Abstract

Gurganus II, Kent Rodgers. Influence of Plant Available Water on Yield Potential and Crop Water Stress Index in Corn. (Under the direction of Dr. Ronnie W. Heiniger)

Understanding and measuring the driving forces behind potential yield within the growing season are vitally important in corn production. The objectives of this study were to (i) quantify the effects of location, year, and water regime on the dynamic temporal changes in plant available water (PAW) over the growing season, (ii) determine if there was a relationship between plant available water per fifteen centimeters of soil depth (PAW15cm) measured at different dates throughout the growing season and corn yield, and (iii) quantify the relationship between plant available water measured at four depths throughout the growing season and crop water stress as determined by crop water stress index. Rainfall, water treatments, and location (related to differences in soil texture and how irrigation treatments were applied) were the main factors influencing the dynamic changes in PAW measured at different sampling depths in 2001 and 2002. Rainfall contributed heavily to changes in PAW at the shallow sampling depths making it difficult to use single measurements of PAW at these depths to determine yield potential. The influence of irrigation was observed at the deeper sampling depths due to the accumulation of water that was not affected by transpiration and evaporation. Significant correlations between PAW15cm and yield were measured. However, the lack of strength of these correlations made it difficult to use them to predict corn yield. Correlation of CWSI and PAW15cm at each measurement date and location indicated significant relationships. The variation in CWSI was accounted for by variation in PAW15cm at the lower sampling depths.

INFLUENCE OF PLANT AVAILABLE WATER ON YIELD POTENTIAL AND CROP WATER STRESS INDEX IN CORN

by

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I dedicate this thesis to my wife Kim, and to our children, Ethan and Maci.

Biography

Kent Rodgers Gurganus II, was born in Beaufort County, North Carolina on the sixth day of April, 1964. He graduated from Bath High School in 1982, and completed his Bachelor of Science degree in Agricultural Business Management at North Carolina State University in 1992. He married Kim Terry in 1993, and they have two children, Ethan and Maci. They live on a family owned farm close to Bath. He currently works as an Agricultural Extension Agent with Cooperative Extension in Beaufort County. After completion of his Masters degree in Crop Science, he hopes to continue on to complete a Doctoral degree at NCSU.

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Chapter 1

Literature Review

Literature Review

Understanding and measuring the driving forces behind potential corn yield within the growing season is vitally important. It allows adjustment of inputs to maximize economic returns. Yield potential of corn is often impacted by limited amounts of water, specifically the amount of available soil water (Roygard et al., 2002). In the mid-Atlantic region, rainfall amounts during the growing season are usually sufficient to produce profitable yields, but can be variable from year to year. Because very little corn in Eastern North Carolina is irrigated, profitable production is heavily dependent on the amount of rainfall and the soil's ability to store water for plant growth. Understanding the soil's ability to hold water, how it varies over time, and quantifying the relationship between water availability and yield are important steps that must be taken to understand the yield potential of corn in the Mid-Atlantic Region. This project was undertaken to understand the dynamics of water stored in the soil profile and its influence on crop stress and yield.

Under ideal conditions for plant growth, a volume of soil generally consists of 50% solids (mineral matter and organic matter), 25% air and 25% water (Hillel, 1998). Soils, in terms of the ability to store water, can be described as a leaky reservoir (Cassel and Nielson, 1986). A soil is considered to be at field capacity (FC) when the "reservoir" is full. Field capacity, as defined in the Glossary of Soil Science Terms (Soil Science Society of America, 1984), is the amount of water remaining in a soil two to three days after having been wetted and after free drainage is negligible (Cassel and Nielson, 1986). This corresponds with the generally accepted standard matric potential of -33 kPa for medium textured soils, -5 to -10 kPa for coarse textured soils, and -50 kPa for fine textured soils (Rivers and Shipp, 1977; Jamison and Kroth, 1958; Coleman, 1947). On the other hand, the permanent wilting point (PWP), defined as the water content of a soil when indicator plants growing in that soil wilt and fail to recover when placed in a humid chamber, is an indicator that the “reservoir” is dry. Therefore, PWP represents the lower limit of the soil’s capacity to store water that can be made available to plants. This corresponds with the generally accepted standard matric potential of -1500 kPa for most soils. Except for some fine textured soils, the changes in soil water content between pressures of -800 and -3000 kPa are negligible (McIntyre, 1974). The available water content (AWC) of a soil is defined as the difference between FC and PWP and represents the potential plant extractable water that a soil can store based on an indicator plant. Available water content can be expressed on the basis of weight or volume.

To determine FC and PWP for a soil, a soil water retention analysis can be performed in a lab on soil samples taken from the field, using a pressure plate apparatus (Cassel and Nielson, 1986). This process establishes FC and PWP measurements for each sample by applying the appropriate suction value and then measuring the equilibrium soil wetness.

Methods of Measuring Soil Moisture. There are many direct and indirect methods to measure the amount of water stored in the soil (Gardner, 1986). The use of gravimetric methods, electrical resistance, neutron scattering, and time-domain reflectometry (TDR) have been the most prevalent methods used to measure soil moisture (Hillel, 1998). Each method has advantages and disadvantages that limit the amount and kind of information that can be obtained regarding soil moisture.

Methods for direct measurement of soil moisture include gravimetry with oven drying (Gardner, 1986), which involves weighing a wet sample, removing the water by oven drying the sample to a constant weight, and then reweighing the sample to determine the amount of water removed. Dividing the difference between wet and dry masses by the mass of the dry sample yields the ratio of the mass of water to the mass of the dry soil, which when multiplied by 100, becomes the percentage of water in the sample on a dry-weight basis. If a measure of volumetric water content is required, the gravimetric water content is multiplied by the ratio of the soil bulk density to the density of water.

Gravimetric methods are widely used because the samples can be easily taken, they are inexpensive to conduct, and soil water content is easily calculated (Scott, 2000). However, this method is both laborious and time consuming, and because of the sampling, transporting, and repeated weighing procedures involved, contains many opportunities for error (Hillel, 1998). The extraction of samples from the field is invasive and destructive, potentially leading to distortion of experiments.

The most practical techniques for soil water monitoring are indirect methods (Yoder et al., 1998; Robinson et al., 1999). Indirect techniques are divided into two categories, tensiometric and volumetric methods, which estimate soil moisture content by a calibrated relationship with some other measurable variable (Muñoz-Carpena, 2004). Tensiometric methods include electrical resistance blocks, tensiometers, soil psychrometers, and granular matrix sensors.

Electrical resistance blocks, comprised of a pair of electrodes embedded in a porous material such as gypsum (Bouyoucos and Mick, 1940) or fiberglass (Colman and Hendrix, 1949) have been used because of their tendency to equilibrate with the matric suction of soil water instead of the water content of the soil. The blocks operate on the principle that the electrical resistance of a porous block is proportional to its water content, which is related to the soil water matric potential of the surrounding soil (Muñoz-Carpena, 2004). After being placed in the soil, the block reaches equilibrium, a state in which soil water ceases to flow into or out of the block, and the electrical or thermal properties of the block are then used as an index of soil water content. Soil water content for the soil must be obtained by pressure plate extractor or gravimetric method and then used to calibrate the block for accurate measurement. Use of electrical resistance blocks are quick, repeatable, and relatively inexpensive, but sensitivity is poor in dry soil conditions, and they do not work well in coarse-textured, high shrink-swell, or saline soils. Block properties such as internal porosity change over time, depending on the effect of soil type and rainfall on the degradation of gypsum. The time required to attain equilibrium limits the accuracy of the measurements.

Tensiometers have been used for years to schedule irrigation of field and orchard crops (Richards and Weaver, 1944). Tensiometers consist of a sealed water-filled tube with a negative pressure gauge at one end and a ceramic cup at the other end which, when placed in the soil, comes into equilibrium with the soil solution (Muñoz-Carpena, 2004). The soil water matric potential is equivalent to the suction inside the tube. Soil water content for the soil must be obtained independently by pressure plate extractor or gravimetric method to calibrate tensiometer readings for soil water measurements. This method allows for frequent and direct measurements of matric potential independent of the use of electronic devices or a power source. Minimal skill is needed to read the vacuum gauge, and the method is inexpensive to operate and maintain. Care must be taken to ensure intimate contact between soil and the ceramic cup for consistent readings in coarse textured soils. Response time is slow, and tubes must be refilled with water frequently in hot, dry weather to maintain the water column inside the tensiometer. Tensiometers have a narrow measurement range of less than 1 bar, restricting its use for precise soil water measurements under extreme stress conditions.

Volumetric methods estimate the volume of water in a sample volume of undisturbed soil (Muñoz-Carpena, 2004). Neutron probes can be used to measure volumetric water content of soils (Gardner, 1970). Neutron probes were developed in the 1950’s, offering an efficient and reliable technique for measuring soil moisture in the field (Holmes, 1956; van Bavel, 1963). Neutron probes are inserted into previously prepared access holes in the soil which are lined with a metal casing (Muñoz-Carpena, 2004). The probe contains a sensor-detector with a decaying radioactive source emitting fast neutrons that pass through the metal casing until being thermalized by hydrogen in the soil and detected by the unit. Since water is the main source of hydrogen in most soils, the density of thermalized neutrons around the probe is nearly proportional to the volume of water contained in the soil. One probe can take measurements at any desired depth, with a large sensing volume, but accuracy at depths within 0.20 m of the surface are unreliable due to the escape of fast neutrons through the soil surface. While offering repeatable measurements at the same locations and depths which were independent of temperature and pressure, the health risk of exposure to radiation coupled with the high initial cost of the instrument are seen as disadvantages. Use of the neutron probe required certification and the equipment is cumbersome and heavy. Soil specific calibration is needed to utilize this technique.

The use of time domain reflectometry (TDR) has increased dramatically over the last 30 years. Since the first application of TDR to measure soil water (Topp et al., 1980), the use of the technology has been applied to measure soil electrical conductivity as well. Based on the high dielectric constant of water, soil water content is inferred from the dielectric permissivity of the soil (Jones et al., 2002). A step voltage pulse is propagated along a transmission line (TDR probe) imbedded in the soil, and the length of the propagation time is equated to soil percent moisture content. Unlike most other techniques, soil specific calibration is usually not required (Muñoz-Carpena, 2004). Measurements are highly accurate, and can be automated. A wide variety of probes are commercially available, and probe installation can be achieved with minimal soil disturbance. However, the equipment is relatively expensive, and the sensing volume of the probe is relatively small.

A detailed investigation of the techniques described above indicates TDR as the superior method to measure soil water content. Each technique has some characteristic that is either equal or superior to TDR. However, no technique is superior to TDR in more than one characteristic. Advantages of TDR over other soil water content measurement methods are: (i) superior accuracy with minimal input; (ii) minimal calibration requirements; (iii) no radiation hazard; (iv) excellent spatial and temporal resolution; (v) easy to obtain measurements; (vi) a wide array of commercially available equipment to accommodate specific needs; and (vii) a non-destructive means of acquiring measurements.

Factors Impacting Stored Soil Moisture. Soil moisture storage is impacted by soil texture, type of clay present, organic matter content, soil aggregation, and evapotranspiration (Hillel, 1998). Loamy textured soils containing appreciable quantities of silt usually hold the most plant available water (PAW), followed by clay, and then sand. Clayey soils retain more water, and for a longer period of time, than do sandy soils. These finer textured soils have a high specific surface, and therefore have a higher FC, yet because the water is held so tightly, most of it is considered unavailable to the plant resulting in a high PWP. Sandy soils have many large pores capable of quickly moving water, hence good internal drainage but low storage capacity. The volume of small pores in which water can be held is very small in sandy soils. Fine-textured clay soils have a greater total volume of pores than coarse-textured sands, with the majority of those pores being very small in size, so water does not move through quickly, and more water can be stored. Some clays, such as montmorillonite, will shrink and crack when drying, which provides for a high initial infiltration rate, and swell when wet, inhibiting infiltration. Other clays, such as kaolinite, do not tend to shrink and swell.

The organic matter content (OMC) of a soil, if in sufficient quantities, can enhance a soil's ability to retain moisture by enhancing soil aggregation, resulting in increased pore space. Soil organic matter physically and chemically binds the primary particles in the aggregate which in turn increases the stability of the aggregate and limits its breakdown during the wetting process (Emerson, 1977). Infiltration is also influenced by soil organic matter. Soils with low aggregate stability are more susceptible to seal formation as a result of raindrop impact, leading to lower infiltration rates (Le Bissonnais, 1996). Hudson (1994) demonstrated that soils high in OMC store significantly more water than soils of similar texture that contain less OMC, and that these soils have more stored water available for plant growth.

The upward extraction of water from the soil surface and from plants by evapotranspiration (ET) constantly impact the amount of water stored in the soil (Hillel, 1998). Evapotranspiration is the total amount of water lost from the field by both evaporation and plant transpiration (Gardner et al., 1985). Evaporation is a direct pathway for water to move from soil to the atmosphere as water vapor (Klocke et al., 1996). Evaporation rates are highest after rainfall or irrigation, when the soil surface is wet and water can evaporate readily and when the soil surface is not shaded. Evaporation at this point is primarily influenced by the energy available for evaporation (Scott, 2000). As the soil surface dries, the evaporation rate declines sharply, and is influenced mainly by the hydraulic properties of the soil near the surface. Evaporation rates from the soil surface also decline as the growing season progresses and canopy cover increases. At this point, ET is comprised primarily of transpiration, defined as the process by which water moves from the soil to the roots, from the roots into various parts of the plant, and then into the leaves where it is released into the atmosphere as water vapor through the stomata (Haman and Izuno, 1990). ET is measured as the atmospheric demand, or potential ET (ET_p), and as the crop's ability to meet the atmospheric demand, actual ET (ET_a). When ET_a rates are high, or close to ET_p, soils are at or near FC and crop yield can be maximized. When ET_a rates are significantly below ET_p, soils are dryer, and plants are under stress.

No-till and minimum-till management practices increase soil water holding capacity by increasing soil aggregation and surface residues. No-till production methods improve precipitation storage efficiency by maintaining more crop residue on the soil surface (Smika, 1990). The residue moderates soil temperature by shading soil from sunlight and increases soil water storage by enhancing precipitation infiltration (Smika and Unger, 1986). Because soil aggregation is not adversely affected under no-till systems, infiltration of rainfall or irrigation is enhanced, and evaporation losses are minimized due to increased amounts of crop residue left on the soil surface (Brady, 1990). Tillage of the soil brings moist soil to the surface which increases soil water evaporation compared to untilled soil (Burns et al., 1971; Papendick et al., 1973).

The temporal variation of soil moisture is influenced by several factors. At any given point in time soil moisture (and thus PAW) is impacted by the precipitation history, the texture of the soil, the slope of the terrain and presence of vegetation (Mohanty and Skaggs, 2001). The dependency of the temporal stability of differences in soil water storage on soil texture (see previous discussion on texture) was observed by Van Pelt and Wierenga (2001). Temporal stability of soil moisture measurements is more stable during dry periods, and less stable during the transition period between dry and wet soil moisture status (Martínez-Fernández and Ceballos, 2003). Precipitation is the single most important climatic factor for soil moisture and its distribution (Mohanty and Skaggs, 2001). The presence of vegetation influences temporal soil moisture variability as it affects infiltration, runoff, and evapotranspiration.

Relationship Between PAW and Corn Yield. Researchers have concluded that climate (temperature and solar radiation) and water availability (soil water storage and rainfall) are the major determining factors in corn production (Carlson, 1990; Dale and Daniels, 1995). Runge (1968) measured the influence of both maximum daily temperatures and precipitation on corn yields and found that high temperatures were not detrimental if soil moisture was not limiting. Yield of corn suffers in response to soil moisture deficits at any growth stage (Howe and Rhoades, 1955). Eck (1984) found that stress imposed on corn at the vegetative stages of growth for 14 and 28 days reduced yields by 23% and 46%, respectively. However, corn is especially sensitive to moisture stress during the time of tasseling and continuing through grain fill (Musik and Dusek, 1980; Nesmith and Ritchie, 1992). Denmead and Shaw (1960) reported that stress at vegetative growth stages, at silking, and after silking reduced corn yield by 25%, 50%, and 21%, respectively. Robins and Domingo (1953) found that corn yields were reduced by 22% when soil moisture was reduced to wilting point for a period of 1 to 2 days during tasseling or pollination, and that yields were reduced by 50% after 6 to 8 days of stress at this stage. Musik and Dusek (1980) found soil moisture stress during periods of tasseling and silking to be most detrimental to yield, and that soil moisture stress during the time of grain fill was more harmful to yield than that during vegetative growth. Runge (1968) and Thompson (1975) concluded that corn yield was highly correlated with water at tasseling.

There is a need for research to understand within-season crop water use and how it affects corn yield (Sadler et al., 2000). Many studies have explored the relationship of seasonal crop water storage and yield. Holt et al. (1964) evaluated corn response to plant available stored moisture at planting and found that yield was highly correlated to the amount of stored soil moisture at planting during a year with below average rainfall. Leeper et al. (1974) found that most of the corn yield variation within a field was correlated with rooting depth, available water holding capacity in the root zone, or weekly plant available stored soil moisture. Frye et al. (1983) reported that during years of low rainfall, yield of corn was highly correlated to sampling depth. Swan et al. (1987) observed that the effective plant rooting depth to corn yield relationships were influenced significantly by climate, with higher correlations between yield and rooting depth during years of low rainfall (Timlin et al., 1998). Roygard et al. (2002) compared yield across three soil types of varying water-holding capacity at the vegetative, tasseling, and grain filling stages of corn growth, and found that differences in water stress between soil types were related to the capacity of the soils to store water. Schneider and Howell (1998) compared the yields of corn across treatments in which soil water was maintained at five levels in 25% increments ranging from 0 to 100% of AWC throughout the growing season. They found that yields were highest when AWC of soils was held close to 100% throughout the growing season.

Researchers have turned to plant growth models to maximize crop management practices and predict yields (Xie et al., 2001). A general crop model called Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) was designed to simulate critical growth processes of a variety of crops (Kiniry et al., 1992). Other models, such as CERES-Maize (Crop-Environment Resource Synthesis) (Jones and Kiniry, 1986) and and SORKAM (SORghum, Kansas, A&M) (Rosenthal et al., 1989a) were designed for specific crop applications. These models predict crop yield by incorporating numerous factors into daily estimates of crop growth and development throughout the life cycle of the crop. One such factor is soil moisture. The effects of soil moisture on crop growth and yield are determined by first calculating ET_p and LAI (Leaf Area Index), followed by the determination of a water stress factor based on soil water supply and ET_a which is used to estimate the decrease in daily crop growth and yield. This water stress factor is a ratio of crop water use, based on PAW and rooting depth of the crop, to crop water demand. If PAW in the current rooting zone is sufficient to meet demand, yield is maximized. If PAW is restricted, then crop growth is restricted to that amount of water. Factors influencing plant assimilation and leaf expansion growth are calculated and applied to determine crop growth and yield predictions. Muchow et al. (1994) used a sorghum growth simulation model to show that sorghum yields were mainly associated with the amount of water stored in the soil at planting. Yields were always higher where the soil water profile was full rather than half full at any planting date and for any available soil water capacity at any location. Paz et al. (1998) used a soybean model to correlate yield variability with variability of simulated water stress. Moore and Tyndale-Brisco (1999), using crop models, observed that much of the variability in wheat response to nitrogen could be explained by differing soil water holding capacities.

Miller and Saunders (1923) reported the use of plant temperature as an indicator of plant water status over 80 years ago. Research into the use of infrared thermometry to remotely sense canopy temperature has continued since the early 1960s (Monteith and Szeicz, 1962; Tanner, 1963; Fuchs and Tanner, 1966). This research has led to the use of the crop water stress index (CWSI) which was first defined and employed to measure water stress in plants by Idso et al. (1981) and Jackson et al. (1981). Idso et al. (1981) documented the linear relationship between the difference in canopy temperature and air temperature ($DT = T_c - T_a$) and the vapor pressure deficit (VPD) of the air for well watered plants transpiring at potential rate during daylight hours. This linear relationship is sometimes called the "non water-stressed" or "lower" baseline, and it represents the maximum rate of transpiration of a well watered, or non-stressed, crop. These lower baselines are crop specific (Idso, 1982). Measurements of air temperature (T_a), canopy temperature (T_c), relative humidity (RH), and wet bulb temperature (T_w) are taken simultaneously to be used to construct the lower baselines needed for CWSI determination. VPD is a measurement of the deficit between the amount of moisture in the air at the time of measurement and the maximum amount of moisture the air can hold. It can be calculated from measurements of RH, T_a, and T_w. To insure consistency, all measurements were gathered following the procedures recommended by Gardner et al. (1992).

As plants become stressed due to soil moisture depletion, the relationship between DT and VPD deviates from that of the lower baseline condition. When soil moisture is depleted this relationship is represented by the "water-stressed" or "upper" baseline. At this level of stress, the baseline represents the DT of plants that are not transpiring, and there is no response by T_c to VPD. Gardner and Shock (1989) found that multiplying the original scale of 0 to 1 by 10 would yield a CWSI scale more easily understood and accepted. On this scale, 0 indicated a crop under no stress and 10 indicated a crop under maximum stress.

Water stress in crops and CWSI have been related to soil water availability (Hatfield, 1983; Reginato and Garrot, 1987). Hatfield found that DT values for a well watered crop of sorghum (*Sorghum bicolor*) remained negative, meaning leaf temperatures were lower than air temperatures, until 65% of the PAW was extracted. After 65% of the PAW was extracted, DT values became positive, meaning leaf temperatures were higher than air temperatures, and increased quickly as PAW decreased, indicating that the crop was under yield reducing stress. He also observed that CWSI values summed over time provided a measure which is closely related to the amount of PAW extracted from the soil. CWSI has also been used to schedule irrigation for various crops including corn (Clawson and Blad, 1982; Neilsen and Gardner, 1987; Yazar et al., 1999; Irmak et al., 2000) and to determine yield potential (Walker and Hatfield, 1983; Irmak et al., 2000).

The purpose of this study is (i) to better understand the dynamic changes in PAW under a crop of corn as the growing season progresses, and how these changes are influenced by date, growth stage of corn, irrigation, and environment, (ii) to examine the relationship of PAW measured at different growth stages and yield, and (iii) to determine if there is a relationship between PAW and CWSI.

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Chapter Two

Location, Year and Water Regime Effects on Plant Available Water

Abstract

Understanding and measuring the driving forces behind potential yield within the growing season are vitally important in corn production. This knowledge allows adjustment of inputs to maximize economic returns. The objective of this study is to quantify the effects of location, year, and water regime on the dynamic temporal changes in plant available water (PAW) over the growing season. Measurements of PAW were taken over time at four sampling depths at Lewiston and Plymouth in 2001 and 2002. Significant date x water regime interactions were measured at Plymouth at the upper two sampling depths in 2001 and only at the 0- to 15-cm sampling depth in 2002. In 2002, date was significant at the upper three sampling depths, and at Plymouth at the upper two sampling depths only. Water regime was a significant factor on plant available water per fifteen centimeters of soil depth (PAW15cm) only during the dry growing season in 2002. This study showed that rainfall, water treatments, and location (related to differences in soil texture and how irrigation treatments were applied) were the main factors influencing the dynamic changes in PAW measured at different sampling depths in 2001 and 2002. Rainfall contributed heavily to changes in PAW at the shallow sampling depths. The influence of irrigation was observed at the deeper sampling depths due to the accumulation of water that was not affected by transpiration and evaporation. Large changes in PAW occur at depths up to 30 cm, therefore it would be difficult to use single measurements of PAW at these depths to determine yield potential.

Introduction

Understanding and measuring the driving forces behind potential corn yield within the growing season is vitally important since it allows adjustment of inputs to maximize economic returns. Yield potential of corn is often impacted by limited amounts of water, specifically the amount of available soil water (Roygard et al., 2002). In the mid-Atlantic region, rainfall amounts during the growing season are usually sufficient to produce profitable yields, but can be variable from year to year. Because very little corn in this region is irrigated, profitable production is heavily dependent on the amount of rainfall and the soils ability to store water for plant growth. Understanding the dynamic temporal changes in plant available water (PAW) over the growing season is vital if we are to quantify a relationship between PAW, crop water stress index (CWSI), and yield potential of corn in the southeastern United States.

Field capacity (FC), as defined in the Glossary of Soil Science Terms (Soil Sci. Soc. Am., 1984), is the amount of water remaining in a soil two to three days after having been saturated and after free drainage is negligible (Cassel and Nielson, 1986). This represents the maximum amount of water that the soil can store. In contrast, the permanent wilting point (PWP) is defined as the water content of a soil when indicator plants growing in that soil wilt and fail to recover when placed in a humid chamber. Therefore, PWP represents the lower limit of the soil's capacity to store water that can be made available to plants. The available water content (AWC) of a soil is defined as the difference between FC and PWP and represents the potential plant extractable water that a soil can store based on an indicator plant.

The amount of water stored in the soil at any given time is impacted by soil texture, type of clay present, organic matter content, soil structure, tillage, and evapotranspiration (Hillel, 1998). Loamy textured soils containing appreciable quantities of silt usually hold the most PAW, followed by clay, and then sand. Clayey soils retain more water, and for a longer period of time, than do sandy soils. These finer textured soils have a high specific surface, and therefore have a higher FC, yet because the water is held so tightly most water is unavailable to the plant, resulting in a high PWP. Sandy soils have many large pores capable of quickly moving water, hence good internal drainage but this results in a low storage capacity. The volume of small pores in which water can be held is very small in sandy soils. Fine-textured clay soils have a greater total volume of pores than coarse-textured sands, with the majority of those pores being very small in size, so water does not move through quickly, and more water can be stored. The organic matter content (OMC) of a soil, if in sufficient quantities, can enhance a soils ability to retain moisture by enhancing soil aggregation, resulting in increased pore space. Infiltration is also influenced by soil organic matter. Hudson (1994) demonstrated that soils high in OMC store significantly more water than soils of similar texture that contain less OMC, and that these soils have more of this stored water available for plant growth.

The upward extraction of water from the soil surface and from plants by evapotranspiration (ET) constantly impact the amount of water stored in the soil (Hillel, 1998). Evapotranspiration is the total amount of water lost from the soil by both evaporation and plant transpiration (Gardner et al., 1985). Evaporation from soil is a direct pathway for water to move to the atmosphere as water vapor (Klocke et al., 1996).

Evaporation rates are highest after rainfall or irrigation, when the soil surface is wet and water can evaporate readily and when the soil surface is shaded. Evaporation at this point is primarily influenced by the energy available for evaporation (Scott, 2000). As the soil surface dries, the evaporation rate declines sharply, and is influenced mainly by the hydraulic properties of the soil near the surface. Evaporation rates from the soil surface also decline as the growing season progresses and canopy cover increases. At this point, ET is comprised primarily of transpiration, defined as the process by which water moves from the soil to the roots, from the roots into various parts of the plant, and finally into the leaves where it is released into the atmosphere as water vapor through the stomata (Haman and Izuno, 1990). ET is measured as the atmospheric demand, or potential ET (ET_p), and the crop's ability to meet the atmospheric demand, actual ET (ET_a). When ET_a rates are high, or close to ET_p, soils are at or near FC and crop yield can be maximized. When ET_a rates are significantly below ET_p, soils are dryer, and plants are under stress.

No-till production methods improve water storage efficiency and soil water availability (Halvorson et al., 1994). Tillage of the soil increases soil water evaporation compared to untilled soil (Burns et al., 1971; Papendick et al., 1973). Because soil aggregation is not adversely affected under no-till systems, infiltration of rainfall or irrigation is enhanced, and evaporation losses are minimized due to increased amounts of crop residue left on the soil surface (Brady, 1990).

There are many direct and indirect methods to measure the amount of water stored in the soil (Gardner, 1986). The use of gravimetric methods, electrical resistance, neutron scattering, and time-domain reflectometry (TDR) have been the most prevalent methods used to measure soil moisture (Hillel, 1998). One method for direct measurement of soil moisture is gravimetry which involves the drying of soil in an oven (Gardner, 1986). Gravimetric methods are widely used because the samples can be easily taken, they are inexpensive to conduct, and soil water content is easily calculated (Scott, 2000). However, this method is both laborious and time consuming, and because of the sampling, transporting, drying, and repeated weighing procedures involved; this method presents many opportunities for error (Hillel, 1998). The extraction of samples from the soil is invasive and destructive, potentially leading to distortion of experiments.

