvest, more accurately reflects the amount of soil moisture utilized through evapotranspiration than does the amount of moisture held between 1/3 and 15 bars tension. Linear regression equations were developed to estimate the amount of extractable soil moisture in the 0-90, 90-180, and 180-270 cm soil depths from soil moisture measurements in early spring of the crop year. Estimates of extractable moisture, together with an estimate of anticipated crop season precipitation, can be used to predict the potential grain yield, which in turn is necessary to calculate the optimum amount of nitrogen fertilizer.

SOIL MOISTURE STORAGE, DISTRIBUTION, AND USE BY WINTER WHEAT IN A 250-350 MM PRECIPITATION ZONE OF EASTERN OREGON

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SOIL MOISTURE STORAGE, DISTRIBUTION, AND USE BY WINTER WHEAT IN A 250-350 MM PRECIPITATION ZONE OF EASTERN OREGON

I. INTRODUCTION

The Pacific Northwest is characterized by diverse climates, topography, and soils. The climates range from a mild, equable, marine-type to a drier continental-type with extreme fluctuations in temperature. Though annual precipitation ranges from 15 to 380 cm, the region is generally characterized by cool, moist winters and dry, hot summers. The summers are excellent for harvesting low moisture grain and seed crops, but limit the choice of crops grown under rainfed conditions.

Most Pacific Northwest wheat is currently produced in the dry-farmed areas of the Columbia Basin, where soft white winter wheat predominates. In the drier subareas, which include north-central Oregon, the Big Bend area of central Washington, and the Columbia Plateau, annual precipitation is generally highly variable and inadequate (200-350 mm) for annual cropping, and farmers have few alternatives to small grain production. The predominant soils are loessal, and permit sufficient moisture storage through the practice of fallowing where depth is adequate. Though considered inefficient, fallowing lessens the risk of crop failure through permitting storage of a portion of the precipitation that occurs during the non-crop period beginning at harvest and ending with planting, usually in September or October for winter grains.

Application of nitrogen, together with increases in soil nitrogen, generally increases wheat yields more than other nutrients when balanced with the limited moisture available to the crop. Insufficient nitrogen will not permit the crop to achieve its yield potential, while heavy vegetative growth caused by excessive nitrogen can result in early depletion of soil moisture, causing shriveled kernels and reduced yields. This problem is accentuated with soft white wheats grown for pastry flour, since high quality pastry flours require grain with less than nine percent protein. Nitrogen fertilizer rates above those required for maximum yields can increase protein content, causing an economic disadvantage for pastry-type wheats.

Farmers have long needed a means to accurately predict the fertilizer needs of their dryland wheat crop. This is a difficult job since fertilizers are usually applied long in advance of knowing what level of moisture will be available to the crop.

Work by Aktan (1976) at the Sherman Branch Station (Moro, Oregon) showed that precipitation during the fallow period affected both nitrate mineralization and the depth at which it accumulated. In an analysis of long-term (1912-1976) weather data from the same station, Glenn (1981) reported that the distribution of precipitation between the fallow and crop periods had an effect on yield. For a given level of total precipitation, the fallow-crop sequence receiving more fallow season precipitation tended to have the higher yield.

At the beginning of the fallow period in 1977, field simulation of five fallow-crop precipitation sequences, accounting for 88% of the actual sequences between 1912 and 1976, was started in a cooperative effort to obtain data necessary in developing improved predictive equations for yield and nitrogen response. Different aspects of this research were reported earlier (D.M. Glenn, 1981; A.H. Senel, 1981).

The objectives of the research reported herein were to investigate the effects of five field-simulated precipitation patterns in a fallow-winter wheat rotation on:

(1) The relative amounts and distribution of soil moisture after the fallow and crop winter storage periods.

(2) Fallow moisture storage efficiencies over time.

(3) Whether percolation losses from the upper soil profile are being used later during the crop season to replenish moisture extracted by the roots.

(4) The influence of nitrogen fertilizer on moisture depletion and the respective water-use-efficiencies.

II. LITERATURE REVIEW

A. Soil Moisture Storage

Historical Use of the Fallow System

Maintaining a balance between man's needs and the productive capacity of the soil is the primary problem facing sustained land use in all dry areas of the world. Evidence that advanced agricultural civilizations have developed, prospered and eventually disappeared in the Near East, India, North America, and Central America indicates that this balance has seldom been achieved. The problem is even more acute today than in the past due to increased population and economic pressure (Arnon, 1972).

The practice of a two-year fallow-crop rotation was introduced in North Africa by the Romans between 200 B.C. to 500 A.D. and used quite regularly in the semi-arid regions. Summer fallow is the practice of keeping a field free of plant growth, usually for one year, to permit a portion of the precipitation that occurs during that period to be stored in the soil profile and available for the succeeding crop. The fallowed North African land was often used as pasture, just as in recent times (Despois, 1961).

One account of an early discovery of the benefits of summer tillage in North America indicates that a Scotch farmer was indirectly forced to use dryland summer tillage in 1885 at Assiniboia, now Indian Head, Saskatchewan (Howard, 1959). No hired labor was available for wheat planting due to a regional war. The farmer was able to plow one field and till it periodically through the summer to control the weeds; this field was then planted the next spring. Even though the growing season was dry, the fallowed field yielded 35 bushels per acre (2.4 metric tons/ha) while a nearby conventionally-tilled field yielded only 2 bushels per acre (134 kg/ha). During the next 35 years, the practice of summer fallow began to spread into the Great Plains area, coming into increasing use during the Montana homestead rush. But even summer fallow failed in many areas during a record drought from 1912 to 1921 in the northern Great Plains.

Wheat was important to the development and economy of early Northwest settlements, being the principal food, the main source of outside revenue, and even legal tender for a time (Hill and Jackman, 1960). Most early settlers were drawn west of the Cascades by stories of the beauty and richness of the area. Wheat was reported to have been planted as early as 1825 on Vancouver Island (Swenson, 1942). Wheat production in Oregon first spread throughout the Willamette Valley and then to settled areas east of the Cascades. Production on the bunch grasslands of eastern Oregon began about 1860, and most early wheat operations were connected with livestock enterprises (Oveson and Hall, 1957). With the completion of the Northern Pacific Railroad in 1881, and others afterward, wheat farming increased substantially in eastern Oregon, eastern Washington, and northern Idaho (Salmon et al., 1953). As more settlers moved into these areas, the land with the lighter soil and lower rainfall was brought into cultivation. Early dryland settlers attempted to grow wheat annually after fall plowing, but yields were so low that the practice of alternating wheat with summer fallow soon became widely adopted (Hunter et al., 1925). Prior to that time, no area in the United States had grown dryland wheat successfully with 28 centimeters of precipitation (Hill and Jackman, 1960).

By the 1980's, farmers had found that fall planting provided higher yields than spring planting when the winters weren't severe enough to cause freeze-outs. However, early farmers generally sowed wheat in the spring since true winter wheat was not available until 1906 when the variety Turkey Red was imported to eastern Oregon (French, 1958).

The practice of summer-fallow, though successful, was criticized as early as 1899 when an Oregon Agricultural College Experiment Station bulletin reported that benefits were transitory and the practice would eventually destroy soil productivity through reduced soil humus and loss of moisture-holding capacity (French, 1958). Dry farming experiment stations were subsequently established at Moro, Oregon, in 1911, at Lind, Washington, in 1916, and at Waterville, Washington, in 1917 to develop a dryland production research base.

It is a credit to the early farmers that the acreage of land fallowed in the Pacific Northwest has not varied much since the mid-1920's when field work was done with horses. Washington has about 951 thousand hectares of fallowed land; Oregon, 386; Idaho, 362; and the panhandle of Utah, 51 thousand hectares (Leggett et al., 1974).

Advantages and Disadvantages of Summer Fallow

Water is usually the most limiting factor to crop production in arid and semi-arid regions. The total amount of water is important, but the distribution of precipitation, fluctuations in soil moisture, and the relationship between available soil moisture and crop response can also influence yield (Leggett, 1959; Johnson and Davis, 1980).

Available soil moisture is defined as the moisture which plants can remove from the soil within a range of limiting soil moisture tensions (Peters, 1965). Throughout this literature review, it is considered as the moisture held in the soil between 1/3 and 15 bars tension.

Annual production of a small grain crop is one of the most effective methods for both efficient use of available moisture and for soil conservation (Papendick, 1975). But, in marginal precipitation areas, the risk of crop failure is great. For this reason, summer-fallow is used to stabilize small grain yields on responsive soils in the drier rainfed areas (Mathews, 1951); responsive soils are those which are not very heavy, very sandy, nor shallow (Mathews and Brown, 1938).

Cropping frequency depends on the amount of water available to the crop and on the degree of risk of crop failure in areas where water is the factor most limiting to production.

In a comparison of two locations with similar amounts of total annual precipitation, Mathews (1951) showed that the use of a fallow-wheat rotation was effective in both increasing wheat yields and stabilizing production. At Pendleton, Oregon, a winter rainfall area, 100% of an unspecified number of wheat yields were under 1.344 metric tons/ha under annual cropping; under fallow-cropping, 100% of the yields were over 1.344 metric tons/ha, and 83% were over 2.688 metric tons/ha. At Akron, Colorado, a summer rainfall area, 44% of the yields were under 336 kg/ha with continuous cropping, and none were over 2.688 metric tons/ha; with fallow cropping only 15% of the yield were below 336 kg/ha, and 5% were over 2.688 metric tons/ha. Thus, under those conditions, the data showed a greater potential in achieving high yields in a winter rainfall area than in a summer rainfall area, and that crop failures (yields less than 336 kg/ha) on fallowed land are more frequent in summer rainfall areas.

In an eight-year comparison in eastern Idaho, annually cropped wheat averaged 753 kg/ha per year, while wheat after fallow yielded 914 kg/ha on a per year basis (Massee and Siddoway, 1966). Higher than average precipitation during this period caused differences between the two cropping systems to be narrower than normal. It was also reported that weed problems, especially cheatgrass, became increasingly severe on the annually cropped plots.

In areas where the use of summer fallow is optional, its value is evident where yields following fallow are 100% or more greater than those obtained from annual cropping. Where yields are less than 100% greater, the practice still may be desirable as it is generally less expensive to fallow part of the land than it is to crop all of the land (Mathews, 1951). Leggett et al. (1974) estimated that an 80% yield increase after fallow may still be economical. The actual economic advantage will vary with the costs of production and grain prices.

Under semi-arid conditions the soil profile in the normal zone of wheat root development is dry at harvest time. The cycle of water accumulation and discharge is an annual event under annual wheat cropping and is usually confined to only a part of the soil profile where roots can freely develop. The practice of alternating a fallow period with a wheat crop lengthens the period of water accumulation, usually enabling deeper penetration into, and sometimes below, the root zone (Cole and Mathews, 1939).

In the Great Plains, a continental-type climate exists where about 75% of the annual precipitation occurs during the months of April through September (Haas et al., 1974a). Soil moisture accumulation continues during the spring of the crop year until the crop reaches a developmental stage where the rate of discharge through evapotranspiration exceeds the rate of recharge from precipitation. The soil moisture content then continues to decrease until complete removal of the available water, which usually occurs at or near crop maturity (Cole and Mathews, 1939).

In the Pacific Northwest, dryland crop production is governed by a Mediterranean-type climate with winter precipitation and dry summers; about 70% of the annual precipitation occurs from November through April (Leggett et al., 1974). Rainfall intensities are relatively low, with an accumulated precipitation of 25 mm or more in a 24-hour period being unusual (Horner et al., 1957). Since most of the precipitation occurs prior to the wheat crop's most active growth, most of the moisture used by the crop must be stored in the soil. Soil moisture storage is dependent upon the amount of total precipitation, the portion that enters the soil, and the ability of the soil to hold the moisture. The grower has some degree of influence on the amount that enters the soil and, once it is stored, on the conservation of that moisture until needed by the crop.

Arnon (1972) describes a winter precipitation region with less than 250-300 mm average annual precipitation as being arid and too dry for crop production. A transition region between aridity and semi-aridity occurs where annual precipitation fluctuates between 250 and 400 mm, and the use of a fallow-wheat rotation decreases the risk of complete crop failure.

In much of the Canadian prairies and the Great Plains, moisture consistently limits crop growth where annual precipitation is less than 400 mm in the north and less than 500 mm in the Southern Great Plains (Staple, 1960). Soil fertility and competition from weeds become more important in the humid areas further north in Canada and east of the 100 meridian in both Canada and the U.S.

Alternate cropping with summer fallow became a standard practice by early settlers in the Columbia Plateau and Palouse and Nez-Perce Prairie regions of the Pacific Northwest where annual precipitation was less than 450 mm (Hunter et at., 1925, as reported by Leggett et al., 1974). Prior to the use of commercial fertilizers, McCall and Holtz (1921) determined that moisture became the most limiting factor in wheat production where there was less than 375 mm of annual precipitation in the dry-farmed areas of eastern Washington. In areas of greater precipitation, the beneficial effects of fallow on grain yield were considered due to the influence of tillage on nitrification rather than on a shortage of moisture.

Because precipitation varies in both amount and distribution from year to year, there is a range of average annual precipitation in which it is difficult to determine whether summer fallow or annual cropping should be used. Leggett and others (1974) indicated that today summer fallowing in the Pacific Northwest is generally practiced in areas receiving less than 325 mm of annual precipitation. Areas receiving from 325 to 400 mm are in a transition zone from the use of summer fallow to annual cropping; areas with more than 400 mm usually do not require the use of summer fallow for successful crop production. Typical wheat yields in the 200 to 300 mm annual precipitation summer fallow areas range from 1.5 to 4.0 metric tons/ha, while yields in areas receiving more than 400 mm of annual precipitation range from 3.0 to 6.0 metric tons/ha (Papendick and Miller, 1977).

Prior to the use of nitrogen fertilizers, summer fallow served three purposes: conservation of soil moisture; maintaining soil conditions conducive to nitrate mineralization; and, preparation of the seedbed (Hunter, 1918; McCall and Wanser, 1924). While the use of summer fallow did help to meet these objectives, it also intensified the problems of soil erosion and loss of organic matter. With the establishment of the dry-farming experiment stations, research was begun to improve the beneficial aspects of summer fallowing and to decrease its disadvantages.

Early tillage experiments at the Moro, Oregon, station showed that yields of Turkey Red winter wheat grown on summer fallowed land increased with early spring plowing followed by secondary cultivation with a knife or rodweeder to control weeds as needed, as compared to both fall plowing and late spring plowing (Hunter, 1918). Dry fall plowing immediately after harvest was suggested as preferable to late spring plowing for farmers who were handling more land than they could timely plow in early spring.

To improve yields, winter wheat was recommended over spring wheat whenever possible. As a rule of thumb, Hunter (1918) suggested that winter wheat should be planted when fall rains were sufficient to germinate mustard seed early enough to establish the stand before cold weather; otherwise, spring wheat should be planted.

In a Washington State College Experiment Station Bulletin entitled The Principles of Summer-Fallow Tillage (1924), McCall and Wanser pointed out that moisture conservation is affected by two phases: (1) absorption of moisture by the soil and (2) retention of absorbed moisture. It was noted that both the volume and distribution of subsequent rainfall are important in determining what tillage practice is best. The timing, depth, and type of tillage to be used during the fallow period must be considered not only with respect to conditions at the moment, but also the goals desired for all events during the crop period. For example, the existence of a soil mulch during the period of fall and winter precipitation tends to inhibit moisture absorption, the degree of inhibition being roughly proportional to the depth of the mulch (McCall and Holtz, 1921; McCall and Wanser, 1924); but, during the summer period of high temperatures, low humidity, and increased evaporation, a soil mulch is beneficial in retaining stored moisture.

Today, initial tillage is usually carried out in the early spring as soon as the soil has dried enough for proper equipment operation (Papendick and Miller, 1977); fall tillage has been found to be of little benefit unless soil freezing is common or weed growth is severe. Secondary tillage to control weeds and to maintain a surface mulch is carried out periodically during the spring and summer.

The yield advantages of fallow-wheat rotations in dryland areas are primarily due to an accumulation of small increases in stored soil moisture; for example, in Saskatchewan, Canada, approximately 13 mm of additional stored moisture was found to increase spring wheat yields by about 134 kg/ha (Staple, 1964).

Extensive Great Plains studies show that, under the environmental conditions where most of the precipitation occurs during the period of greatest evaporative demand, there is a greater correlation between crop season precipitation and grain yield than between stored soil moisture and grain yield (Cole and Mathews, 1923; Lavake and Wiese, 1979; Mathews and Brown, 1938). The value of stored moisture as a reservoir is evident though in areas where the crop season precipitation often only approaches or slightly exceeds the minimum threshold requirement for crop growth prior to grain production. Mathews and Brown (1938) estimated this minimum requirement in the southern Great Plains to be approximately 25 cm of combined stored moisture and crop season precipitation; each additional 25 mm of moisture above this level, up to a maximum total of 500 mm, was estimated to increase grain yields by approximately 235 kg/ha where moisture was yield-limiting.

In contrast to the Great Plains, Leggett (1959) demonstrated that stored soil moisture, with a correlation coefficient of 0.77, was a good predictor of wheat yields in the Palouse winter rainfall area of eastern Washington, while crop season precipitation had a correlation coefficient of only 0.53. In an analysis of the relationship between wheat yield and available soil moisture measured to a depth of 180 cm in the spring of the crop year, plus the rainfall that fell during the growing season after the spring sampling, Leggett found that about 10 cm of moisture were required to grow the crop to the heading stage, with each additional 25 mm of water increasing grain yield by 390 kg/ha (r^2 = 0.87) where nitrogen fertility did not limit yields.

In a statistical analysis where the soil moisture and crop season precipitation were kept separate, 25 mm of soil moisture supported a yield increase of 363 kg/ha, while the same amount of precipitation increased yields by 470 kg/ha. Thus, rainfall during the growing season is more effective in increasing wheat yields, but its smaller correlation coefficient and its smaller average value make it less closely related to total yield than stored moisture (Leggett, 1959).

Massee and Siddoway (1969) showed that spring wheat yields in southeastern Idaho were also best expressed as a function of stored available moisture in the 180 cm soil profile in the spring of the crop year (Massee and Siddoway, 1969). In analyzing the 0 to 120 cm and 120 to 180 cm soil profiles separately, they noted that correlation coefficients were equal, thus indicating that total available soil moisture wa a good yield predictor under these conditions.

Using the derived regression equation, each centimeter of additional stored moisture increased the grain yield by 50 kg/ha (r^2 = 0.68).

While increased soil moisture storage is the most important function of summer fallow under conditions of low precipitation, it was also found to promote crop yields through favoring an accumulation of nitrate nitrogen (McCall and Wanser, 1924); nitrate mineralization was found to be increased by conditions of adequate soil moisture and warm soil temperatures. Prior to the use of commercial nitrogen fertilizers, the distribution of precipitation during the winter months in the Pacific Northwest was one factor that affected the feasibility of annual cropping. During the summer months, precipitation is quite low and the soils are dry after harvest; without a fallow period to build up the level of soil moisture, insufficient moisture exists for much nitrification to take place until fall, at which time temperatures become too low for bacterial action. McCall and Wanser (1924) found that early spring plowing (about March 15) favored the largest accumulation of nitrates, while fall plowing or waiting until about April 15 were 10 to 15% less efficient.