The most practical techniques for soil water monitoring are indirect methods (Yoder et al., 1998; Robinson et al., 1999). Indirect techniques are divided into two categories, tensiometric and volumetric methods. Both types estimate soil moisture content by a calibrated relationship with some other measurable variable (Muñoz-Carpena, 2004). Tensiometric methods include electrical resistance blocks and tensiometers. Electrical resistance blocks have been used because of their tendency to equilibrate with the matric suction of soil water instead of the water content of the soil. Use of electrical resistance blocks are quick, repeatable, and relatively inexpensive, but sensitivity is poor in dry soil conditions, and they do not work well in coarse-textured, high shrink-swell, or saline soils. Soil water content for the soil must be obtained by pressure plate extractor or gravimetric method and then used to calibrate the block for accurate measurement. Block properties such as internal porosity change over time, depending on the effect of soil type and rainfall on the degradation of gypsum, a component of the blocks. The time required to attain equilibrium limits the accuracy of the measurements.

Tensiometers have been used for years to schedule irrigation of field and orchard crops (Richards and Weaver, 1944). This method allows for frequent and direct measurements of matric potential, defined as the pressure potential of soil moisture (Hillel, 1998). Matric potential results from the interactive capillary and adsorptive forces between water and the soil matrix which bind water in the soil and lower it's potential energy below that of bulk water. Tensiometer readings can be taken without the use of electronic devices or a power source. Minimal skill is needed to read the vacuum gauge and the method is inexpensive to operate and maintain. Care must be taken to ensure intimate contact between soil and the ceramic cup for consistent readings in coarse textured soils. Like electrical resistance blocks, soil water content for the soil must be obtained independently, by pressure plate extractor or gravimetric methods, to calibrate tensiometer readings for soil water measurements. Response time is slow and tubes must be refilled with water frequently in hot, dry weather to maintain the water column inside the tensiometer. Tensiometers have a narrow measurement range of less than 1 bar, restricting its use for precise soil water measurements under extremely dry conditions.

Volumetric methods include neutron probes and TDR. Neutron probes can be used to measure volumetric water content of soils (Gardner, 1970). One probe can take measurements at any desired depth, with a large sensing volume, but accuracy at depths within 0.20 m of the surface are unreliable due to the escape of fast neutrons through the soil surface. While offering repeatable measurements at the same locations and depths which were independent of temperature and pressure, the health risk of exposure to radiation coupled with the high initial cost of the instrument are disadvantages. Use of the neutron probe requires certification and the equipment is cumbersome and heavy. Soil specific calibration is needed to utilize this technique.

The use of TDR has increased dramatically over the last 30 years. Unlike most other techniques, soil specific calibration is usually not required (Muñoz-Carpena, 2004). Measurements are highly accurate and can be automated. A wide variety of probes are commercially available and probe installation can be achieved with minimal soil disturbance. However, the equipment is relatively expensive and the sensing volume of the probe is relatively small.

A detailed investigation of the techniques described above indicates TDR as the superior method with which to measure soil water content for this project. Advantages of TDR over other soil water content measurement methods are: (i) superior accuracy with minimal input; (ii) minimal calibration requirements; (iii) no radiation hazard; (iv) excellent spatial and temporal resolution; (v) easy to obtain measurements; (vi) a wide array of commercially available equipment to accommodate specific needs; and (vii) a non-destructive means of acquiring measurements.

The temporal variation of soil moisture is influenced by several factors. At any given point in time soil moisture (and thus PAW) is impacted by the precipitation history, the texture of the soil, the slope of the terrain and presence of vegetation (Mohanty and Skaggs, 2001). In the Mid-Atlantic region, rainfall is known to vary temporally and spatially (Roygard et al., 2002). Precipitation is the single most important climatic factor for soil moisture and its distribution (Mohanty and Skaggs, 2001). The dependency of the temporal stability of differences in soil water storage on soil texture (see previous discussion on texture) was observed by Van Pelt and Wierenga (2001). Temporal stability of soil moisture measurements is more stable during dry periods, and less stable during the transition period between dry and wet soil moisture status (Martínez-Fernández and Ceballos, 2003). The presence of vegetation influences temporal soil moisture variability as it affects infiltration, runoff, and evapotranspiration. The objective of this study is to quantify the effects of location, year, and water regime on the dynamic temporal and spatial changes in PAW over the growing season.

Materials and Methods

Experiments were conducted at two locations in 2001 and 2002 at the Peanut Belt Research Station (PBRS) at Lewiston, North Carolina and the Tidewater Research Station (TRS) at Plymouth, North Carolina. At Lewiston in 2001, the predominate soil types at the site were a Norfolk sandy loam (Fine-loamy, siliceous, thermic Typic Paleudults) and a Goldsboro sandy loam (Fine-loamy, siliceous, thermic Aquic Paleudults). At Plymouth in 2001, the experiment was conducted on a Portsmouth sandy loam (Fine-loamy over sandy or sandy-skeletal, mixed, thermic Typic Umbraquults). In 2002, the soil types at Lewiston were Goldsboro and Lynchburg sandy loams (Fine-loamy, siliceous, thermic Aeric Paleaquults), and a Rains sandy loam (Fine-loamy, siliceous, thermic Typic Paleaquults). Soils at the Plymouth site in 2002 were a Portsmouth sandy loam and a Cape Fear loam (Clayey, mixed, thermic Typic Umbraquults).

Fields were prepared and planted using conventional tillage methods. Row width for both years at Lewiston was 91 cm and row width for both years at Plymouth was 96 cm. Pioneer 31G98 field corn was planted at a population of 67,500 seeds per hectare on 4 April 2001 and 6 April 2002 at Lewiston, and 30 April 2001 and 27 April 2002 at Plymouth. Production practices were consistent with those generally used for profitable corn production in eastern North Carolina. Weed control at both test sites in both years was excellent due to proper timing and application of herbicides. Plots at Lewiston in 2001 received 168 kg 0-0-60 ha^{-1}, 112 kg 0-46-0 ha^{-1}, and 224 kg N ha^{-1} pre-plant, with an additional 224 kg N ha^{-1} applied at growth stage VT (Ritchie et al., 1993). In 2002, plots received 112 kg 0-0-60 ha^{-1} and 112 kg 18-46-0 ha^{-1} pre-plant, with 145 kg N ha^{-1} applied at growth stage V3. Plots at Plymouth in 2001 received 336 kg 9-23-30 ha^{-1} pre-plant and 224 kg N ha^{-1} applied at growth stage VT. In 2002, plots received 81 kg N ha^{-1} pre-plant and 49 kg N ha^{-1} applied at growth stage V3.

In 2001, the experimental design of the test was a modified Randomized Complete Block with three water regimes as the main treatments replicated in three blocks (Steel et al., 1997). Water regime treatments were comprised of no irrigation (0X), normal irrigation (1X) and double irrigation (2X). At Lewiston, this was accomplished using gated furrow irrigation by positioning the test on a slight grade with the rows directed downhill and the 2X plots above the 1X plots. Alleys for each treatment were flooded until water began to exit the far end of the plots. This system worked well for providing two different levels of irrigation, but did not provide a way to accurately measure the amount of water applied to each treatment. Irrigation in 1X plots was estimated to be 1.5 cm and 2X plots received an estimated 3.0 cm per irrigation (Barnes, 2004, personal communication). At Plymouth, plots were irrigated using an overhead linear irrigation system which delivered 0.8 (1X) and 1.5cm (2X) of water per irrigation. In 2002, the experimental design of the test was a modified Randomized Complete Block with two water regimes (0X and 1X) as the main treatments, replicated six times. Both locations were irrigated using overhead linear irrigation systems in 2002. The system at Lewiston delivered an average of 1.4 cm of water at every event except one, which measured 2.5 cm. The system at Plymouth applied 0.8 cm of water during each irrigation. At both locations in both years, irrigations were scheduled when cumulative rainfall during the the previous three to four days did not exceed 1.3 cm.

Rainfall data used for this study was measured and recorded by personnel at TRS and PBRS.

The goal for this study is to simultaneously take canopy temperature (discussed later) and soil moisture measurements at least weekly at both locations. Canopy temperature measurements require near cloudless conditions for an accurate measurement to be made (Gardner et al., 1992). Measurements were taken on sunny days between 1100 hours and 1400 hours. In 2001, clear sunny days were rare. Uncooperative weather for data collection allowed only three measurement dates at Lewiston and four measurement dates at Plymouth. The same phenomena affected data collection in 2002 with only three measurement dates at Lewiston and five measurement dates at Plymouth.

Soil water content was measured using time domain reflectometry (TDR) probes (MP-917, Environmental Sensors Inc., Victoria, BC, Canada) at 0- to 15-cm, 15- to 30-cm, 30- to 45-cm, and 45- to 60-cm sampling depths. After harvest, the probes were removed and a 0.6-m deep hole was excavated to gather undisturbed samples from each of the four sampling depths. A soil water retention analysis of the samples was performed to determine PAW on a volume basis (Cassel and Nielson, 1986). Published bulk density measurements for each soil (United States Department of Agriculture, 1981; 1990; 1995) were used for these calculations.

Grain yield was determined by harvesting the two center rows of each plot using a Gleaner (AGCO Corp., Duluth, GA) two row combine. Moisture content and grain yield were recorded using a HarvestMaster Grain Gauge (Juniper Systems, Inc., Logan, UT). Grain yield was adjusted to a moisture content of 155 g kg^{-1}.

To understand the effect of sampling date on PAW15cm the data were separated by location and year and analyzed using a split plot design with sampling date as the main effect and water regimes as the sub-treatments. This resulted in the data being separated into four groups: Lewiston 2001, Lewiston 2002, Plymouth 2001, and Plymouth 2002. Each sampling depth at an individual location was tested for sampling date and water regime main effects as well as sampling date X water regime interactions using PROC GLM (SAS version 8.2, SAS Institute Inc, Cary, NC).

Planting dates differed across years and locations and it was impossible to measure canopy temperatures and soil moisture at both locations on the same day. Therefore, before examining the effects of location and year on PAW15cm, the data from both years and locations were combined by crop growth stage to minimize the effects of plant size and physiological development on the amount of PAW15cm present at differing depths in the soil. Growing degree days (GDD) were calculated for each measurement date and location, and the data was separated into as many identifiable growth stages as possible. The data represented growth stages I (V15), II (V19/VT), III (R1), IV (R2/R3), and V (R4) (Ritchie et al., 1993). All data collected for growth stage I came from 19 June 2001 at Plymouth, so it was tested for water regime effects only using PROC GLM (SAS version 8.2 SAS Institute Inc,, Cary, NC). Growth stage II included data from both Plymouth and Lewiston in 2001, so it was tested for location and water regime effects and a location X water regime interaction. Growth stages III and IV included data collected at both locations and both years, so it was tested for location, water regime, and year effects, as well as location X water regime and year X water regime interactions. Growth stage V included data from both Plymouth and Lewiston in

2002, so it was tested for location and water regime effects and location X water regime interaction.

Results and Discussion

Effects of Sampling Date and Water Regime on Plant Available Water at Lewiston in 2001.

There were no sampling date by water regime interactions at any of the four sampling depths at Lewiston in 2001 (Table 2.1). Sampling date was the only factor that significantly ($p = 0.05$) impacted PAW15cm. There were significant differences in PAW15cm by sampling date at all four sampling depths. At the 0- to 15-cm sampling depth, the PAW15cm measurement of 2.0 cm taken on 18 June was significantly higher than the 11 June measurement of 1.0 cm and the 6 July measurement of 1.1 cm (Fig. 2.1). At the 15- to 30-cm sampling depth, the PAW15cm measurement of 2.1 cm taken on 18 June was significantly higher than the 11 June measurement of 1.2 cm and the 11 June measurement was significantly higher than the 6 July measurement of 0.0 cm. At the 30- to 45-cm sampling depth, PAW15cm measurements of 2.0 cm taken on 18 June and 1.7 cm taken on 11 June did not differ significantly from each other. Both of these measurements were significantly higher than the 6 July measurement of 1.2 cm. At the 45- to 60-cm sampling depth, the PAW15cm measurement of 2.4 cm taken on 18 June was significantly higher than the 11 June measurement of 1.9 cm and the 11 June measurement was significantly higher than the 6 July measurement of 1.4 cm.

Rainfall over the 5-day period prior to each sampling date influenced the effect of sampling date on PAW15cm (Fig. 2.1). Rainfall accumulation during the 5-day period prior to 11 June totaled 5.1 cm, with all of the measurable rainfall occurring on the first 2 days of the 5-day period. Rainfall accumulation during the 5-day period prior to 18 June totaled 18.5 cm, with 17.7 cm of the measurable rainfall occurring on the last 2 days of the 5-day period. Rainfall accumulation during the 5-day period prior to 6 July totaled 1.0 cm of rainfall, with all of the measurable rainfall occurring on the final day of the 5-day period.

Plymouth 2001.

A sampling date X water regime interaction significantly impacted PAW15cm measurements at the 0- to 15-cm and 15- to 30-cm sampling depths at Plymouth in 2001 (Table 2.2) and the sampling date main effect was significant at all four sampling depths. At the 0- to 15-cm sampling depth, PAW15cm measured on 19 June in the 0X (2.8 cm) and 1X (2.9 cm) water regimes were significantly greater than the amount measured in the 2X (2.2 cm) regime (Fig. 2.2). In comparison, there were no differences in PAW15cm among water regimes on 27 June when 1.4 cm, 1.3 cm, and 1.5 cm of water were measured in the 0X, 1X, and 2X regimes, respectively. There was no irrigation applied at this location before 29 June 2001. When PAW15cm was measured on 6 July and 17 July plots in the 0X water regime had significantly less PAW15cm at the 0- to 15-cm sampling depth than those in the 1X and 2X treatments, due to the beginning of irrigation on 29 June. On 6 July there was 1.1 cm, 1.6 cm, and 1.9 cm of PAW15cm in the 0X, 1X, and 2X regimes, respectively. On 17 July there was –0.5 cm, 0.0 cm, and 0.5 cm of PAW15cm in the 0X, 1X, and 2X treatments, respectively.

There was also a date by water regime interaction at the 15- to 30-cm sampling depth which followed a pattern similar to that seen at the 0- to 15-cm sampling depth (Fig. 2.2). On 19 June, PAW15cm for the 0X and 1X treatments (2.6 and 2.7 cm) were significantly greater than that measured in the 2X treatment (1.9 cm). By 27 June there were no differences in PAW15cm among any of the three treatments (0X = 1.6 cm, 1X = 1.6 cm, and 2X = 1.4 cm). However, measurements taken on 6 July and 17 July following irrigation beginning on 29 June, found that PAW15cm was significantly greater in the 2X water regime (1.9 cm on 6 July and 0.6 cm on 17 July) than that measured in the 0X or 1X water regimes (0.7 and 0.9 cm, respectively, on 6 July and -0.2 and 0.0 cm, respectively, on 17 July).

It is important to note the influence of rainfall and irrigation on the date by water regime interactions found at the 0- to 15- cm and 15- to 30- cm sampling depths. The measurements on 19 June were preceded by 8.0 cm of rainfall and no irrigation during the preceding 5 day period (Fig. 2.2). On 27 June, the measurements were preceded by 1.2 cm of rainfall and no irrigation during the previous 5 days. In comparison, the measurements taken on 6 July received no measureable rainfall during the preceding 5 day period. However, 0.8 cm of water was applied to 1X irrigated treatments, and 1.5 cm of water was applied to the 2X irrigated treatments on the third day (3 July) of the 5 day period prior to measurement date. The 17 July measurements were preceded by 0.2 cm of rainfall and one irrigation event (0.8 cm applied to 1X treatments and 1.5 cm applied to 2X treatments on 13 July) during the preceding 5 day period. The overall decrease in PAW15cm across measurement dates was primarily the result of less rainfall that occurred as the season progressed and the interaction among water regimes resulted from the application of irrigation water to the 1X and 2X regimes made between 29 June and 13 July.

There were significant differences in PAW15cm by sampling date at all four sampling depths (Table 2.2). At the 0- to 15-cm sampling depth, average PAW15cm measured on 19 June (2.6 cm) was significantly higher than the averaged measured on 27 June (1.4 cm). While the average PAW15cm measured on 6 July (1.5 cm) was not significantly different from the 27 June measurement, it was significantly higher than the average measurement taken on 17 July (0.0 cm). At the 15- to 30-cm sampling depth, the average PAW15cm measured on 19 June (2.4 cm) was significantly greater than the average measurements taken on the other three dates (1.5, 1.1, and 0.2 cm, respectively). Likewise, PAW15cm on 27 June was significantly greater than the average measurements taken on 6 July and 17 July and PAW15cm on 6 July was significantly greater than the average PAW15cm measured on 17 July. At the 30- to 45-cm sampling depth, there was no significant difference between PAW15cm measured on 19 June and that measured on 27 June (2.4 and 2.3 cm, respectively). PAW15cm measured on 6 July (2.0 cm) was significantly lower than that measured on 19 June but was not different from the measurement taken on 27 June. PAW15cm measured on 17 July (1.4 cm) was significantly lower than the PAW15cm measured at any of the other three dates. Rainfall during the 5-day period prior to measurement dates of 19 June, 27 June, 6 July, and 17 July totaled 8.0 cm, 1.2 cm, 0.1 cm, and 0.2 cm, respectively. In general, the decline in rainfall matches the decrease in PAW15cm across the measurement dates.

Lewiston 2002.

While there were no significant sampling date by water regime interactions at any of the four sampling depths at Lewiston in 2002, there were significant differences in

PAW15cm by water regime at the 30- to 45-cm and 45- to 60-cm sampling depths and differences in PAW15cm by sampling date at the 0- to 15- cm, 15- to 30- cm, and 30- to 45- cm sampling depths (Table 2.3). At both the 30- to 45-cm and 45- to 60-cm sampling depths, PAW15cm in the 1X water regimes (0.9 and 1.1 cm, respectively) were significantly greater than PAW15cm found in the 0X regimes (0.4 and 0.4 cm, respectively) (Fig. 2.3).

The effect of water regime on PAW15cm is explained by the lack of rainfall and irrigation events since planting. Over the 94-day period, between the 6 April planting date and 9 July measurement date, 13.8 cm of rainfall was measured (Fig. 2.3). Over the same 94 day period, the 1X treatments received an additional 13.7 cm of water. Over the 21-day period preceding the 9 July measurement, rainfall and irrigation totals were 0.2 cm and 6.6 cm, respectively.

Among sampling dates, at the 0- to 15-cm sampling depth, PAW15cm measured 9 July (0.3 cm) was similar to the measurement taken on 17 July (0.6 cm) (Fig. 2.3). However, PAW15cm measured on 17 July was significantly lower than the measurement taken on 29 July (1.0 cm). At the 15- to 30-cm and 30- to 45-cm sampling depths, PAW15cm measurements taken on 9 July (0.1 and 0.2 cm, respectively) were significantly lower than those taken on 17 July (0.8 and 0.7 cm, respectively). In contrast, the PAW15cm measurements taken on 17 July were similar to those taken on 29 July (1.1 and 1.0 cm, respectively).

Rainfall was the main factor that influenced the effect of sampling date on PAW15cm. Rainfall during 5 day and 21 day periods prior to 9 July measurement totaled 0.0 cm and 0.2 cm, respectively. Rainfall during the 5 day period prior to 17 July measurement date totaled 2.1 cm, and rainfall during the 5 day period prior to 29 July measurement date totaled 4.2 cm. The increase in the amount of rainfall received between sampling dates as the season progressed matches the increase in the average PAW15cm measured across sampling dates.

Plymouth 2002.

There was a date X water regime interaction effecting PAW15cm at the 0- to 15-cm sampling depth, water regime effects on PAW15cm at the 0- to 15-cm, 30- to 45-cm and 45- to 60-cm sampling depths, and sampling date effects on PAW15cm at the 0- to 15-cm and 15- to 30-cm sampling depths at Plymouth in 2002 (Table 2.4). At the 0- to 15-cm sampling depth, PAW15cm measurements taken on 1 July, 8 July, 16 July, and 22 July in the 0X (-0.1, -0.6, 0.1, and 2.1 cm, respectively) and 1X (0.3, -0.3, 0.4, and 1.8 cm, respectively) water regimes were not significantly different. However, PAW15cm measurements taken on 3 July from the 0X (-0.4 cm) water regime were significantly lower than those taken in the 1X (0.7 cm) regime The significant difference between PAW15cm measurements taken on 3 July were the result of 0.8 cm of water applied to the 1X treatments on 2 July.

Because interactions were consistent, we examined the water regime main effect independently. While water regime had a significant impact on the amount of PAW15cm at the 0- to 15-cm, 30- to 45-cm, and 45- to 60-cm sampling depth, it was not a significant factor at the 15- to 30-cm sampling depth (Fig. 2.4). At the 0- to 15-cm, 30- to 45-cm, and 45- to 60-cm sampling depths, PAW15cm measurements in the 0X regime (0.2, 0.7, and 0.5 cm, respectively) were significantly lower than those taken in the 1X water regime (0.6, 1.4, and 1.3 cm, respectively). The application of 0.8 cm of irrigation water to the 1X regime on 2 July clearly resulted in the differences in PAW15cm at the 0- to 15-cm sampling depth. The significant differences in PAW15cm by water regime at the 30- to 45-cm and 45- to 60-cm sampling depths were probably due to the consistent application of irrigation water which replaced the moisture lost to evapotranspiration in the 1X water regime and reduced the amount of PAW15cm lost from the lower soil layers.

There were also significant differences in average PAW15cm across sampling dates at the 0- to 15-cm and 15- to 30-cm sampling depths (Fig. 2.4). At the 0- to 15-cm sampling depth, average PAW15cm measured on 1 July (0.1 cm) was not significantly different from measurements taken on 3 July (0.2 cm) and 16 July (0.2 cm). However, average PAW15cm measured on these three dates were all greater than the average PAW15cm measured on 8 July (-0.5 cm) but were lower than the average PAW15cm measured on 22 July (2.0 cm). At the 15- to 30-cm sampling depth, the average PAW15cm measured on 1 July (-0.4 cm) was not significantly different from measurements taken on 3 July (–0.4 cm), 8 July (-0.5 cm), and 16 July (–0.5 cm). However, all of these measurements were significantly lower than the average PAW15cm measured on 22 July (0.9 cm).

Rainfall 5 days prior to the 1 July and 3 July sampling dates totaled 2.1 cm. Rainfall during the 5-day period prior to the 8 July sampling date totaled 0.2 cm. Rainfall during the 5-day period prior to the 16 July sampling date totaled 1.4 cm, with 1.1 cm of that rainfall occurring on the second day of the 5-day period. Rainfall during the 5-day period prior to the 22 July sampling date totaled 3.8 cm, with 3.7 cm of that rainfall occurring on the final day of the 5-day period.

The Effect of Year and Location on Plant Available Water.

When the data were separated into five subsets based on plant growth stages, significant main effects of location, year and water regime on PAW15cm were found at all four sampling depths at several of the growth stages (Tables 2.5, 2.6, 2.7, 2.8, 2.9). A year by water regime interaction was not found at either Growth Stage III or IV where year was a factor in the analysis. However, among the four growth stages where location was a factor in the analysis (Stages II, III, IV, and V), location by water regime interactions were only found at Growth Stage V in the 0- to 15-cm and 15- to 30-cm sampling depths (Table 2.9). At the 0- to 15-cm sampling depth, PAW15cm measurements in the Lewiston 0X treatments (0.0 cm) were significantly lower than measurements in the Lewiston 1X (0.6 cm), Plymouth 0X (2.1 cm), and Plymouth 1X (1.8 cm) treatments. The Lewiston 1X treatment was significantly lower than either of the Plymouth treatments. There were no significant differences between the Plymouth treatments. At the 15- to 30-cm sampling depth, PAW15cm measurements in the Lewiston 1X (0.4 cm), Lewiston 0X (-0.1 cm), and Plymouth 1X (0.5 cm) treatments did not differ significantly. There was no significant difference between the Plymouth 1X and Plymouth 0X (1.3 cm) treatments. The Plymouth 0X treatment was significantly higher than the Lewiston 1X and Lewiston 0X treatments. Lewiston received 0.2 cm of rainfall and 6.6 cm of irrigation over the 21 day period preceding the 9 July 2002 measurement date. Over the same period of time, Plymouth received 8.7 cm of rainfall and 3.8 cm of irrigation.

Location.

At growth stage II (VT), location was a significant factor affecting the amount of PAW15cm measured at the 30-to 45-cm and 45- to 60-cm sampling depths (Table 2.6). There were no significant differences due to location found at the 0- to 15-cm and 15- to 30-cm sampling depths. Growth stage II PAW15cm measurements at Plymouth were significantly higher than at Lewiston at the 30-to 45-cm and 45- to 60-cm sampling depths. The Plymouth stage II PAW15cm measurements for the 30-to 45-cm and 45- to 60-cm sampling depths were 2.3 cm (88% of AWC) and 2.8 cm (90% of AWC), respectively, while the Lewiston stage II PAW15cm measurements for the 30-to 45-cm and 45- to 60-cm sampling depths were 1.7 cm (68% of AWC) and 1.9 cm (79% of AWC), respectively. The available water capacity per fifteen centimeters of soil (AWC15cm) of the 30- to 45-cm soil depth at Lewiston (2.5 cm) was not different from Plymouth (2.6 cm). However, the AWC15cm of the 45- to 60-cm soil depth at Lewiston (2.4 cm) was lower than at Plymouth (3.1 cm). The higher PAW15cm measurements at Plymouth were attributable primarily to the 29.1 cm of rainfall accumulation measured over the 58 day period between planting (30 April 2001) and the 27 June 2001 growth stage II measurement date, compared to the 16.5 cm of rainfall accumulation measured at Lewiston over the 68 day period between planting (4 April 2001) and the 11 June 2001 growth stage II measurement date. Rainfall amounts within the 14 day period prior to measurement dates at Plymouth (9.2 cm) and Lewiston (8.8 cm) were not substantially different. Rainfall amounts within the 5 day period prior to measurement dates was greater at Lewiston (5.1 cm) than at Plymouth (1.2 cm). No irrigation was applied before these measurement dates.

At growth stage III (R1), location was a significant factor affecting the amount of PAW15cm measured at the shallow 0- to 15-cm and 15- to 30-cm sampling depths (Table 2.7). The growth stage III PAW15cm measurements at Lewiston were significantly higher than at Plymouth. Lewiston growth stage III PAW15cm measurements at the 0- to 15-cm (2.0 cm, 100% of AWC) and 15- to 30-cm (2.1 cm, 95% of AWC) soil depths indicated both soil depths were at or close to field capacity. Lewiston received 23.7 cm of rainfall over the 14 day period prior to sampling on 18 June 2001, with 17.7 cm of this rainfall occurring over the final two days of the period. The Plymouth location at growth stage III was represented by data from both 2001 and 2002. PAW15cm measurements at the 0- to 15-cm (0.5 cm, 18% of AWC) and 15- to 30-cm (0.0 cm, 0% of AWC) soil depths indicated severe moisture stress Rainfall accumulation over the 14 day period prior to samplings at Plymouth on 6 July 2001, 1 July 2002, and 3 July 2002 totaled 1.4 cm, 3.5 cm, and 3.5 cm, respectively. Two irrigation events over the 14 day period prior to sampling at Plymouth on 6 July 2001 added 1.5- and 3.0-cm of water to 1X and 2X treatments, respectively. Three irrigation events over the 14 day period prior to 1 July 2002 and 3 July 2002 sampling dates added 2.3 cm of water to 1X treatments. It is interesting to note that despite the difference in PAW15cm between locations at the shallow sampling depths, there were no differences in PAW15cm at the 30- to 45-cm and 45- to 60-cm sampling depths.

At growth stage IV (R2/R3), location was a significant factor affecting the amount of PAW15cm measured only at the 0- to 15-cm sampling depth (Table 2.8). The growth stage IV PAW15cm measurement at Lewiston was significantly higher than at Plymouth. Growth stage IV PAW15cm measurements at the 0- to 15-cm sampling depth were 1.1 cm at Lewiston (55% of AWC) and -0.1 cm at Plymouth (0% of AWC). Again, rainfall and irrigation influenced the PAW15cm measurements at each location in stage IV. The Lewiston location received 1.9 cm of rainfall and 4 gated irrigation events over the 14 day period prior to sampling on 6 July 2001, with 1.0 cm of the measurable rainfall occurring on the final day of the period. The site at Plymouth received 0.8 cm, 2.5 cm, and 1.6 cm of rainfall during the 14 day period prior to each sampling date (17 July 2001, 8 July 2002, and 16 July 2002,). There were no measurable accumulations of rainfall over the final two days of the 14 day period prior to the 17 July 2001 or 8 July 2002 sampling dates at Plymouth, and only 0.3 cm of rainfall fell over the final two days of the 5 day period prior to 16 July 2002. Irrigation at Plymouth over the 14 day period was applied 3 times prior to 17 July 2001 (2.3 cm on 1X treatments; 4.6 cm on 2X treatments), 2 times prior to 8 July 2002 (1.5 cm on 1X treatments), and 3 times prior to 16 July 2002 (2.3 cm on 1X treatments).

At growth stage V (R4), Plymouth measurements of PAW15cm were significantly greater than those at Lewiston at the 0- to 15-cm, 15- to 30-cm and 30- to 45-cm sampling depths but did not differ at the 45- to 60-cm sampling depth. At Plymouth, PAW15cm at the 0- to 15-cm, 15- to 30-cm, and 30- to 45-cm sampling depths were 1.9 cm (65% of AWC), 0.9 cm (31% of AWC), and 1.3 cm (43% of AWC), respectively. At Lewiston PAW15cm at the 0- to 15-cm, 15- to 30-cm, and 30- to 45-cm sampling depths were 0.3 cm (18% of AWC), 0.1 cm (5% of AWC), and 0.3 cm (17% of AWC), respectively. Again, rainfall was the key factor that influenced PAW15cm at each location in growth stage V. Lewiston received 1.8 cm of rainfall over the 14 day period prior to sampling on 9 July 2002, with no rain accumulating over the final 9 days before measurement. The 1X irrigated treatments received an additional 5.0 cm of water over the same period. Plymouth received 5.6 cm of rainfall over the 14 day period prior to sampling on 22 July 2002, with 3.7 cm received on the final day of the period. Irrigation applied to 1X treatments over the same period totaled 3.0 cm.

Year.

Growth stages III (R1) and IV (R2, R3) were the only stages which allowed testing of the effect of year on PAW15cm (Table 2.7, 2.8). Year was a significant factor affecting the amount of PAW15cm measured at all four sampling depths at growth stage III, but was not significant at growth stage IV at any depth. In 2001, measurements of PAW15cm were significantly higher at all four sampling depths than those found in 2002 (Figure 2.5). In 2001, PAW15cm at the 0- to 15-cm, 15- to 30-cm, 30- to 45-cm, and 45- to 60-cm sampling depths were 1.8 cm, 1.6 cm, 2.0 cm, and 2.5 cm, respectively. In 2002, PAW15cm at the 0- to 15-cm, 15- to 30-cm, 30- to 45-cm, and 45- to 60-cm sampling depths were 0.2 cm, -0.4 cm, 1.0 cm, and 0.9 cm, respectively. The significance of year on PAW15cm at growth stage III is related to the amount of rainfall received during the growing season for each year. Because there was no 2002 Lewiston sampling date represented in growth stage III, the data set is unbalanced, and the 18 June 2001 Lewiston sampling date was not included in this analysis At Plymouth in 2001, rainfall accumulation totaled 29.2 cm over the 67 day period between 30 April planting date and 6 July sampling date. In 2002, rainfall accumulation at Plymouth totaled 13.6 cm over the 65 day period between 27 April planting date and 1 July sampling date.

Water Regime.

The effects of changes in water regime on PAW15cm were not significant at any sampling depth in growth stages II or IV. However, differences in water regime were significant at the 15- to 30-cm sampling depth measured at growth stage I, at the 0- to 15-cm and 15- to 30-cm sampling depths at growth stage III, and at the 30- to 45-cm and 45- to 60-cm sampling depths measured at growth stage V.

Growth stage I included only one sampling date, 19 June 2001. While a significant relationship between water regimes was detected, the difference was not due to the impact of water regimes since irrigation did not begin at this location until 29 June, 2001 (See discussion in “Plymouth 2001”). At growth stage III, changes in water regime significantly impacted PAW15cm at the 0- to 15-cm and 15- to 30-cm sampling depths (Table 2.7). At the 0- to 15-cm sampling depth, the measurement of PAW15cm for the 2X treatment (2.0 cm) was significantly higher than the measurement for the 1X treatment (1.0 cm), and the 1X treatment measurement was significantly higher than the measurement for the 0X treatment (0.3 cm) (Figure 2.5). At the 15- to 30-cm sampling depth, the measurement of PAW15cm for the 0X (0.1 cm) and 1X (0.3 cm) treatments were not significantly different, but both measurements were significantly lower than the measurement for the 2X (2.0 cm) treatment. There was no irrigation applied to plots at Lewiston prior to the 18 June 2001 measurement date. Two irrigation events over the 14 day period prior to sampling at Plymouth on 6 July 2001 added 1.5- and 3.0-cm of water to 1X and 2X treatments, respectively. Three irrigation events over the 14 day period prior to 1 July 2002 and 3 July 2002 sampling dates added 2.3 cm of water to 1X treatments.

At growth stage V, which was represented only by sampling dates at Lewiston and Plymouth in 2002, measurements of PAW15cm in the 0X water regime at 30- to 45-cm and 45- to 60-cm sampling depths were 0.4 cm and 0.5 cm, respectively (Table 2.9). In comparison, measurements of PAW15cm in the 1X water regime at 30- to 45-cm and 45- to 60-cm sampling depths were significantly greater at 1.1 cm and 1.4 cm, respectively. The 1X irrigated treatments at Lewiston received 5.0 cm of water over the 14 day period prior to sampling on 9 July 2002. At Plymouth, irrigation applied to 1X treatments over the 14 day period prior to the 22 July 2002 sampling date totaled 3.0 cm.

Conclusion

Significant date x water regime interactions were only measured at Plymouth at the upper two sampling depths in 2001 and only at the 0- to 15-cm sampling depth in 2002. These interactions were due to the influence of rainfall and irrigation treatments at these uppermost sampling depths during the time period over which measurements were taken during both years. During periods of low rainfall the irrigated treatments had significantly more PAW15cm. However, following large rainfall events the non-irrigated treatment either had similar levels of PAW15cm or in one or two cases had more PAW15cm. This could have occurred due to lower infiltration rates in the irrigated treatments caused by repeated applications of water.

Significant date effects were prominent at both Lewiston and Plymouth during 2001 and 2002. In 2001, date was a significant factor in the difference in PAW15cm at all four sampling depths at both Lewiston and Plymouth. In 2002, date was significant in the upper three sampling depths, and at Plymouth at the upper two sampling depths only. These effects were influenced primarily by the amount of rainfall received over a period of time prior to each measurement date, and further explained by the amount of water infiltrating the soil, the amount of internal drainage, and the amount of surface runoff (Roygard et al., 2002).

Water regime was a significant factor on PAW15cm only during the dry growing season in 2002. At Lewiston, water regime was significant at the lowest two sampling depths, and at the 0- to 15-cm, 30- to 45-cm, and 45- to 60-cm sampling depths at Plymouth. The low amount of irrigation water applied per event at Plymouth and the coarse, moderately well drained and well drained soils at Lewiston contributed to a shallow rooted crop, which allowed accumulation of irrigation water in lower sampling depths that was unavailable for crop growth.

Year was a significant factor on PAW15cm at growth stage III at all four sampling depths. Temporal differences in rainfall from 2001 to 2002 were responsible, with 2001 receiving over twice as much rainfall as 2002 through growth stage III. Year was not significant at growth stage IV, due mainly to late season rains in 2002 which raised PAW15cm measurements, and a lack of significant rainfall over the 2001 growth stage IV measurement period which depleted PAW15cm from previous levels. Even though irrigation events occurred throughout these growth stages, the amount of water applied at each event was not sufficient to influence the effect of year on PAW15cm.

The location x water regime interaction at the growth stage V 0- to 15-cm and 15- to 30-cm sampling depths can be explained by the lack of significant rainfall over the 24 day period prior to the 9 July 2002 measurement taken at Lewiston, the influence of irrigation events on PAW15cm over the same 24 day period, and the impact of 3.71 cm of rainfall which fell one day before the 22 July 2002 measurement date at Plymouth. Location was significant at growth stage II (30- to 45-cm and 45- to 60-cm sampling depths), growth stage III (0- to 15-cm and 15- to 30-cm sampling depths), growth stage IV (0- to 15-cm sampling depth), and growth stage V (0- to 15-cm, 15- to 30-cm, and 30- to 45-cm sampling depths). These differences can be attributed to timing of rainfall in respect to measurement date, soil textural differences between the two locations (Hillel, 1998), the increased available water holding capacity of the soils at Plymouth due to higher organic matter content (Hudson,1994), and the amount of rainfall received and stored throughout the respective growing season.

Water regime was significant at growth stages I, III, and V. The significance at growth stage I was not due to water regime as irrigation had not yet been applied. Water regime had a significant impact on PAW15cm at the 0- to 15-cm and 15- to 30-cm sampling depths at growth stage III. While the measurement date at Lewiston in 2001 had not received irrigation, the measurement date at Plymouth in 2001 received no significant rainfall and two irrigation events over the 10 day period prior to measurement, and the Plymouth 2002 measurement dates received only 4.1 cm of rainfall and 3.0 cm of irrigation water over the 18 days prior to the 1 July measurement date. At growth stage V, water regime effects on PAW15cm were significant at the 30- to 45-cm and 45- to 60-cm sampling depths. Both measurement dates for this stage were during the very dry 2002 growing season, and reflect the difference the irrigation events made on stored soil moisture at the lower sampling depths.

This study showed that rainfall, water treatments, and location (related to differences in soil texture and how irrigation treatments were applied) were the main factors influencing the dynamic changes in PAW measured at different sampling depths in 2001 and 2002. In this study we observed the influence of rainfall (and irrigation) on PAW, and that this influence was similar to the observations of Mohanty and Skaggs (2001) that rainfall is the single most important climatic factor for soil moisture and its temporal distribution. As noted by Roygard et al. (2002), we observed the spatial and temporal distribution of rainfall in the Mid-Atlantic region. Our documentation of the impact of soil texture (as it varied between locations) on PAW coincided with Hillel (1998), Roygard et al. (2002), and Van Pelt and Wierenga (2001).

Rainfall contributed heavily to changes in PAW at the shallow sampling depths whereas the influence of irrigation was observed at the deeper sampling depths due to the accumulation of water that was not affected by transpiration and evaporation. While rainfall and irrigation would also be expected to impact yield and potential and crop stress, it is clear that large changes in PAW occur at depths up to 30 cm and that it would be difficult to use single measurements of PAW at these depths to determine yield potential.

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Table 2.1. Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Lewiston in 2001.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Date	2.7928	<0.0001	6.2952	<0.0001	1.6255	0.0068	2.0147	0.0006
Water Regime	0.1446	0.1107	0.3421	0.2062	0.6331	0.1018	0.4360	0.1084
Date X Water Regime	0.1016	0.1823	0.2345	0.3517	0.1446	0.6713	0.2187	0.3203

† = Mean Square Error

Table 2.2. Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Plymouth in 2001.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Date	10.5246	<0.0001	7.8636	<0.0001	1.7606	0.0004	3.3491	0.0003
Water Regime	0.3592	0.1448	0.1120	0.6033	0.3540	0.1857	0.1116	0.7425
Date X Water Regime	0.4461	0.0435	0.5608	0.0448	0.1399	0.6416	0.7517	0.1007

† = Mean Square Error

Table 2.3. Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Lewiston in 2002.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Date	1.5034	0.0004	3.1456	0.0058	1.5325	0.0009	0.2060	0.4398
Water Regime	0.2813	0.1714	0.0038	0.9311	2.7417	0.0004	4.0572	0.0003
Date X Water Regime	0.4258	0.0665	0.5417	0.3600	0.3485	0.1478	0.0029	0.9880

† = Mean Square Error

Table 2.4. Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Plymouth in 2002.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Date	9.4448	<0.0001	4.3468	<0.0001	0.2880	0.4427	0.6405	0.6487
Water Regime	1.7851	0.0005	0.0888	0.6336	7.3273	<0.0001	9.2746	0.0042
Date X Water Regime	0.6344	0.0021	0.4830	0.3017	0.0368	0.9741	0.0215	0.9991

† = Mean Square Error

Table 2.5. Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Growth Stage I (V15).

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Water Regime	0.4649	0.1080	0.5809	0.0149	0.1720	0.3464	0.3244	0.2327

† = Mean Square Error

Table 2.6 . Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Growth Stage II (V19/VT).

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location	0.5809	0.0662	0.5132	0.2062	1.6100	0.0055	3.4971	0.0011
Water Regime	0.0164	0.8919	0.2178	0.4897	0.0652	0.6411	0.0987	0.6084
Location X Water Regime	0.0157	0.8964	0.1717	0.5657	0.4505	0.0776	0.4546	0.1342

† = Mean Square Error

Table 2.7. Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Growth Stage III (R1).

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location	1.1420	0.0100	4.9152	0.0001	0.0062	0.8737	0.1844	0.5888
Water Regime	1.3355	0.0009	0.9344	0.0397	0.3478	0.2557	0.8303	0.2751
Location X Water Regime	0.1276	0.4429	0.0384	0.8647	0.0940	0.6839	0.0959	0.8571
Year	6.7941	<0.0001	6.3373	<0.0001	4.9497	<0.0001	14.1417	<0.0001
Year X Water Regime	0.0469	0.5832	0.0042	0.9002	0.0946	0.5382	0.4924	0.3779

† = Mean Square Error

Table 2.8. Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Growth Stage IV (R2/R3).

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location	5.5512	<0.0001	0.2761	0.3715	0.1952	0.4279	0.0599	0.7808
Water Regime	0.3844	0.1350	0.5157	0.2307	0.5562	0.1753	1.0592	0.2630
Location X Water Regime	0.2534	0.2603	0.2822	0.4412	0.3346	0.3434	1.0100	0.2792
Year	0.0411	0.6363	1.1479	0.0736	0.9767	0.0817	1.2315	0.2123
Year X Water Regime	0.0418	0.6336	0.0525	0.6954	0.3271	0.3064	0.1333	0.6784

† = Mean Square Error

Table 2.9. Factors influencing PAW15cm (plant available water per fifteen centimeters of soil depth) at Growth Stage V (R4).

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location	15.7281	<0.0001	3.4552	0.0173	5.9398	<0.0001	2.7071	0.0747
Water Regime	0.1316	0.3986	0.0960	0.6699	3.0614	0.0015	3.9605	0.0341
Location X Water Regime	1.2010	0.0173	2.4276	0.0418	0.2593	0.2971	0.0666	0.7711

† = Mean Square Error

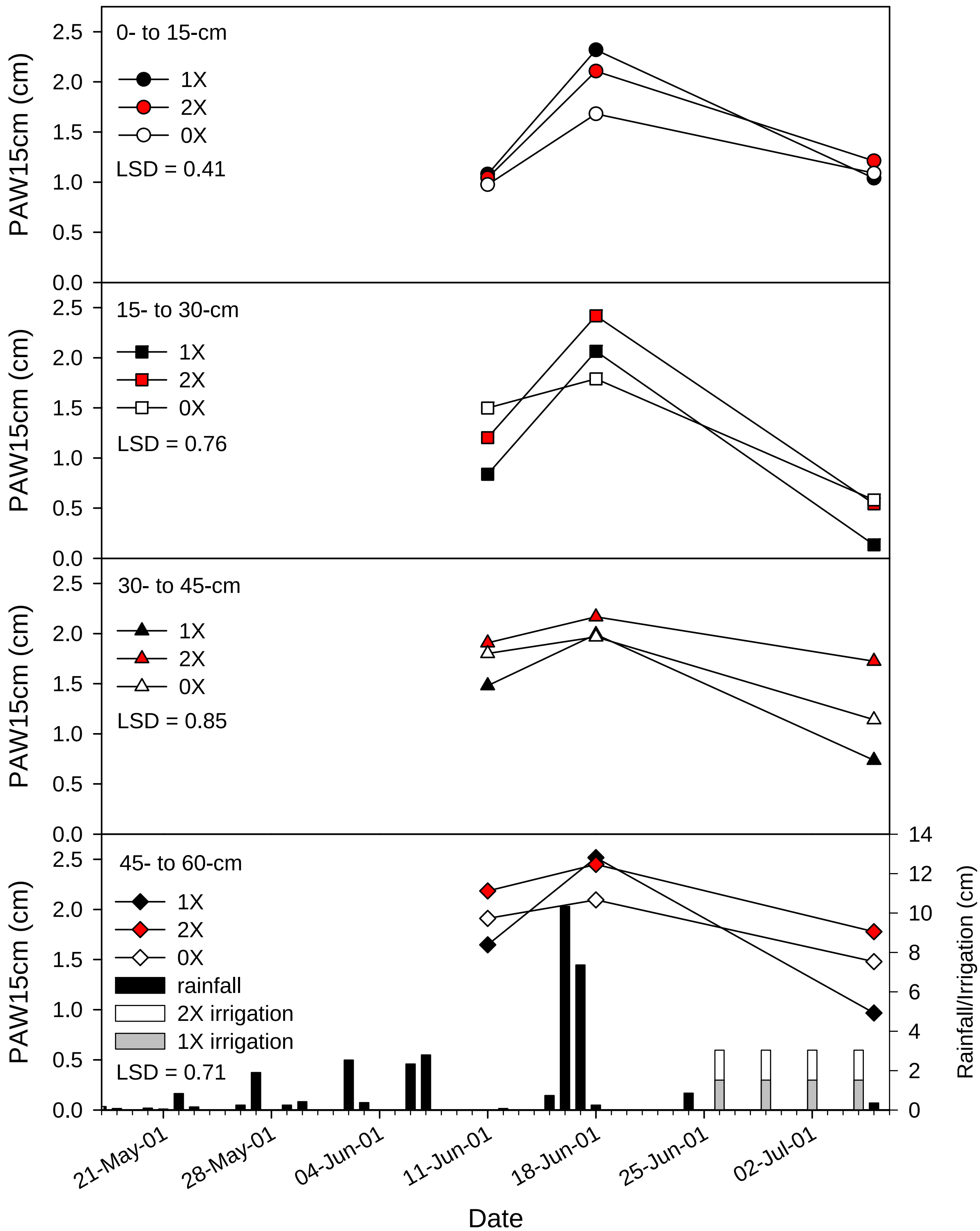

Figure 2.1. PAW15cm (plant available water per fifteen centimeters of soil depth), measured rainfall, and irrigation at Lewiston in 2001.

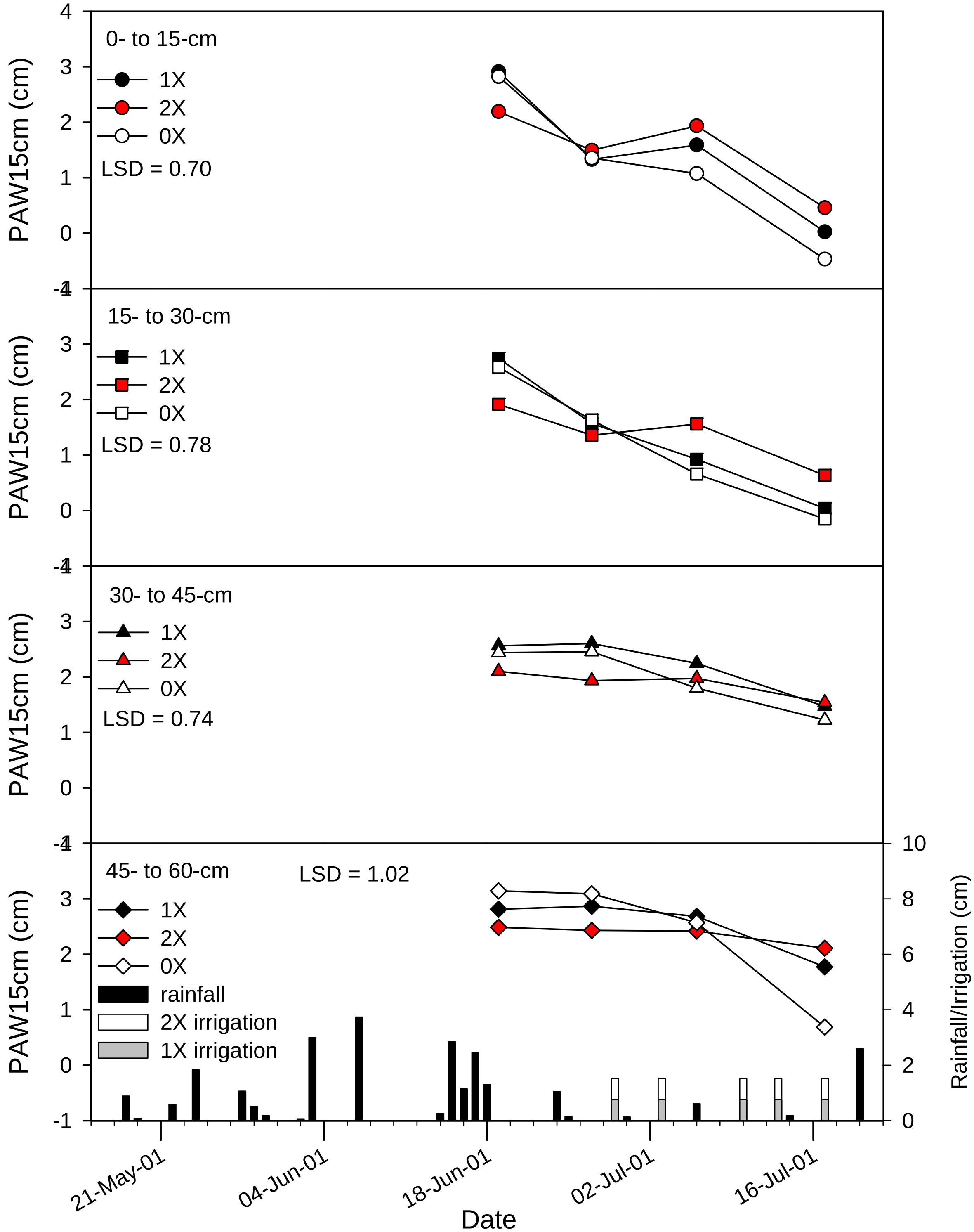

Figure 2.2. PAW15cm (plant available water per fifteen centimeters of soil depth), measured rainfall, and irrigation at Plymouth in 2001.

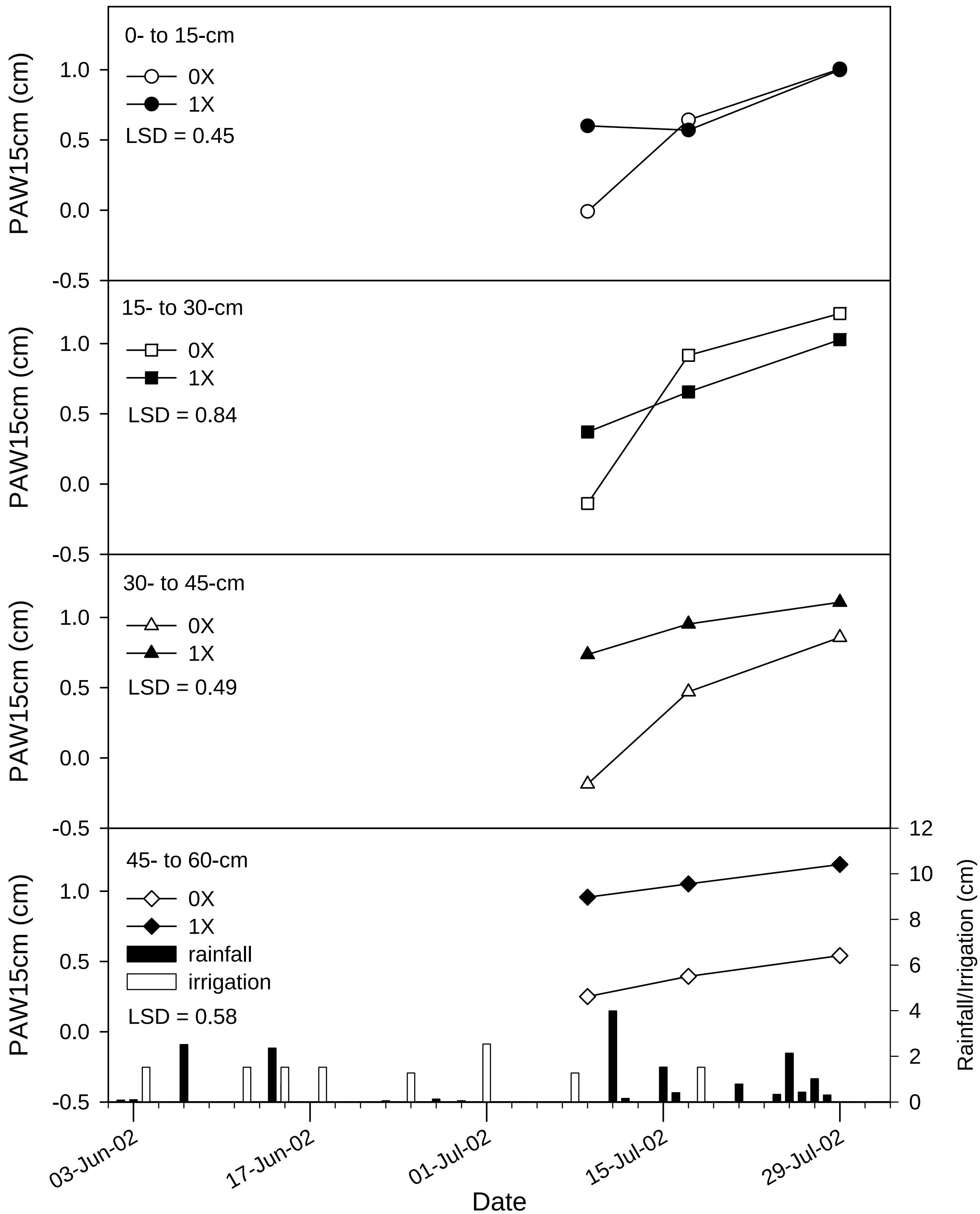

Figure 2.3. PAW15cm (plant available water per fifteen centimeters of soil depth), measured rainfall, and irrigation at Lewiston in 2002.

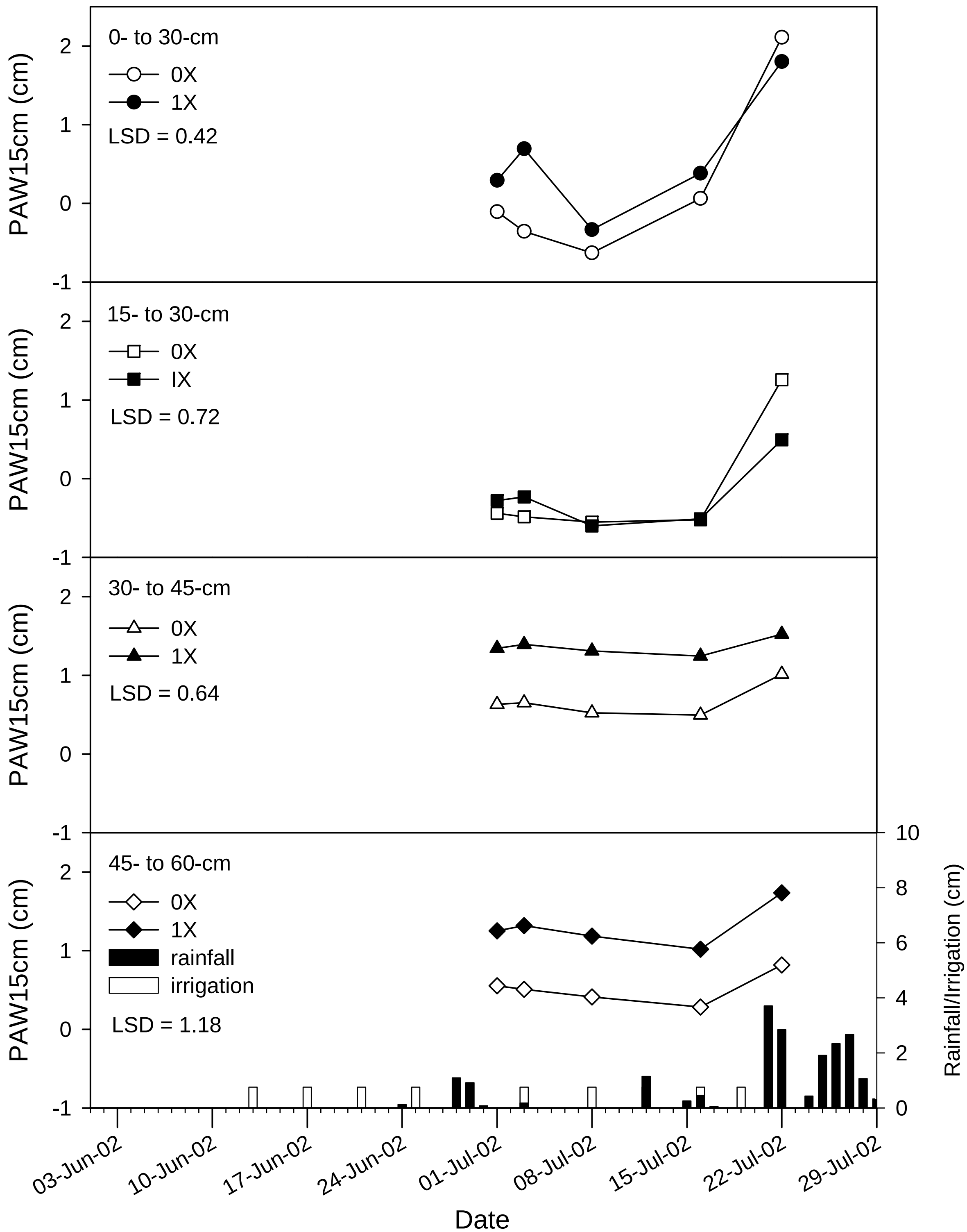

Figure 2.4. PAW15cm (plant available water per fifteen centimeters of soil depth), measured rainfall, and irrigation at Plymouth in 2002.