Experiments from 1930 through 1933 with spring wheat grown in pots at the Sherman Branch Experiment Station (Moro, Oregon) showed that the addition of nitrogen carrying fertilizers produced more grain and straw, with water being used more efficiently, than was produced on fallowed soils without additional fertilizer. Thus, it was concluded that even with sufficient moisture, the average low-nitrogen dryland soils in the area would not produce a heavy crop unless the soil had been fallowed for a long enough period to allow adequate nitrate accumulation or enough nitrogen fertilizers had been added (Stephens et al., 1943). Field studies in the area showed that sufficient nitrification usually occurred on early spring-plowed, weed-free fallow to meet the requirements for the amount of plant growth permitted by the available moisture; in fact, excessive nitrogenous fertilizer adversely affected yields through stimulation of nearly excessive vegetative growth which depleted the soil moisture prematurely.

But greater nitrate mineralization and increased yields of both grain and straw brought additional problems. In the Pendleton, Oregon, area it became a standard practice to burn the straw residue prior to plowing the land for the fallow period; growers indicated that they obtained higher yields when they burned the straw, and the difficulties of handling the straw encountered with the older moldboard plows were eliminated. This practice was discouraged by agricultural leaders who pointed out the long-term destructive aspects (Oveson, 1966).

During a 34-year period of study at the Pendleton Experiment Station, Oveson (1966) and others showed a continuous downward trend in the soil nitrogen level, both where the wheat straw was burned before plowing and where it was plowed into the soil without burning and without added nitrogen; the low nitrogen content straw appeared to be completely lost in the decomposition process. Only where some form of nitrogenous fertilizer was added to the straw did this trend slow, or actually reverse, as with the addition of heavy amounts of strawy manure. Wheat yields also responded favorably to larger amounts of soil nitrogen.

Massee and Siddoway (1966) also reported a downward trend in the organic matter content under different fallow tillage systems in eastern Idaho; even after 20 years organic matter levels had not stabilized under most treatments. Only plots which had been maintained at a level of 4480 kg straw/ha did not lose organic matter.

Beginning about 1950, the use of commercial nitrogen fertilizers increased greatly in the dryland wheat producing areas of the Pacific Northwest. By the end of that decade, most farmers were using it as a part of their normal operation. But maximum yields, high milling and baking quality, and efficient use of both nitrogen and available water was found to depend on balancing the addition of nitrogen fertilizer with the amount of available moisture (Leggett, 1959; Ramig and Rhoades, 1963). Obtaining a proper balance is more difficult in the drier regions as available moisture is usually a greater limiting factor (Horner et al., 1957).

Since the amount of nitrogen fertilizer necessary for maximum yields depends on the amount of mineralized nitrogen in the soil, and on the amount of moisture available to the crop, Leggett (1959) studied the relationship of each of these factors to wheat yields, and then the relationship of one to the other. With this information, it was possible to calculate the optimum amount of nitrogen fertilizer to apply to achieve the potential yield, based on a soil test for nitrate nitrogen and moisture and an estimate of anticipated precipitation. In a linear regression analysis of 62 fertility experiments in eastern Washington, Leggett found that 1.0 kg of nitrogen per hectare was required to increase the wheat yield 20.7 kg/ha where nitrogen limited yields.

In a similar project in that area, Koehler and Guettinger (1967) found that 1.0 kg of nitrogen was required to produce 22.2 kg of grain with semi-dwarf wheat varieties, while other varieties needed 1.0 kg of nitrogen per 20.0 kg of grain.

A study by Hunter and others (1961) in the dry farmed areas of Oregon showed that nitrogen applied in the fall of the crop year was more efficient in producing grain than when applied later in the spring.

Despite its beneficial yield effects, summer fallow is generally regarded as a poor conservation practice due to soil erosion and organic matter destruction.

Soil erosion on summer fallowed land has been a perennial problem. High runoff and soil erosion losses can be associated with bare soil during the fallow period because of precipitation, tillage and seedbed preparations which tend to pulverize the soil, lower infiltration rates during the crop winter period due to a higher soil moisture content in the fallowed soil, and minimal vegetative cover during the early crop season (Horner, 1960). Both wind and water-caused soil erosion are largely due to the pulverizing effect of several tillage operations on fine-textured, weakly aggregated soils (Leggett et al., 1974). Areas with less than 330 mm annual precipitation are most prone to wind erosion; the greatest hazard is during the early spring and mid-fall when high winds are common. Water erosion is most severe on unprotected steep slopes; Papendick and Miller (1977) reported that up to 80% of the dry-farmed cropland in the Pacific Northwest has slopes ranging from 8 to 30%.

Stubble mulching leaves the crop residue on and in the surface soil and is extensively used in the fallow-wheat areas of the Pacific Northwest. The surface residues not only help control wind erosion, but also conserve soil moisture (Papendick and Miller, 1977). The development of specialized farm machinery has made stubble mulch operations more effective and routine. Initial tillage implements include stubble cultivators, subsurface sweeps, and one-way disks, and tend to determine the proportion of stubble left on the soil surface; secondary tillage for weed control is generally performed with a rod weeder (Massee et al., 1966).

In eastern Idaho trials, Massee et al. (1966) found that the moldboard plow buries almost all of the stubble, the one-way and off-set disks leave about 20% on the surface; and the sweep or other sub-surface tillage implements leave about 80 to 90% of the stubble.

Early stand establishment of winter wheat is also important in erosion control. Good stand establishment is dependent on adequate moisture in the seed and root zone, which in turn is favored by soil management practices which maximize both water infiltration and retention (Lindstrom, 1974).

Principles of Moisture Conservation

Early research workers realized that conservation of precipitation in the Pacific Northwest for later use by a crop involved two distinct periods of the year, emphasizing either absorption or retention of moisture (McCall and Holtz, 1921).

Figure 1 shows the relationship between the long-term average monthly precipitation at the Sherman Branch Experiment Station at

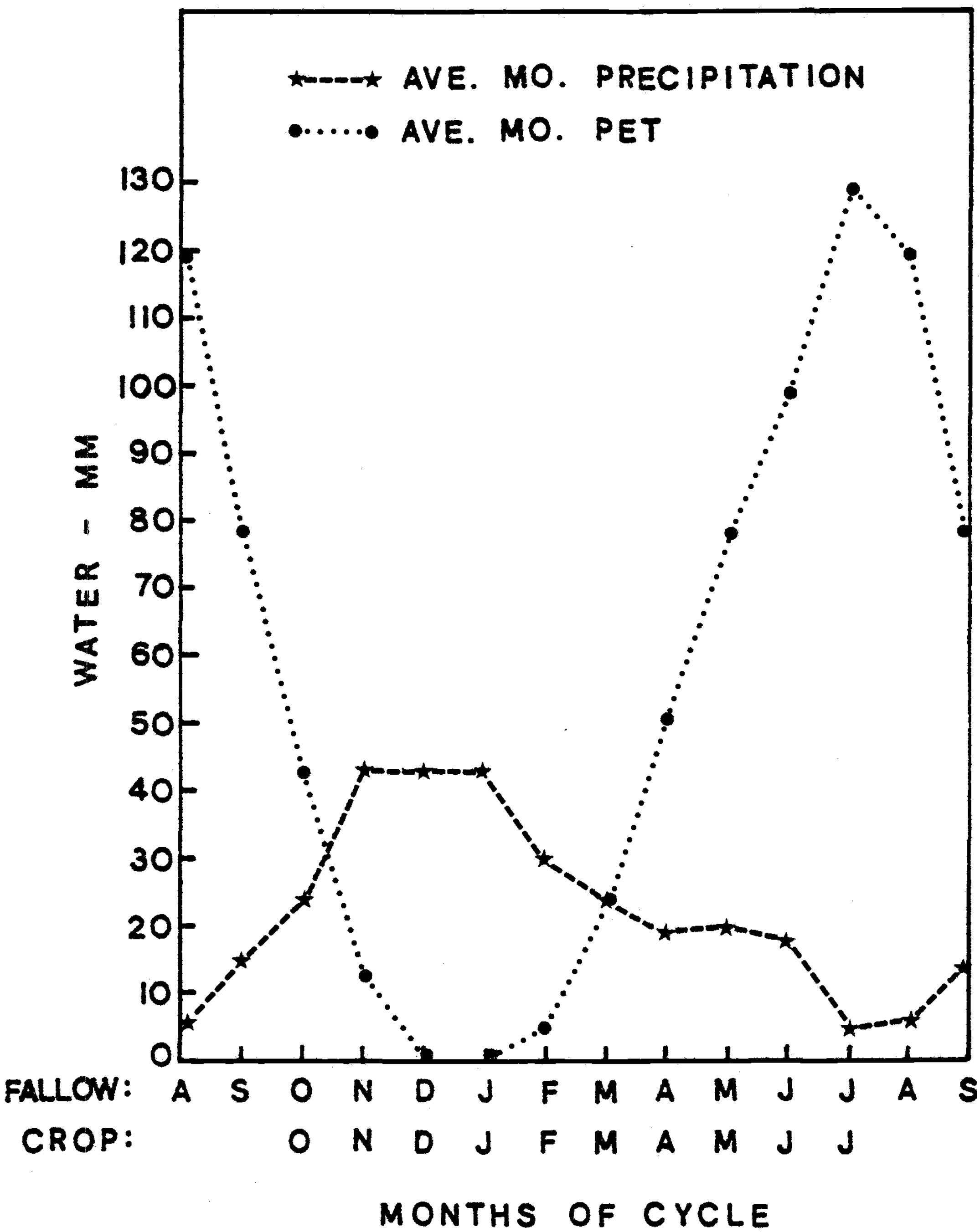

Figure 1. Average monthly precipitation and potential evapotranspiration (PET) at Moro, Oregon. (Data from G. A. Johnsgard, 1963.)

Moro, Oregon, and the potential evapotranspiration (PET) as calculated with the Thornthwaite-Mather (1955) procedure by Johnsgard (1963). PET is an expression of the potential total moisture loss through evaporation and transpiration from a completely vegetated area with a soil moisture content of approximately field capacity. Though limited in use by definition, the calculation of PET allows a visual representation of wet and dry seasons (Eagleman, 1973). The actual evapotranspiration rate may be considerably lower than the potential rate since evapotranspiration decreases with declining soil moisture content.

Tillage practices must be considered with respect to their effect on both moisture absorption and retention. McCall and Holtz (1921) recommended that in areas with marginal precipitation, the fallow land should not be tilled in the fall since a firm soil condition would favor absorption of fall and winter precipitation by capillary movement. Only where runoff was a potential problem was fall plowing suggested in an attempt to catch more water in a rough cloddy surface.

When precipitation, and thus the opportunity for absorption, drops off, retention of the stored moisture becomes the major consideration. Evaporation accounts for most of the water loss during the fallow period, though runoff and deep percolation account for a significant amount in areas of higher precipitation (Papendick et al., 1977).

Intensive field measurements by Idso et al. (1974) supported the concept of evaporation occurring in three stages as reported earlier for laboratory studies (Hide, 1954; Kolasew, 1941, as reported by Lemon, 1956; and Penman, 1941). The first evaporative stage is characterized by a relatively high evaporative rate controlled by atmospheric conditions. The second stage begins when the soil moisture cannot be transmitted to the soil surface fast enough to meet the evaporative demand; the soil surface dries quickly as the evaporation rate slows, and the transfer of soil moisture changes from liquid to vapor movement. The third stage is characterized by a low and relatively constant evaporation rate which is controlled by absorptive forces at the solid-liquid interfaces in the soil.

Work by Penman (1941) showed that movement of free water depends upon capillary conductivity and the tension gradient; both are functions of moisture content. Vapor movement depends upon the relative humidity of the soil air, and is not as dependent on the soil moisture content.

The potential for conserving moisture lies with the first two stages of evaporation (Lemon, 1956). Conservation may be divided into three categories: (1) decreasing the turbulent transfer of water vapor above ground through slowing wind speed with standing stubble, increasing soil surface roughness, etc.; (2) disrupting capillary continuity in the surface soil layers to reduce the flow of liquid to the surface, causing moisture to move more slowly in the vapor form through a diffusional barrier; and (3) decreasing capillary flow and moisture holding capacity of the surface soil by the application of surfactants to enable a soil to self-mulch through rapid drying. Some research using surfactants has looked encouraging (Kolasew, 1941; Lemon, 1956), but further work is needed.

Tillage practices using the first two concepts have been in use for a number of years. Tilling the soil surface to create a loose soil structure causes rapid drying and the development of a soil mulch which acts as a diffusional barrier. Where such a barrier is not maintained, as in the Central Great Plains, evaporation from fallow land is greatest during periods of frequent rains (Hanks et al., 1968). Papendick and Miller (1977) estimated that summer evaporative loss in the Pacific Northwest averages about one centimeter per month after a 10 to 15 cm thick dry surface layer has developed. The practice of stubble mulch tillage has generally replaced plowing to create a soil mulch, primarily to help control erosion.

Soil texture also influences the effectiveness of a tillage mulch. The higher unsaturated conductivities of fine-textured soils causes the first stage evaporative drying period to be longer, and during dry periods, these soils dry deeper than coarse-textured soils (Papendick and Miller, 1977).

While a soil mulch has a positive effect in retaining soil moisture, it has an inhibitory effect on soil moisture absorption since individual rains in the summer fallow areas are not usually sufficient to fill and penetrate through the mulch; on the contrary, moisture from a rainfall is held near the soil surface where it is more readily exposed to evaporative conditions (McCall, 1925). In general, the deeper the mulch, the greater the inhibiting effect on absorption. If a heavy rain penetrates through the dry mulch, reestablishment of the mulch immediately after the rainfall is important to decrease the rate of evaporative loss.

Elimination of weed growth during the fallow period is important in conserving stored soil moisture; it also helps to maintain a higher soil moisture content near the soil surface, which in turn will aid movement of subsequent rainfall into the subsoil (Staple, 1964).

Rydrych (1978) reported that there are more than 50 different kinds of broadleaf and grassy weeds found in eastern Oregon cereal fields which can reduce the grain yield through competition if not controlled. Broadleaf weeds can reduce yields by 30 to 60%. Grassy weeds, such as downy brome (*Bromus tectorum*) are more difficult to control and can reduce wheat yields by 15 to 35%. Under stubble mulch or minimum tillage conditions, downy brome was one of the more difficult weeds to control prior to the recent development of selective herbicides.

Soil Moisture Storage Efficiency

Fallow efficiency is defined as the ratio of an increase in soil moisture to the amount of precipitation occurring during the fallow period. It is affected by various factors, including the properties of the soil, precipitation amount and frequency, runoff, deep percolation, and evaporative demand. Efficient moisture conservation depends upon factors that favor accumulation and retention of moisture in the soil until needed by the crop. The inefficiency of summer fallow in conserving moisture is well known, but its benefit in stabilizing and increasing yields with small accumulations of stored moisture has made it invaluable in areas with marginal precipitation.

In Saskatchewan, where spring wheat is predominantly grown, only 20% of the precipitation received during a 21-month fallow period is conserved (Staple, 1964). Hide (1954) reported that fallow efficiencies in the Great Plains, where precipitation occurs during the spring and summer period of high evaporative demand, average between 20 and 25%. During a three-year study in the Central Great Plains, Hanks et al. (1968) reported that soil moisture storage efficiencies were found to increase as the total amount of precipitation increased.

In the Pacific Northwest, fallow efficiency is favored by the Mediterranean-type climate with precipitation occurring during the winter when the evaporative demand is low (Lindstrom et al., 1974); this allows a fallow-small grain rotation to be successful in lower rainfall areas than would be possible in a summer rainfall region (Leggett et al., 1974).

Moisture storage efficiency for a 12-month fallow period with stubble mulch tillage was measured as 46% following a mild winter near Lind, Washington; during a cold winter with extensive soil freezing and fewer precipitation events, but in greater amount, the efficiencies were 64, 48, and 40% for chiseling, disking, and no tillage, respectively (Lindstrom et al., 1974).

Relatively high storage efficiencies are obtained during the winter portion of the fallow period in the Pacific Northwest since the soil is initially dry, evaporative demand is low, and precipitation usually occurs in effective amounts (Leggett et al., 1974).

In reviewing studies of available moisture storage to a depth of 180 cm at four different sites in the Pacific Northwest, Leggett et al. (1974) found that storage efficiencies from after harvest to the spring of the fallow period ranged from 52 to 73%. During the spring and summer period there was a net loss in stored moisture at all sites, even though there was additional rainfall; at the end of the fallow period, the moisture storage efficiencies ranged from 27 to 48%. During the succeeding fall and winter storage period, all sites accumulated additional moisture, and the cumulative storage efficiency from the beginning of the fallow period to early spring of the crop season ranged from 30 to 41%. In examining the post-fallow crop-season storage period separately, the moisture storage efficiencies ranged from 17 to 41%. Thus, moisture accumulation during the second winter period was considerably less than the first winter when infiltration rates on the dry soil were high. In general, as the soil profile becomes wetter, the rate of infiltration decreases (Parr, 1960).

Many late spring and summer storms are ineffective in soil moisture accumulation since they fail to fully rewet the surface soil mulch sufficiently to establish a continuous water film with the moisture below (Massee and Siddoway, 1970). The main benefit of this late precipitation is to provide a temporary delay in profile evaporation while the surface water is being evaporated.

Loss of soil moisture during the summer months is positively related to the amount of moisture present in the spring of the fallow period (Massee and Siddoway, 1969 and 1970; Leggett et al., 1974).

Estimation of available soil moisture can be difficult without an actual measurement. In a fallow tillage trial in southeast Idaho, Massee and Siddoway (1970) showed that, even though the six-year average increase in soil moisture stored to a 180 cm depth from harvest to May of the fallow year was 80.5% of the 20 cm of precipitation during that period, this amount, together with that which had been left unused at the end of harvest, averaged only 56% of the potential storage of available moisture within the soil profile; by late October, following fall seeding, the soil moisture storage had decreased to 44% of the potential profile storage, and the fallow efficiency had dropped to 45% of the cumulative precipitation.

The concept of fallow efficiency is a useful tool in comparing moisture storage amounts under different tillage practices, but the actual amount of moisture stored is the factor important to crop yields.

Improvement of Root Zone Soil Moisture Storage

Soil moisture storage depends on practices which favor the accumulation and retention of precipitation within the soil profile. Moisture losses occur primarily through evaporation, and the greatest potential for reducing these losses occurs during the first two stages of evaporation. In all cases, the timing, method, and effect of tillage are critical.

Tillage implements which were available to farmers at the turn of the century were limited primarily to the moldboard plow, disk harrow, and the spike-tooth harrow; the spring tooth harrow, subsoilers, and spring-tooth cultivators were just coming into use. Homemade knife implements were also being used for fallow tillage (Salmon et al., 1953). Many of the early concepts of dry farming developed from experience with humid farming; for example, deep plowing was considered a good farming practice, but with time, both on-farm experience and research data showed no advantage for deep plowing in the drier areas (McCall and Holtz, 1921). Today a number of different tillage implements are available to help achieve the desired tillage goal.

While large increases in stored soil moisture through tillage are not likely, small increases in seed zone moisture can have a beneficial effect on stand establishment, and small amounts of available moisture are important in relationship to crop yield. Several tillage practices have been studied by research workers in the Pacific Northwest summer fallow areas, and some basic concepts have developed.

While weed control is one of the chief functions of tillage, the total effect of that tillage must be considered (McCall and Holtz, 1921). Where precipitation is normally light and gentle, as is characteristic of most of the Pacific Northwest summer fallow areas, capillary conductivity is the most important factor in absorption and is favored by a firm soil condition.

In areas where snowfall provides a major portion of the moisture stored in the soil, standing stubble has increased both stored moisture and average winter wheat yields through retaining more snow and preventing deep frost penetration (Massee and Siddoway, 1966).

Several research workers have concluded that initial fallow tillage performed in early spring (by about April 1) is superior to both fall tillage and later spring tillage in terms of total moisture storage and wheat yields under normal conditions of intermittant rainfall (Hunter, 1918; Massee and Siddoway, 1966; McCall, 1925; McCall and Holtz, 1921; Oveson and Hall, 1957). Average wheat yields over a 42-year period on land plowed by April 1 at Moro, Oregon, were 114 kg/ha more than on land plowed May 1, and 504 kg/ha more than on soil plowed as late as June 1 (Oveson and Hall, 1957); in addition, fall disking stubble prior to early spring plowing reduced winter wheat yields at Moro and Pendleton as compared with no fall disking.

Only when soil freezing was associated with runoff did fall chiseling, rotary subsoiling, and, to a lesser extent, disking increase both stored moisture and wheat yields (Lindstrom, 1974; Massee and Siddoway, 1966). Lindstrom (1974) observed that the increased soil moisture in both the total soil profile and the seed zone in the fall chiseled plots promoted substantially greater vegetative cover and plant vigor as compared with plots not chiseled. Collection of spring runoff made possible by fall chiseling in southeastern Idaho permitted successful annual cropping of spring wheat on deep soils (Massee and Siddoway, 1966 and 1969).

In an examination of soil hydraulic properties of a Walla Walla silt loam soil in an untilled fallow plot, Allmaras et al. (1977) found that the hydraulic conductivity was 10 to 1000 times lower at soil depths above 30 cm than below. Chiseling to 43 cm improved the hydraulic conductivity above the 30 cm depth, and the calculated average hydraulic conductivity of a 120 cm soil profile was about five times greater on the chiseled plot after two days of drainage following saturated soil conditions. The increased internal drainage was expected to improve soil moisture storage and to decrease surface evaporation. The benefits of fall chiseling were believed not to persist past the first winter, due to secondary tillage traffic in the spring (Allmaras et al., 1977b).

Early attempts to increase the storage and use of precipitation in the Great Plains centered on tillage management studies, but a number of researchers found little difference between tillage methods when done on a timely basis, and storage efficiency improvements were not large (Aasheim, 1949; Hide, 1954; Wiese and Army, 1958). Somewhat similar results have been found in the Pacific Northwest summer fallow areas (Lindstrom, 1974), primarily because effective secondary tillage which creates a dry soil mulch tends to mask any differential results between initial spring tillage methods (Papendick et al., 1973). Recorded differences in yield due to tillage have been small, and may be due to factors other than, or in addition to, moisture storage; for example, Oveson and Hall (1957) reported that plowed fallow land yielded an average of 81 kg/ha more than disked fallow land over a 29-year period. This difference could have been due to differences in seed zone moisture content, seedbed preparation, problems with straw decomposition, etc. Lindstrom et al. (1974) concluded that proper timing of tillage is probably much more important than method of tillage in storage efficiency.

Shallow spring tillage is recommended to develop a dry mulch evaporation barrier, to prevent exposure of subsurface moisture, and to achieve good weed control (McCall and Holtz, 1921; McCall and Wanser, 1924; Staple, 1964); in general, the lighter the average annual precipitation, the shallower tillage should be. In southeastern Idaho, Massee and Siddoway (1966) found no significant differences in moisture storage and yield due to spring tillage depth in a Tetonia silt loam. Shallow tillage was therefore recommended since it requires less horsepower.

In a comparison of no tillage with stubble mulch tillage at different times, Oveson and Appleby (1971) found that plots which received no tillage tended to store less moisture than plots receiving conventional stubble mulch tillage which included rod weeding two or three times during the fallow season; weeds were effectively controlled in the no-till plots with nonpersistent herbicides. Rydrych (1979) found that chemical fallow treatments applied in the fall or early spring saved soil moisture which could be lost through weed growth, and it reduced spring tillage by two or more operations.

Greater amounts of surface residues have been found to increase over-winter storage efficiencies through reduction of evaporation when the soil surface is wet during the winter (Massee et al., 1966; Papendick and Miller, 1977; Ramig and Elkin, 1973).

Improvement of Seed Zone Soil Moisture Storage

The initial benefit of effective soil moisture storage in the Pacific Northwest dryland areas occurs at fall seeding time (September or October) when germination and stand establishment must depend on moisture stored since the previous winter. In studies on a Ritzville silt loam, Lindstrom et al. (1974) found that an 8 to 9% volumetric moisture content in the seed zone was inadequate for good winter wheat emergence, with only a 50% stand being established in three weeks. Rapid establishment is important in areas where unpredictable showers can cause soil crusting which can restrict seedling emergence. In general, seed zone moisture contents tend to be higher with greater amounts of total profile storage (Lindstrom et al., 1974; Massee and Siddoway, 1966).

In a study at the Sherman Branch Experiment Station, Russelle (1978) reported that though soil moisture losses are relatively small during the summer if an effective mulch has been developed, and seed zone moisture content remains relatively high, a rapid drop in the level of soil moisture is reported by growers to occur in late August and September before planting. Russelle hypothesized that nighttime vapor pressure gradients from the moist seed zone to the soil surface increase during the time of year where warm days and cool nights predominate. Though abnormally wet weather during late summer and fall both years of a two-year study prevented significant losses of seed zone moisture, a computer program simulation indicated that redistribution of soil moisture below the seed zone may be a significant factor in the observed losses.

Papendick et al. (1973) pointed out that the key factor in conserving seed zone soil moisture through hot summer periods of high evaporative demand is to balance the loss rate with upward unsaturated flow from deeper layers. In this regard, the goal of tillage is to maintain a seed zone with good capillary continuity with the deeper soil layers and to create a tillage mulch which provides optimum thermal insulation and resistance to evaporation. The action of a rod weeder seems very effective in achieving this goal.

In a study which compared different tillage methods with chemical fallow, the seed zone moisture content was higher at seeding time where spring tillage created a mulch, even though the loss of moisture from the total measured profile was not greatly influenced by tillage. Thus, distribution of the soil moisture is an important consideration in determining a tillage practice (Lindstrom et al., 1974).

Over a period of five crop years, Massee and Siddoway (1966) observed that seed zone moisture content and both stand establishment and yields of winter wheat were positively correlated with increases in stored soil moisture as a result of early spring tillage.

Papendick et al. (1973) reported that the application of a straw mulch (4000 kg/ha) decreased seed zone temperatures under conditions where only a shallow soil mulch (6 cm) had been established. By increasing the soil mulch to 11 cm, seed zone drying was reduced, wheat emergence was improved, and the addition of a straw mulch did not lower seed zone temperatures further. In the southern

Great Plains, Army et al. (1961) reported that surface residues improved seed zone moisture and reduced soil crusting, even though the soil profile moisture was not affected below the seed zone. They concluded that surface residues increase resistance to evaporation by thickening the layer of nonturbulent air above the soil surface and decreasing the vapor pressure gradient by lowering daytime soil temperatures.

Other Factors Affecting Soil Moisture Storage

While there are some general principles which can be used to aid the accumulation and retention of moisture, there are also noncontrollable factors which affect both moisture storage and storage efficiency.

A deep soil profile is necessary to serve as an effective reservoir in collecting precipitation and protecting it from evaporation. Lindstrom et al. (1974) reported that the greater amounts of moisture stored on plots which were fall chiseled prior to runoff conditions on frozen soil were positively related to over-summer moisture losses. Graphical profiles of water distribution indicate that some of this loss may have been due to percolation below the 180 cm maximum depth of measurement but not necessarily below the depth of extraction by wheat roots.

The soil texture and rate of water infiltration can affect storage efficiency (Cole and Mathews, 1939). Topography also affects storage. Mayers (1964) indicated that precipitation falling on north-facing slopes in Sherman County, Oregon, is much more effective than that on south-facing slopes; gently sloping areas are intermediate in effectiveness. In addition, the topographical differences in soil moisture and soil temperature differentially affect the rate of soil development which is largely dependent on chemical and biological activity.

The seasonal distribution, frequency, intensity, and amount of precipitation all affect the storage effectiveness of precipitation (Hopkins, 1940; Staple, 1964; Staple and Lehane, 1944). Lindstrom et al. (1974) pointed out that soil moisture storage is enhanced by steady and substantial rainfall when the soil is relatively dry. With intermittent showers, even when the evaporative demand is relatively low, the storage efficiency is reduced.

The extent to which soil moisture below the root zone may eventually supply part of the crop's needs is difficult to determine. A number of researchers have indicated that upward flow of moisture either was or might have been involved in supplying available moisture (Bauer and Young, 1969; Cole and Mathews, 1939; Johnson and Davis, 1980; Rickman et al., 1978; Van Bavel et al., 1968).

Bauer and Young (1969) pointed out that a lack of change or slight change in soil moisture content at the maximum rooting depth did not necessarily mean that only a small amount of water was withdrawn from that depth.

Rickman et al. (1978) conducted a detailed study of soil water uptake by dryland winter wheat which included calculations of vertical redistribution of moisture between soil layers. The study was conducted on a Ritzville silt loam which had a cemented layer located between 150 to 180 cm in soil depth; this layer prevented root extension below 180 cm, but was porous enough to allow water movement. The study showed that approximately one-third of the total change in moisture content of the 180 cm soil profile during the early crop season could be attributed to drainage to the deeper layers. Drainage from the 120 to 180 cm depth zone continued until shortly after the end of April. As the wheat crop continued to extract moisture, the water flux reversed, and by mid-season the moisture moving back up into the 0-180 cm profile was supplying as much as 10% of the net soil water use. Rickman (1977) concluded that if water stored deep in the soil profile remains within 30 to 60 cm of the bottom of the rooting zone, it can move back up into this zone to provide needed moisture critical to grain production during the later stages of plant growth.

B. Crop Use of Stored Moisture

Root Studies

Effective utilization of stored soil moisture under dryland conditions depends on efficient uptake by plant roots and the plant's ability to withstand diurnal moisture stress common under these conditions (Hurd, 1968).

While extensive work has been done in developing improved dryland wheat varieties, little is known about the variation in root systems among varieties and what roles these differences play. Hurd (1968) suggested that improved knowledge of root systems could be important in selecting varietal characteristics suitable to dryland conditions.

A study by Hurd (1968) using different varieties of spring wheat grown under high and low moisture levels in glass-faced boxes showed variety x soil type and variety x moisture interactions. Hurd suggested that breeders should grow and select their segregating populations in the soil type and natural growing conditions of the respective production areas.

Hurd's studies showed no consistent relationship between time of heading and cessation of root growth. In terms of the energy budget, it would seem beneficial to have an extensive root system developed prior to heading (Hurd, 1968).

While an extensive root system will help to reduce yield losses under dry conditions, timing of root system development could also be important. Hurd (1968) speculated that an extensive root system early in the season could potentially lead to a shortage of water later.

Massee and Siddoway (1966) reported that, when grown after a fallow period, winter wheat usually outyields spring wheat, and because of a deeper root system and early maturity, is less susceptible to drought. In eastern Idaho, winter wheat roots penetrated to at least 180 cm with adequate soil moisture, while spring wheat roots extracted very little below 120 cm.

In a large number of trials with spring wheat, Bauer and Young (1969) found that moisture was still available below 90 cm. In support of this finding, they cited an unpublished study by Wilkinson at North Dakota State University which reported that the maximum depth of rapid water extraction was 80 cm and that this level was reached by the heading stage. Wilkinson suggested that the lack of deeper penetration might be due to either a genetic expression or to an external factor such as soil temperature.

Rickman (1978) suggested that rooting characteristics desirable for a dryland wheat variety involve: (1) root penetration to at least 180 cm; (2) uniform distribution throughout the rooting depth; and (3) few roots in the surface layers (e.g., about 5.39 meters of roots per liter of soil; some varieties have four times this amount).

Rooting depth of wheat depends on several factors, including the type of wheat and available soil moisture. When sufficient moisture is available in the upper soil profile, wheat roots will not develop to their maximum possible depth (Cole and Mathews, 1939). On the other hand, wheat which is severely stressed, or is placed under a sudden stress late in its development will also not root deeply. Cole and Mathews concluded that a deep feeding root system is induced by a continuous need for water over a long time, but one which is not so severe as to seriously inhibit crop growth. Other studies (Hurd, 1968; Kmoch et al., 1957; Salim et al., 1965) also showed that root depth depends on the depth of soil moisture. Under favorable moisture conditions, Kmoch et al. found roots penetrating as deep as 390 cm.

In field studies, even where the soil moisture tension was greater than 15 bars at depths greater than 30 cm, a dense system of roots developed with roots reaching 75 cm deep (Kmoch et al., 1957). In a trial using glass-fronted observation boxes, Salim et al. (1965) found little penetration by barley, oat, or wheat roots into a soil layer where the moisture content was at or above 15 atmospheres tension, though barley varieties did penetrate the most. They also found that drought resistant cultivars tended to have long and numerous seminal roots.

Under low soil moisture tension, total wheat root volume was greater (Hurd, 1968; Sharma and Ghildyal, 1977) and total soil moisture extraction during a given period was greater (Sharma and Ghildyal, 1977) than under drier conditions.

Under relatively dry soil conditions, wheat roots were finer, more branched, and longer than under more favorable conditions (Kmoch et al., 1957; Sharma and Ghildyal, 1977). Salim et al. (1965) found that roots of barley and oats also branched more in the upper soil profile than under drier soil treatments.

In western Australia, Tennant (1976) described two stages of wheat root penetration. During the first stage, rapid root penetration to 5 to 10 cm within the first week after planting was followed by slower penetration during the next five weeks to a depth of 15 to 30 cm. In the second stage, the rate of penetration increased after about six weeks from planting to a maximum rate of increase between the ninth and tenth weeks; the rate of increase then tapered off around the twelfth week. The average maximum depths of root penetration seldom exceeded 180 cm, despite deeper water penetration.

Kmoch et al. (1957) noted an almost complete renewal of the wheat root system during the winter in central Nebraska. By the beginning of spring growth in mid-April, the primary root system present in late fall had completely disintegrated and had been replaced with an adventitious root system.

In trials comparing the relative influence of soil moisture and nitrogen fertilization on the development of winter wheat roots, nitrogen fertilization was found to increase the amount of roots produced by at least 50% (Kmoch et al., 1957). Root weights seemed to be influenced more by nitrogen application than by the level of soil moisture, and increases occurred at nearly all soil depths and under different soil moisture conditions. Root weight and depth of penetration increased greatly during the spring growth period from April to June. Root penetration was not limited by the relatively high fertilizer rate of 90 kg of nitrogen per hectare.

Crop Use of Soil Moisture

Crop water use depends on the amount of available soil moisture, the rate of evaporation, the crop growth stage, and the rooting of the crop. Using the root-sink method of calculating periodic water use, which also considered vertical moisture flow from one soil layer to another, Rickman (1977) measured daily water use by dryland winter wheat as well as moisture flow within the soil profile. In early April, stored moisture was lost from all depths; flow calculations indicated that moisture near the surface was being lost from upward flow, while below 60 cm the moisture was being redistributed downward. In early May the downward flow was considerably decreased, occurring only below the 90 cm level. By the end of May there had been a shift from downward flow to upward flow, with maximum water use occurring throughout the soil profile during the wheat heading period. The greatest extraction by the wheat roots at this date was between the 90 and 120 cm soil depth level. By late June the moisture supply in the rooting zone had been exhausted. The last moisture available to the crop was furnished by upward flow beneath this zone. Any moisture made available from this depth during the period of grain filling can be quite valuable in increasing yield, especially where rooting depth is restricted.

Normally the time of maximum crop leaf area occurs during heading, but under conditions of limited moisture the leaf area can decline prematurely due to early drying of the leaves (Rickman, 1977).

Rickman et al. (1978) pointed out that the exclusive use of soil moisture content measurements to calculate periodic moisture uptake by the crop can over-estimate early season uptake (due to continued downward flow) and under-estimate mid-season soil moisture use (through upward flow from below the root zone). However, soil moisture content measurements made at the beginning and end of the crop season can be used to determine the total seasonal water use if they accurately measure the zone of active water uptake.

Moisture distribution within the soil profile greatly affects crop yield. The Mediterranean-type climate and the average precipitation levels in the summer fallow areas of the pacific Northwest dictate that a growing wheat crop depend on moisture in the lower soil depths in the latter part of the growing season. Stephens et al. (1943) found that a given amount of soil moisture was dramatically more beneficial to crop yield when distributed somewhat equally throughout a 180 cm soil profile compared to a concentration primarily in the surface 60 to 90 cm. An abundance of moisture in the upper profile during early spring can stimulate excessive vegetative growth which may later cause the plant to be subject to severe drought injury if adequate moisture is not available. During a year when the soil moisture was fairly evenly distributed within the soil profile, Stephens et al. (1943) noted that the plants started to use more moisture in the 70 to 120 cm depth zone after the last of April; the crop did not start to use moisture in the 120 to 180 cm zone until the fourth week of May, approximately when the plants started heading. Without this moisture, the grain would most likely be shriveled unless there were adequate spring rains.

Cole and Mathews (1939) studied the average reduction in soil moisture between spring and harvest under continuously cropped and alternately fallowed wheat land in the Great Plains. They found that the heaviest use of water under continuous cropping occurred in the surface 60 cm. Under alternate fallow cropping conditions, the active feeding range was increased by 30 to 90 cm, the actual depth being proportional to the amount of fallow period rainfall. Cole and Mathews observed that the normal development of spring wheat roots did not allow the crop to remove all of the available moisture in the lower soil profile, but that winter wheat could use it.

Bauer and Young (1969) showed that spring wheat in North Dakota can extract soil moisture to at least 150 cm when root restrictions do not exist; but, on the average, available moisture was depleted only to a depth of 90 cm.

Brown (1971) reported that winter wheat extracted more soil moisture than spring wheat, and that varieties differed in the ability to extract moisture from the lower soil profile.

Johnson and Davis (1980) found that in Texas adequate fall rains were important in the development of an efficient winter wheat root system and in the plant's ability to extract stored moisture from below 90 cm. During falls with less than normal rainfall, moisture stored below 90 cm was not utilized; when fall rainfall was above normal, moisture was extracted to at least 150 cm, with higher grain yields as a result. The greatest depth of moisture extraction from a Pullman clay loam was approximately 180 cm.

Soil moisture measurements made soon after harvest in Tetonia, Idaho, showed that winter wheat had used most of the available moisture to a depth of 180 cm (Massee and Siddoway, 1966).