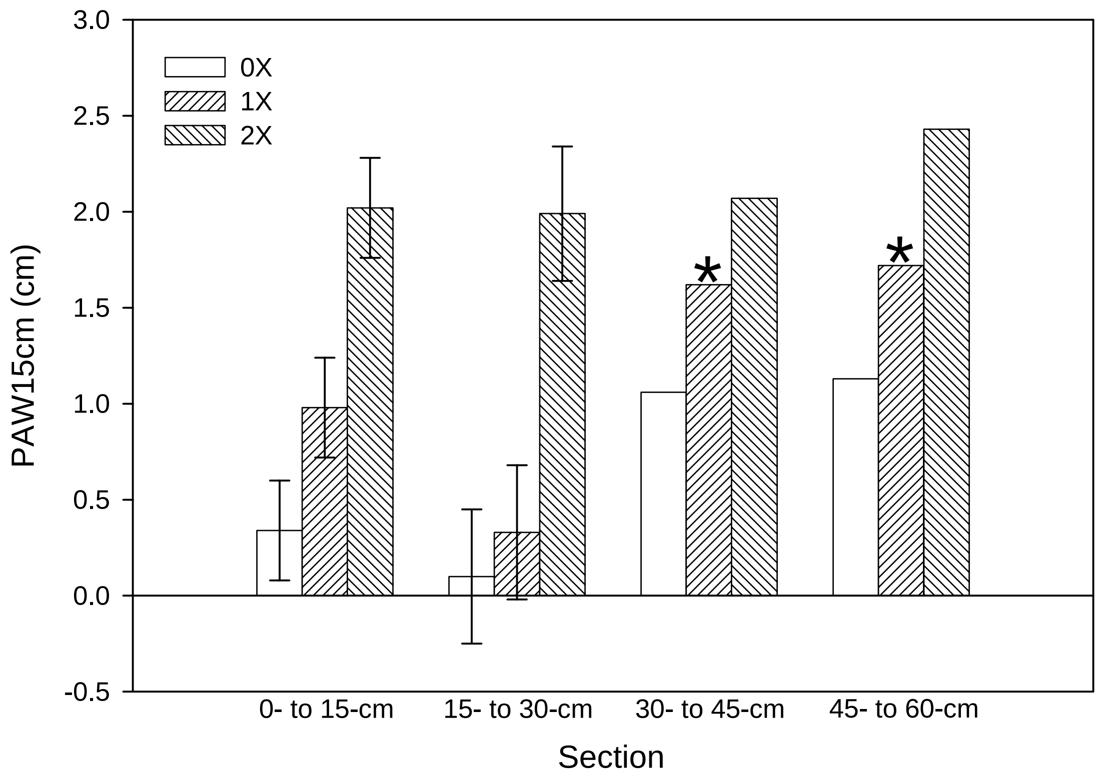

Figure 2.5. PAW15cm (plant available water per fifteen centimeters of soil depth) at three water regimes and four sampling depths at Growth Stage III (R1).
* signifies F-test did not indicate significant differences at this sampling depth.

Chapter Three

Relationship Between Plant Available Water Measured Throughout the Growing Season and Yield

Abstract

Understanding and measuring the driving forces behind potential corn yield within the growing season is vitally important because it allows adjustment of inputs to maximize economic returns. The goal of this study was to determine if there was a relationship between plant available water per fifteen centimeters of soil depth (PAW15cm) measured at different dates throughout the growing season and corn yield. Measurements of plant available water were taken over time at four sampling depths at Lewiston and Plymouth in 2001 and 2002 and compared to yield. An analysis of covariance found PAW15cm had a significant influence on yield at the two deepest profile levels within growth stages II (V19/VT), III (R1), and IV(R2/R3). The only stage with strong linear relationships between PAW15cm and yield was growth stage III which represents R1 or silking stage. To narrow the search for significant relationships, the data were divided into individual locations and dates and tested for linear correlations between PAW15cm and yield at each sampling depth. Three of the four sampling depths (0- to 15-cm, 15- to 30-cm, and 45- to 60-cm) at Lewiston on the 18 June 2001 measurement date (corresponding to the R1 growth stage) indicated significant correlations between PAW15cm and yield. Significant correlations were also observed at the 30- to 45-cm sampling depth at each 2002 Plymouth measurement date corresponding to the R1 and R2/3 growth stages, indicating the 2002 crop was dependent on soil moisture stored deeper in the soil profile. The lack of strength of these relationships makes it difficult to use them to predict corn yield, but they could be used as indicators of potential yield problems and as aids to irrigation recommendations.

Introduction

Understanding and measuring the driving forces behind potential corn yield within the growing season is vitally important in that it allows adjustment of inputs to maximize economic returns. Yield potential of corn is often impacted by limited amounts of water, specifically the amount of available soil water (Roygard et al., 2002). In the mid-Atlantic region, rainfall amounts during the growing season are usually sufficient to produce profitable yields, but can be variable from year to year. Because very little corn in this region is irrigated, profitable production is heavily dependent on the amount of rainfall and the soils ability to store water for plant growth. Understanding the relationship between plant available water (PAW) measured throughout the growing season and yield would assist growers in managing irrigation and nitrogen applications.

Researchers have concluded that temperature, solar radiation and water availability (soil water storage and rainfall) are the major determining factors in corn production (Carlson, 1990; Dale and Daniels, 1995). Runge (1968), measuring the influence of both maximum daily temperatures and precipitation on corn yields, found that high temperatures were not detrimental if soil moisture was not limiting. Yield of corn suffers in response to soil moisture deficits at any growth stage (Howe and Rhoades, 1955). Eck (1984) found that stress imposed on corn at the vegetative stages of growth for 14 and 28 days reduced yields by 23 and 46%, respectively. However, corn is especially sensitive to moisture stress during the time of tasseling and continuing through grain fill (Musik and Dusek, 1980; Nesmith and Ritchie, 1992). Denmead and Shaw (1960) reported that stress at vegetative growth stages, at silking, and after silking reduced corn yield by 25, 50, and 21%, respectively. Robins and Domingo (1953) found that corn yields were reduced by 22% when soil moisture was reduced to wilting point for a period of 1 to 2 days during tasseling or pollination, and that yields were reduced by 50% after 6 to 8 days of stress at this stage. Musik and Dusek (1980) found soil moisture stress during periods of tasseling and silking to be most detrimental to yield, and that soil moisture stress during the time of grain fill was more harmful to yield than that during vegetative growth. Runge (1968) and Thompson (1975) concluded that corn yield was highly correlated with water availability at tasseling.

There is a need for research to understand within-season crop water use and how it affects corn yield (Sadler et al., 2000). Many studies have explored the relationship of seasonal crop water storage and yield. Holt et al. (1964) evaluated corn response to plant available stored moisture at planting and found that yield was highly correlated to the amount of stored soil moisture at planting during a year with below average rainfall. Leeper et al. (1974) found that most of the corn yield variation within a field was correlated with rooting depth, available water holding capacity in the root zone, or weekly plant available stored soil moisture. Frye et al. (1983) reported that during years of low rainfall, yield of corn was highly correlated to sampling depth. Swan et al. (1987) observed that the effective plant rooting depth to corn yield relationships were influenced significantly by climate, with higher correlations between yield and rooting depth during years of low rainfall (Timlin et al., 1998). Roygard et al. (2002) compared yield across three soil types with varying water-holding capacities at the vegetative, tasseling, and grain filling stages of corn growth, and found that differences in water stress between soil types were related to the capacity of the soils to store water. Schneider and Howell

(1998) compared the yields of corn across treatments in which soil water was maintained at five levels in 25% increments ranging from 0 to 100% of available water capacity (AWC) throughout the growing season. They found that yields were highest when AWC of soils was held close to 100% throughout the growing season.

Researchers have turned to plant growth models to maximize crop management practices and predict yields (Xie et al., 2001). A general crop model called Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) was designed to simulate critical growth processes of a variety of crops (Kiniry et al., 1992). Other models, such as CERES-Maize (Crop-Environment Resource Synthesis) (Jones and Kiniry, 1986) and and SORKAM (SORghum, Kansas, A&M) (Rosenthal et al., 1989a) were designed for specific crop applications. These models predict crop yield by incorporating numerous factors into daily estimates of crop growth and development throughout the life cycle of the crop.

One such factor is soil moisture. The effects of soil moisture on crop growth and yield are determined by first calculating potential evapotranspiration (ET_p) and LAI (Leaf Area Index), followed by the determination of a water stress factor based on soil water supply and actual evapotranspiration (ET_a) which is used to estimate the decrease in daily crop growth and yield. This water stress factor is a ratio of crop water use, based on PAW and rooting depth of the crop, to crop water demand. If PAW in the current rooting zone is sufficient to meet demand, yield is maximized. If PAW is restricted, then crop growth is restricted based on the PAW. Factors influencing plant assimilation and leaf expansion growth are calculated and applied to determine crop growth and yield predictions. Muchow et al. (1994) used a sorghum growth simulation model to show that sorghum yields were mainly associated with the amount of water stored in the soil at planting. Yields were always higher where the soil water profile was full rather than half full at any planting date and for any available soil water capacity at any location. Paz et al. (1998) used a soybean model to correlate yield variability with variability of simulated water stress. Moore and Tyndale-Brisco (1999), using crop models, observed that much of the variability in wheat response to nitrogen could be explained by differing soil water holding capacities.

The ability to predict yield potential of corn based on soil moisture status at a given time during the growing season would enable producers to maximize inputs such as irrigation, fertilizer, insecticides and fungicides. This ability would enable growers to remain profitable while continuing to meet the ever-increasing environmental standards of today's society. The objective of this study was to quantify the relationship between plant available water per fifteen centimeters of soil depth (PAW15cm) measured at four depths throughout the growing season and yield of corn.

Materials and Methods

Experiments were conducted at two locations, the Peanut Belt Research Station (PBRS) at Lewiston, North Carolina and the Tidewater Research Station (TRS) at Plymouth, North Carolina, in both 2001 and 2002. At Lewiston in 2001, the predominate soil types at the site were a Norfolk sandy loam (Fine-loamy, siliceous, thermic Typic Paleudults) and a Goldsboro sandy loam (Fine-loamy, siliceous, thermic Aquic Paleudults). At Plymouth in 2001, the experiment was conducted on a Portsmouth sandy loam (Fine-loamy over sandy or sandy-skeletal, mixed, thermic Typic Umbraquults). In 2002, the soil types at Lewiston were Goldsboro and Lynchburg sandy loams (Fine-loamy, siliceous, thermic Aeric Paleaquults), and a Rains sandy loam (Fine-loamy, siliceous, thermic Typic Paleaquults). Soils at the Plymouth site in 2002 were a Portsmouth sandy loam and a Cape Fear loam (Clayey, mixed, thermic Typic Umbraquults).

Fields were prepared and planted using conventional tillage methods. Row width for both years at Lewiston was 91 cm, and row width for both years at Plymouth was 96 cm. Pioneer 31G98 was planted at a population of 67,500 seeds per hectare on 4 April 2001 and 6 April 2002 at Lewiston, and 30 April 2001 and 27 April 2002 at Plymouth. Production practices were consistent with those generally used for profitable corn production in eastern North Carolina (Heiniger et al., 2002). Weed control at both test sites in both years was excellent due to proper timing and application of herbicides. Plots at Lewiston in 2001 received 168 kg 0-0-60 ha^{-1}, 112 kg 0-46-0 ha^{-1}, and 224 kg N ha^{-1} pre-plant, with an additional 224 kg N ha^{-1} applied at growth stage VT (Ritchie et al., 1993). In 2002, plots received 112 kg 0-0-60 ha^{-1} and 112 kg 18-46-0 ha^{-1} pre-plant, with 145 kg N ha^{-1} applied at growth stage V3. Plots at Plymouth in 2001 received 336 kg 9-23-30 ha^{-1} pre-plant and 224 kg N ha^{-1} applied at growth stage VT. In 2002, plots received 81 kg N ha^{-1} pre-plant and 49 kg N ha^{-1} applied at growth stage V3.

In 2001, the experimental design of the test was a modified Randomized Complete Block (Steel et al., 1997) with three water regimes as the main treatments replicated in three blocks. Water regime treatments were comprised of no irrigation (0X), normal irrigation (1X) and double irrigation (2X). At Lewiston, this was accomplished using gated furrow irrigation by positioning the test on a slight grade with the rows directed downhill and the 2X plots above the 1X plots. Alleys for each treatment were flooded until water began to exit the 1X plots at the far end of the field. This system worked well for providing two different levels of irrigation, but did not provide a way to accurately measure the amount of water applied to each treatment. Irrigation in 1X plots was estimated to be 1.5 cm, and 2X plots received an estimated 3.0 cm per irrigation (Barnes, 2004, personal communication).

At Plymouth, plots were irrigated using an overhead linear irrigation system which delivered 0.8 (1X) and 1.5cm (2X) of water. In 2002, the experimental design of the test was a modified Randomized Complete Block with two water regimes as the main treatments (0X and 1X) replicated six times. Both locations were irrigated using overhead linear irrigation systems in 2002. The system at Lewiston delivered an average of 1.4 cm of water at every event except one, which measured 2.5 cm. The system at Plymouth applied 0.8 cm of water during each irrigation. At both locations in both years, irrigations were scheduled when cumulative rainfall during the previous three to four days did not exceed 1.3 cm.

The goal for this study was to simultaneously take canopy temperature and soil moisture measurements at least weekly at both locations. Canopy temperature measurements require near cloudless conditions for an accurate measurement to be made (Gardner et al., 1992). Measurements must be taken on sunny days between 1100 hours and 1400 hours. In 2001, clear sunny days were rare events. Uncooperative weather for data collection allowed only three measurement dates at Lewiston and four measurement dates at Plymouth. The same phenomena affected data collection in 2002 with only three measurement dates at Lewiston and five measurement dates at Plymouth.

Soil water content was measured using time domain reflectometry (TDR) probes (MP-917, Environmental Sensors Inc., Victoria, BC, Canada) at 0- to 15-cm, 15- to 30-cm, 30- to 45-cm, and 45- to 60-cm sampling depths. After harvest, the probes were removed, and a 0.6-m deep hole was excavated to gather undisturbed samples from each of the four sampling depths. A soil water retention analysis of the samples was performed to determine the maximum amount of plant available water per fifteen centimeters of soil depth on a volume basis (Cassel and Nielson, 1986). Published bulk density measurements for each soil (United States Department of Agriculture, 1981; 1990; 1995) were used for these calculations.

Grain yield was determined by harvesting the two center rows of each plot using a Gleaner (AGCO Corp., Duluth, GA) two row combine. Moisture content and grain yield were recorded using a HarvestMaster Grain Gauge (Juniper Systems, Inc., Logan, UT). Grain yield was adjusted to a moisture content of 155 g kg^{-1}.

To determine the influence of year, location and water regime on grain yield, an analysis of variance (ANOVA) was performed on the overall data set using the PROC GLM procedure in SAS (SAS version 8.2, SAS Institute Inc, Cary, NC). This analysis was performed with year and location considered as the main plot factors and water regime as the subplot factor.

The first step in analyzing the relationships between PAW15cm measured on different dates and yield was to determine if PAW15cm was a significant factor in describing the variability in yield not already accounted for by year, location, and water regime. Planting dates differed across years and locations and it was impossible to measure canopy temperatures and soil moisture at both locations on the same day. Therefore, the data from both years and locations were combined by crop growth stage to minimize the effects of plant size and physiological development on the amount of PAW15cm present at differing depths in the soil. Growing degree days (GDD) were calculated for each measurement date and location, and the data was separated into as many identifiable growth stages as possible. This resulted in five data groups representing growth stages I (V15), II (V19/VT), III (R1), IV (R2/R3), and V (R4). An analysis of covariance (ANCOVA) was then performed to test the effects of PAW15cm on yield at all five growth stages with either year or location or both (depending on the availability of data by growth stage) as main effects and water regime as the subplot effect. Finally, each stage was separated into individual locations, years and sampling dates. This allowed us to perform tests for linear correlations between PAW15cm and yield using the PROC CORR and PROC REG procedures in SAS.

Results And Discussion

Location X Water Regime Interaction.

An examination of the effects of year, location, and water regime on grain yield found significant location X water regime and year X water regime interactions and a significant water regime main effect (Table 3.1). The 0X, 1X, and 2X water regime treatments at Lewiston yielded 9.92, 14.31, and 13.35 Mg ha^{-1}, respectively (Figure 3.1). At Lewiston, yields for the 1X and 2X treatments were significantly higher than the yield of the 0X treatment. In contrast, at Plymouth, yields for 0X, 1X, and 2X irrigation treatments were 8.84, 8.93, and 9.94 Mg ha^{-1}, respectively. The yields for the Plymouth treatments were not significantly different from each other. At both locations there was a trend toward increasing yields as irrigation levels increased. However, differences between the non-irrigated and irrigated treatments were greater at Lewiston. This was probably caused by the fact that the soils at the PBRS are very sandy and well drained, while at the TRS the soil had higher organic matter content and was finer textured.

Year X Water Regime Interaction.

In 2001, yields for the 0X, 1X, and 2X water regimes were 11.11, 11.32, and 11.65 Mg ha^{-1}, respectively, with no significant difference among the treatments, and only a slight trend toward increasing yields as irrigation increased (Figure 3.2). This was due primarily to adequate rainfall received during the 2001 growing season. In 2002, yields for the 0X and 1X irrigation treatments were 8.30 and 10.92 Mg ha^{-1}, respectively, with the yield for the 1X treatment significantly higher than that of the 0X treatment.

Rainfall during the growing season was very low in 2002 and there was a clear trend toward increasing yields as irrigation levels increased .

Water Regime Main Effect.

Since there was a general trend toward increases in yield with increasing amounts of irrigation applied in both the location by water regime and year by water regime interactions we felt that consideration of the water regime main effect was in order. A trend toward increasing yields as irrigation levels increased was evident (Figure 3.3). The 0X, 1X and 2X irrigation treatments yielded 9.30, 11.08, and 11.65 Mg ha^{-1}, respectively. The yields for the 1X and 2X treatments were significantly higher than the yield of the 0X treatment. Based on two completely different growing seasons and two entirely different soils, yield increased as more irrigation water was applied.

Effect of PAW15cm Measured at different Growth Stages on Corn Yield.

An analysis of covariance only found significant effects of PAW15cm on grain yield at Stage II at the 45- to 60-cm (Table 3.2) sampling depth, Stage III at the 30- to 45-cm (Table 3.3) and 45- to 60-cm (Table 3.2) sampling depths, and Stage IV at the 30- to 45-cm (Table 3.3) sampling depth. At growth stage II, plots with PAW15cm as the independent variable and yield as the dependent variable found a weak relationship with PAW15cm only explaining 16% of the variability in yield at the 45- to 60-cm sampling depth (Fig. 3.4). In addition, this relationship had a negative slope indicating that as PAW15cm increased yield decreased.

Both measurements in Stage II were taken during the 2001 growing season. Rainfall was ample for corn production through 18 June which was the date of the last measurement. Even though differences in PAW15cm measurements were observed at the different sampling depths at both Plymouth and Lewiston, no irrigation was applied before either of the Stage II measurements. It is important to note that all calculations for PAW15cm were determined using published bulk density measurements for the appropriate soil mapping units (United States Department of Agriculture, 1981; USDA 1990; USDA 1995). It has been reported that soil map units are not homogenous with respect to water relations and that a single soil description for an entire soil map unit will not likely explain variance within a field (Sadler, 2000). Therefore, spatial differences in soil bulk density likely contributed to the negative trend observed here. Since the maximum plant available water that the soils at these locations can hold ranges from 1.7 to 3.5 cm^3 cm^{-3} (Table 3.4) and since a corn crop can transpire over 0.9 cm of water per day (Heiniger et al., 2002), it is not surprising that the amount of PAW15cm measured at this stage would have little impact on corn yield.

At growth stage III, the relationships between PAW15cm and yield at the 30- to 45-cm and 45- to 60-cm sampling depths were stronger than those found at Stage II or IV and had a positive slope (Fig. 3.5). At both sampling depths, PAW15cm accounted for 46 to 47% of the variability in yield. It is interesting to note that the linear trend between PAW15cm and yield is mostly the result of differences in yield and PAW15cm in samples taken in the 0X water regime. While there were strong positive relationships between PAW15cm and yield at the 0- to 15-cm and 15- to 30-cm sampling depths, the analysis of covariance indicated that the water regime treatments accounted for most of the differences in PAW15cm and yield in these relationships.

At growth stage IV, there was a weak but positive relationship between PAW15cm and grain yield at the 30- to 45-cm sampling depth (Fig. 3.6). Differences in PAW15cm accounted for only 15% of the variability in yield at the 30- to 45-cm sampling depth in this stage. The significant covariate relationship found at this stage was weaker than those identified at either Growth Stage II or III.

The negative relationship found at growth stage II and the low r^2 values of the positive relationship at growth stage IV indicate that comparisons at neither of these stages have much promise for predicting yield based on stored soil moisture. Only at growth stage III was there a reasonable relationship between PAW15cm and grain yield. Unfortunately, the strength of the relationship between PAW15cm and yield at growth stage III does not indicate that PAW15cm is a strong factor in terms of yield determination.

Analysis of the Relationship Between Yield and PAW15cm by Location and Date.

To better understand the relationship between PAW15cm and grain yield, the data were separated into individual locations and dates and tests for linear correlation between PAW15cm and grain yield were performed. Because all Lewiston 2002 PAW15cm measurement dates occurred at GS V (R4) or later, and since our covariate analysis failed to reveal any indication that PAW15cm impacted yield at GS V, the Lewiston 2002 measurement dates were not included in our test for linear correlations. Data taken from Lewiston in 2001 on 11 June (V19/VT) and 6 July (R2/R3) indicated no significant correlations between PAW15cm and grain yield at any sampling depth. However, data taken from Lewiston on 18 June (R1) (Figure 3.7) indicated significant correlations between PAW15cm and grain yield at the 0- to 15-cm (r^2 = 0.80), 15- to 30-cm (r^2 = 0.45), and 45- to 60-cm (r^2 = 0.76) sampling depths, with significant correlation coefficient values ranging from 0.67 to 0.89 (Table 3.5). The significance of these correlations at R1 verifies our earlier covariate analysis which indicated that the early reproductive period (GS III) offered the strongest relationship between PAW15cm and yield. It is interesting to note that this measurement date received no irrigation prior to the measurement of PAW15cm. Rainfall over the two day period prior to that measurement date measured 17.7 cm. Differences in PAW15cm as measured at this location can be partially explained by spatial variations of soil water holding capacity within the Norfolk and Goldsboro soils found there. Also, the slight grade of the field, with the 1X treatment at the bottom of the grade, allowed for excessive run-off from other treatments during heavy rainfall events onto the 1X treatment. Infiltration of additional run-on water artificially raised the PAW15cm of the 1X treatment measurements.

Data taken from Plymouth in 2001 on 27 June (V19/VT), 6 July (R1) and 17 July (R2/R3) indicated no significant correlations between PAW15cm and grain yield at any sampling depth. Growing conditions in 2001 were ideal for corn production with ample rainfall through VT. While rainfall after this stage was limited, the amount of stored soil moisture was adequate to supply the crop through the critical moisture dependent stages of growth. As a result, we did not detect a relationship between yield and PAW15cm at any date in Plymouth in 2001.

Data taken from Plymouth in 2002 on 1 July (Figure 3.8), 3 July (Figure 3.9), 8 July (Figure 3.10), and 16 July (Figure 3.11) indicated significant correlations between PAW15cm and grain yield at the 30- to 45-cm sampling depth on all measurement dates (1 July r^2=0.43; 3 July r^2=0.47; 8 July r^2=0.45; 16 July r^2=0.45), with significant correlation coefficient values ranging from 0.65 to 0.68 (Table 3.6). The significance of these dates at the 30- to 45-cm sampling depth indicates a crop at R1 to R3 responding to a dry growing season by extending roots into the lower sampling depths for needed moisture. As of 1 July, only 13.6 cm of rainfall had been measured since the 27 April planting date with an additional 5.3 cm of water applied to irrigated treatments. Of the rainfall total, 2.1 cm had fallen within the three day period prior to the 1 July measurement date. Dry conditions persisted throughout this period with an additional 1.6 cm of rainfall accumulating between 1 July and 16 July. Irrigation amounts over the period between 1 July and 16 July were 3.0 cm. Due to the lack of rainfall, the amount of stored moisture in the lower profile was important in 2002. This corresponds to the general trend found in the covariate analysis where PAW15cm was more often significant at the two lower depths in the profile.

Conclusion

The goal of this study was to determine if there was a relationship between PAW15cm measured at different dates throughout the growing season and corn yield. Such a relationship could be used to predict yield potential based on measured soil moisture and could aid growers in determining when to irrigate and in adjusting nitrogen rates to match the condition of the crop. Analysis of the data found significant effects of location X water regime and year X water regime interactions and water regime main effects. Differences in soil organic matter and texture, and therefore PAW15cm, between locations contributed to these effects. The two growing seasons were completely different climatologically, as abundance of rainfall nullified any stress until late in 2001 while 2002 was extremely dry until well into the critical stages of crop growth.

An analysis of covariance with PAW15cm included as a covariate found PAW15cm had a significant influence on yield at certain sampling depths within growth stages II, III, and IV. It is important to realize that the significant covariate was found at the two deepest profile levels and that the only stage with strong linear relationships between PAW15cm and yield was growth stage III which represents R1 or silking stage. This is consistent with research indicating that corn is especially sensitive to moisture stress during the time of tasseling and continuing through grain fill (Musik and Dusek, 1980; Nesmith and Ritchie, 1992). Corn yields can be reduced by 50% when moisture stress is imposed over a 6 to 8 day period at VT (Robins and Domingo, 1953). Denmead and Shaw (1960), Runge (1968), and Thompson (1975) concluded that corn yield was highly correlated with water availability at the VT to R1 stages. Our research indicated the same conclusions, and this result, at least, confirms that if PAW15cm is to be used to predict yield measurements at this stage appear to offer the most promise.

To narrow the search for significant relationships further, the data were divided into individual locations and dates and tested for linear correlations between PAW15cm and yield at each sampling depth. Three of the four sampling depths (0- to 15-cm, 15- to 30-cm, and 45- to 60-cm) at Lewiston on the 18 June 2001 measurement date (corresponding to the R1 growth stage) indicated significant correlations between PAW15cm and yield. This was despite the fact that no irrigation had been applied prior to the measurement date and 17.7 cm of rainfall fell over the two previous days. This is also consistent with research by Denmead and Shaw (1960), Runge (1968), and Thompson (1975) indicating that corn yield is highly correlated with water availability at the VT to R1 stages.