Rickman et al. (1978) found that the root distribution of

Nugaines dryland winter wheat measured before and during flowering did not fully correspond with moisture extraction patterns. While root distribution measurements made on May 1 showed a fairly uniform rooting density from 30 to 150 cm in depth, water extraction measurements made nine days earlier showed water being removed selectively from the surface 60 cm, with little or no removal below 120 cm. By May 5 the soil moisture uptake was uniform, and by may 20 (time of flowering) the quantity of water needed to allow the crop to mature was found only below 90 cm. As the surface soil layers dried, the roots extracted moisture from progressively deeper layers.

A number of researchers have reported that nitrogen-fertilized wheat extracted more soil moisture than did unfertilized wheat (Brown, 1971; Kmoch et al., 1957; Koehler, 1960; Olson et al, 1964; Singh, 1978; and Singh et al., 1975). Nitrogen fertilization also increased the soil depth from which moisture was removed (Brown, 1971; Koehler, 1960; Singh et al., 1975). Kmoch et al. (1957) and Singh (1978) reported that most of the increased extraction due to nitrogen occurred within the surface 60 cm of soil, but Brown (1971) and Koehler (1960) reported that the greatest differences in extraction occurred in the 60 to 122 cm depth and 150 to 240 cm depth, respectively. Koehler (1960) found that in eastern Washington, during a year with favorable growing conditions, both unfertilized wheat and wheat fertilized with 179 kg/ha of nitrogen removed all available soil moisture to a depth of 150 cm.

Water Use Efficiency

The efficiency with which a dryland grain crop uses the moisture available to it depends upon several factors including the genetic water use potential, yield potential, root distribution, soil type and depth, nutrient balance, and climatic conditions.

Water lost through evaporation, runoff, and use by weeds is as much a part of the total crop production use of water as is transpiration (Cole and Mathews, 1923). The amount of water used in crop production is, therefore, the sum of the quantity of water lost from the soil and the quantity of water lost from the soil and the quantity supplied by precipitation during the growing season. The term evapotranspiration (ET) is used in the broad sense to represent the amount of water used by the crop.

Water use efficiency (WUE) is calculated by dividing the grain yield (Y) by the amount of water used by the crop (ET). Early work by Cole and Mathews (1923) showed that WUE increased as yield increased; the primary reason for this is that a certain amount of water is required by the crop before any yield is produced, and that yields increase in proportion to the quantity of water consumed above this minimum threshold amount. In addition, conditions that favor maximum production tend to increase WUE. Cole and Mathews reported that this minimum amount of water required before any yield was produced in the Great Plains area varied from about 10 cm in the northern states to as much as 25 cm in the southern areas. However, others report this minimum amount to be as little as 5 cm in the production of winter wheat in Texas (Johnson and Davis, 1980) and approximately 10 cm in eastern Washington (Leggett, 1959), while spring wheat in southeastern Idaho required a minimum of 11.3 cm (Massee and Siddoway, 1969).

When only transpirational uses of soil moisture are considered, WUE is measured as the ratio of net photosynthesis to transpiration, and this depends greatly on light intensity, temperature, and humidity. High efficiency requires a slow growth rate and can be expected only for plants with deep root systems free from competition; these plants also usually have a longer vegetative period favoring optimum production of seed (Cohen, 1970). Stephens et al. (1943) reported that winter wheat had a higher WUE than spring wheat; winter wheat also matures earlier than spring wheat, and the temperatures are cooler during its development.

The Pacific Northwest climate generally favors higher water use efficiencies than does the continental climate of the Great Plains. Most soil moisture loss occurs through plant transpiration after the soil surface dries. Transpiration is increased by a large plant surface area, high temperatures, wind, low relative humidity, and by plentiful soil moisture (Koehler and Guettinger, 1967).

In north-central Oregon, Stephens et al. (1943) considered light rains which did not penetrate the soil very deeply as possibly having the same effect on the growing crop as an equal amount of moisture stored in the soil, since these rains usually lowered ambient temperatures and increased the humidity, thus reducing transpiration. Leggett (1959) also found that spring rains, which are usually associated with cool humid weather, were effective in increasing the moisture use efficiency by wheat; while transpiration and evaporation losses were decreased, considerable crop growth still occurred. Extended spring rains provided ideal growing conditions for the record wheat crops in Oregon in 1980 and 1981.

While the amount of soil moisture stored in Pacific Northwest dryland wheat production areas is more closely related to final grain yields, rainfall during the growing season is slightly more effective in increasing yields (Leggett, 1959). But the timing of those spring rains is also important. Ramig and Pumphrey (1977) found that, in a wheat-pea rotation, precipitation in April caused decreased wheat yields by keeping the soil wet and cold, thus slowing plant growth, and by leaching soluble nutrients to below the root zone of the small plants; rainfall in both May and June increased wheat yields.

High WUE requires sufficient available moisture and plant nutrients for optimum stand development, growth, and yield (Leggett et al, 1959; Staple, 1964). When the nutrient supply is inadequate, production of starch and protein is reduced, even though transpiration may continue at a high level (Koehler and Guettinger, 1967).

Several studies have shown that nitrogen fertilization increased water use efficiency as well as yields (Bauer and Young, 1969; Brown, 1971; Koehler, 1960; Massee and Siddoway, 1969; Olson et al. (1964); Singh et al., 1975). In a study of 90 wheat fertility experiments under dryland conditions in eastern Washington, Leggett (1959) showed that each additional centimeter of water above 10 cm increased wheat yields by an average of 158 kg/ha. In a single trial in eastern Washington during a year when the growing conditions were exceptionally favorably, unfertilized wheat produced 169 kg grain per hectare for each centimeter of water used above 10 cm, and wheat fertilized with 90 kg nitrogen per hectare produced 190 kg/cm (Koehler, 1960).

Koehler and Guettinger (1967) reported that semi-dwarf wheat varieties produced approximately 185 kg grain/ha and standard varieties 159 kg grain/ha for each additional centimeter of available water above 10 cm. Massee and Siddoway (1969) reported that each centimeter of water used above 11.3 cm was expected to increase spring wheat yields by 66 kg/ha in southeastern Idaho.

Brown (1971) reported that daily water use rates for winter wheat were increased by increasing rates of nitrogen fertilizer. These water use rates increased through the growing season, reaching maximum values during the head-to-flowering stage. Wheat growing without nitrogen fertilizer reached its maximum daily water use rate slightly earlier than the fertilized wheat. It was also found that nitrogen fertilization increased the functional life of the upper leaves; only the flag leaf remained green and functional at heading time on the unfertilized wheat while the upper two or three leaves were still green on the fertilized wheat.

Heavy rates of nitrogen fertilizer can reduce yields and WUE in areas of very limited moisture by stimulating excessive vegetative growth which can exhaust the moisture supply early in the season, causing premature ripening and lower yields (Olson et al., 1964).

Timely planting and good weed control can also increase WUE since a well established stand will make rapid growth earlier in the spring when air temperatures are low and the relative humidity is high compared to later in the spring and summer.

Available Soil Moisture

The soil's ability to absorb and retain moisture provides a reservoir from which plant roots can draw the necessary water for survival and growth. The range of soil moisture content which a plant can remove from the soil reservoir is called the plant available water, or simply, available soil moisture (Peters, 1965).

The upper limit of available moisture is commonly termed field capacity, and is defined as the water content of a soil after draining for approximately two days after the addition of sufficient water to completely wet the soil to the depth being studied. Laboratory determination of the soil moisture content at 1/3 bar tension has been found to be closely related to field capacity for many soils (Peters, 1965).

Sykes and Loomis showed that the capillary conductivity, and thus field capacity because of its relationship to capillary conductivity, can vary widely in different soils. Miller and Aarstad (1973) found that soil profiles continued to drain for several days after being wetted to saturation and that the drainage could occur at soil moisture contents less than that calculated a field capacity.

The lower limit of plant available water is termed the permanent wilting point; this is defined as the soil moisture content when plants growing in that soil first wilt to the extent that all leaves cannot recover when the plant is placed in a saturated atmosphere.

There is a considerable range in the soil moisture content from the beginning to end points of permanent wilting. Though there are some small differences between plant species in their ability to extract moisture (Briggs and Shantz, 1912), a generally accepted direct procedure for determining the permanent wilting point of various soils utilizes the dwarf sunflower, Helianthus annus, at the growth stage when three pairs of leaves have fully developed (Peters, 1965).

Plant wilting is caused by a soil moisture supply too low to meet the plant demand rate for maintaining cell turgor pressure. At low soil moisture contents, where moisture retention is high, the rate of water movement is very slow, and for practical purposes a retention value approximates the wilting point. The soil moisture content at 15 bars tension has been found to be closely related to the permanent wilting point, especially in medium textured soils (Peters, 1965).

In reviewing the conclusions of several workers, Sykes and Loomis (1967) pointed out that there is much discrepancy concerning the concept of field capacity and the accuracy of 15 bars tension as the end point of available soil moisture.

Briggs and Shantz (1912) concluded that the variation exhibited by different plants in their ability to extract soil moisture prior to permanent wilting is small and not great enough to be of practical importance in drought resistance; differences were considered not due to an ability to exert greater extractive forces, but rather to better root distribution of a particular species or variety.

Sykes and Loomis (1967) asserted that many agronomists assume that the availability of soil moisture is a property of the soil and independent of the plant. Richards et al. (1949) and Slatyer

(1957), as reported by Sykes and Loomis (1967), pointed out that the distance that soil moisture must travel to be used by the plant depends on the permeation of the soil by actively absorbing roots. Papendick et al. (1971) found that steep moisture potential gradients existed near harvest in the root zone where abundant fresh root material was found. Below this zone there existed only a trace of root material. While capillary conductivity is the major soil factor affecting soil moisture availability, Sykes and Loomis (1967) hypothesized that variable plant factors include resistance to wilting and an ability to transmit the osmotic potential of the leaves to the roots.

The use of a fixed permanent wilting point is inadequate in determining the lower limit of available soil moisture (Papendick et al., 1971) since it more accurately reflects a rate of absorption (Sykes and Loomis, 1967). Several researchers have reported soil moisture extraction or permanent wilting of plants at tensions greater than 15 bars (Bauer and Young, 1969; Lehane and Staple, 1960; Papendick et al., 1971; Ramig and Rhoades, 1963; Sykes and Loomis, 1967). Papendick et al. (1971) found that dryland wheat extracted soil moisture to levels much lower than that equivalent to a 15 bar tension in the upper soil profile, while deeper layers of the root zone had a moisture tension often less than 2 bars. Where no nitrogen fertilizer was applied, the moisture tensions between the 30 to 150 cm soil depth as measured about two weeks prior to harvest ranged between 30 and 33 bars. The addition of 112 and 224 kg nitrogen per hectare caused moisture tensions to range between 135 and 146 bars. The increased moisture extraction under nitrogen fertilization was thought due to nitrogen-induced root density differences as reported by Kmoch et al. (1957).

Johnson and Davis (1980) reported that the minimum points of soil moisture exhaustion for a winter wheat crop, as measured with a neutron probe, were highly variable, even in a relatively uniform soil. Papendick et al. (1971) reported that the soil moisture contents do not reflect soil depth extraction patterns as well as moisture potential measurements. They concluded that it is difficult to obtain a close relationship between water content and water potential measurements in the field because of soil heterogeneity between soil depths and between sample sites. In addition, the mobility of water in the root zone or in the area underlying the root zone is probably more important to the concept of plant available water than the energy status alone.

Extraction of the available soil moisture in a 180 cm soil profile by wheat has been found by some workers to be incomplete. Both spring and winter wheat extraction of available soil moisture measured at harvest was seldom complete to the equivalent of 15 bars tension (Bauer and Young, 1969; Massee and Siddoway, 1970; Olson et al., 1964; Singh et al., 1975). Bauer and Young suggested that this should be taken into account when assessing the amount of available moisture to which a crop has access. Based on their study of spring wheat in North Dakota, it was proposed that the amount of soil moisture contributed by soil profile depths greater than 90 cm might best be evaluated at 50% or less of the available moisture present. Their data showed that, in an average of 102 trials over five years, less than half of the available moisture present at seeding time, in general, was removed from the 90 to 120 cm depth by harvest; even less was removed from the 120 to 150 cm depth.

Ritchie (1981) defined the term "extractable water" as the difference between the highest volumetric moisture content measured in the field following drainage and the lowest measured moisture content following harvest of a dry crop. This concept more accurately reflects the amount of soil moisture available and, subsequently, removed through evapotranspiration during the growing season.

Though the concepts of field capacity and permanent wilting point, and their representation by soil moisture contents at 1/3 bar and 15 bars tension, respectively, are limited and may not be fully accurate under various field conditions, they do help in obtaining an estimate of the amount of soil moisture available to a crop, a necessary consideration at the practical agronomic level.

C. Methods of Study

Methods of study by Cole and Mathews (1923) showed that even in quite uniform soils duplicate gravimetric determinations of soil moisture often varied by at least 0.5%; the variation was much greater in less uniform soils. Staple (1964) found that field soil moisture contents were so variable that the standard error of sampling was large in comparison to the small amounts of moisture which can increase wheat yields. It was found that in order to detect a 1.3 cm difference in stored soil moisture between two treatments 30 or more samples taken to root depth were required.

The neutron scattering method of measuring soil water content came into general use about 1960 and enabled researchers to expand the scope and precision of their soil moisture measurements; previously, extensive measurements had often been prohibitive due to the labor involved. This method is non-destructive and reduces the effect of soil variability through sampling a larger soil volume than commonly sampled with the gravimetric method. Van Bavel (1963), as reported by Johnson and Davis (1980), indicated that seven to fifty times as many gravimetric soil samples would be required to obtain a similar level of precision as the neutron scattering method. Gardner (1965) believed that the neutron probe access tube should have only a minor influence on the soil moisture content measured around the tube unless temperature conditions were extreme.

While most soil moisture studies with wheat have measured soil moisture to a maximum depth of 180 cm, Lindstrom et al. (1974)

reported that it is important to be able to account for the total amount of moisture stored to the greatest depth of extraction, including moisture which may move to lower depths, in order to accurately determine storage efficiencies.

III. MATERIALS AND METHODS

Five fallow-crop precipitation patterns characteristic of the 250-350 mm precipitation zone of eastern Oregon were simulated on a commercial dryland wheat farm near Moro, Oregon, from 1977-1980. Two 24-month fallow-crop cycles were completed during this period; the 1977-79 cycle was located on a south-sloping field and the 1978-80 cycle on a adjacent north-sloping field. The slope of each experimental site averaged about 3%, and the soil was a very deep Walla Walla silt loam (coarse-silty, mixed, mesic Typic Haploxeroll) typical of the area and well adapted to moisture storage. The simulations (Table 1) were based on an analysis of the area's long-term weather record by Glenn (1981), who used a categorization of seasonal precipitation developed by Aktan (1976); these five precipitation patterns (dry fallow-normal crop, DFNC; normal fallow-dry crop, NFDC; normal fallow-normal crop, NFNC; normal fallow-wet crop, NFWC: wet fallow-normal crop, WFNC) accounted for approximately 88% of the recorded fallow-crop precipitation levels between 1912-1976. In each fallow or crop period, rainfall was excluded where necessary by rolling plastic tarps over the 6 x 15 m plots at the onset of a precipitation event and removed at the conclusion of each event. A PVC support grid was used to keep the tarps above the crop. When needed, additional moisture was applied to the plots with a solid set irrigation grid with low-pressure, low-angle nozzles that provided 200% overlap. Moisture was regulated on a monthly basis, primarily during the winter months. The non-treated control plot received only normal precipitation. A split-plot

Table 1. Fallow-crop precipitation pattern categorization and realized treatment levels.

Precipitation pattern	Lower and upper categorization boundary: 14 mo. fallow	10 mo. crop	Realized level of precipitation: 1977-79 Fallow	1977-79 Crop	1978-80 Fallow	1978-80 Crop
	mm					
Dry fallow Normal crop (DFNC)	206-261	219-320	306	180	237	389
Normal fallow Dry crop (NFDC)	262-370	179-218	371	133	301	351
Normal fallow Normal crop (NFNC)	262-370	219-320	371	180	301	389
Normal fallow Wet crop (NFWC)	262-370	321-403	371	290	301	426
Wet fallow Normal crop (WFNC)	371-429	219-320	488	201	418	389
Control	-	-	422	180	263	389

design was established with four blocks. The main plots were the precipitation patterns. The subplots (2.4 x 6 m) included six levels (0, 15, 45, 60, 75, 105 kg N/ha) of nitrogen fertilizer (Solution 32; 32% N) that were injected into the soil prior to seeding. In the 1978-80 simulation, the NFWC treatment was duplicated ($NFWC_2$) and split applications of Solution 32 and ammonium nitrate were applied (0, 15, 45, 45 + 15, 45 + 30, 45 + 60 kg N/ha).

Neutron probe access tubes were installed according to Glenn et al. (1980) and soil moisture measured in 15 cm increments to a depth of 270 cm in the 0 and 105 kg N/ha subplots and to 360 cm in the 60 kg N/ha subplots. The 0-15 and 15-30 cm increments were measured gravimetrically. Soil moisture contents were measured periodically throughout the fallow and crop periods, including at the beginning of the fallow period (August), in the spring of the fallow period (March), at planting (September), in the spring of the crop period (March), and following harvest (July). Available soil moisture was estimated by subtracting the initial, post-harvest soil moisture content for each access tube from each subsequent measurement.

All stubble-mulch tillage and planting operations were conducted by the farmer as part of his normal farm operations. Stephens variety soft white winter wheat was planted in late September both in 1978 on the south field and in 1979 on the north field; the stands emerged within 10 days in both years. In July of the respective crop year, grain was harvested from the center of each subplot with a self-propelled combine.

Soil moisture desorption characteristic curves for each 30 cm increment to a soil depth of 270 cm were determined by pressure plate, pressure membrane, and vapor equilibrium techniques. Bulk density measurements of the soil profile were made using standard gravimetric techniques.

IV. RESULTS AND DISCUSSION

Field Uniformity

Each of the two experimental sites covered approximately 1.9 ha and lay on opposite sides of a hill near the crest. Statistical analyses of the total soil moisture present at the beginning of the fallow period indicated that the sites were fairly uniform; the CV's for moisture in the 0-180 cm soil profile were 3.3% and 8.5% in the south and north fields, respectively.

Significant subplot differences in moisture were expressed in the 90-180 cm soil depth increment on both fields and in the 180-270 cm increment on the north field. Differences were not expected at that time and were considered to be due to either coincidental random variation, or perhaps to the unequal access tube depth on the north field, where slightly less moisture was measured in subplots with deeper tubes. However, the maximum mean difference between subplots was only about 6 mm of moisture in the 180-270 cm soil depth increment.

Significant differences in block means were present with the block nearest the hill crest being slightly drier.

Soil Moisture Storage

Both historic and current mean monthly precipitation levels and temperatures at Moro, Oregon, are summarized in Table 2. Categorization of natural precipitation indicates that a WFDC pattern occurred during the 1977-79 trial on the south field, and that a NFWC pattern occurred during the 1978-80 trial on the north field.

Table 2. Mean monthly precipitation and temperature at Moro, Oregon.

Period	Month	Precipitation			Temperature		
		1912-76	1977-79	1978-80	1941-70	1977-79	1978-80
		mm			°C		
Fallow	Aug.	6	23	34	19.4	21.9	19.0
	Sept.	15	22	8	15.8	13.2	14.0
	Oct.	24	6	0	9.8	10.7	9.7
	Nov.	43	51	20	3.9	2.1	0.1
	Dec.	43	82	18	0.7	0.9	- 0.7
	Jan.	43	71	40	- 1.3	- 1.2	- 9.3
	Feb.	30	33	39	2.4	2.7	0.9
	Mar.	24	19	25	4.8	6.8	6.1
	Apr.	19	36	27	8.4	8.1	8.3
	May	20	11	7	12.5	10.8	13.2
	June	18	11	3	16.2	16.6	16.4
	July	5	15	2	20.2	20.0	20.6
	Aug.	6	34	27	19.4	19.0	19.3
	Sept.	15	8	13	15.8	14.0	16.7
	Total	311	422	263			
Crop	Oct.	24	0	66	9.8	9.7	11.5
	Nov.	43	20	57	3.9	0.1	1.2
	Dec.	43	18	17	0.7	- 0.7	2.2
	Jan.	43	40	87	- 1.3	- 9.3	- 4.1
	Feb.	30	39	46	2.4	0.9	0.6
	Mar.	24	25	24	4.8	6.1	4.4
	Apr.	19	27	22	8.4	8.3	9.7
	May	20	7	32	12.5	13.2	11.8
	June	18	3	35	16.2	16.4	13.7
	July	5	2	4	20.2	20.6	19.6
	Total	269	181	390			
Fallow-Crop	Total	580	603	653			

Net soil moisture storage (i.e., the net change since the beginning of the fallow period) measured at various times during the total storage period on the north field, together with cumulative amounts of natural and simulated precipitation on each of the main plots, is shown in Table 3. Soil moisture measurements on 12-29-78 indicated a net loss of soil moisture, especially in the 180-270 cm depth increment, on the DF and NF plots which had only received natural precipitation. It is unclear whether the moisture moved up out of the soil profile or down below the depth of measurement. The mean soil moisture content at the beginning of the fallow period indicates that the tension gradient favored upward movement during the pre-winter period (Fig. 2). This evaporation presumably fluctuated between stages II and III (Idso et al., 1974) as the soil surface was periodically rewet by fall rains.

Post-winter moisture measurements on 3-17-79 indicated that the incremental fallow efficiency (F.E.) on the DF plots was considerably higher than the amount of precipitation allowed to fall on the plots. This might indicate that moisture had moved up into the measured profile from below. However, there may also have been lateral movement of moisture into the drier plots, where precipitation had been excluded, from the surrounding 15.7 meter-wide border areas which received normal precipitation. The NF plots had received only natural precipitation up to this date, and also had a high incremental F.E., which indicated that either moisture had moved up from the deeper profile, or the precipitation was very effectively stored during the winter, or both.

Table 3. Cumulative precipitation, net soil moisture storage, fallow efficiency (F.E.), and incremental period F.E. since the beginning of fallow (8-17-78) on the north field for the respective precipitation patterns.

	Fallow period																					Crop period 3-20-80				
	12-29-78			3-17-79			4-29-79			5-26-79			7-06-79			8-18-79			9-13-79							
	DF	NF	WF	DF	NF	WF	DF	NF	WF	DF	NF	WF	DF	NF	WF	DF	NF	WF	DF	NF	WF	DF NC	NF DC	NF NC	NF WC	WF NC
	mm																									
Cumulative precipitation	68	68	123	116	164	219	155	242	326	162	249	333	165	252	336	170	258	342	206	294	411	500	549	587	624	704
Cumulative net storage[†]																										
a) 0-180 cm	-5	-2	33	86	82	94	73	68	79	57	59	78	46	51	72	35	39	63	35	43	86	184	203	186	181	207
b) 0-270 cm	-19	-14	45	87	80	92	72	62	71	53	54	72	42	47	69	29	31	59	30	36	82	188	224	190	192	226
Cumulative storage F.E.[‡]																										
a) 0-180 cm	-7	-3	27	74	50	43	47	28	24	35	24	23	28	20	21	21	15	18	17	15	21	37	37	32	29	29
b) 0-270 cm	-28	-21	37	75	49	42	46	26	22	33	22	22	25	19	20	17	12	17	15	12	20	38	41	32	31	32
	%																									
Incremental F.E.[§]																										
a) 0-180 cm	-7	-3	27	194	88	64	-33	-18	-14	-2	-1	0	-3	-2	-2	-2	-2	-2	0	0	33	51	63	49	42	41
b) 0-270 cm	-28	-21	37	226	98	49	-38	-23	-20	-3	-1	0	-3	-2	-1	-2	-2	-2	0	0	33	54	74	52	47	49

[†] Cumulative net soil moisture storage is measured in both the 0-180 and 0-270 cm soil profiles.

[‡] Cumulative storage F.E. is calculated as the portion of cumulative precipitation that is stored in the respective soil profile.

[§] Incremental F.E. is calculated as the portion of precipitation occurring since the last date of measurement that is stored in the soil.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

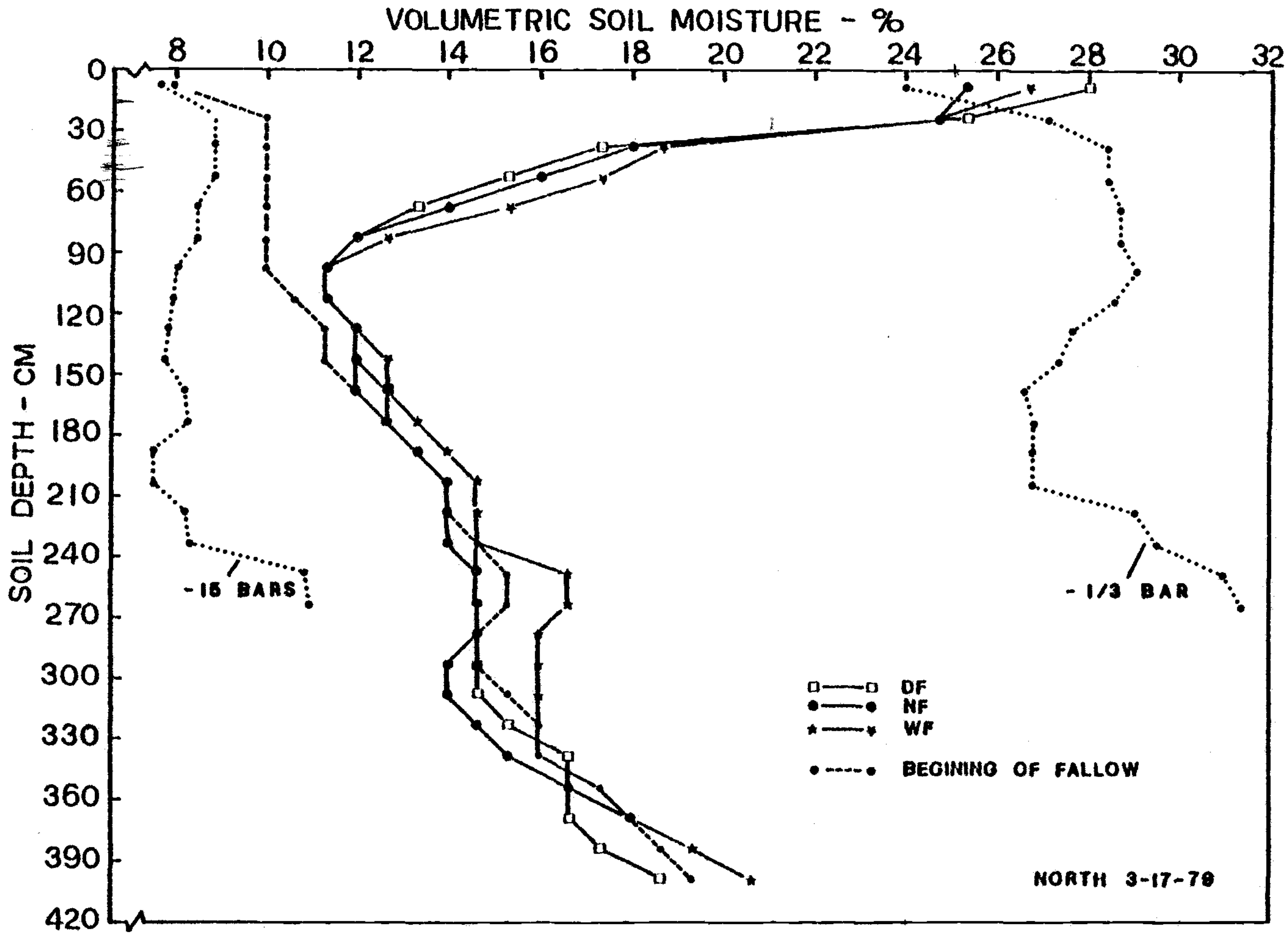

Figure 2. Average soil moisture content in early spring of the fallow period. (North field, 3/17/79.)

After the fallow winter storage period, stored soil moisture continually declined. By the end of the fallow period, only an average of 49% of the mean net storage of 84 mm measured in March in the north field's 0-270 cm profile still remained (Fig. 3); this accounted for an average of only 14% of the cumulative fallow season precipitation.

Comparative values on the south field were 52% of the 268 mm net storage measured in March still remaining at planting, accounting for 36% of the cumulative precipitation.

Use of linear regression analysis to estimate the amount of net soil moisture storage (mm) in the 0-270 cm profile at the end of the fallow period (SM_3) showed the relationship to the net soil moisture stored in the respective profile in late March of the fallow period (SM_2) for all main plots on both fields by the following equation:

$$SM_3 = -4.80 + 0.526\ (SM_2)$$

equation (1)

$$r^2 = 0.90$$

The equation indicates that an average of approximately 47% of the net soil moisture stored in the 0-270 cm profile in early spring, above a 9 mm minimum, was lost from the profile by the end of the fallow period, even though an average of 121 mm of precipitation fell on the plots over the spring and summer months.

The greatest inefficiencies in moisture storage occurred immediately following the winter storage period when the soil profile had been partially filled (Fig. 2), thus slowing moisture infiltration; the soil surface was also wet at this time, which

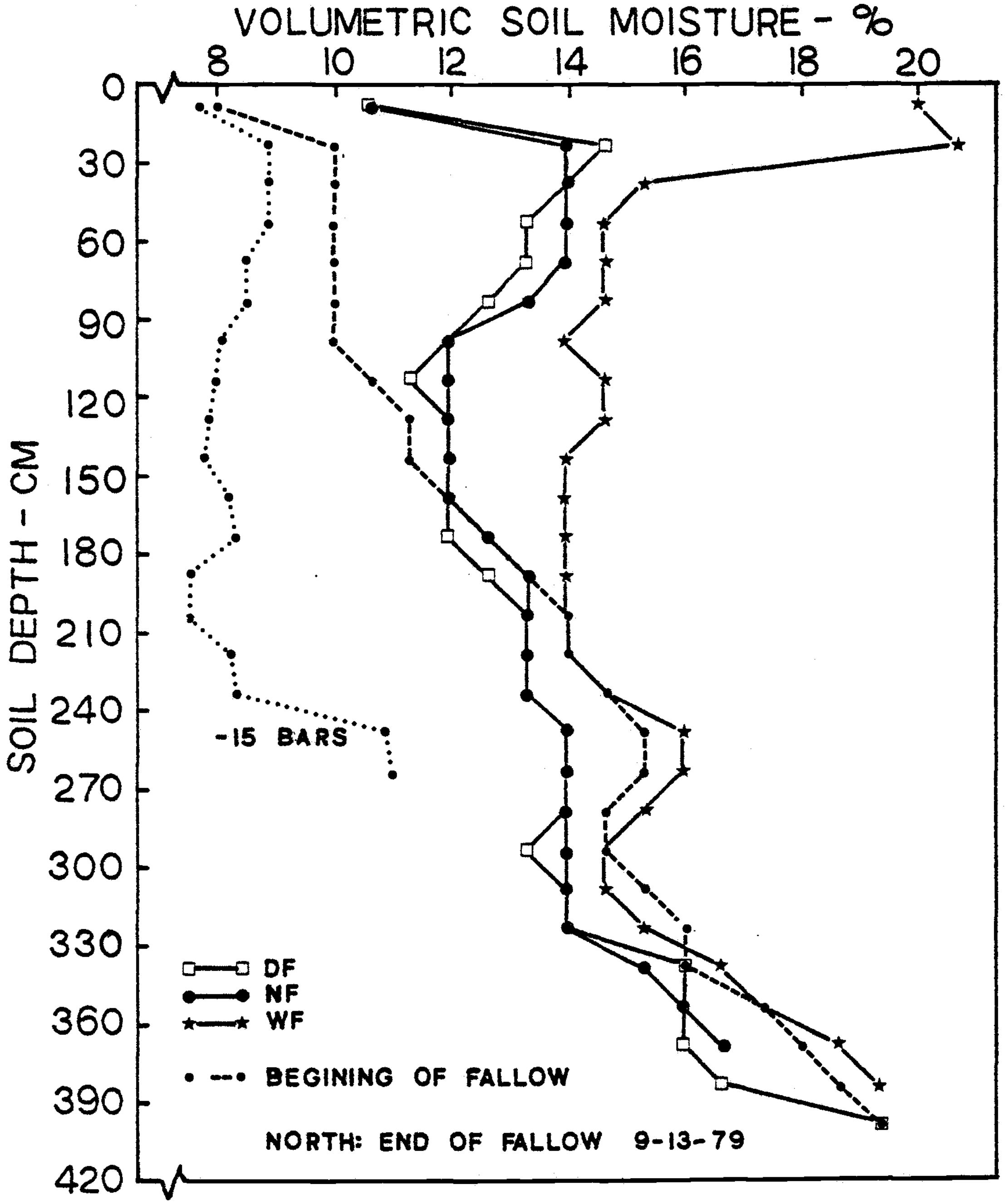

Figure 3. Average soil moisture content at the end of the fallow period. (North field, 9/13/79.)

promoted rapid evaporation. As reported in an early publication by Hunter (1918), tillage practices should be most effective in reducing evaporative losses by disrupting capillary continuity as soon as possible after the winter storage period.

Figure 2 also shows that soil moisture tension gradients may have permitted both evaporative and downward percolation losses from the measured profile following the winter precipitation period.

By the end of the second winter storage period (3-20-80), heavy precipitation promoted more than twice as much net moisture storage on the north field as was stored by mid-March of the fallow period (Table 3). However, on the south field, net moisture storage measured in March of the crop period was less than that measured in March of the fallow period. This may have been due to drier than normal conditions during the crop period.

While the amounts of precipitation can be regulated to conform to the categories being simulated, other environmental conditions that affect evaporative demand cannot be controlled in a field study. Presumably, these environmental conditions are closely associated with the pattern of natural precipitation and may not affect soil moisture storage or crop response in a simulated precipitation pattern in the same way as a naturally-occurring pattern.

The mean cumulative F.E. in the north field's 0-180 cm soil profile in mid-March of the fallow period was 56%, while in mid-March of the crop period it was 33% in the 0-180 cm profile and 35% in the 0-270 cm profile. Both the cumulative and incremental storage efficiencies were lower during the second winter storage period due to decreased infiltration rates when the soil was moister

(Parr and Bertrand, 1960). Soil moisture measurements to depths greater than 180 cm may be necessary on deep soils in order to calculate moisture storage under tillage or other differential treatments, especially where precipitation amounts are high or information is desired on deep profile moisture movement.

Figure 4 shows the correlation between the level of net moisture storage in the 0-270 soil profile in the spring of the fallow period (March) and subsequent gains or losses measured in the spring of the crop period. On the average, there would have been no moisture storage advantage to fallowing when the level of net storage in the spring of the fallow period was 194 mm or greater. Except for potential yield differences between spring and winter wheat crops, potential weed or other cultural problems, and the disruption of the established fallow-crop cycle, it might be economically feasible to plant spring wheat on an annual basis when the quantity of net stored moisture in the 270 cm soil profile was above 194 mm.

Table 4 summarizes the net soil moisture storage by depth in early spring of the fallow period. Significant storage increases occurred in the 0-90 cm and 90-180 cm depths on the south field, with the DF plots increasing the least; increases also occurred in the 180-270 cm depth. These increases were primarily due to the heavier than normal natural precipitation. Precipitation treatment differences on the north field were not significant at any depth. Small net increases occurred in the 0-90 and 90-180 cm depths, with losses generally occurring at deeper depths, primarily due to smaller than normal amounts of natural precipitation.

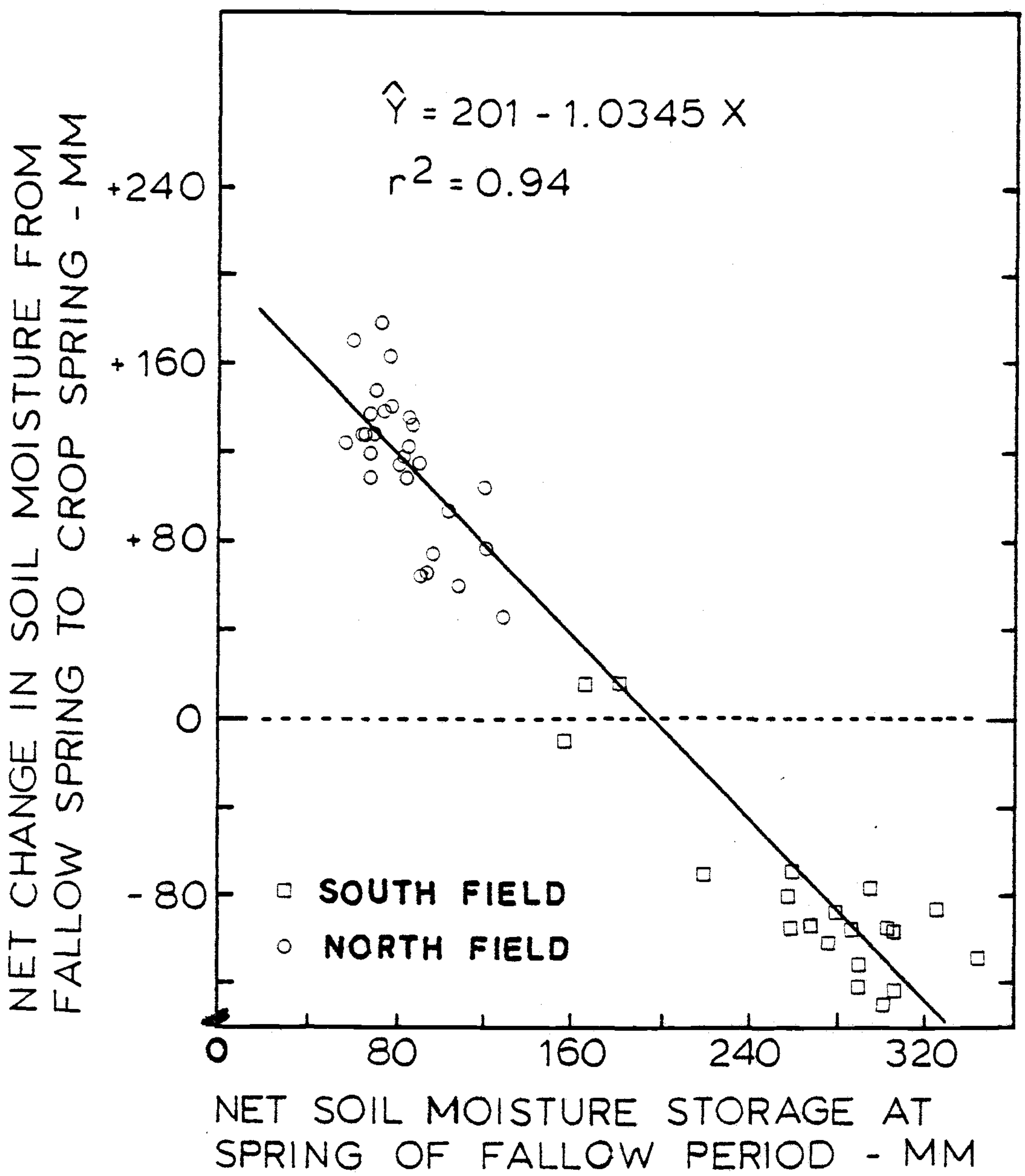

Figure 4. Relationship between net moisture storage in the 0-270 cm soil profile in the spring of the fallow period and subsequent change to spring of the crop period.