Significant correlations were also observed at the 30- to 45-cm sampling depth at 2002 Plymouth measurement dates corresponding to the R1 and R2/3 growth stages, indicating the 2002 crop was dependent on soil moisture stored in the deeper sampling depths. This is consistent with the work of Swan et al. (1987) who observed that the effective plant rooting depth to corn yield relationships were influenced significantly by climate, and of Timlin et al. (1998), who documented higher correlations between yield and rooting depth during years of low rainfall.

The lack of consistent correlations between PAW15cm and yield were most likely the result of the rapidly changing moisture status of the soil caused by rainfall, sandy textured soils, and high PET. It was also interesting to note the lack of consistency of available water content per fifteen centimeters of soil and, therefore, PAW15cm measurements among soils of the same series. Variations of measurements within soils of the same map unit were observed and noted by Sadler et al. (2000), and these variations within soil map units contributed to the lack of consistency within our measurements. Also, soil survey maps used for determining soils within the experiments were not of a scale sufficient to insure precise knowledge of a boundary between soils. Therefore, AWC15cm and PAW15cm measurements often did not match those of neighboring measurement sites that were mapped as the same soil. By using the very general published bulk density measurements accuracy was compromised. Individual soil samples for each sampling depth at each TDR probe site should have been measured for bulk density. This would have allowed for improved precision and accuracy of AWC15cm and PAW15cm measurements. The use of published bulk density measurements for soils was not accurate enough for our study.

Despite this problem, the fact that we found some relationships (though weak) at the lower depths in the profile and that they were associated with the early reproductive stage of the crop is encouraging. Clearly the lack of strength of these relationships makes it difficult to use them to predict corn yield, but they could be used as indicators of potential yield problems and as aids to irrigation recommendations.

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Table 3.1. Effects of year, location and water regime on yield at Lewiston and Plymouth in 2001 and 2002.

	DF‡	MSE†	p-value
Year	1	1792.0877	0.2604
Location	1	18980.2178	0.0843
Year X Location	1	336.8172	0.3959
Water Regime	2	2923.6983	0.0054
Year X Water Regime	1	4494.7372	0.0041
Location X Water Regime	2	5172.1568	0.0003
Year X Location X Water Regime	1	95.8142	0.6490

‡ = Degrees of Freedom
† = Mean Square Error

Table 3.2. Effect of various factors on yield using PAW15cm (plant available water per fifteen centimeters of soil depth) as a covariate for different growth stages at 45- to 60-cm sampling depth at Lewiston and Plymouth in 2001 and 2002. Factors tested depending on data sets available at each stage.

	Growth Stage									
	Stage I		Stage II		Stage III		Stage IV		Stage V	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location (Loc)			6350.02	<0.0001	8627.15	<0.0001	7854.45	0.0005	6674.86	0.0015
Water Regime (WR)	626.18	0.1383	162.84	0.3354	952.41	0.1108	1606.90	0.0630	17555.04	<0.0001
Loc X WR			1886.02	0.0012	1798.06	0.0200	1923.69	0.0385	14052.81	<0.0001
Year					18.49	0.8316	2127.97	0.0541		
Year x WR					2674.77	0.0150	2239.88	0.0485		
PAW15cm	704.05	0.1231	802.89	0.0340	4217.36	0.0029	256.73	0.4924	3.57	0.9326

† = Mean Square Error

Table 3.3. Effect of various factors on yield using PAW15cm (plant available water per fifteen centimeters of soil depth) as a covariate for different growth stages at 30- to 45-cm sampling depth at Lewiston and Plymouth in 2001 and 2002. Factors tested depending on data sets available at each stage.

	Growth Stage									
	Stage I		Stage II		Stage III		Stage IV		Stage V	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location (Loc)			5373.41	0.0004	8185.51	<0.0001	9291.73	<0.0001	2183.57	0.0449
WR	748.53	0.2023	148.19	0.4984	649.25	0.1805	1259.14	0.0750	11100.33	0.0001
Loc. x WR			1882.70	0.0049	2042.71	0.0077	2168.03	0.0146	12473.74	<0.0001
Year					81.99	0.6361	854.50	0.1768		
Year x WR					1034.01	0.0995	1139.81	0.1205		
PAW15cm	221.39	0.4429	153.16	0.4001	5796.09	0.0003	2960.30	0.0150	256.59	0.4708

† = Mean Square Error
WR = Water Regime

Table 3.4. Maximum amount of PAW15cm (plant available water per fifteen centimeters of soil depth) at various sampling depths at Lewiston and Plymouth in 2001 and 2002.

	Sampling depth			
	0- to 15-cm	15- to 30-cm	30- to 45-cm	45- to 60-cm
	$cm^3\ cm^{-3}$			
Lewiston 2001	2.0	2.2	2.5	2.4
Lewiston 2002	1.7	1.7	1.7	1.7
Plymouth 2001	2.6	2.4	2.6	3.1
Plymouth 2002	2.9	2.9	3.0	3.5

Table 3.5. Lewiston 2001 correlation coefficients for relevance between PAW15cm (plant available water per fifteen centimeters of soil depth) and yield.

		Date		
Location and Year	Sampling depth	11 June	18 June	6 July
Lewiston 2001	0- to 15-cm	-0.09	0.89**	-0.33
	15- to 30-cm	-0.48	0.67*	-0.23
	30- to 45-cm	-0.06	0.31	-0.04
	45- to 60-cm	-0.18	0.87**	-0.01

* denotes significance at the $\alpha = 0.05$ level.
** denotes significance at the $\alpha = 0.01$ level.

Table 3.6. Plymouth 2002 correlation coefficients for relevance between PAW15cm (plant available water per fifteen centimeters of soil depth) and yield.

		Date			
Location and Year	Sampling depth	1 July	3 July	8 July	16 July
Plymouth 2002	0- to 15-cm	-0.05*	0.33*	0.03*	-0.04*
	15- to 30-cm	-0.09*	0.33*	0.12*	-0.17*
	30- to 45-cm	-0.65*	0.68*	0.67*	-0.67*
	45- to 60-cm	-0.49*	0.57*	0.50*	-0.47*

* denotes significance at the $\alpha = 0.05$ level.

Table 3.7. Analysis of the effects of water regime and PAW15cm (plant available water per fifteen centimeters of soil depth) as a covariate on CWSI (crop water stress index) on three dates at Plymouth in 2001.

		Sampling depth							
		0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
Location/Date		MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Plymouth 27 June 2001	Water Regime	514.98	0.3334	893.66	0.0965	613.67	0.2925	724.65	0.1206
	PAW15cm	38.16	0.7584	640.23	0.1491	0.03	0.9926	674.34	0.1348
Plymouth 6 July 2001	Water Regime	638.04	0.2818	679.02	0.2519	582.54	0.3062	909.80	0.1061
	PAW15cm	1.41	0.9532	77.07	0.6598	1.83	0.9466	566.65	0.1835
Plymouth 17 July 2001	Water Regime	564.02	0.2416	624.59	0.1725	571.85	0.1802	486.61	0.3548
	PAW15cm	354.94	0.3175	558.07	0.1879	601.81	0.1664	11.73	0.8652

† = Mean Square Error

Table 3.8. Analysis of the effects of water regime and PAW15cm (plant available water per fifteen centimeters of soil depth) as a covariate on CWSI (crop water stress index) on four dates at Plymouth in 2002 .

		Sampling depth							
		0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
Location/Date		MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Plymouth 1 July 2002	Water Regime	753.05	0.3600	438.14	0.4881	277.39	0.4677	351.87	0.4982
	PAW15cm	293.72	0.5618	31.42	0.8508	3235.49	0.0292	1477.22	0.1842
Plymouth 3 July 2002	Water Regime	621.22	0.3414	246.86	0.5850	287.25	0.4434	171.09	0.6192
	PAW15cm	1228.83	0.1926	651.18	0.3817	3555.72	0.0200	1949.04	0.1192
Plymouth 8 July 2002	Water Regime	533.42	0.4448	501.29	0.4561	365.87	0.3916	269.49	0.5528
	PAW15cm	60.35	0.7942	141.30	0.6889	3512.67	0.0211	1454.00	0.1881
Plymouth 16 July 2002	Water Regime	727.93	0.3686	471.32	0.4669	294.53	0.4459	316.90	0.5263
	PAW15cm	265.82	0.5813	227.26	0.6106	3407.09	0.0240	1295.09	0.2173

† = Mean Square Error

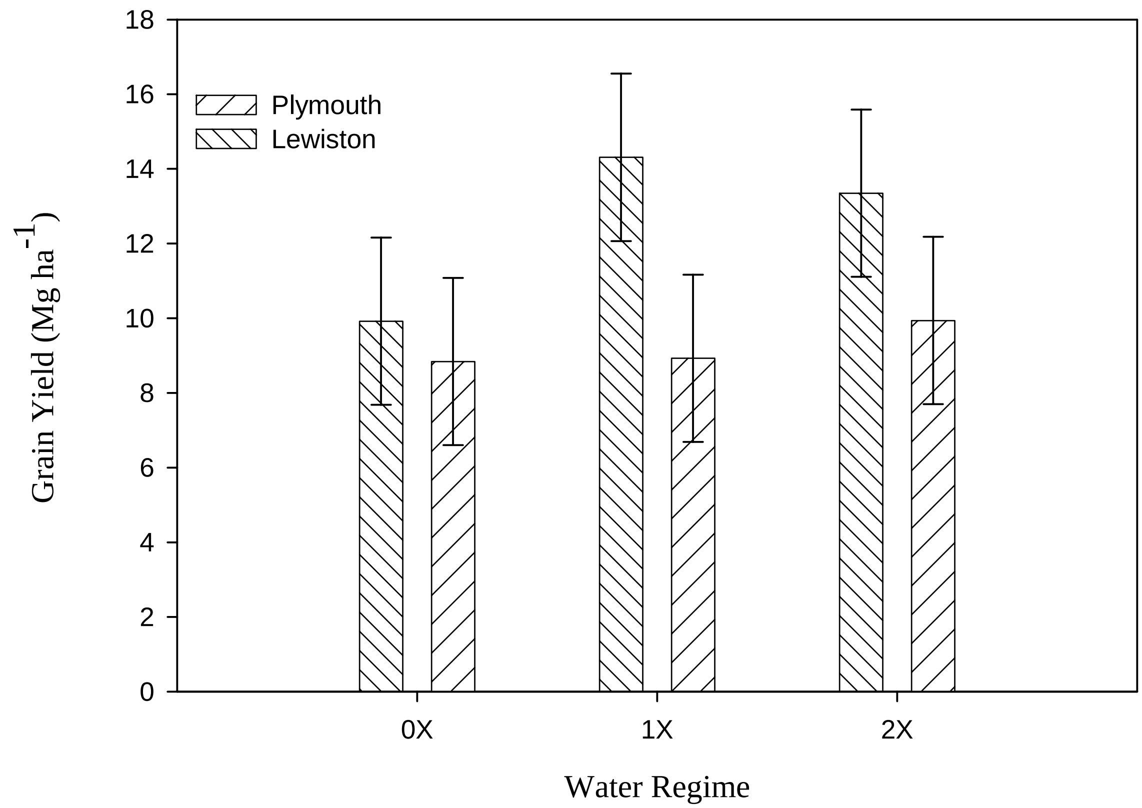


Figure 3.1. Differences in grain yield across three different water regimes at Lewiston and Plymouth in 2001 and 2002. Error bars represent LSD = 1.74 Mg ha-1.

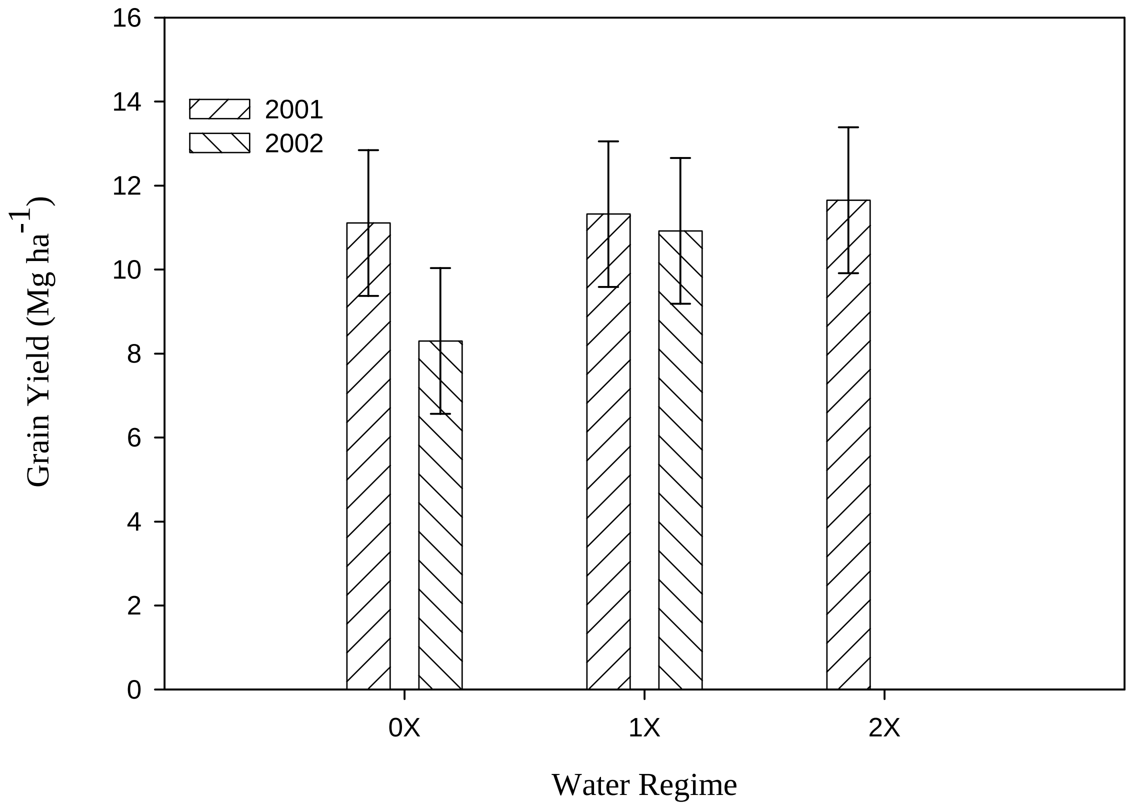


Figure 3.2. Differences in grain yield between 2001 and 2002 at the 0X, 1X and 2X irrigated treatments. Error bars represent LSD = 1.74 Mg ha^{-1}.

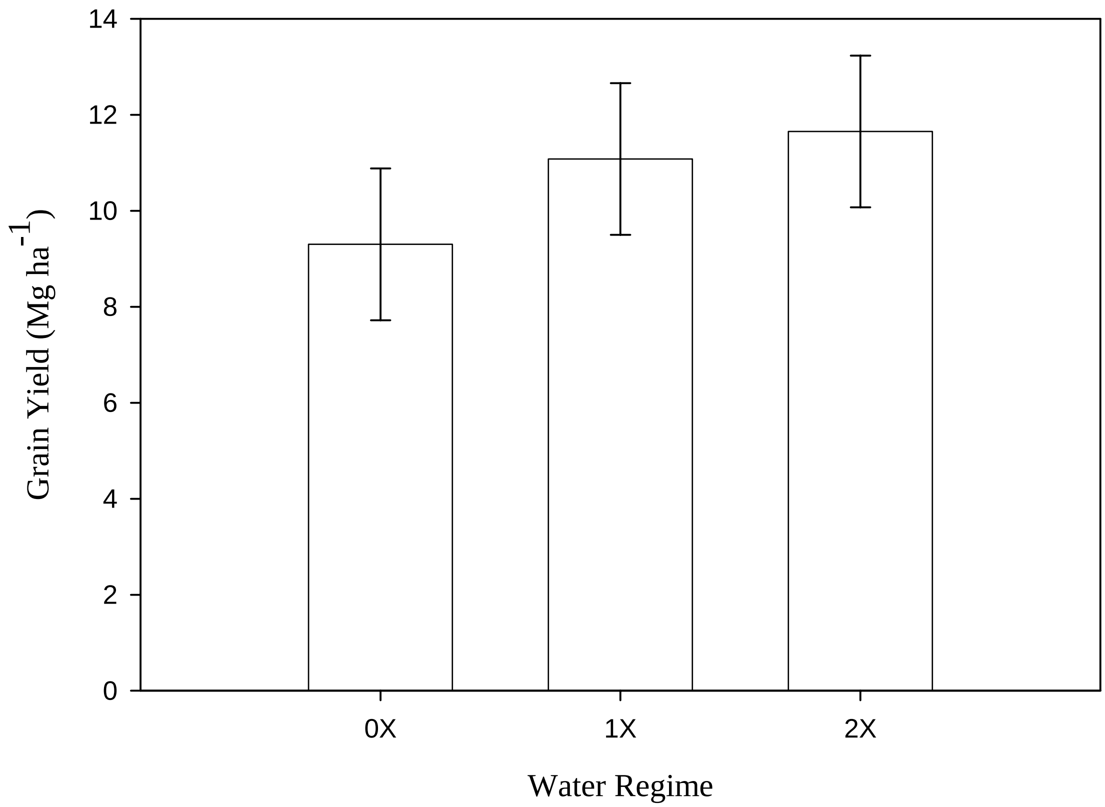


Figure 3.3. Differences in grain yield across three water regimes at Plymouth and Lewiston in 2001 and 2002. Error bars represent LSD = 1.58 Mg ha^{-1}.

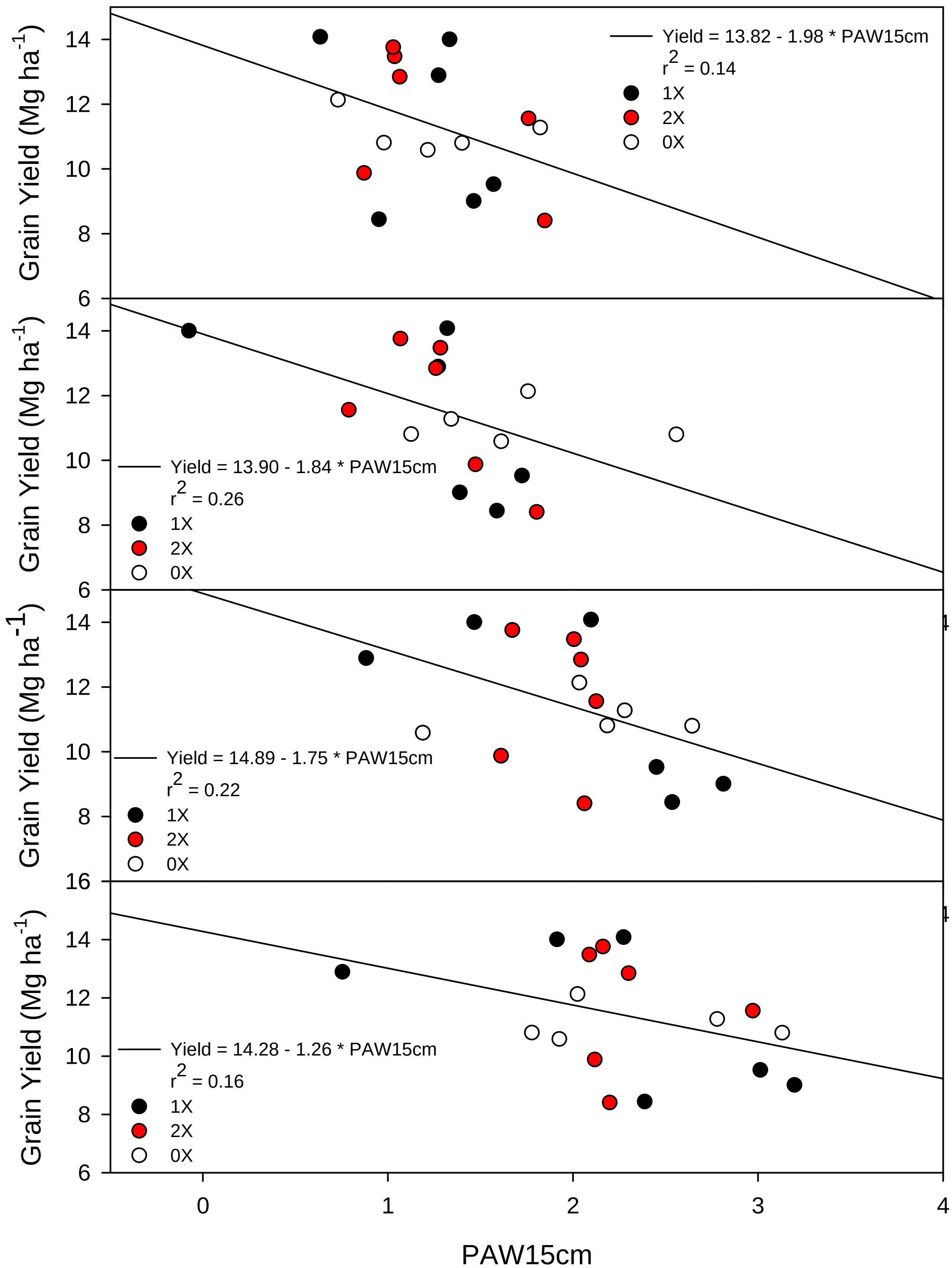


Figure 3.4. The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at growth stage II.

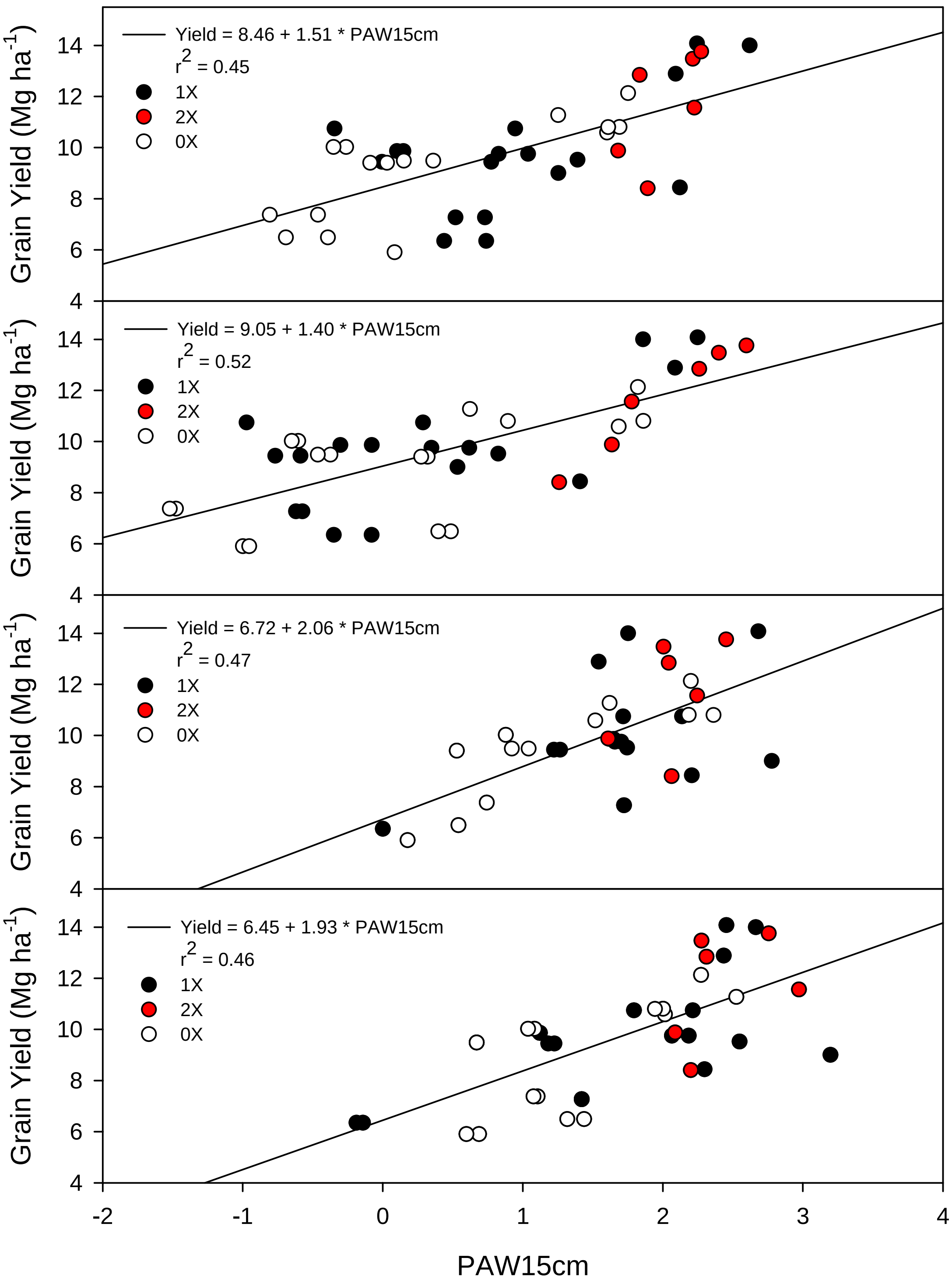


Figure 3.5. The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at growth stage III.

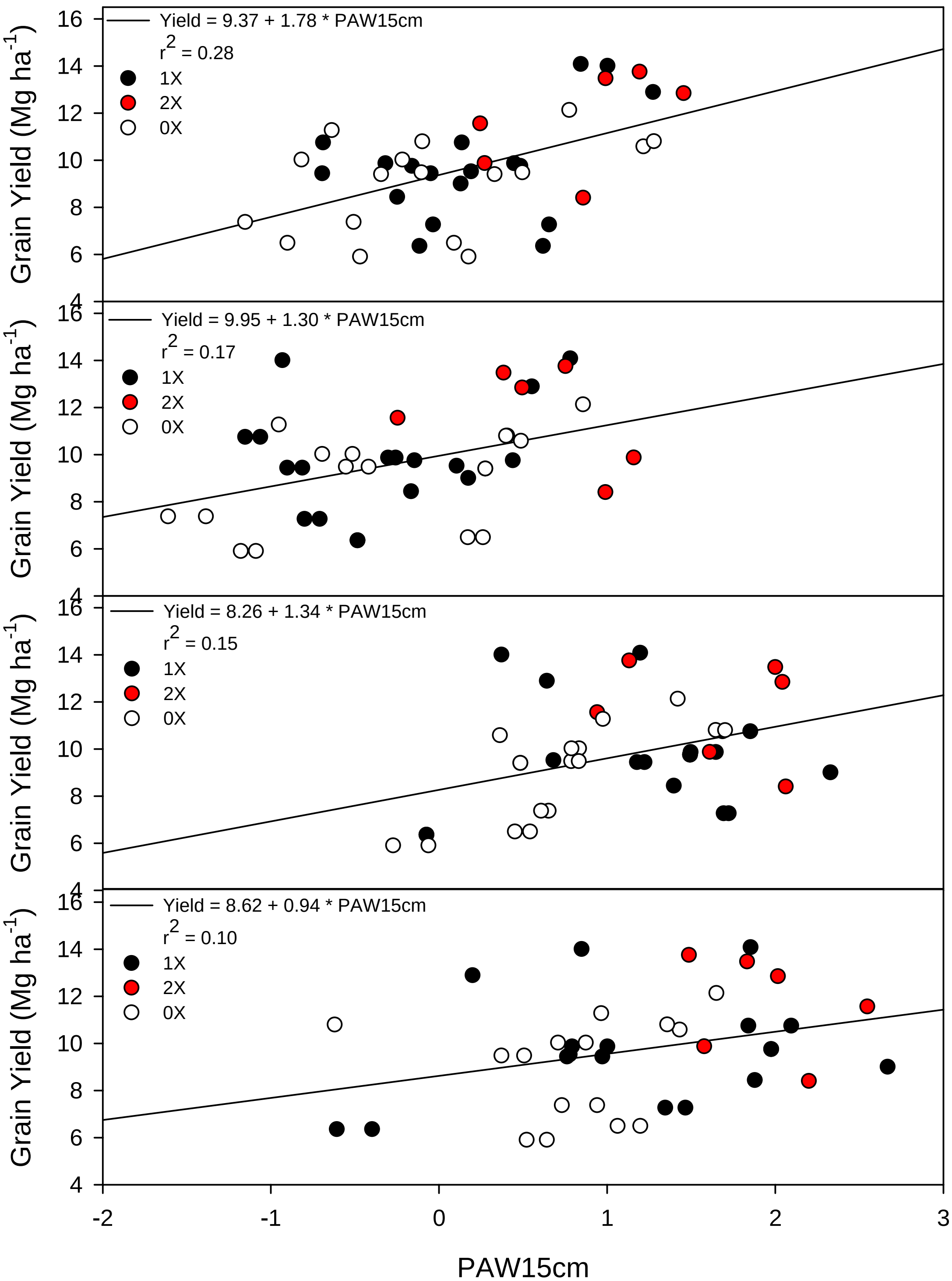


Figure 3.6. The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at growth stage IV.