Table 4. Average net change in soil moisture in the respective soil depth increment from the beginning to spring of the fallow period.

Precipitation pattern	Soil depth increment (cm)						
	South field (3/28/78)			North field (3/17/79)			
	0-90	90-180	180-270	0-90	90-180	180-270	270-360
	mm						
DFNC	112.5b*	80y**	8	78.0	8.5	0.2	3
NFDC	125.5a	119x	26	75.5	9.0	-2.8	- 6
NFNC	127.5a	117x	31	78.5	3.8	-2.5	- 6
$NFWC_1$	128.8a	124x	43	75.0	2.0	-2.0	- 4
$NFWC_2$	-	-	-	79.5	6.8	-1.8	- 2
WFNC	130.2a	122x	46	86.5	7.0	-2.0	- 6
Control	-	-	-	79.2	5.5	1.2	-15
$LSD_{.05}$	9.8	18.0	NS	NS	NS	NS	NS
$LSD_{.01}$	NS	25.3	NS	NS	NS	NS	NS

*,** Means in the same column followed by a common letter a,b or x,y are not significantly different at the 5% and 1% level of probability, respectively, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

WC_1 = Wet crop, single fertilizer application.

WC_2 = Wet crop, split fertilizer application.

By the end of the fallow period, net storage was still considerably greater on the south field (Table 5). The WF plots on both fields had significantly more stored moisture at the 0-90 cm depth than the drier treatments, and the NF plots tended to have more net storage in the total profile than the DF plots.

Significant differences between treatments in early spring of the crop period varied between the fields (Table 6). However, comparisons between treatments which eventually would receive similar amounts of cumulative precipitation (DFNC vs NFDC; NFWC vs WFNC) indicated that the treatments with the wetter fallow period tended to store more moisture in the 0-270 cm soil profile than those with drier fallow periods; the storage differences between treatments were significantly greater in the 90-180 cm depth on the north field.

Comparison between treatments with equal crop season precipitation on the north field showed that the WFNC plots stored significantly more total net moisture and had significantly greater storage in the 90-180 and 180-270 cm soil depths than either the NFNC or DFNC plots.

Treatments with wetter crop periods tended to accumulate less moisture than treatments with less crop precipitation. On the north field, the net storage was significantly greater in the NFDC plots than in either the NFNC or NFWC plots in the 0-270 cm profile; much of this difference occurred between the 90-180 cm depth. These differences were probably caused by the greater amounts of crop season precipitation which kept the soil surface wet and promoted more rapid evaporation for a longer period of time.

Table 5. Average net change in soil moisture in the respective soil depth increment from the beginning to the end of the fallow period.

Precipitation pattern	Soil depth increment (cm)						
	South field (9/19/78)			North field (9/13/79)			
	0-90	90-180	180-270	0-90	90-180	180-270	270-360
	mm						
DFNC	62.8b*	55	0	29y**	6.5y	-5.8	- 6
NFDC	68.8b	68	10	42y	10.5y	-7.8	-10
NFNC	63.5b	67	16	32y	8.8y	-7.0	-10
$NFWC_1$	63.5b	64	6	28y	5.5y	-7.0	- 8
$NFWC_2$	-	-	-	34y	11.5y	-6.5	- 7
WFNC	76.8a	63	25	62x	24.0x	-4.3	-12
Control	63.5b	62	6	32y	5.5y	-5.5	-20
$LSD_{.05}$	7.9	NS	NS	12.5	8.2	NS	NS
$LSD_{.01}$	NS	NS	NS	17.1	11.2	NS	NS

*,** Means in the same column followed by a common letter a,b or x,y are not significantly different at the 5% and 1% level of probability, respectively, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

WC_1 = Wet crop, single fertilizer application.

WC_2 = Wet crop, split fertilizer application.

Table 6. Average net change in soil moisture in the respective depth increment from the beginning of the fallow period to spring of the crop period.

Precipitation pattern	Soil depth increment (cm)							
	South field (3/19/79)				North field (3/20/80)			
	0-90	90-180	180-270	270-360	0-90	90-180	180-270	270-360
	mm							
DFNC	102.4b*	72	12	- 2	125.8	58c	5b	- 8
NFDC	108.9a	72	10	19	131.5	72ab	21a	- 9
NFNC	104.8ab	69	16	-18	124.1	62bc	4b	-10
$NFWC_1$	98.8c	67	10	- 1	124.9	55c	9ab	- 4
$NFWC_2$	-	-	-	-	122.1	60bc	11ab	- 6
WFNC	102.0b	72	25	8	131.1	76a	19a	-12
Control	105.5ab	74	13	8	128.3	58c	8ab	-24
$LSD_{.05}$	5.0	NS	NS	NS	NS	11.9	12.2	NS

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NS = F test nonsignificant.

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WC_1 = Wet crop, single fertilizer application.

WC_2 = Wet crop, split fertilizer application.

Soil Moisture Extraction

Soil moisture removed by evapotranspiration from the soil profile between spring of the crop year and harvest did not differ between precipitation treatments on the south field (Table 7). However, significant differences did exist for all soil depth increments to 270 cm on the north field (Table 8). Comparison of treatments with similar amounts of total precipitation (DFNC vs NFDC; NFWC vs WFNC) showed that a wet fallow period significantly promoted more moisture removal; more moisture was extracted from both the 90-180 and 180-270 cm depth increments in treatments with the wetter fallow period.

Where treatments received equal crop period precipitation, significantly more moisture was extracted from the WFNC plots than from either the NFNC or DFNC plots in the 0-270 cm profile; the difference in extraction was fairly equally distributed between the 90-180 cm and 180-270 cm depths.

Comparison of treatments with equal fallow period precipitation indicates that significantly more moisture was extracted from the NFDC plots than from either the NFNC or NFWC plots, probably because there was more moisture available in the NFDC plots, and the crops on the other two treatments would have received a greater proportion of their moisture needs from the greater growing season precipitation. Some of these same trends can be observed on the south field, though they are not significant at the 5% level of probability.

The application of additional amounts of nitrogen fertilizer significantly increased moisture extraction in the 0-270 cm soil profile on both fields, as well as in the 90-180 cm depth increment

Table 7. Average net change in soil moisture between spring of the crop period and harvest (7/24/79): south field.

Precipitation treatment	Soil depth increment (cm)						
	0-90	90-180	180-270	270-360	0-180	0-270	0-360
	mm						
DFNC	-102.9	-62.5	-13.5	-6	-165	-179	-185
NFDC	-108.8	-59.6	-15.0	-5	-168	-183	-188
NFNC	-106.2	-63.9	-19.8	+6	-170	-190	-184
NFWC	-102.2	-60.4	-10.8	+2	-163	-174	-170
WFNC	-104.2	-64.8	-18.2	-6	-169	-187	-192
Control	-105.2	-60.4	-18.2	-8	-166	-184	-192
$LSD_{.05}$	NS	NS	NS	NS	NS	NS	NS

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

Table 8. Average net change in soil moisture between spring of the crop period and harvest (7/28/80): north field.

Precipitation treatment	Soil depth increment (cm)						
	0-90	90-180	180-270	270-360	0-180	0-270	0-360
	mm						
DFNC	-145.8ab*	-55.3b	- 3.5c	5.0	-201bc	-205c	-200c
NFDC	-149.9a	-74.2a	-19.5a	7.5	-224a	-244a	-236a
NFNC	-140.9bc	-60.4ab	- 3.1c	4.5	-201bc	-104c	-200c
$NFWC_1$	-146.3ab	-57.7b	- 8.5bc	1.2	-204bc	-212bc	-211bc
$NFWC_2$	-139.2c	-59.6ab	- 7.1bc	8.0	-199c	-206c	-198c
WFNC	-145.8ab	-73.7a	-17.5ab	9.5	-219ab	-237ab	-227ab
Control	-146.0ab	-59.9ab	- 8.0bc	7.2	-206abc	-214bc	-206bc
$LSD_{.05}$	6.0	13.9	9.9	NS	17.3	24.0	23.6

* Means in the same column followed by a common letter are not significantly different at the 5% level of probability, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

WC_1 = Wet crop, single fertilizer application.

WC_2 = Wet crop, split fertilizer application.

in the south field (Table 9) and in all depth increments in the north field (Table 10). The greatest increases in soil moisture extraction occurred in the 90-180 cm increment. The 60 kg N/ha treatment caused significantly more moisture extraction from the 0-270 cm profile on both fields, but the 105 kg N/ha treatment caused more extraction only on the north field, presumably due to the availability of more moisture and the ideal cool, moist environmental conditions in the spring of 1980.

A slight increase in the level of soil moisture in the 270-360 cm depth increment occurred in two of the six precipitation treatments on the south field during the crop growing season (Table 7); similar increases occurred for all precipitation treatments on the north field (Table 8). Whether these increases developed from moisture percolation from the profile above or from upward movement from below depends on the specific time period during the spring growing season and the respective soil moisture tension gradient. After the winter storage period the tension gradient normally allows downward movement; but late in the spring, after the crop has extracted a considerable amount of moisture, upward movement would be favored. Rickman (1977) reported that the shift from downward flow to upward flow occurred by the end of May, and that by late June the majority of the moisture made available to the wheat crop was furnished by upward flow from beneath the root zone.

Wheat Yields and Water Use Efficiency

Grain yields did not differ significantly between precipitation treatments in either 1979 on the south field or in 1980 on the north

Table 9. Average net change in soil moisture, by nitrogen fertilization rate, from spring of the crop period to harvest (7/24/79): south field.

Nitrogen fertilization rate	Soil depth increment (cm) 0-90	90-180	180-270	0-180	0-270
	mm				
0 kg N/ha	-103.2	-56.7y**	-14.8	-159.9y	-174.7b*
60 kg N/ha	-105.0	-64.8x	-17.7	-169.8x	-187.5a
105 kg N/ha	-106.7	-64.3x	-15.3	-171.0x	-186.2a
$LSD_{.05}$	NS	4.6	NS	6.6	10.0
$LSD_{.01}$	NS	6.1	NS	8.8	NS

*,** Means in the same column followed by a common letter a,b or x,y are not significantly different at the 5% and 1% level of probability, respectively, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

Table 10. Average net change in soil moisture, by nitrogen fertilization rate, from spring of the crop period to harvest (7/28/80): north field.

Nitrogen fertilization rate	Soil depth increment (cm)				
	0-90	90-180	180-270	0-180	0-270
	mm				
0 kg N/ha	-142.1b**	-51.4c	- 5.5b	-193.6c	-199.1c
60 kg N/ha	-145.2a	-64.1b	-10.7a	-209.4b	-220.0b
105 kg N/ha	-147.2a	-73.3a	-12.8a	-220.6a	-233.4a
$LSD_{.05}$	1.7	3.6	3.7	4.2	6.4
$LSD_{.01}$	2.3	4.8	4.9	5.6	8.6

*,** Means in the same column followed by a common letter are not significantly different at the 1% level of probability, based on Duncan's Multiple Range Test.

field (Table 11). This may have been due to the similarity of moisture storage achieved in the greater soil depths on the south field, and to the greater than normal crop season precipitation and ideal growing conditions for the north field. Mean yields were significantly different (P = .01) between nitrogen fertilizer rates on both fields (Table 12), with both the 60 and 105 kg N/ha treatments yielding more than the 0 kg N/ha treatment on the south field. On the north field, both the 60 and 105 kg N/ha treatments yielded more than the 0 kg N/ha rate, and the 105 kg N/ha treatment yielded more than the 60 kg N/ha rate, probably because the additional soil moisture and spring precipitation enabled better utilization of the higher rate of nitrogen without early depletion of available soil moisture.

Water use efficiency (WUE) is defined as the percent ratio of grain yield (kg) to evapotranspiration, ET (mm), where ET was calculated as the sum of the soil moisture depletion in the 0-270 cm soil profile from spring of the growing season to harvest, plus the precipitation during the same period. Calculated in this manner, WUE is a tool useful in comparing the effect of various treatments. Runoff was not a problem during either crop period. The NFWC treatments on the south field had a significantly lower WUE, probably due to greater evaporation from a moist soil surface during the spring growing season (Table 11). However, the WFNC treatment on the north field had the significantly lowest WUE, possibly because a high level of moisture storage on those plots caused greater evaporation due to the prolonged soil surface wetting action by heavier than normal spring rains. Differences in WUE between nitrogen

Table 11. Mean grain yields and water-use-efficiencies (WUE) for five precipitation patterns.

Precipitation treatment	South Field Yield (metric ton/ha)	South Field WUE (kg/mm)	North Field Yield (metric ton/ha)	North Field WUE (kg/mm)
DFNC	2.98	13.03a*	4.74	16.66x*
NFDC	3.13	13.34a	4.83	14.11x
NFNC	2.99	12.40a	4.66	15.41x
$NFWC_1$	3.44	11.36b	4.81	15.60x
$NFWC_2$	-	-	4.58	15.15x
WFNC	3.30	12.61a	4.43	13.17y
Control	3.19	13.57a	4.74	15.27x
$LSD_{.05}$	NS	1.34	NS	1.15
$LSD_{.01}$	NS	NS	NS	1.57

*,** Means in the same column followed by a common letter a,b or x,y are not significantly different at the 5% and 1% level of probability, respectively, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

WC_1 = Wet crop, single fertilizer application.

WC_2 = Wet crop, split fertilizer application.

Table 12. Mean grain yields and water-use-efficiencies (WUE) for three nitrogen fertilization rates.

Nitrogen fertilization rate	South Field		North Field	
	Yield (metric ton/ha)	WUE (kg/mm)	Yield (metric ton/ha)	WUE (kg/mm)
0 kg N/ha	2.68b**	11.16b	3.48c	11.87c
60 kg N/ha	3.43a	13.57a	5.04b	16.00b
105 kg N/ha	3.40a	13.43a	5.53a	16.86a
$LSD_{.05}$	0.18	0.64	0.18	0.53
$LSD_{.01}$	0.24	0.86	0.24	0.71

** Means in the same column followed by a common letter are not significantly different at the 1% level of probability, based on Duncan's Multiple Range Test.

fertilizer rates were similar to differences in grain yields on both fields (Table 12).

The threshold amount of moisture required by the crop to begin grain production must be identified in order to more accurately account for the potential yield increase from each additional increment of available moisture. In an analysis of the relationship between grain yield and ET, the maximum yield in each main plot was plotted against its respective level of ET; this data thus represented the point where soil nutrients were presumed not limiting and moisture was used most efficiently. Linear regression analysis showed that, where ET consisted of the sum of precipitation (P) and soil moisture depletion (SM) in the 0-180 cm soil the profile, the equation derived accounted for 80% of the total variation in yield. This relationship is shown in Figure 5 and indicates that approximately 62 mm of available moisture were required to grow the crop to the point where grain production could begin. Assuming a linear relationship, each millimeter of moisture available to the crop above the minimum threshold level produced about 21.1 kg grain. This threshold value is lower than either Leggett (1959) found for winter wheat (102) or Massee and Siddoway (1969) found for spring wheat (113 mm). However, the regression coefficient for moisture available above the threshold level (i.e., 21.1 kg/ha) is similar to that found by Leggett (18.54 kg/ha). The difference in threshold levels between that observed in this study and those reported by Leggett (1959) and Massee and Siddoway (1969) may be due to the ideal growing conditions during the spring of 1980 or a limited number of data-years without extremely low yields. However, a

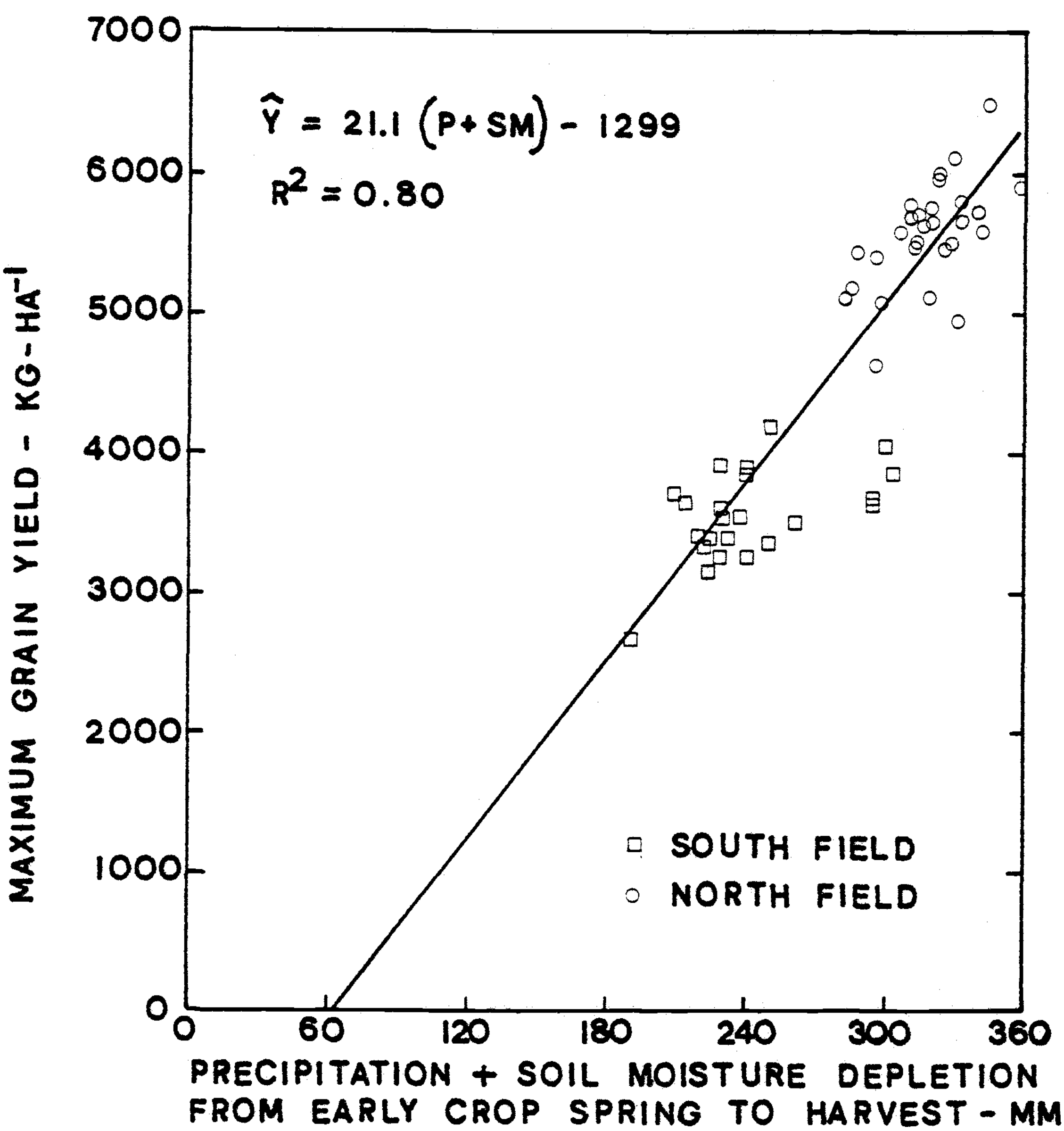

Figure 5. Relationship between the sum of the precipitation and moisture depletion in the 0-270 cm soil profile from early spring of the crop year to harvest and maximum wheat yield.

similar threshold value was reported by Johnson and Davis (1980) in Texas.