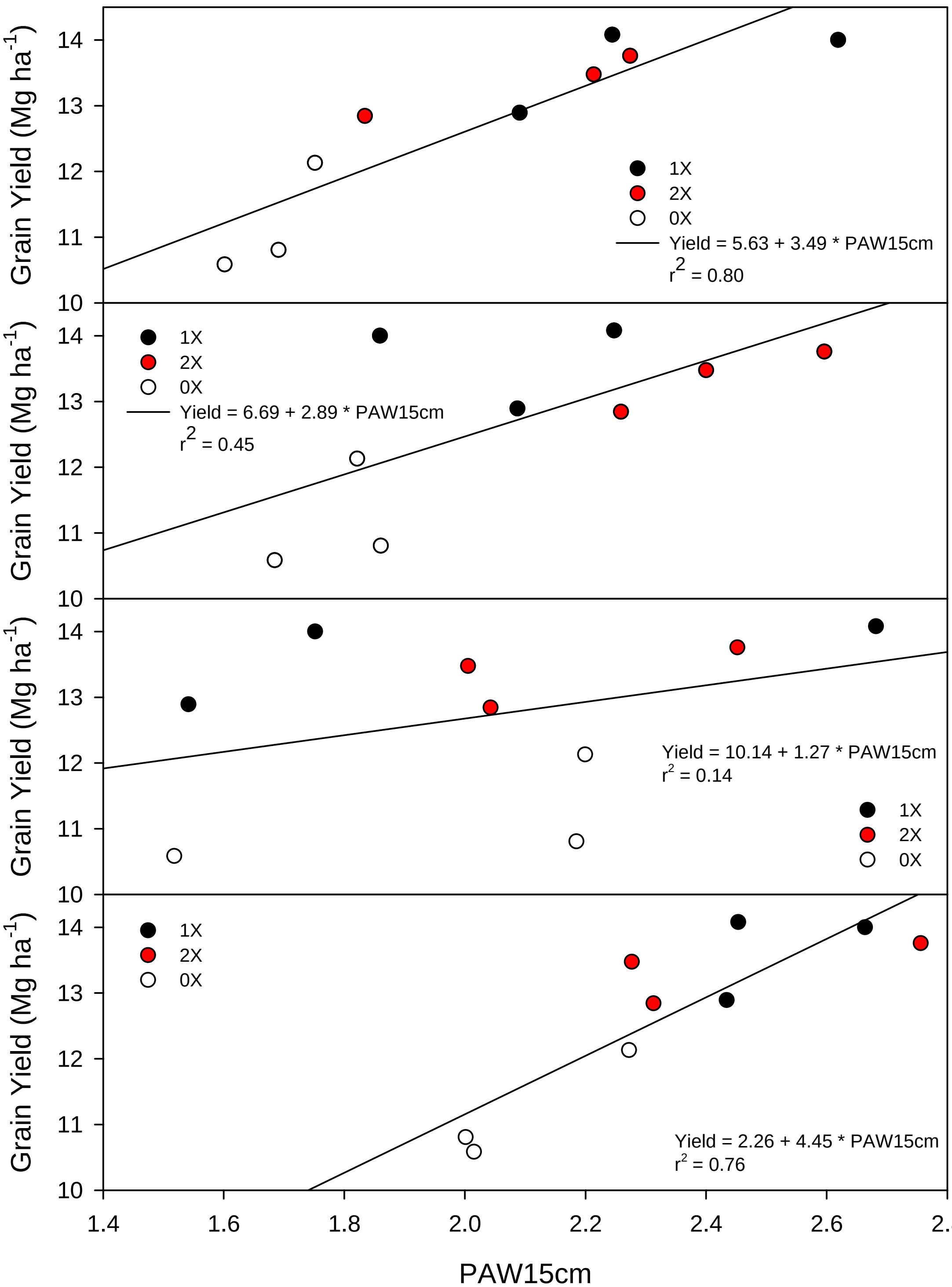


Figure 3.7. The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Lewiston on 18 June 2001.

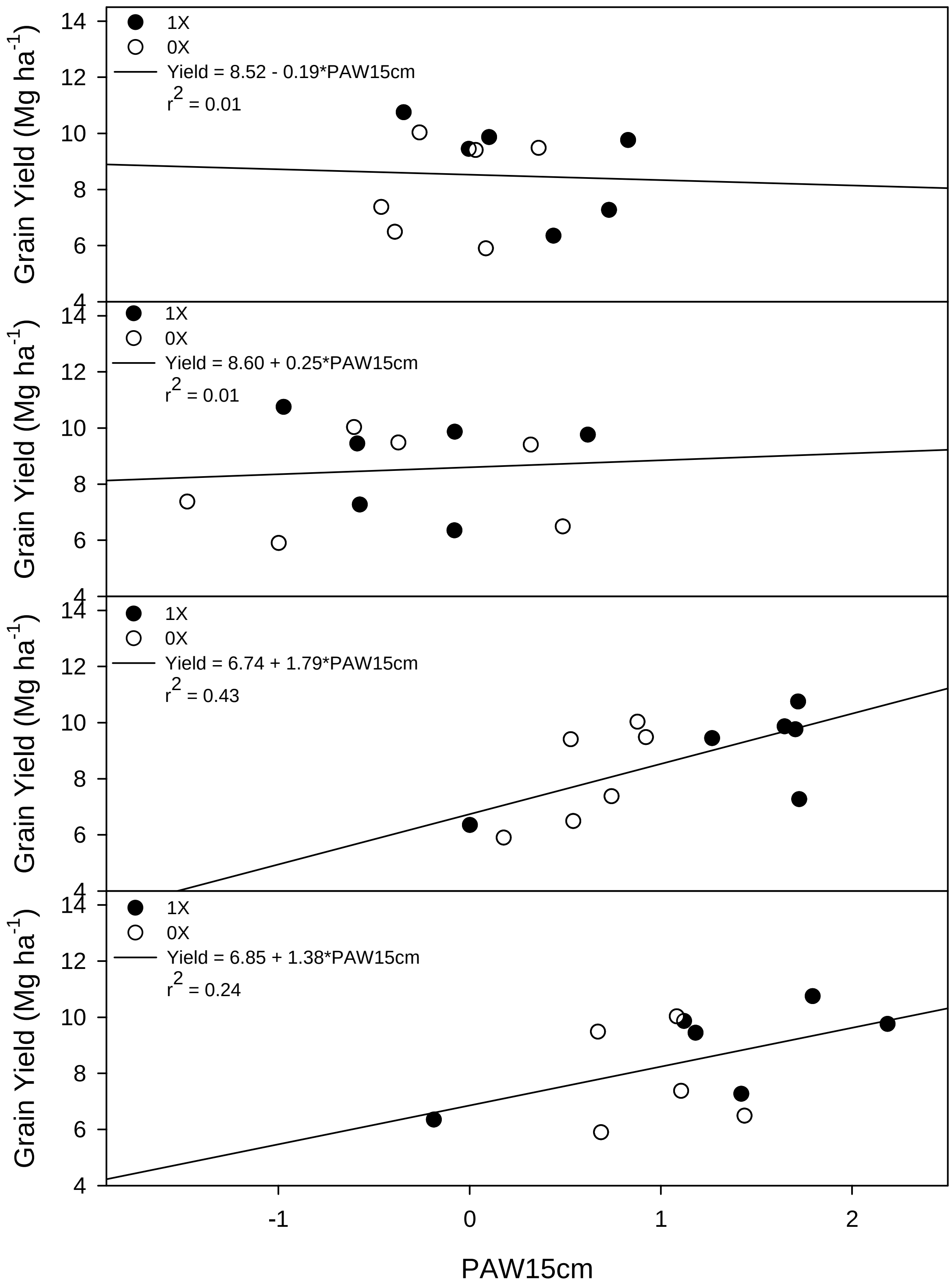


Figure 3.8. The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Plymouth on 1 July 2002.

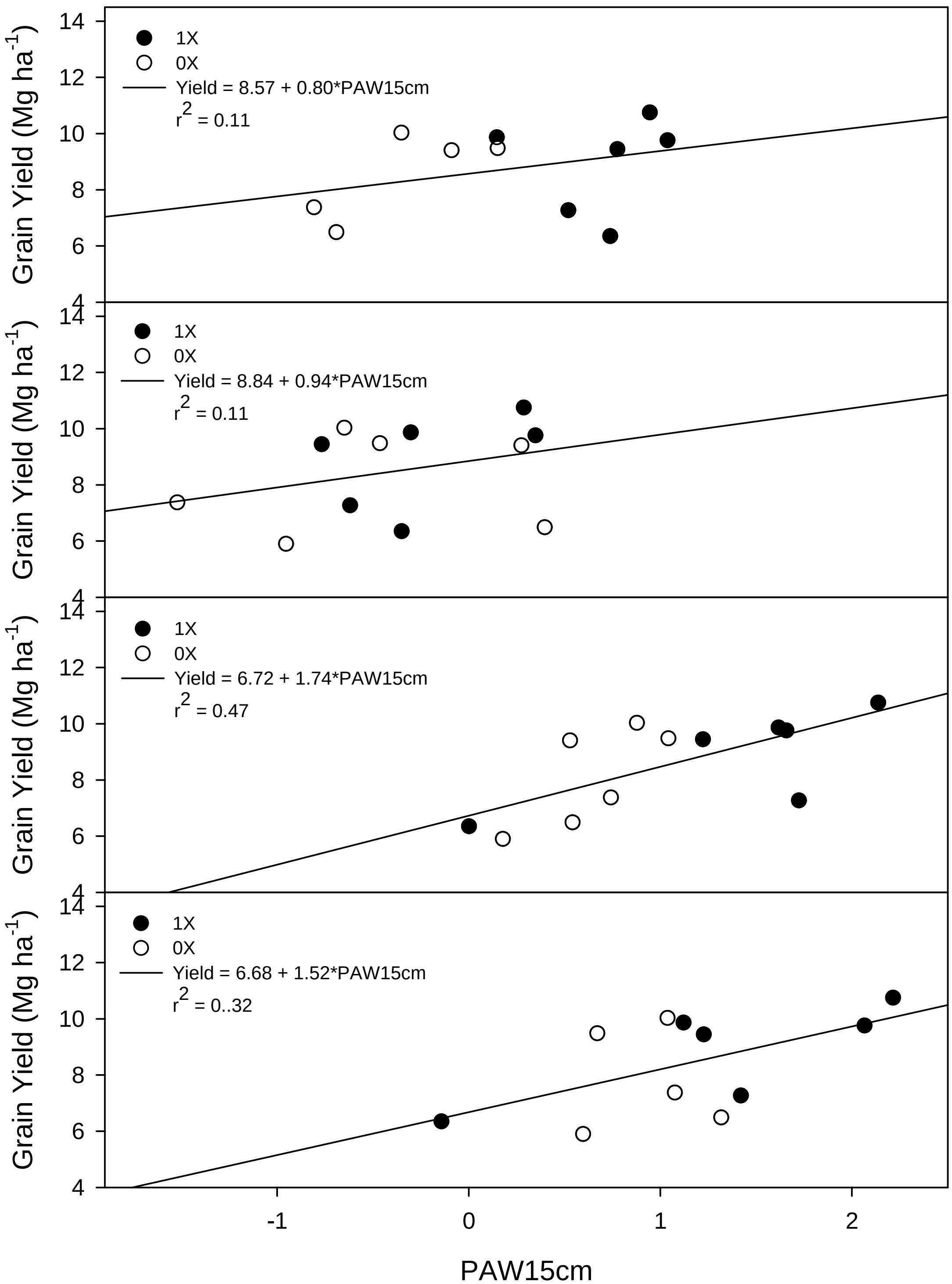


Figure 3.9. The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Plymouth on 3 July 2002.

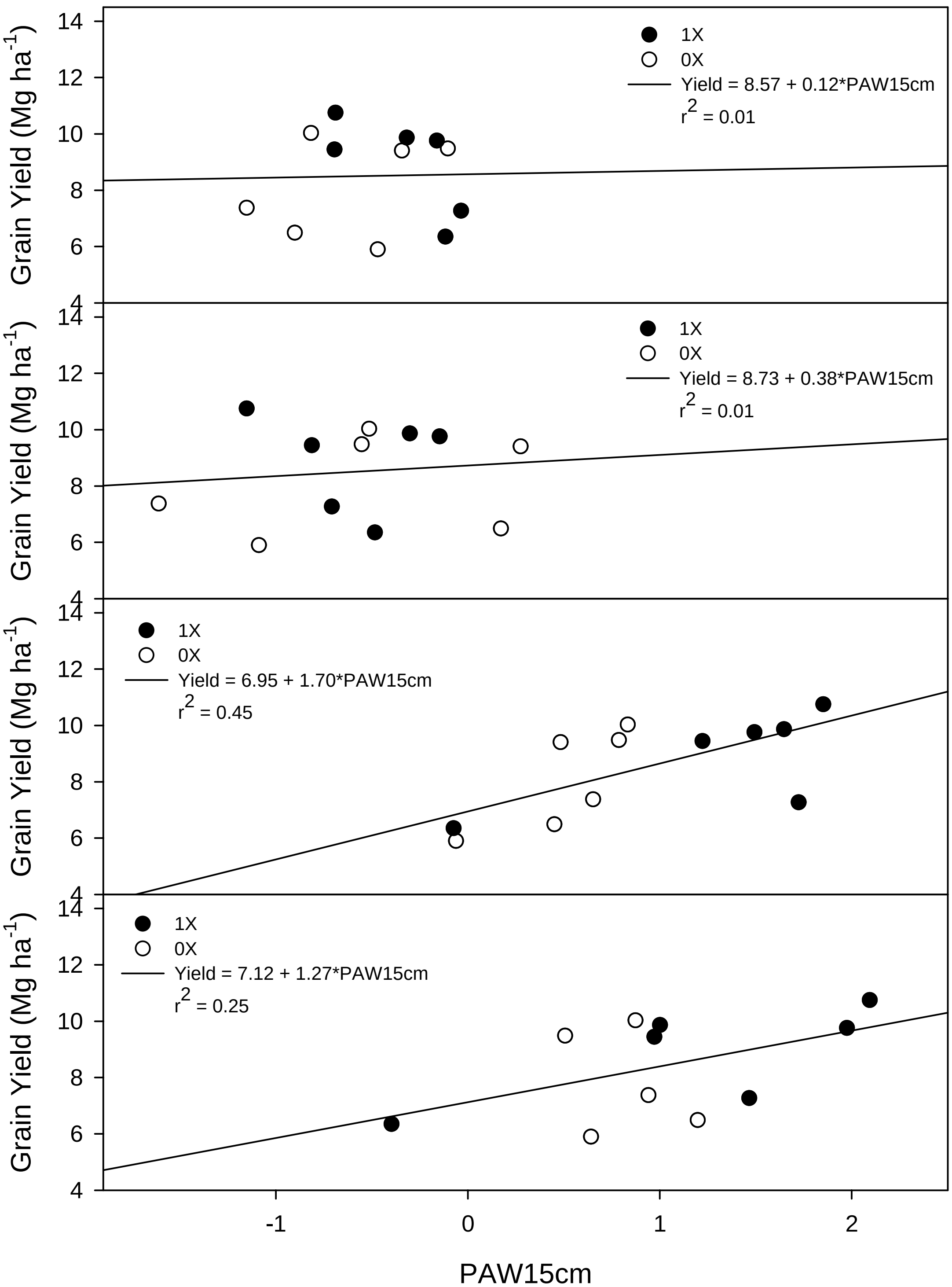


Figure 3.10. The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Plymouth on 8 July 2002.

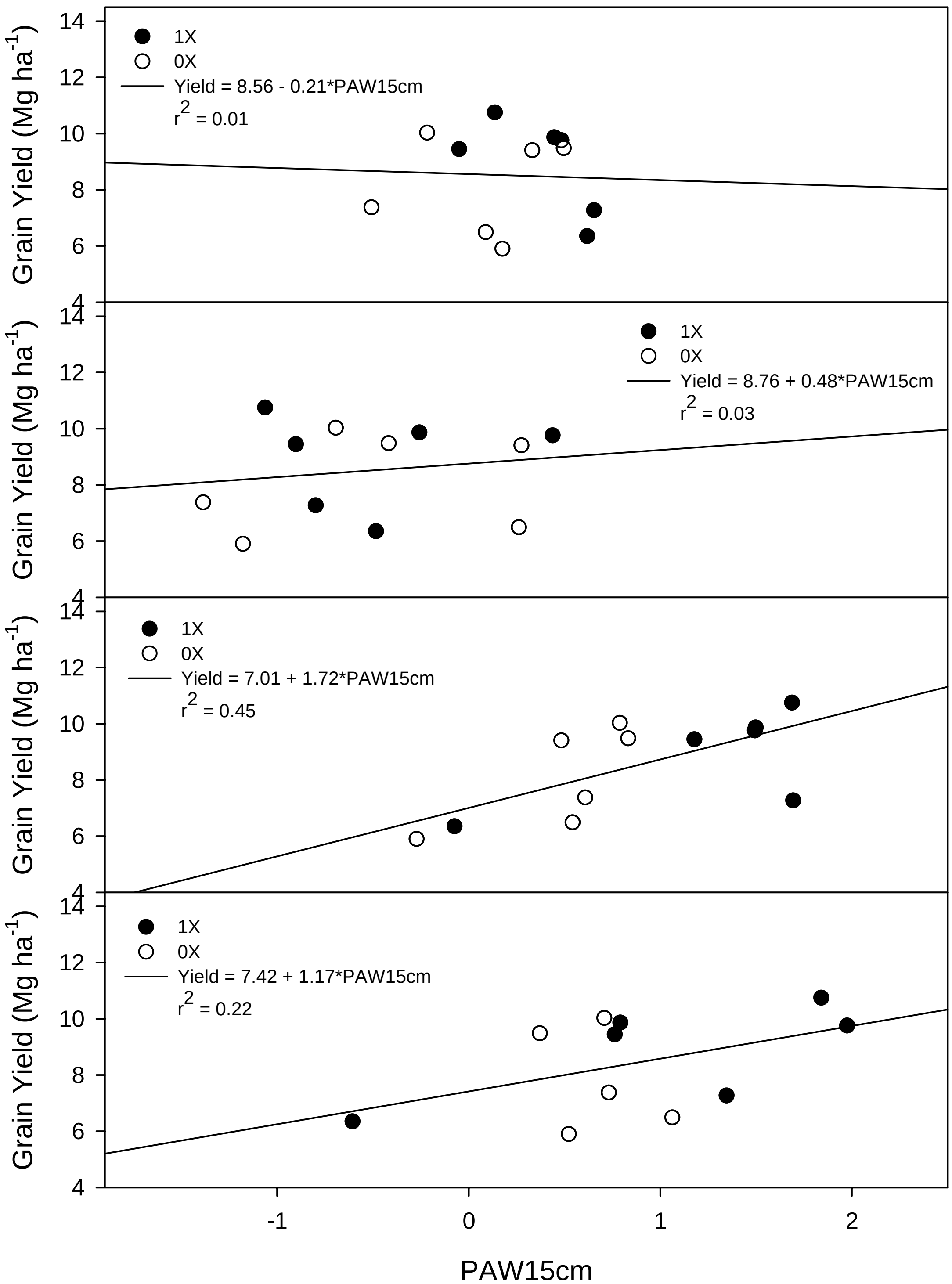


Figure 3.11. The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Plymouth on 16 July 2002.

Appendices

Factors influencing yield at the 0- to 15-cm sampling depth with PAW15cm (plant available water per fifteen centimeters of soil depth) included as a covariate in the analysis.

	Growth Stage									
	Stage I		Stage II		Stage III		Stage IV		Stage V	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location			4535.93	0.0009	6319.93	0.0014	6510.53	0.0013	4488.12	0.0030
WR	847.22	0.1128	104.56	0.6250	714.47	0.2618	1906.95	0.0381	19794.69	<0.0001
Loc. x WR			1748.58	0.0077	1680.97	0.0505	1548.51	0.0671	14839.39	<0.0001
Year					340.18	0.4205	2231.17	0.0477		
Year x WR					1423.68	0.1050	1981.15	0.0612		
PAW15cm	588.28	0.1729	15.04	0.7954	112.05	0.6427	454.10	0.3599	875.91	0.1477

† = Mean Square Error
WR = Water Regime
Loc = Location

Factors influencing yield at the 15- to 30-cm sampling depth with PAW15cm (plant available water per fifteen centimeters of soil depth) included as a covariate in the analysis.

	Growth Stage									
	Stage I		Stage II		Stage III		Stage IV		Stage V	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location			4804.77	0.0004	3558.86	0.0137	7531.52	0.0007	6198.85	0.0021
Water Regime	903.99	0.1089	56.67	0.7328	1360.31	0.0897	1743.73	0.0527	22094.22	<0.0001
Loc. x WR			1730.75	0.0044	1790.34	0.0449	1797.85	0.0485	11649.77	0.0001
Year					502.28	0.3343	2042.94	0.0605		
Year x WR					2017.72	0.0582	2076.26	0.0586		
PAW15cm	554.97	0.1895	369.76	0.1786	568.46	0.3048	28.17	0.8207	7.65	0.9015

† = Mean Square Error
WR = Water Regime
Loc = Location

Factors influencing yield on three dates at Lewiston in 2001 at four sampling depths with PAW15cm (plant available water per fifteen centimeters of soil depth) included as a covariate with water regime in the analysis.

		Sampling depth							
		0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
Location/Date		MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Lewiston 11 June 2001	Water Regime	1513.76	0.0057	1011.06	0.0322	1486.51	0.0081	1462.56	0.0066
	PAW15cm	251.86	0.1512	6.70	0.8336	183.19	0.2370	237.70	0.1664
Lewiston 18 June 2001	Water Regime	160.57	0.2172	644.63	0.0600	1287.48	0.0073	225.13	0.1479
	PAW15cm	309.68	0.1000	71.51	0.4817	273.39	0.1302	298.94	0.1084
Lewiston 7 July 2001	Water Regime	1485.36	0.0004	1313.58	0.0198	1405.81	0.0166	1470.82	0.0100
	PAW15cm	554.08	0.0064	0.47	0.9555	13.59	0.7642	137.89	0.3150

† = Mean Square Error

PAW15cm (plant available water per fifteen centimeters of soil depth) as a covariate influencing yield at four sampling depths.

	Growth Stage									
	Stage I		Stage II		Stage III		Stage IV		Stage V	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value	MSE	p-value
0- to 15-cm PAW15cm	588.28	0.1729	15.04	0.7954	112.05	0.6427	454.10	0.3599	875.91	0.1477
15- to 30-cm PAW15cm	554.97	0.1895	369.76	0.1786	568.46	0.3048	28.17	0.8207	7.65	0.9015
30- to 45-cm PAW15cm	221.39	0.4429	153.16	0.4001	5796.09	0.0003	2960.30	0.0150	256.59	0.4708
45- to 60-cm PAW15cm	704.05	0.1231	802.89	0.0340	362.61	0.4139	256.73	0.4924	3.57	0.9326

† = Mean Square Error

Factors influencing yield at five growth stages without PAW15cm (plant available water per fifteen centimeters of soil depth) as a covariate in the analysis.

	Growth Stage									
	Stage I		Stage II		Stage III		Stage IV		Stage V	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location (Loc)			7925.54	<0.0001	7925.54	0.0005	7925.54	0.0005	7996.13	0.0005
Water Regime (WR)	643.63	0.2035	0105.06	0.5956	1729.70	0.0494	1729.70	0.0494	22381.04	<0.0001
Loc x WR			1809.82	0.0043	1809.82	0.0435	1809.82	0.0435	14084.30	<0.0001
Year					2301.71	0.0439	2301.71	0.0439		
Year x WR					2048.78	0.0564	2048.78	0.0564		

† = Mean Square Error

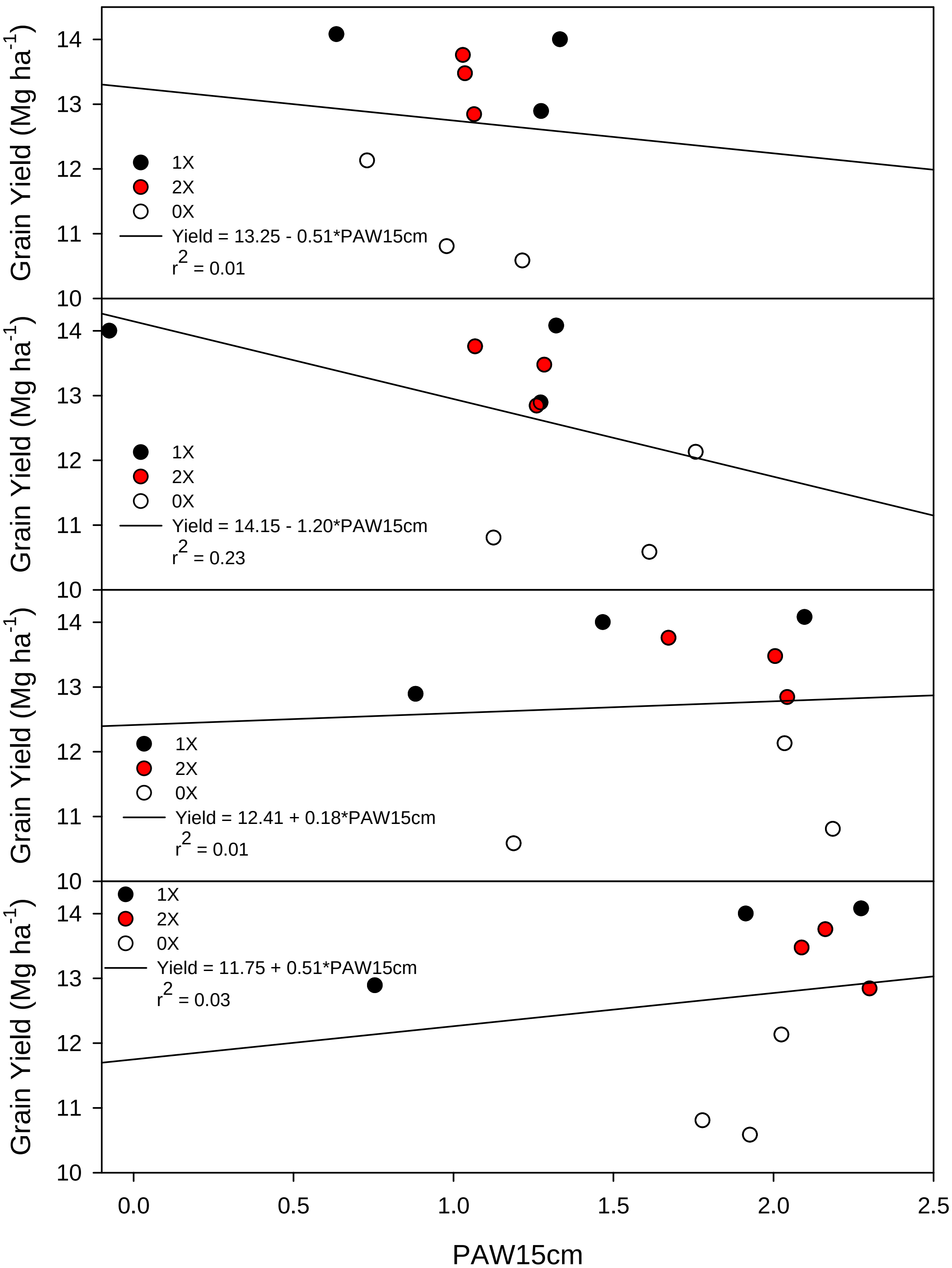
Plymouth 2001 correlation coefficients for relevance between PAW15cm (plant available water per fifteen centimeters of soil depth) and yield.