Where ET was separated into the separate variables of precipitation, P (mm), and moisture depletion (mm) in the 0-90 cm, 90-180 cm, and 180-270 cm soil depth increments (SM_a, SM_b, SM_c, respectively), SM_a made the greatest contribution to reduction of yield variability. Equation 2 indicates the relationship found:

$$Y = 7.62\ P + 39.40\ SM_a + 9.02\ SM_b - 9.37\ SM_c - 1524.12 \quad \text{equation 2}$$

S.E.: 2.38 2.81 5.63 6.40 332.85

$r^2 = 0.91$

Moisture removed from the 0-90 cm depth had the greatest effect on yield due both to the greater partial regression coefficient and to the greater amount of moisture extracted in the 0-90 cm depth (SM_a). While moisture extraction from the 90-180 cm depth increment (SM_b) had a partial regression coefficient slightly larger than that for precipitation, the standard errors of the regression coefficients (S.E.) indicate that the variables P and SM_a would contribute the most to estimating yields accurately. Equation 3 shows the relationship between yield and these two variables:

$$Y = 8.66\ P + 41.32\ SM_a - 1361.35$$

S.E.: 2.27 2.53 282.27 equation 3

$r^2 = 0.91$

Available Soil Moisture

Figure 6 shows that, even though soil profiles generally

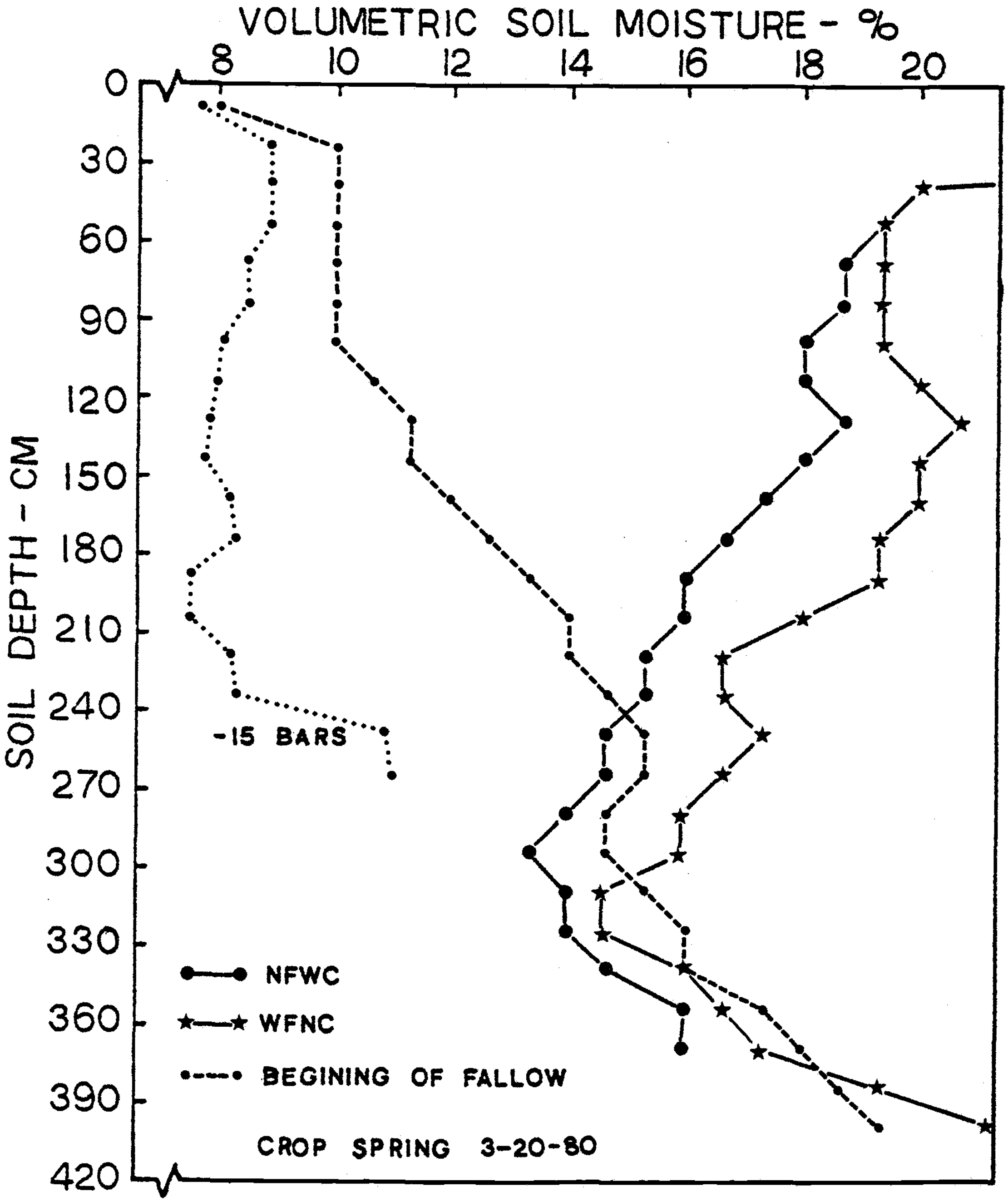

Figure 6. Average soil moisture content in early spring of the crop period. (North field, 3/20/80.)

contain the most moisture following the second winter storage period, the range of precipitation common to this location does not allow the deep soils to fill to field capacity. Perhaps of more importance is the fact that soil moisture is not uniformly depleted to the -15 bar moisture content throughout the root zone, but rather the amount removed tends to decrease with increasing soil depth. This pattern is probably indicative of the density pattern of the winter wheat roots and their activity. But practically, where yield potential estimates are based on the amount of moisture available to a crop, utilization of the -1/3 bar and -15 bar soil moisture contents as the beginning and end points of available soil moisture will tend to overestimate the amount of moisture actually available or removed.

Ritchie's (1981) concept of extractable water, defined as the difference between the highest measured volumetric moisture content in the field following drainage, and the lowest measured moisture content following harvest of a dry crop, more accurately reflects the amount of soil moisture available and subsequently removed by the crop.

In order to more accurately predict potential yields and thus enable evaluation of the need to apply additional fertilizer early in the spring, especially in cases where the average post-harvest soil moisture content is not known, the amount of moisture removed from the 0-90 cm (SM_a), 90-180 cm (SM_b), and 180-270 cm (SM_c) soil depth increments between early spring of the crop period and harvest was plotted against the total amount of soil moisture in early spring of the crop period (SM_4) in the respective soil depth increment for the subplot which yielded the most grain in each of the main plots. Equations 4, 5, and 6 show this relationship:

$SM_a = 1.11\ (SM_{4a} - 83);\ r^2 = 0.92$ equation 4

$SM_b = 0.576\ (SM_{4b} - 44);\ r^2 = 0.29$ equation 5

$SM_c + 0.160\ (SM_{4c} - 68);\ r^2 = 0.24$ equation 6

By using these equations, the amount of moisture expected to be extracted from the 0-90 cm soil profile can be estimated with a good deal of confidence ($r^2 = 0.92$), while estimated extraction in the 90-180 and 180-270 cm soil profiles will have a lesser degree of confidence. These estimated values can then be used, together with an estimate of anticipated spring precipitation, in equation 2 or similar equations, to predict the potential grain yield.

V. SUMMARY

Simulation of the five fallow-crop precipitation patterns, which account for approximately 88% of the recorded precipitation levels between 1912-76 at Moro, Oregon, provided useful information on soil moisture storage and use by winter wheat over a three-year period comprised of two complete fallow-crop cycles. However, while the data collected provides a valuable estimate of the moisture storage and crop-use response under different precipitation levels, precision of moisture storage and crop-use predictions is likely to be improved by long-term measurements, since climatic conditions that affect moisture storage and crop response, other than precipitation, can not practically be controlled in a field study.

After the beginning of the fallow period, moisture loss in the 0-270 cm soil profile continued; the soil moisture content at each depth increment indicated that the associated tension gradient favored loss through upward movement prior to the winter storage period.

The greatest efficiency of moisture storage occurred during the first winter storage period when the fallow soil was generally dry; cumulative storage efficiency was highest on the plots which had received less precipitation than other plots. During the second winter storage period, both the cumulative and incremental storage efficiencies were lower than during the first winter, since infiltration rates decrease with increased soil moisture content.

The greatest rate of measured moisture loss occurred immediately following the fallow winter storage period. The soil moisture content continued to decline during the remainder of the fallow period, especially in the 0-90 cm depth increment, but at a much lower rate due primarily to the development of a soil mulch through spring tillage.

Linear regression analysis showed that, on the average, there would have been no moisture storage advantage to fallowing when the level of net storage in the spring of the fallow period was 194 mm or greater in the 0-270 cm soil profile; where greater than normal precipitation levels and deep silt loam soils enable moisture storage amounts to exceed this level, planting a spring grain crop may warrant economic consideration.

After the crop winter storage period, comparison between precipitation treatments which eventually would receive similar amounts of cumulative precipitation (DFNC vs NFDC; NFWC vs WFNC) indicated that the treatments with the wetter fallow period tended to promote more moisture storage in the 0-270 cm soil profile than those with the drier fallow period; the greatest differences between treatments in moisture storage were in the 90-180 cm soil profile.

Comparison of the amount of soil moisture removed from these same plots from early spring of the crop year until harvest showed that plots with the wetter fallow period significantly promoted moisture removal in the 1978-80 simulation; The greatest difference in moisture extraction in the plots with the wetter fallow period, as compared to those with the drier fallow period, were in both the 90-180 and 180-270 cm soil profiles. However, grain yields did not differ significantly, possibly because of the greater than normal natural precipitation and ideal growing conditions.

A significant increase occurred in grain yield, water-use-efficiency, and soil moisture extraction in the 0-180 cm soil profile as the level of nitrogen applied increased from 0 to 60 kg N/ha and from 60 to 105 kg N/ha in the 1978-80 simulation; similar increases occurred only with applied nitrogen increases from 0 to 60 kg N/ha in the 1977-79 simulation. The greatest increases in soil moisture extraction between fertilizer rates occurred in the 90-180 cm soil profile in both simulations. Thus, increases in the rate of nitrogen applied increased both the amount and depth of moisture extraction.

Linear regression analysis between the maximum grain yield in each main plot and the sum of the precipitation and soil moisture depletion from the 0-180 cm soil profile between early spring and harvest indicated that approximately 62 mm of available moisture were required to grow the crop to the point where grain production could begin, and that each millimeter of moisture available above 62 mm produced about 21.1 kg grain/ha (r^2 = 0.80).

Stepwise linear regression analysis between maximum yields and precipitation plus soil moisture extraction in each of the 90 cm soil depth increments in the 0-270 cm profile showed that a unit value of soil moisture removed from the 0-90 cm soil profile was a little over four times as effective in increasing grain yields as the same amount of moisture removed from the 90-180 cm profile, and five times as effective as the spring precipitation.

Vertical soil moisture movement depends on the tension gradient within the soil profile. After the winter storage period, the tension gradient normally allows downward movement, but late in the spring of the crop period, extraction of moisture in the upper soil profile favors upward movement from below the root zone, thus potentially supplementing the amount of moisture available to the crop from below the root zone.

The range of precipitation most common to the experimental area did not allow the deep soil profile to fill to field capacity; additionally, soil moisture was not uniformly depleted to the -15 bar moisture content throughout the root zone, but rather the amount extracted tended to decrease with increasing soil depth. Thus, yield predictions based on the amount of soil moisture within the -1/3 and -15 bar moisture contents would have tended to over-estimate yield.

Extractable moisture, defined as the difference between the highest measured volumetric soil moisture content in early spring of the crop period and the soil moisture content at harvest, more accurately reflects the amount of soil moisture utilized through evapotranspiration. Linear regression equations were developed to estimate the amount of extractable moisture in the 0-90, 90-180, and 180-270 cm soil profiles from soil moisture measurements in early spring of the crop year. Estimates of extractable moisture, together with an estimate of anticipated crop season precipitation, can then be used to predict the potential grain yield; this in turn is needed to calculate the optimum level of nitrogen fertilizer necessary to achieve maximum yields and grain quality.

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A P P E N D I X

Table 13. Mean dry bulk soil density (Pb), number of determinations (n), and standard deviation (s) for different depths at the beginning of the fallow period at the trial sites, 1977-78. (L.E. Kaseberg Farm, Wasco, OR)

Soil depth	Pb	n	s
cm	$g\text{-}cm^{3}$		$g\text{-}cm^{3}$
0-15	1.23	18	0.05
15-30	1.39	19	0.07
30-45	1.39	20	0.07
45-60	1.39	20	0.06
60-75	1.42	19	0.07
75-90	1.42	19	0.06
90-105	1.45	20	0.06
105-120	1.43	20	0.09
120-135	1.41	20	0.07
135-150	1.40	20	0.07
150-165	1.47	18	0.08
165-180	1.48	17	0.08
180-195	1.52	8	0.10
195-210	1.52	8	0.10
210-225	1.53	7	0.06
225-240	1.55	6	0.05
240-255	1.49	6	0.08
255-270	1.51	5	0.05
270-285	1.49	1	

Table 14. Average gravimetric soil moisture desorption content (θ), number of determinations (n), and standard deviation (s) of the Walla Walla silt loam soil from the trial site.†

Soil depth (cm)		0.1	0.33	0.5	1.0	5.0	10.0	15.0	143.6	891.0	1544.1
0-30	θ	35.1	19.5	17.6	12.2	7.0	6.8	6.4	3.1	2.5	1.6
	n	8	7	8	4	8	6	8	8	8	8
	s	0.7	1.2	2.0	0.4	0.4	0.2	0.2	0.3	0.2	0.1
30-60	θ	37.0	20.4	17.6	11.5	6.7	6.8	6.4	3.4	2.7	1.7
	n	8	8	8	4	8	6	8	8	7	8
	s	0.8	1.9	2.3	0.2	0.2	0.1	0.28	0.32	0.16	0.24
60-90	θ	37.1	20.2	17.7	11.2	6.1	6.3	6.0	3.2	2.6	1.6
	n	8	8	8	4	8	4	8	8	8	8
	s	0.54	1.59	2.72	0.41	0.34	0.13	0.15	0.42	0.13	0.21
90-120	θ	35.6	20.0	17.4	10.9	5.6	6.1	5.6	3.1	2.4	1.5
	n	8	8	8	4	6	6	8	8	8	8
	s	0.52	2.26	2.66	0.33	0.22	0.36	0.07	0.22	0.17	0.17
120-150	θ	33.6	19.6	17.2	11.0	5.9	6.3	5.6	3.1	2.3	1.6
	n	8	8	8	4	6	6	8	8	8	8
	s	0.85	1.58	2.71	0.16	0.13	0.43	0.12	0.27	0.21	0.18
150-180	θ	32.9	18.1	16.3	10.8	5.9	6.2	5.6	3.0	2.3	1.6
	n	8	8	8	4	6	6	8	8	8	8
	s	1.62	2.06	2.41	0.67	0.24	0.25	0.09	0.20	0.18	0.16
180-210	θ	34.7	17.6	16.0	9.9	4.8	5.7	5.0	2.8	2.1	1.4
	n	8	8	8	4	6	6	8	8	8	8
	s	1.74	1.97	2.22	0.38	0.33	0.75	0.59	0.38	0.24	0.27

Table 14 (cont.)

210-240	θ	36.2	19.0	16.4	10.0	4.9	6.0	5.4	3.1	2.3	1.6
	n	8	8	8	4	6	6	8	8	8	8
	s	2.06	2.61	2.28	1.56	0.46	1.10	0.92	0.62	0.35	0.41
240-170	θ	38.1	20.8	19.6	13.7	7.2	8.4	7.3	3.7	2.7	1.8
	n	8	8	8	4	6	6	8	8	8	8
	s	2.30	3.19	2.97	4.35	2.68	2.55	1.99	1.19	0.73	0.60

† Data obtained from pressure plate, pressure membrane, and vapor equilibrium techniques.

Table 15. Approximate moisture tension (Ψ) for volumetric moisture contents (Θ) in the respective soil depth increment as obtained from smoothed hand-drawn moisture depletion characteristic graphs of the laboratory data for the trial site.