		Date		
Location and Year	Sampling depth	27 June	6 July	17 July
Plymouth 2001	0- to 15-cm	-0.33	-0.07	-0.43
	15- to 30-cm	-0.23	-0.05	-0.47
	30- to 45-cm	-0.15	-0.21	-0.52
	45- to 60-cm	-0.43	-0.11	-0.35

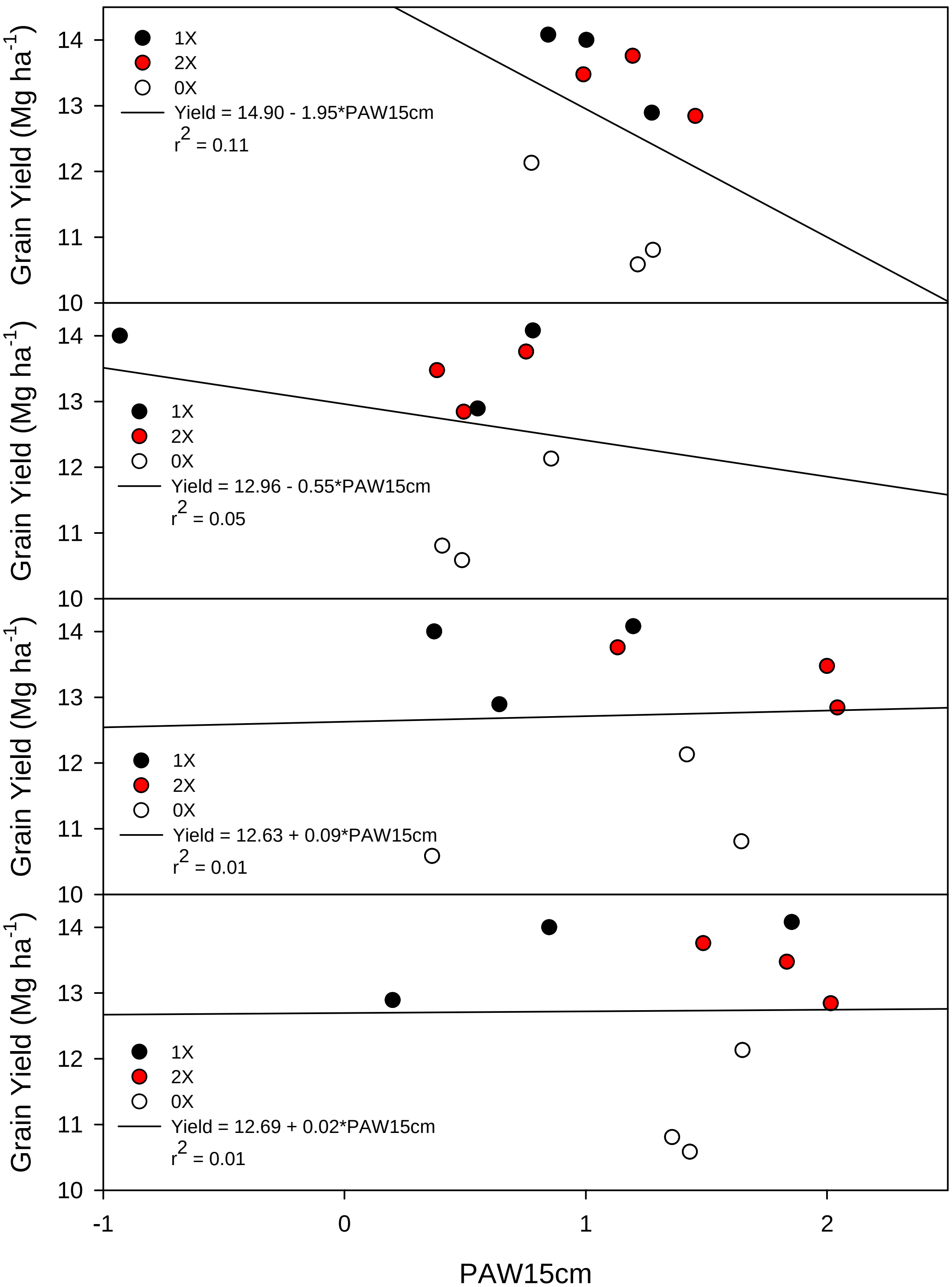
Results of analysis of variance testing PAW15cm (plant available water per fifteen centimeters of soil depth) and water regime effects on yield.

		Sampling depth							
		0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
Location/Date		MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Lewiston 2001	Water Regime	4142.25	<0.0001	4185.88	<0.0001	4235.83	<0.0001	4152.66	<0.0001
	PAW15cm	32.25	0.5525	0.06	0.9787	183.48	0.1487	205.20	0.1256
Lewiston 2002	Water Regime	107489.07	<0.0001	107978.63	<0.0001	79003.06	<0.0001	60247.50	<0.0001
	PAW15cm	692.28	0.0284	17.22	0.7387	162.10	0.3026	1245.85	0.0024
Plymouth 2001	Water Regime	2577.92	0.0001	2564.94	0.0001	2435.73	0.0002	2736.62	<0.0001
	PAW15cm	7.68	0.8483	65.35	0.5760	70.78	0.5605	328.98	0.2043
Plymouth 2002	Water Regime	1363.14	0.1503	2465.85	0.0582	405.46	0.3488	1737.48	0.0882
	PAW15cm	7.46	0.9144	289.99	0.5100	11995.02	<0.0001	5421.75	0.0034

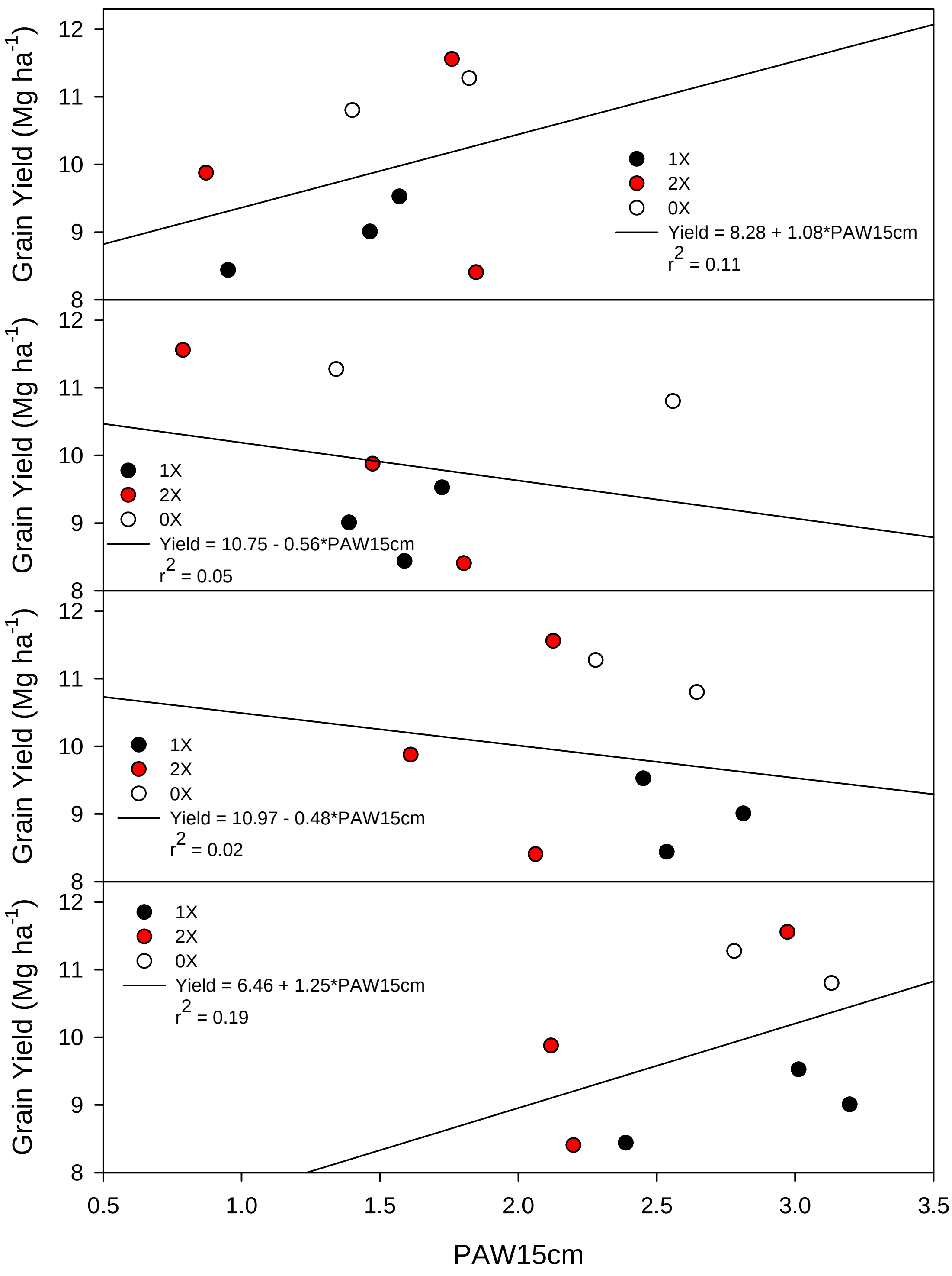
† = Mean Square Error



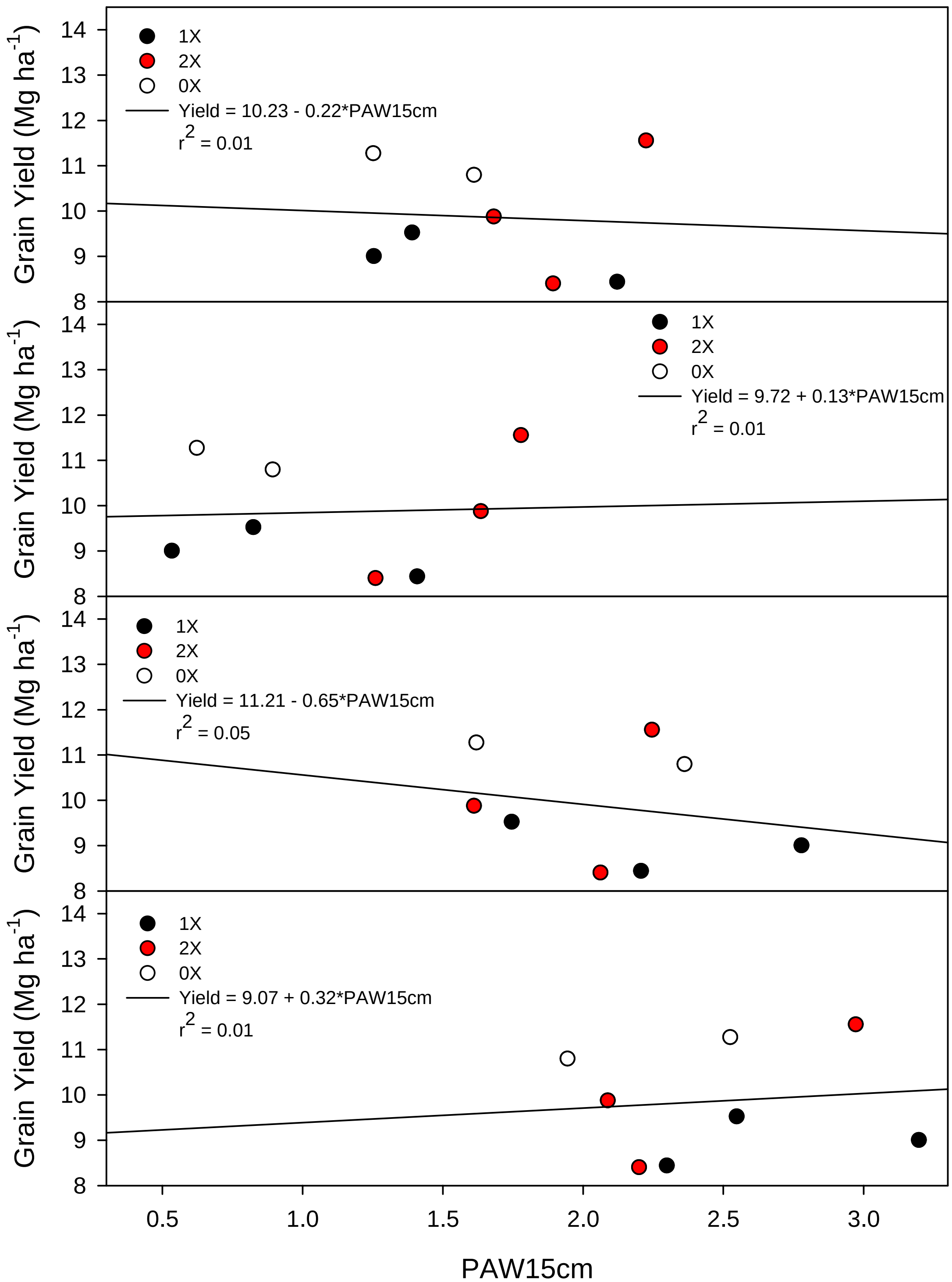
The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Lewiston on 11 June 2001.



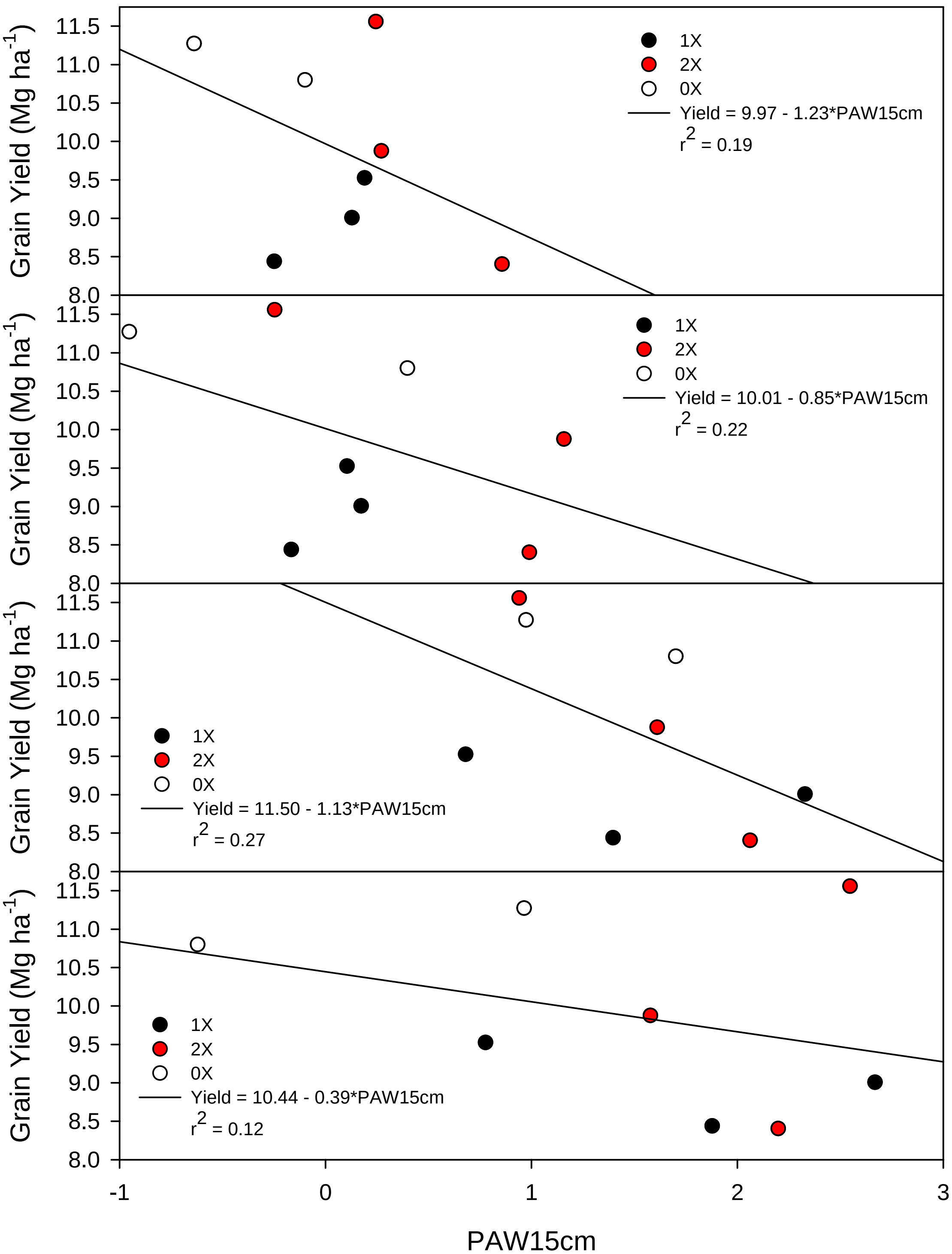
The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Lewiston on 6 July 2001.



The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Plymouth on 27 June 2001.



The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Plymouth on 6 July 2001.



The relationship between PAW15cm (plant available water per fifteen centimeters of soil depth) measured at four sampling depths and grain yield at Plymouth on 17 July 2001.

Chapter Four

Relationship Between Plant Available Water Measured Throughout the Growing Season and Crop Water Stress

Abstract

Understanding and measuring the driving forces behind potential corn yield within the growing season is vitally important in that it allows adjustment of inputs to maximize economic returns. The objective of this study was to quantify the relationship between plant available water measured at four depths throughout the growing season and crop water stress as determined by crop water stress index. Measurements of plant available water were taken over time at four sampling depths at Lewiston and Plymouth in 2001 and 2002 and compared to crop water stress index (CWSI) measurements taken simultaneously. Correlation of CWSI and PAW15cm at each measurement date and location indicated significant relationships on three occasions in 2002, none of which included PAW15cm as a significant covariate. All slopes were negative, indicating CWSI values decreased as PAW15cm increased and linear regressions of the data revealed that much of the variation in CWSI was accounted for by variation in PAW15cm at these lower sampling depths. It was evident that the dates which exhibited strong correlations between CWSI and PAW15cm were those dates which (i) already exhibited substantial moisture stress and (ii) had received enough irrigation to create measurable differences in canopy temperature for calculation of CWSI.

Introduction

Understanding and measuring the driving forces behind potential corn yield within the growing season is vitally important in that it allows adjustment of inputs to maximize economic returns. Yield potential of corn is often impacted by limited amounts of water, specifically the amount of available soil water (Roygard et al., 2002). In the mid-Atlantic region, rainfall amounts during the growing season are usually sufficient to produce profitable yields, but can be variable from year to year. Because very little corn in this region is irrigated, profitable production is heavily dependent on the amount of rainfall and the soils ability to store water for plant growth. Understanding the relationship between plant available water (PAW) measured throughout the growing season and the crop water stress index (CWSI) would assist growers in determining critical levels of soil moisture for managing irrigation and crop inputs.

Researchers have concluded that temperature, solar radiation and water availability (soil water storage and rainfall) are the major determining factors in corn production (Carlson, 1990; Dale and Daniels, 1995). Runge (1968), measuring the influence of both maximum daily temperatures and precipitation on corn yields found that high temperatures were not detrimental if soil moisture was not limiting. Yield of corn suffers in response to soil moisture deficits at any growth stage (Howe and Rhoades, 1955). Eck (1984) found that stress imposed on corn at the vegetative stages of growth for 14 and 28 days reduced yields by 23 and 46%, respectively. However, corn is especially sensitive to moisture stress during the time of tasseling and continuing through grain fill (Musik and Dusek, 1980; Nesmith and Ritchie, 1992). Denmead and Shaw (1960) reported that stress at vegetative growth stages, at silking, and after silking reduced corn yield by 25, 50, and 21%, respectively. Robins and Domingo (1953) found that corn yields were reduced by 22% when soil moisture was reduced to wilting point for a period of 1 to 2 days during tasseling or pollination, and that yields were reduced by 50% after 6 to 8 days of stress at this stage. Musik and Dusek (1980) found soil moisture stress during periods of tasseling and silking to be most detrimental to yield, and that soil moisture stress during the time of grain fill was more harmful to yield than that during vegetative growth. Runge (1968) and Thompson (1975) concluded that corn yield was highly correlated with water availability at tasseling.

Miller and Saunders (1923) reported the use of plant temperature as an indicator of plant water status over 80 years ago. Research into the use of infrared thermometry to remotely sense canopy temperature has continued since the early 1960s (Monteith and Szeicz, 1962; Tanner, 1963; Fuchs and Tanner, 1966). This research has led to the use of the crop water stress index (CWSI) which was first defined and employed to measure water stress in plants by Idso et al. (1981) and Jackson et al. (1981). Idso et al. (1981) documented the linear relationship between the difference in canopy temperature (T_c) and air temperature (T_a) ($dT = T_c - T_a$) and VPD of the air for well watered plants transpiring at potential rate during daylight hours. This linear relationship is sometimes called the "non water-stressed" or "lower" baseline, and it represents the maximum rate of transpiration of a well watered, or non-stressed, crop. Idso et al. (1981) used the equation dT = A (the intercept of the non-water stressed baseline) + B (the slope of the non-water stressed baseline) x VPD (°C) to construct the lower baseline, which shows the dependency of dT on vapor pressure deficit (VPD). These lower baselines are crop specific. Measurements of air temperature, canopy temperature, relative humidity (RH), and wet bulb temperature (T_w) are taken simultaneously to be used to construct the lower baselines needed for CWSI determination. VPD is a measurement of the deficit between the amount of moisture in the air at the time of measurement and the maximum amount of moisture the air can hold. It can be calculated from measurements of RH, T_a, and T_w. To insure consistency, all measurements were gathered following the procedures recommended by Gardner et al. (1992).

As plants become stressed due to soil moisture depletion, the relationship between dT and VPD deviates from that described by the lower baseline. When plants are at the stage of maximum water deficit the relationship between dT and VPD is represented by the “water-stressed” or “upper” baseline. At this level of stress the baseline represents the dT of plants that are not transpiring. At this point there is no response in dT to changes in VPD.

CWSI is calculated using the equation CWSI = (dT – MIN / MAX – MIN) x 10. MIN is the non-water stressed baseline, and MAX is the upper limit of dT in °C. A CWSI close to 10 (near the upper baseline) indicates the crop is under maximum water stress. A CWSI closer to zero (approaching the lower baseline) indicates the crop is under minimum water stress.

Water Stress in crops and CWSI have been related to soil water availability (Hatfield, 1983; Reginato and Garrot, 1987). Hatfield found that dT values for a well watered crop of sorghum (*Sorghum bicolor*) remained negative, meaning leaf temperatures were lower than air temperatures, until 65% of the PAW was extracted. After 65% of the PAW was extracted, dT values became positive, meaning leaf temperatures were higher than air temperatures, and increased quickly as PAW decreased, indicating that the crop was under yield reducing stress. He also observed that CWSI values summed over time provided a measure which is closely related to the amount of PAW extracted from the soil.

Crop Water Stress Index has also been used to schedule irrigation for various crops including corn (Clawson and Blad, 1982; Neilsen and Gardner, 1987; Yazar et al., 1999; Irmak et al., 2000) and has been related to potential yield (Walker and Hatfield, 1983; Irmak et al., 2000). Understanding the relationship between CWSI and PAW would help in examining the key factors that limit corn yield in North Carolina. The ability to determine soil moisture status at a given time during the growing season using canopy temperature would enable producers to maximize inputs such as irrigation, fertilizer, insecticides and fungicides. This ability would enable growers to remain profitable while continuing to meet the ever-increasing environmental standards of today's society. The objective of this study was to quantify the relationship between plant available water measured at four soil depths throughout the growing season and crop water stress as determined by crop water stress index.

Materials and Methods

Experiments were conducted at two locations, the Peanut Belt Research Station (PBRS) at Lewiston, North Carolina and the Tidewater Research Station (TRS) at Plymouth, North Carolina, in both 2001 and 2002. At Lewiston in 2001, the predominate soil types at the site were a Norfolk sandy loam (Fine-loamy, siliceous, thermic Typic Paleudults) and a Goldsboro sandy loam (Fine-loamy, siliceous, thermic Aquic Paleudults). At Plymouth in 2001, the experiment was conducted on a Portsmouth sandy loam (Fine-loamy over sandy or sandy-skeletal, mixed, thermic Typic Umbraquults). In 2002, the soil types at Lewiston were Goldsboro and Lynchburg sandy loams (Fine-loamy, siliceous, thermic Aeric Paleaquults), and a Rains sandy loam (Fine-loamy, siliceous, thermic Typic Paleaquults). Soils at the Plymouth site in 2002 were a Portsmouth sandy loam and a Cape Fear loam (Clayey, mixed, thermic Typic Umbraquults).

Fields were prepared and planted using conventional tillage methods. Row width for both years at Lewiston was 91 cm, and row width for both years at Plymouth was 96 cm. Pioneer 31G98 was planted at a population of 67,500 seeds per hectare on 4 April 2001 and 6 April 2002 at Lewiston, and 30 April 2001 and 27 April 2002 at Plymouth. Production practices were consistent with those generally used for profitable corn production in eastern North Carolina (Heiniger et al., 2002). Weed control at both test sites in both years was excellent due to proper timing and application of herbicides. Plots at Lewiston in 2001 received 168 kg 0-0-60 ha^{-1}, 112 kg 0-46-0 ha^{-1}, and 224 kg N ha^{-1} pre-plant, with an additional 224 kg N ha^{-1} applied at growth stage VT (Ritchie et al., 1993). In 2002, plots received 112 kg 0-0-60 ha^{-1} and 112 kg 18-46-0 ha^{-1} pre-plant, with

145 kg N ha^{-1} applied at growth stage V3. Plots at Plymouth in 2001 received 336 kg 9-23-30 ha^{-1} pre-plant and 224 kg N ha^{-1} applied at growth stage VT. In 2002, plots received 81 kg N ha^{-1} pre-plant and 49 kg N ha^{-1} applied at growth stage V3.

In 2001, the experimental design of the test was a modified Randomized Complete Block (Steel et al., 1997) with three water regimes as the main treatments replicated in three blocks. Water regime treatments were comprised of no irrigation (0X), normal irrigation (1X) and double irrigation (2X). At Lewiston, this was accomplished using gated furrow irrigation by positioning the test on a slight grade with the rows directed downhill and the 2X plots above the 1X plots. Alleys for each treatment were flooded until water began to exit the 1X plots at the far end of the field. This system worked well for providing two different levels of irrigation, but did not provide a way to accurately measure the amount of water applied to each treatment. Irrigation in 1X plots was estimated to be 1.5 cm, and 2X plots received an estimated 3.0 cm per irrigation (Barnes, 2004, personal communication). At Plymouth, plots were irrigated using an overhead linear irrigation system which delivered 0.8 (1X) and 1.5 cm (2X) of water.

In 2002, the experimental design of the test was a modified Randomized Complete Block with two water regimes as the main treatments (0X and 1X) replicated six times. Both locations were irrigated using overhead linear irrigation systems in 2002. The system at Lewiston delivered an average of 1.4 cm of water at every event except one, which measured 2.5 cm. The system at Plymouth applied 0.8 cm of water during each irrigation. At both locations in both years, irrigations were scheduled when cumulative rainfall during the previous three to four days did not exceed 1.3 cm.

The goal for this study was to simultaneously take canopy temperature, air temperature, relative humidity, wet bulb temperature, and soil moisture measurements weekly at both locations. At each plot, six T_c measurements taken from the upper side of the uppermost leaves in full sun were recorded using a portable infrared thermometer (IRT) (Model RAYMX2U, Raytek, Santa Cruz, CA). At the same time and location, measurements of T_a, T_w and RH were taken using a digital thermometer/ psychrometer (Model # 990DW, Mannix Testing and Measurement, Lynbrook, NY). Canopy temperature measurements require near cloudless conditions for an accurate measurement to be made (Gardner et al., 1992). Measurements must be taken on sunny days between 1100 hours and 1400 hours. In 2001, clear sunny days were rare events. Uncooperative weather for data collection allowed only three measurement dates at Lewiston and four measurement dates at Plymouth. The same phenomena affected data collection in 2002 with only three measurement dates at Lewiston and five measurement dates at Plymouth.

Canopy temperature and air temperature measurements were collected and the lower baselines were determined for each location using the method described by Meijer (2004). Data for calculating the seasonal lower baseline for Plymouth in 2001 resulted in the equation dT = 0.839 – 2.103 x VPD and at Lewiston in 2001 resulted in the equation dT = 2.170 – 2.441 x VPD. Because of abundant rainfall and in 2001 it was impossible to determine the upper baselines from our data. A published water-stressed baseline of dT = $^{+}$4.6°C was used (Irmak et al., 2000). In 2002, the seasonal lower baselines determined for the 2001 Lewiston and Plymouth locations were again used, as well as the same published water-stressed upper baseline.