	Soil depth increment (cm)									
	0-15	15-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270
cm^3-cm^{-3}	Soil (bars)									
0.04	145.	240.	350.	450.	300.	200.	250.	250.	360.	910.
0.05	69.5	140.	130.	120.	110.	79.	82.	80.	86.	225.
0.06	36.5	55.	62.	64.	60.	42.	44.	37.	34.	76.
0.07	23.0	33.8	36.	34.5	31.	25.	27.	17.	16.	37.
0.08	11.5	19.5	21.0	21.0	15.0	14.0	17.	4.4	6.1	21.
0.09	4.8	11.9	11.5	5.0	3.8	3.55	6.0	2.88	3.2	12.8
0.10	3.2	5.6	4.0	2.9	2.68	2.62	3.1	2.25	2.41	8.4
0.11	2.35	3.40	2.6	2.25	2.13	1.98	2.4	1.84	1.95	5.7
0.12	1.84	2.68	2.0	1.80	1.72	1.67	1.91	1.53	1.59	4.08
0.13	1.51	2.10	1.60	1.50	1.46	1.41	1.53	1.31	1.39	3.21
0.14	1.24	1.70	1.32	1.27	1.26	1.22	1.32	1.41	1.20	2.65
0.15	1.07	1.40	1.10	1.10	1.09	1.07	1.15	1.00	1.06	2.19
0.16	0.90	1.19	0.96	0.97	0.98	0.94	0.97	0.89	0.94	1.84
0.17	0.78	1.06	0.85	0.865	0.86	0.84	0.85	0.80	0.85	1.60
0.18	0.69	0.91	0.76	0.780	0.78	0.745	0.77	0.705	0.77	1.38
0.19	0.60	0.81	0.69	0.705	0.71	0.670	0.67	0.639	0.70	1.19
0.20	0.53	0.71	0.62	0.643	0.645	0.615	0.60	0.583	0.642	1.06
0.21	0.475	0.635	0.57	0.585	0.591	0.555	0.547	0.525	0.590	0.93
0.22	0.425	0.565	0.515	0.540	0.540	0.515	0.495	0.480	0.545	0.82
0.23	0.385	0.510	0.475	0.495	0.501	0.468	0.451	0.443	0.505	0.73
0.24	0.349	0.465	0.445	0.458	0.462	0.433	0.412	0.402	0.470	0.652
0.25	0.320	0.420	0.411	0.430	0.435	0.399	0.380	0.378	0.437	0.590
0.26	0.298	0.385	0.382	0.398	0.402	0.369	0.351	0.350	0.410	0.432
0.27	0.272	0.355	0.356	0.372	0.373	0.345	0.326	0.325	0.383	0.480
0.28	0.250	0.327	0.334	0.348	0.352	0.322	0.305	0.305	0.361	0.437
0.29	0.235	0.303	0.313	0.325	0.329	0.298	0.286	0.288	0.339	0.403
0.30	0.220	0.282	0.293	0.307	0.308	0.278	0.268	0.260	0.321	0.370

Table 16. Soil test values for the Walla Walla silt loam at the simulation site, 1979-80. (L.E. Kaseberg Farm, Wasco, OR)

	Soil depth (cm)								
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270
pH	6.3	6.7	6.9	6.9	7.2	8.1	8.2	8.4	8.4
P (ppm)	28	27	26	20	13	13	11	12	16
K (ppm)	390	304	246	238	242	226	176	160	195
Ca (meq/100 gr)	7.2	8.1	7.3	7.1	6.8	14.5	14.1	14.2	33.9
Mg (meq/100 gr)	2.3	3.1	3.4	3.8	4.2	5.1	5.6	6.2	6.6
Salts (mmhos/m)	0.67	0.75	0.78	0.70	0.68	0.90	0.92	0.87	1.20
CEC (meq/100 gr)	11.31	11.31	10.95	10.19	10.29	11.00	13.33	10.60	12.22
Organic matter (%)	1.37	1.48	1.01	0.11	0.48	0.48			
Sulfate-sulfur (ppm)	9.70	10.78	6.76	6.86	5.16	5.46	6.06	5.96	5.14
Total N (%)	0.07	0.05	0.05	0.03	0.03	0.03	0.01	0.02	0.01

Table 17. Mean squares from the analysis of variance for soil moisture (mm) at the beginning of the fallow period (8/13/77): south field.

		Soil depth increment (cm)		
Source of variation	df	0-90	90-180	0-180
Total	59			
Main plots	19			
Blocks	3	8.95	388.95**	392.11**
Precip.	4	8.06	12.75	36.10
Error a	12	17.77	28.62	35.00
N level	2	2.72	11.52*	18.15
Precip. x N level	8	0.57	2.41	2.71
Error b	30	2.42	2.63	5.89
C.V.(a)		5.5%	5.4%	3.4%
C.V.(b)		2.0%	1.6%	1.4%

*,** Significant at the 5% and 1% levels of probability, respectively.

NOTE: The significant value expressed for nitrogen levels in the 90-180 cm depth increment is not logically expected at this time and is considered a coincidence in the random variation across the experimental site.

Table 18. Average soil moisture (mm), by block, at the beginning of the fallow period (8/13/77): south field.†

Block	Soil depth increment (cm)		
	0-90	90-180	0-180
S1	76.0	92.8	168.8
S2	75.8	101.1	176.9
S3	76.0	105.0	181.0
S4	77.5	99.4	176.9
Average	76.3	99.6	175.9

† Block means are determined from 15 sites per block for all soil depths. The average slope of this experimental area is 3 to 4% and faces south. The blocks run across the slope and are labeled in successive order from S1 to S4 down the slope.

NOTE: After the initial soil moisture measurements at the beginning of the fallow period, longer neutron probe access tubes were installed in each plot. To calculate the net increase in soil moisture for succeeding measurements in the 180 to 360 cm soil depth, the means of the post-harvest measurements in the 60 kg N/ha subplots in each block were used as the initial soil moisture contents for the respective blocks and soil depths.

Table 19. Mean squares for the net change in soil moisture (mm) between the beginning and spring of the fallow period (3/28/78): south field.†

Source of variation	df	Soil depth increment (cm)				
		0-90	90-180	180-270	0-180	0-270
Total	19					
Blocks	3	74.73	105	711	217	1078
Precip.	4	204.32*	1375**	1813	1619**	6411*
Error	12	40.86	137	955	240	1675
C.V.		5.1%	10.4%	100%	6.5%	15.3%

*,** Significant at the 5% and 1% levels of probability, respectively.

† Data recorded for each plot consists of the mean of three subplot measurements, except for a single measurement in the 270-360 cm depth increment.

Table 20. Average net change in soil moisture between the beginning and spring of the fallow period (3/28/78): south field.

Precipitation treatment	Soil depth increment (cm) 0-90	90-180	180-270	0-180	0-270
DFNC	112.5b*	80y**	8	192y	200b
NFDC	125.5a	119x	26	244x	270a
NFNC	127.5a	117x	31	245x	276a
NFWC	128.8a	124x	43	253x	296a
WFNC	130.2a	122x	46	252x	298a
$LSD_{.05}$	9.8	18.0	NS	23.9	63.1
$LSD_{.01}$	NS	25.3	NS	33.5	NS

*,** Means in the same column followed by a common letter a,b or x,y are not significantly different at the 5% and 1% level of probability, respectively, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

Table 21. Mean squares for the net change in soil moisture (mm) between the beginning and end of the fallow period (9/19/78): south field. †

Source of variation	df	Soil depth increment (cm) 0-90	90-180	180-270	0-180	0-270
Total	23					
Blocks	3	82.15	153	380	330	1323
Precip.	5	120.94*	86	299	256	1024
Error	15	27.25	82	377	171	990
C.V.		7.9%	14.3%	183%	10.1%	22.4%

* Significant at the 5% level of probability.

† Data recorded for each plot consists of the mean of three subplot measurements.

Table 22. Average net change in soil moisture (mm) between the beginning and end of the fallow period (9/19/78): south field.

Precipitation treatment	Soil depth increment (cm)				
	0-90	90-180	180-270	0-180	0-270
DFNC	62.8b	55	0	118	118
NFDC	68.8b	68	10	137	147
NFNC	63.5b	67	16	130	146
NFWC	63.5b	64	6	127	133
WFNC	76.8a	63	25	140	165
Control	63.5b	62	6	126	132
$LSD_{.05}$	7.9	NS	NS	NS	NS

* Means in the same column followed by a common letter are not significantly different at the 5% level of probability, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC - Dry, normal, and wet crop, respectively.

Table 23. Mean squares for the net change in soil moisture between the beginning of the fallow period and spring of the crop period (3/19/79): south field.†

Source of variation	df	Soil depth increment (cm) 0-90	90-180	180-270	270-360	0-180	0-270	0-360‡
Total	71				-			-
Main Plots	23				-			-
Blocks	3	243.04**	281	168	65	780	845	423
Precip.	5	145.42*	79	373	611	344	729	1117
Error a	15	33.39	225	1063	275	365	2233	966
N level	2	13.18	11.35	188.76	-	1.68	172	-
P x N	10	14.80	87.25	74.33	-	98.06	276	-
Error b	36	34.53	74.62	180.96	-	127.71	565	-
C.V.(a)		5.6%	21.2%	226%	631%	10.9%	25.2%	16.2%
C.V.(b)		5.7%	12.2%	93.2%	-	6.5%	12.7%	-

*,** Significant at the 5% and 1% levels of probability, respectively.

† A randomized block design was used since only one access tube per main plot extended to a depth of 360 cm.

‡ The average of three subplot measurements per main plot was used to a depth of 270 cm; a single subplot measurement per main plot was used in the 270-360 cm soil depth increment.

Table 24. Average net change in soil moisture (mm) between the beginning of the fallow period and spring of the crop period (3/19/79): south field.

Precipitation treatment	Soil depth increment (cm) 0-90	90-180	180-270	270-360	0-180	0-270	0-360
DFNC	102.4b*	72	12	- 2	174	187	186
NFDC	108.9a	72	10	19	181	190	210
NFNC	104.8ab	69	16	-18	174	189	171
NFWC	98.8c	67	10	- 1	166	176	175
WFNC	102.0b	72	25	8	174	200	208
Control	105.5ab	74	13	8	179	192	201
$LSD_{.05}$	5.0	NS	NS	NS	NS	NS	NS

* Means in the same column followed by a common letter a,b,c are not significantly different at the 5% level of probability, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

Table 25. Mean sqaures for the net change in soil moisture (mm) between spring of the crop period and harvest (7/24/79): south field.†

		Soil depth increment (cm)						
Source of variation	df	0-90	90-180	180-270	270-360†	0-180	0-270	0-360‡
Total	71				-			-
Main Plot	23				-			-
Blocks	3	116.68*	10.48	32.68	68	149	128	110
Precip.	5	68.85	54.69	140.08	132	92	415	275
Error a	15	27.80	134.46	109.57	102	251	511	281
N level	2	73.51	495.26**	55.51	-	890.17**	1188.93*	-
P x N	10	16.41	69.38	41.85	-	114.65	196.00	-
Error b	36	25.67	61.33	61.75	-	125.77	290.80	-
C.V.(a)		5.0%	18.7%	65.7%	366%	9.5%	12.4%	9.0
C.V.(b)		4.8%	12.6%	49.3%	-	6.7%	9.3%	-

*,** Significant at the 5% and 1% levels of probability, respectively.

† A randomized block design was used since only one access tube (in the 60 kg N/ha subplot) per main plot extended to a depth of 360 cm.

‡ The average of three subplot measurements per main plot was used to a depth of 270 cm; a single subplot measurement (in the 60 kg N/ha subplot) per main plot was used in the 270-360 cm soil depth increment.

Table 26. Mean squares for soil moisture (mm) at the beginning of the fallow period (8/17/78): north field.

Source of variation	df	Soil depth increment (cm) 0-90	90-180	180-270	270-360†	0-180	0-270	0-360‡
Total	83				-			-
Main Plots	27				-			-
Blocks	3	236.25**	774	295	161	1840	3425	1357
Precip.	6	24.72	64	239	210	143	577	647
Error a	18	33.71	264	396	280	448	1479	1229
N Level	2	16.44	214.43*	326.80**	-	315.94	1237	-
P x N	12	13.88	99.34	53.99	-	171.05	364.39	-
Error b	42	11.73	56.64	38.11	-	108.88	226.64	-
C.V.(a)		6.6%	15.9%	15.3%	11.9%	11.1%	12.0%	7.6%
C.V.(b)		3.9%	7.4%	4.7%	-	5.5%	4.7%	-

*, ** Significant at the 5% and 1% levels of probability, respectively.

† A randomized block design was used since only one tube per main plot extended to a depth of 360 cm

‡ The average of three subplot measurements per main plot was used to a depth of 270 cm; a single subplot measurement per main plot was used in the 270-360 cm soil depth increment.

NOTE: The significant values expressed for nitrogen level means are not logically expected at this point in time; thus, the null hypothesis is accepted as true and the significant differences indicated are considered as a coincidence in the random variation across the experimental site.

Table 27. Average soil moisture content (mm), by block, at the beginning of the fallow period (8/17/78): north field.†

Block		Soil depth increment (cm)					
		90-180	180-270	270-360	0-180	0-270	0-360
N1	83.1	93	125	141	176	302	443
N2	90.6	105	135	147	195	330	476
N3	88.3	104	130	141	192	323	464
N4	90.1	106	130	135	196	326	461
Average	88.0	102	130	141	190	320	461

† Averages are determined from measurements at 21 sites per block for all soil depths except the 270-360 cm increment, which consists of measurements at 7 sites per block. The average slope of this experimental area is 3% and faces north. The blocks run across the slope and are labelled in successive order from N1 to N4 down the slope.

Table 28. Mean squares for the net change in soil moisture (mm) between the beginning and spring of the fallow period (3/17/79): north field.†

		Soil depth increment (cm)						
Source of variation	df	0-90	90-180	180-270	270-360	0-180	0-270	0-360
Total	27							
Blocks	3	67.08	689.95**	97.95**	170	1,144**	1,908**	3,027**
Precip.	6	57.32	25.39	9.07	119	99	114	210
Error	18	67.64	35.42	8.01	124	128	166	406
C.V.		10.4%	98.0%	208%	221%	13.3%	18.1%	25.6%

** Significant at the 1% level of probability.

† Data recorded for each plot consists of the average of three subplot measurements, except for a single measurement in the 270-360 cm depth increment.

Table 29. Average net change in soil moisture (mm) between the beginning and spring of the fallow period (3/17/79): north field.

Precipitation treatment	Soil depth increment (cm) 0-90	90-180	180-270	270-360	0-180	0-270	0-360
DFNC	78.0	8.5	0.2	3	86	87	90
NFDC	75.5	9.0	-2.8	- 6	84	82	76
NFNC	78.5	3.8	-2.5	- 6	82	80	74
$NFWC_1$	75.0	2.0	-2.0	- 4	77	75	72
$NFWC_2$	79.5	6.8	-1.8	- 2	86	84	82
WFNC	86.5	7.0	-2.0	- 6	94	92	85
Control	79.2	5.5	1.2	-15	85	86	71
$LSD_{.05}$	NS	NS	NS	NS	NS	NS	NS

NS = F test nonsignificant.

Table 30. Mean squares for the net change in soil moisture (mm) between the beginning and end of the fallow period (9/13/79): north field.†

Source of Variation	df	Soil depth increment (cm) 0-90	90-180	180-270	270-360	0-180	0-270	0-360
Total	27							
Blocks	3	77	70.99	57.75**	115	91	244	585
Precip.	6	580**	168.06**	5.50	89	1345	1449**	1410**
Error	18	70	30.27	2.94	121	96	109	232
C.V.		22.6%	53.3%	27.5%	107%	20.7%	25.3%	49.3%

** Significant at the 1% level of probability.

† Data recorded for each plot consists of the average of three subplot measurements, except for a single measurement in the 270-360 cm depth increment.

Table 31. Average net change in soil moisture (mm) between the beginning and end of the fallow period (9/13/79): north field.

Precipitation treatment	Soil depth increment (cm) 0-90	90-180	180-270	270-360	0-180	0-270	0-360
DFNC	29b**	6.5b	-5.8	- 6	35b	30b	24b
NFDC	42b	10.5b	-7.8	-10	52b	44b	35b
NFNC	32b	8.8b	-7.0	-10	41b	34b	24b
$NFWC_1$	28b	5.5b	-7.0	- 8	34b	27b	19b
$NFWC_2$	34b	11.5b	-6.5	- 7	45b	38b	32b
WFNC	62a	24.0a	-4.3	-12	86a	82a	70a
Control	32b	5.5b	-5.5	-20	38b	32b	13b
$LSD_{.05}$	12.5	8.2	NS	NS	14.6	15.5	22.6
$LSD_{.01}$	17.1	11.2	NS	NS	20.0	21.2	31.0

** Means in the same column followed by a common letter are not significantly different at the 1% level of probability, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

WC_1 = Wet crop, single fertilizer application.

WC_2 = Wet crop, split fertilizer application.

Table 32. Mean squares for the net change in soil moisture (mm) from the beginning of the fallow period to spring of the crop period (3/20/80): north field.

Source of variation	df	Soil depth increment (cm) 0-90	90-180	180-270	270-360†	0-180	0-270	0-360‡
Total	83				-			-
Main plots	27				-			-
Blocks	3	260.41*	819*	720*	224.99	1461*	3972*	1162*
Precip.	6	154.77	740*	548*	172.57	1403*	3437**	1184*
Error a	18	81.36	192	203	117.57	415	781	395
N level	2	15.05	92.39	154.54	-	102	396.51	-
P x N	12	23.89	94.64	28.81	-	191	272.86	-
Error b	42	17.57	61.86	65.42	-	105	217.75	-
C.V.(a)		7.1%	22.0%	132%	104%	10.7%	13.9%	10.4%
C.V.(b)		3.3%	12.5%	75.0%	-	5.4%	7.4%	-

*,** Significant at the 5% and 1% levels of probability, respectively.

† A randomized block design was used since only one access tube per main plot extended to a depth of 360 cm.

‡ The average of three subplot measurements per mainplot was used to a depth of 270 cm; a single subplot measurement per main plot was used in the 270-360 cm soil depth increment.

Table 33. Average net change in soil moisture between the beginning of the fallow period and spring of the crop period (3/20/80): north field.

Precipitation treatment	Soil depth increment (cm)						
	0-90	90-180	180-270	270-360	0-180	0-270	0-360
DFNC	125.8	58c**	5b	- 8	184c	188z**	181b
NFDC	131.5	72ab	21a	- 9	203ab	224xy	215b
NFNC	124.1	62bc	4b	-10	186bc	190yz	180b
$NFWC_1$	124.9	55c	9ab	- 4	180c	188z	184ab
$NFWC_2$	122.1	60bc	11ab	- 6	182c	195xyz	188ab
WFNC	131.1	76a	19a	-12	207a	226x	214a
Control	128.3	58c	8ab	-24	187bc	195xyz	170b
$LSD_{.05}$	NS	11.9	12.2	NS	17.5	24.0	29.5
$LSD_{.01}$	NS	NS	NS	NS	NS	32.8	NS

*,** Means in the same column followed by a common letter a, b, c, or x, y, z are not significantly different at the 5% and 1% level of probability, respectively, based on Duncan's Multiple Range Test.

NS = F test nonsignificant.

DF, NF, WF = Dry, normal, and wet fallow, respectively.

DC, NC, WC = Dry, normal, and wet crop, respectively.

WC_1 = Wet crop, single fertilizer application.

WC_2 = Wet crop, split fertilizer application.

Table 34. Mean squares for the net change in soil moisture between spring of the crop period and harvest (7/28/80): north field.

Source of variation	df	Soil depth increment (cm)						
		0-90	90-180	180-270	270-360†	0-180	0-270	0-360‡
Total	83				-			-
Main Plot	27				-			-
Blocks	3	489.54**	276.	156.52	135.71**	1165.	2038.	442.
Precip.	6	155.91*	707.	490.54*	30.49	1172.	3116.	869.
Error a	18	48.67	263.	132.94	26.08	405.	784.	252.
N level	2	185.08**	3384.	393.58**	-	5152.**	8365.**	-
P x N	12	15.18	31.43	43.74	-	74.40	162.88	-
Error b	42	10.40	44.02	46.51	-	61.39	142.61	-
C.V.(a)		4.8%	25.8%	126%	83.2%	9.7%	12.9%	7.5%
C.V.(b)		2.2%	10.5%	74.3%	-	3.8%	5.5%	-

*,** Significant at the 5% and 1% levels of probability, respectively.

† A randomized block design was used since only one access tube per main plot (in the 60 kg N/ha subplot) extended to a depth of 360 cm.

‡ The average of three subplot measurements per mainplot was used to a depth of 270 cm; a single subplot measurement (in the 60 kg N/ha subplot) per main plot was used in the 270-360 cm soil depth increment.