Soil water content was measured using time domain reflectometry (TDR) probes (MP-917, Environmental Sensors Inc., Victoria, BC, Canada) at 0- to 15-cm, 15- to 30-cm, 30- to 45-cm, and 45- to 60-cm sampling depths. After harvest, the probes were removed, and a 0.6-m deep hole was excavated to gather undisturbed samples from each of the four sampling depths. A soil water retention analysis of the samples was performed to determine the plant available water capacity per fifteen centimeter sampling depth (PAW15cm) on a volume basis (Cassel and Nielson, 1986). Published bulk density measurements for each soil (United States Department of Agriculture, 1981; 1990; 1995) were used for these calculations.

To determine the influence of date and water regime on CWSI, an analysis of variance (ANOVA) was performed on the individual location and year data sets using the PROC GLM procedure in SAS (SAS version 8.2, SAS Institute Inc, Cary, NC). This analysis was performed with date considered as the main plot factor and water regime as the subplot factor.

The first step in analyzing the relationships between CWSI and PAW15cm measured on different dates was to determine if PAW15cm was a significant factor in describing the variability in CWSI not already accounted for by the effects of date and water regime. Planting dates differed across years and locations and it was impossible to measure canopy temperatures and soil moisture at both locations on the same day. Therefore, the data from both years and locations were combined by crop growth stage to minimize the effects of plant size and physiological development on the amount of PAW15cm present at differing depths in the soil. Growing degree days (GDD) were calculated for each measurement date and location, and the data was separated into as many identifiable growth stages as possible. This resulted in five data groups representing growth stages I (V15), II (V19/VT), III (R1), IV (R2/R3), and V (R4).

An ANOVA was then performed to test the effects of year, location and water regime, as well as the year X water regime and location X water regime interactions (when appropriate), on CWSI at all five growth stages with either year or location or both (depending on the availability of data within each growth stage) as main effects and water regime as the subplot effect. An analysis of covariance (ANCOVA) was then performed to test the effects of PAW15cm on CWSI at all five growth stages with either year or location or both (depending on the availability of data by growth stage) as main effects and water regime as the subplot effect. Finally, each stage was separated into individual locations and dates. This allowed us to perform tests for linear correlations between PAW15cm and yield using the PROC CORR and PROC REG procedures in SAS.

Results and Discussion

Effects of Sampling Date and Water Regime by individual Site-Year.

Of the three measurement dates at Lewiston in 2001 (11 June, 18 June, and 6 July) only the 6 July data consisted of a complete set of temperature and relative humidity readings (T_a, T_c, T_w and RH) with which CWSI could be calculated. Subsequently, we could only test for the water regime main effect on CWSI at this date. In this case, water regime had no influence on CWSI at Lewiston in 2001 (Table 4.1).

At Plymouth in 2001 we were able to gather the appropriate data for CWSI calculation on four measurement dates which allowed testing for date, water regime and the interaction of the two main effects. Neither the interaction between date and water regime nor the date main effects were significant. Water regime was not significant at $\alpha = 0.05$ but was significant if alpha was set at 0.10 ($p = 0.0525$) (Table 4.2). The 2X treatment (1.3) had a significantly lower CWSI than the 0X treatment (2.8). The 1X treatment was not different from either of the 0X or 1X treatment. This fits with the rainfall pattern over the growing season at Plymouth in 2001. Rainfall over the five day period prior to the 19 June measurement date measured 8.0 cm. Over the next 28 days (to 17 July measurement date) only 2.2 cm of rainfall was measured. This dry period which coincided with the period of time over which measurements were taken resulted in a water regime impact on CWSI.

While we were able to gather complete datasets from three measurement dates at Lewiston in 2002, only the first measurement date (9 July) was within the final growth stage (GS V) by which we grouped the data into for this study. Growth Stage V, or R4, represents the dough stage, which is well past the stages indicated in previous research as critical in terms of the relationship between water stress and yield (Robins and Domingo, 1953; Runge, 1968; and Thompson, 1975). Even so, the date X water regime interaction and both main effects were all highly significant at Lewiston in 2002 (Table 4.1).

In general, CWSI for the 0X irrigation treatments were higher than the CWSI measured for the 1X treatments at most of the sampling dates. On 9 July (7.7), 17 July (8.1) and 29 July (7.9), measured CWSI were similar among the 0X treatments and significantly higher than CWSI in the 1X irrigation treatment measured on 9 July (2.2) and 17 July (4.0). Within the 1X treatments CWSI measured on 29 July (8.4) was significantly higher than the CWSI measured on 17 July, which, in turn, was significantly higher than the CWSI measured on 9 July. It is interesting to observe the differences in CWSI between irrigation treatments over time. On 9 July, the greatest difference in CWSI between treatments was found, with the 1X treatments (2.2) significantly lower than the 0X treatments (7.7) due to the 6.6 cm of irrigation (including 1.3 cm the day before measurement date) applied over the 21 days prior to 9 July and the absence of rainfall (0.2 cm) over the same period. At the 17 July measurement date, the difference (4.1) between treatments (8.1 for 0X; 4.0 for 1X) was less than that recorded on 9 July but was still significant. While no irrigation was applied between the 9 July and 17 July measurement dates, rainfall over the same period totaled 2.1 cm. By the time the 29 July measurements were taken, the difference between treatments (7.9 for 0X; 8.4 for 1X) was not significant. Although 1.5 cm of water was applied to the 1X treatment on 18 July (11 days prior to 29 July measurement date), it was not enough to cause a difference between treatments. In addition, 5.0 cm of rainfall accumulation was measured over the same period of time.

CWSI measurements increased significantly with each sampling date. Measurements taken on 9 July (5.0) were significantly lower than those taken on 17 July (6.1), and those taken on 17 July were significantly lower than those taken on 29 July (8.1). The same factors that affected the date X water regime interaction influenced the effect of sampling date on CWSI. Prior to 9 July, very little rainfall had accumulated over the previous 21 day period (0.2 cm), and irrigation provided enough water (6.6 cm) over the same 21 day period to hold CWSI down to lower levels. Therefore the average between the two treatments was significantly lower than the average of the 17 July measurements, which received more rainfall but no irrigation since 9 July. The average of the 29 July measurements was significantly higher than that of the 17 July measurement date as the irrigation on 18 July (1.5 cm) was too far in advance to cause differences in CWSI between treatments, and so the average CWSI for 29 July was much higher.

The water regime main effect was also found to be significant, with the 0X treatment (7.9) significantly higher than the 1X treatment (4.9). The effect of water regime on CWSI is explained by deficient rainfall amounts early in the growing season as well as the addition of water to irrigated treatments. Over the 94-day period between the 6 April planting date and 9 July measurement date, 13.8 cm of rainfall was measured. Over the same 94 day period, the 1X treatments received an additional 13.7 cm of water. Over the 21-day period preceding the 9 July measurement, rainfall and irrigation totals were 0.2 cm and 6.6 cm, respectively.

At Plymouth in 2002, date and water regime contributed significantly to differences in CWSI but the date X water regime interaction was not significant (Table

4.1). The measurement of CWSI on 22 July (6.6) was significantly higher than the 16 July measurement (5.1), while the 1 July measurement (4.7) was not significantly different from 16 July. The 3 July CWSI measurement (3.6), while not significantly higher than the 8 July measurement (3.4), was significantly lower than the 1 July measurement. These differences were attributable to timing of rainfall and irrigation in relation to measurement date. The significant reduction in CWSI from 1 July (4.7) to 3 July (3.6) was influenced by the 0.8 cm irrigation applied the morning of 3 July just prior to measurement. This irrigation contributed to lower CWSI values for the 1X treatments significantly lowering the average CWSI for 3 July below the 1 July level. Rainfall for the entire growing season from 27 March until 1 July totaled 13.6 cm. Another irrigation (0.8 cm) on the morning of the 8 July measurement date did not significantly change CWSI from 3 July (3.6) to 8 July (3.4). Furthermore, no measurable rainfall accumulated between these two dates. CWSI values increased significantly from 8 July to 16 July (5.1), with only 1.4 cm of rainfall accumulating between 8 July and 16 July. Even though an irrigation event (0.8 cm) was applied on the morning of 16 July, it was not able to influence CWSI values enough to avert the substantial increase from the previous measurement date. Another significant increase in CWSI measurements occurred from the 16 July measurements to the 22 July measurement date (6.6), despite the 3.7 cm rainfall which occurred on 21 July. The CWSI measurements for the 0X treatments (5.2) were significantly higher than the 1X treatments (4.1). This again was attributable to the low rainfall amounts throughout most of the 2002 growing season (19.5 cm) and the timing of irrigation in relation to timing of measurement dates as described previously.

Analysis of Treatment Effects by Growth Stage.

Growth stage I was comprised of measurements from Plymouth on 19 June 2001 only, and could be tested only for the water regime main effect (Table 4.2). Growth stage II originally included two measurement dates but only one of those dates (27 June 2001 at Plymouth) included a complete set of temperature measurements for calculating CWSI and it too could only be tested for the water regime main effect (Table 4.2). At neither of these growth stages was there a significant effect of water regime on CWSI.

Growth stage III originally included four dates, but like GS II there was an incomplete dataset for one date, so for the analysis only three measurement dates were used (6 July 2001 at Plymouth; 1 July and 3 July 2002 at Plymouth) (Table 4.2). At this stage it was possible to test for year and water regime main effects and the interaction of the two. While the year X water regime interaction and water regime effects were not significant, there was a significant year effect with the CWSI value for 2002 (4.2) significantly higher than for 2001 (1.9). This difference in year follows the differences in the two growing seasons with respect to rainfall. Rainfall at Plymouth in 2001 from 30 April planting date to 6 July measurement date totaled 29.2 cm. Rainfall at Plymouth in 2002 from 27 April planting date to 1 July measurement date totaled 13.6 cm, less than half of the previous years precipitation. It is evident that the abundant rainfall of 2001 resulted in low CWSI values, and the stressful conditions of the 2002 growing season led to much higher CWSI values.

Growth stage IV was comprised of four dates (6 July 2001 at Lewiston, 17 July 2001 at Plymouth, 8 July and 16 July 2002 at Plymouth) and allowed testing of the three main effects (year, location, and water regime) and the interactions (year x water regime and location x water regime) (Table 4.2). Neither of the interaction terms were significant nor was the water regime main effect. The ANOVA indicated location was a significant contributor to the differences in CWSI. Year was also shown to be significant at GS IV, with a CWSI value for 2001 (3.3) significantly lower than for 2002 (4.3). This again is indicative of the differences in the two growing seasons.

Growth stage V contained measurements from two dates at different locations (9 July 2002 at Lewiston and 22 July 2002 at Plymouth) allowing testing for location, water regime and the interaction between the two (Table 4.2). The location X water regime interaction significantly impacted CWSI values. The Lewiston (7.7) and Plymouth (7.1) 0X treatments did not differ from each other. The Plymouth 0X treatment did not differ from the Plymouth 1X treatment (6.2). However, the Lewiston 0X treatment did differ significantly from the Plymouth 1X treatment. All three of these treatments were significantly higher than the Lewiston 1X treatment (2.2). Of particular interest were the higher CWSI values for Plymouth 1X treatments compared to the Lewiston 1X treatments and the differences between the treatments at both locations. The 9 July measurement date at Lewiston was preceded by extremely dry conditions. Rainfall over the previous 21 day period totaled 0.2 cm. Irrigated plots had received 6.6 cm of water over the same period (1.3 cm of this water was applied on 8 July), thus the difference in CWSI values between treatments at Lewiston. However, at Plymouth the difference between treatments was not significant. On the day before the 22 July measurement, 3.7 cm of rainfall accumulated, negating the effects of an otherwise dry growing season on CWSI values at that date.

Location and water regime were both significant at GS V. The Plymouth CWSI value (6.6) was higher than the Lewiston CWSI value (5.0). CWSI values for the 1X treatments (4.2) were significantly lower than those for the 0X treatments (7.4). The explanations for these significant effects have been discussed previously.

Growth Stage Covariate Analysis.

PAW15cm was included in the growth stage analysis as a covariate to determine any influence on CWSI. Of the four sampling depths in each of the five growth stages, PAW15cm was found to have a significant impact on CWSI only at the 0- to 15-cm sampling depth in GS IV (Table 4.3). However, the correlation coefficient between CWSI and PAW15cm (0.09) at this sampling depth was not significant ($p = 0.5469$) (Table 4.4). Linear regression of CWSI on PAW15cm showed a slightly positive slope ($r^2 = 0.01$), indicating an increase in CWSI as PAW15cm increased (Figure 4.1) and revealed that changes in PAW15cm at this sampling depth were not responsible for changes in CWSI.

Individual Location and Year Covariate Analysis.

Further investigation of possible relationships between CWSI and PAW15cm included an examination of individual locations and years using PAW15cm as a covariate. Among the sampling depths at each location-year, PAW15cm was found to have a significant impact on CWSI only at the 45 to 60-cm sampling depth at Lewiston in 2002 (Table 4.5). Although the correlation was weakly negative (-0.12) indicating a trend toward increasing CWSI with decreasing PAW15cm, it was not significant (Table

4.6), and the variation in PAW15cm could only explain 2% of the variability in CWSI (Figure 4.2).

Individual Measurement Date Covariate Analysis.

Finally, the data was separated into individual measurement dates to further determine the significance of PAW15cm as a covariate. Only at the 45- to 60-cm sampling depth at Lewiston on 17 July 2002 was PAW15cm found to be a significant covariate (Table 4.7). A test for correlation of PAW15cm on CWSI indicated a correlation coefficient of -0.19, with CWSI decreasing as PAW15cm increased (Table 4.8). As before, the correlation was not significant, and a linear regression indicated the PAW15cm measurements were only able to account for 3.0% of the variation in CWSI (Figure 4.3).

Because of the significant relationship between water regime and CWSI and the significant relationship between water regime and PAW15cm, it was appropriate to analyze the correlations between PAW15cm and CWSI at each measurement date and location, even at sampling depths and locations where PAW15cm was not found to be a significant covariate. Correlation of CWSI and PAW15cm for each measurement date and location indicated significant relationships on three occasions in 2002, none of which included PAW15cm as a significant covariate. At Lewiston on 9 July, significant correlation coefficients of -0.82 ($p = 0.0010$) and -0.64 ($p = 0.0261$) were identified at the 30- to 45-cm and 45- to 60-cm sampling depths, respectively (Table 4.8). Both slopes were negative, indicating PAW15cm increased as CWSI values decreased. At the 30- to 45-cm depth, 68% of the variation in CWSI was accounted for by the linear regression on

PAW15cm (Figure 4.4). At the 45- to 60-cm depth, 41% of the variation in CWSI was accounted for by the linear regression on PAW15cm. Rainfall over the 47 day period prior to this measurement date totaled 6.1 cm. Irrigation applied to 1X treatments over the same period totaled 13.7 cm, with 1.3 cm of this water applied one day before measurement date. Given the tendency for a crop to root deeply on drier years, the coarse textured soil found at the PBRS, and the lack of rainfall throughout the growing season, it is reasonable that significant correlations between CWSI and PAW15cm at the lower sampling depths were observed. Also, this was the only date at Lewiston in 2002 that was measured under severely stressful conditions; the 17 July and 29 July measurement dates were preceded by no irrigation and moderate to substantial rainfall over the seven day period prior to each measurement date (17 July, 6.1 cm; 29 July, 4.2 cm).

Two dates at Plymouth in 2002 displayed significant correlations between CWSI and PAW15cm. On 3 July, significant correlation coefficients of -0.73 ($p = 0.0110$) and -0.66 ($p = 0.0203$) were identified at the 0- to 15-cm and 30- to 45-cm sampling depths, respectively (Table 4.9). Both slopes were negative, indicating CWSI values decreased as PAW15cm increased. At the 0- to 15-cm depth, 53% of the variation in CWSI was accounted for by the linear regression on PAW15cm, and was attributable to a 0.8 cm irrigation applied to the 1X treatments on the morning of the measurement date (Figure 4.5). At the 30- to 45-cm depth, 43% of the variation in CWSI was accounted for by the linear regression on PAW15cm (Figure 4.5). The same relationship was observed at the 30- to 45-cm sampling depth on 16 July, when significant correlation coefficients of -0.72 ($p = 0.0082$) were identified (Table 4.9), and 52% of the variation in CWSI was accounted for by the linear regression on PAW15cm (Figure 4.6). It is evident that the low amount of irrigation applied per event was unable to meet peak daily crop ET demands of corn in North Carolina (0.9 cm) (Heiniger et al., 2002), and only influenced the shallow (0- to 15-cm) sampling depth in terms of the CWSI to PAW15cm relationship during the critical stages of early reproductive growth. However, it is interesting to note that the differences in PAW15cm at the 30- to 45-cm and 45- to 60-cm sampling depth were attributable to irrigation treatments, indicating that while unable to impact PAW15cm measurements during the early reproductive stages of corn growth, earlier irrigation events seemed to have a positive impact on stored soil moisture at these lower sampling depths. This effect is clearly observable throughout the period of time over which measurements were taken at Lewiston and Plymouth in 2002. The dry 2002 growing season influenced deep rooting of the crop at Plymouth just as it had at Lewiston, despite the difference in soils. The significance of the relationships at this depth indicates the depth to which crop roots can penetrate the soil in search of moisture.

Conclusion

Understanding the relationship between CWSI and PAW would help in examining the key factors that limit corn yield in North Carolina. The ability to determine soil moisture status at a given time during the growing season using canopy temperature would enable producers to maximize inputs such as irrigation, fertilizer, insecticides and fungicides. This ability would enable growers to remain profitable while continuing to meet the ever-increasing environmental standards of today's society. The objective of this study was to quantify the relationship between plant available water measured at four depths throughout the growing season and crop water stress as determined by crop water stress index.

An ANOVA on the effects of water regime and, where testable, date and the date X water regime interaction on CWSI was performed on data sets from individual years and locations. In 2001, no significant effects were detected at Lewiston, and only water regime was significant at Plymouth at $p < 0.10$. In 2002 the date X water regime interaction and both main effects were highly significant at Lewiston while at Plymouth, only the date and water regime main effects contributed significantly to differences in CWSI.

An ANOVA was then performed to test the effects of year, location and water regime, as well as the year X water regime and location X water regime interactions (when appropriate), on CWSI at all five growth stages. At GS I and GS II, no effects were determined to significantly influence CWSI. At GS III, there was a significant year effect on CWSI. Year was shown to be significant at GS IV. The main effects location and water regime, as well as the location X water regime interaction significantly impacted CWSI at GS V.

Next, PAW15cm was added to the analysis by growth stage as a covariate to test for significance by sampling depth. Of the four sampling depths in each of the five growth stages, PAW15cm was found to have a significant impact on CWSI only at the 0- to 15-cm sampling depth in GS IV. However, the correlation coefficient between CWSI and PAW15cm at this sampling depth was not significant, and had a positive slope, indicating an increase in CWSI as PAW15cm increased. Further investigation of possible relationships between CWSI and PAW15cm included an examination of individual locations and years using PAW15cm as a covariate. Among the sampling depths at each location-year, PAW15cm was found to have a significant impact on CWSI only at the 45 to 60-cm sampling depth at Lewiston in 2002 Although the weakly negative correlation indicated a trend toward increasing CWSI with decreasing PAW15cm, it was not significant.

Finally, the data was separated into individual measurement dates to further determine the significance of PAW15cm as a covariate. Only at the 45- to 60-cm sampling depth at Lewiston on 17 July 2002 was PAW15cm found to be a significant covariate. A test for correlation of PAW15cm on CWSI indicated the correlation had a negative slope (CWSI decreased as PAW15cm increased) but was not significant.

Correlation of CWSI and PAW15cm at each measurement date and location indicated significant relationships on three occasions in 2002, none of which included PAW15cm as a significant covariate. At Lewiston on 9 July, significant correlation coefficients were identified at the 30- to 45-cm and 45- to 60-cm sampling depths. Both slopes were negative, indicating CWSI values decreased as PAW15cm increased, and linear regressions of the data revealed that much of the variation in CWSI was accounted for by variation in PAW15cm at these lower sampling depths.

Two dates at Plymouth in 2002 displayed significant correlations between CWSI and PAW15cm. On 3 July, significant correlation coefficients were identified at the 0- to 15-cm and 30- to 45-cm sampling depths. On 16 July, significant correlation coefficients were again identified at the 30- to 45-cm sampling depths. All slopes were negative, indicating CWSI values decreased as PAW15cm increased. Again, linear regression indicated much of the variation in CWSI was accounted for by the variation in PAW15cm in each case.

The 3 July measurement date at Plymouth was the only date of the three that occurred during GS III (R1). Because the crop measured at Lewiston on 9 July and at Plymouth on 16 July was at GS IV (R2-R3), the significance of the relationships measured are less important as they occur at a stage less critical than GS III (R1) in terms of yield reduction due to water stress, as Denmead and Shaw (1960) observed when they reported that stress at vegetative growth stages, at silking, and after silking reduced corn yield by 25, 50, and 21%, respectively.

Hatfield (1983) found that dT values for a well watered crop of sorghum (*Sorghum bicolor*) remained negative, meaning leaf temperatures were lower than air temperatures, until 65% of the PAW was extracted. At this point, dT values became positive, meaning leaf temperatures were higher than air temperatures, and increased quickly as PAW decreased, indicating that the crop was under yield reducing stress. While determining this value for corn was beyond the scope of this study, it was evident that the dates which exhibited strong correlations between CWSI and PAW15cm were those dates which were (i) already under substantial moisture stress and (ii) had received enough irrigation to create measurable differences in canopy temperature for calculation of CWSI. Since the 2001 growing season was well watered, and the 2002 growing season was not, it is easy to understand why all the significant correlations came from 2002 measurements. Still, 2002 did not offer stressful conditions over the entire growing season as rainfall late in the season impacted measurements at Lewiston after the first measurement date on 9 July. In addition, inadequate irrigation amounts at Plymouth were not enough to continually alleviate stressful conditions in irrigated treatments.

The fact that we found some relationships at the lower depths (30- to 45-cm and 45- to 60-cm) in the profile and that they were associated with the early reproductive stages of the crop is encouraging. The ability to determine soil moisture status at a critical growth stage for corn using canopy temperature would enable producers to maximize inputs such as irrigation, fertilizer, insecticides and fungicides, remaining profitable while continuing to meet the ever-increasing environmental standards of today’s society.

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Table 4.1. Analysis of variance (ANOVA) of crop water stress index (CWSI) at each of four locations and years.

Growth Stage		MSE†	p-value
Lewiston 2001	Water Regime	1.1815	0.4735
Plymouth 2001	Date	5.0598	0.1074
	Water Regime	7.4810	0.0525
	Date X Water Regime	0.1673	0.9981
Lewiston 2002	Date	30.6657	<0.0001
	Water Regime	82.8652	<0.0001
	Date X Water Regime	29.5985	<0.0001
Plymouth 2002	Date	20.1337	<0.0001
	Water Regime	16.2688	<0.0001
	Date X Water Regime	1.1453	0.1832

† = Mean Square Error

Table 4.2. Analysis of variance (ANOVA) of crop water stress index (CWSI) at each of five growth stages.

Growth Stage		MSE†	p-value
I	Water Regime	1.5783	0.5464
II	Water Regime	2.3733	0.5859
III	Year	15.6974	0.0008
	Water Regime	2.9738	0.0845
	Year X Water Regime	1.8333	0.2073
IV	Location	10.2753	0.0131
	Year	8.0597	0.0266
	Water Regime	3.3015	0.1261
	Year X Water Regime	1.6224	0.3056
	Location X Water Regime	2.1967	0.2453
V	Location	16.9742	<0.0001
	Water Regime	60.6370	<0.0001
	Location X Water Regime	32.5372	<0.0001

† = Mean Square Error

Table 4.3. Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at growth stage IV with plant available water per fifteen centimeters of soil depth (PAW15cm) as a covariate.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location	0.2443	0.6711	9.3435	0.0188	9.5545	0.0177	10.1695	0.0150
Year	6.8271	0.0302	8.5528	0.0241	6.4058	0.0490	7.3817	0.0359
Water Regime	4.9673	0.0346	3.2569	0.1349	2.8216	0.1747	3.1268	0.1478
Year X Water Regime	1.1047	0.3689	1.4933	0.3302	1.3116	0.3617	1.6630	0.3067
Location X Water Regime	2.8068	0.1375	2.2497	0.2443	2.3850	0.2262	2.2312	0.2500
PAW15cm	7.0569	0.0278	0.5215	0.5632	0.3847	0.6198	0.0713	0.8310

† = Mean Square Error

Table 4.4. Overall correlation coefficients for relevance between PAW15cm (plant available water per fifteen centimeters of soil depth) and CWSI (crop water stress index) at five growth stages.

	Growth Stage				
Sampling depth	I	II	III	IV	V
0- to 15-cm	0.20	-0.44	-0.72**	0.09	0.10
15- to 30-cm	0.18	0.46	-0.55**	-0.12	-0.01
30- to 45-cm	0.16	0.13	-0.63**	-0.29	-0.12
45- to 60-cm	0.29	-0.14	-0.47**	-0.26	-0.08

** denotes significance at the 0.01 level.

Table 4.5. Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at Lewiston in 2002.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Date	15.0896	0.0004	19.3820	<0.0001	16.1283	0.0003	24.8208	<0.0001
Water Regime	81.4852	<0.0001	83.1594	<0.0001	64.8874	<0.0001	77.5416	<0.0001
Date X Water Regime	29.2764	<0.0001	30.1760	<0.0001	29.5421	<0.0001	30.0195	<0.0001
PAW15cm	0.7035	0.4947	1.1816	0.3748	1.4343	0.3275	6.3405	0.0338

† = Mean Square Error

Table 4.6. Correlation coefficients for relevance between CWSI (crop water stress index) and PAW15cm (plant available water per fifteen centimeters of soil depth) at four locations and years.

Location and Year	Sampling depth	Correlation Coefficient
Lewiston 2001	0- to 15-cm	-0.50
	15- to 30-cm	0.27
	30- to 45-cm	0.31
	45- to 60-cm	0.19
Plymouth 2001	0- to 15-cm	-0.33*
	15- to 30-cm	-0.12
	30- to 45-cm	-0.05
	45- to 60-cm	-0.08
Lewiston 2002	0- to 15-cm	0.13
	15- to 30-cm	0.22
	30- to 45-cm	-0.09
	45- to 60-cm	-0.12
Plymouth 2002	0- to 15-cm	0.49**
	15- to 30-cm	0.41**
	30- to 45-cm	-0.11
	45- to 60-cm	-0.02

* denotes significance at the 0.05 level.
** denotes significance at the 0.01 level.

Table 4.7. Analysis of covariance (ANCOVA) of crop water stress index (CWSI) on 17 July 2002 at Lewiston.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Water Regime	49.7495	0.0013	45.2898	0.0014	44.8156	0.0016	56.2439	0.0001
PAW15cm‡	0.0009	0.9845	1.4964	0.4300	1.0243	0.5163	8.6502	0.0346

† = Mean Square Error
‡ = plant available water per fifteen centimeters of soil depth

Table 4.8. Correlation coefficients for relevance between CWSI (crop water stress index) and PAW15cm (plant available water per fifteen centimeters of soil depth) on three measurement dates at Lewiston in 2002.

		Date		
Location and Year	Sampling depth	9 July	17 July	29 July
Lewiston 2002	0- to 15-cm	-0.48	0.08	0.07
	15- to 30-cm	-0.30	0.30	0.12
	30- to 45-cm	-0.82**	-0.30	0.53
	45- to 60-cm	-0.63*	-0.19	0.41

* denotes significance at the 0.05 level.
** denotes significance at the 0.01 level.

Table 4.9. Correlation coefficients for relevance between CWSI (crop water stress index) and PAW15cm (plant available water per fifteen centimeters of soil depth) on five measurement dates at Plymouth in 2002.

		Date				
Location and Year	Sampling depth	1 July	3 July	8 July	16 July	22 July
Plymouth 2002	0- to 15-cm	-0.19	-0.72*	-0.03	-0.28	-0.18
	15- to 30-cm	0.21	-0.22	0.01	-0.14	0.05
	30- to 45-cm	-0.28	-0.65*	0.05	-0.72**	0.17
	45- to 60-cm	-0.03	-0.27	0.24	-0.33	0.05

* denotes significance at the 0.05 level.
** denotes significance at the 0.01 level.

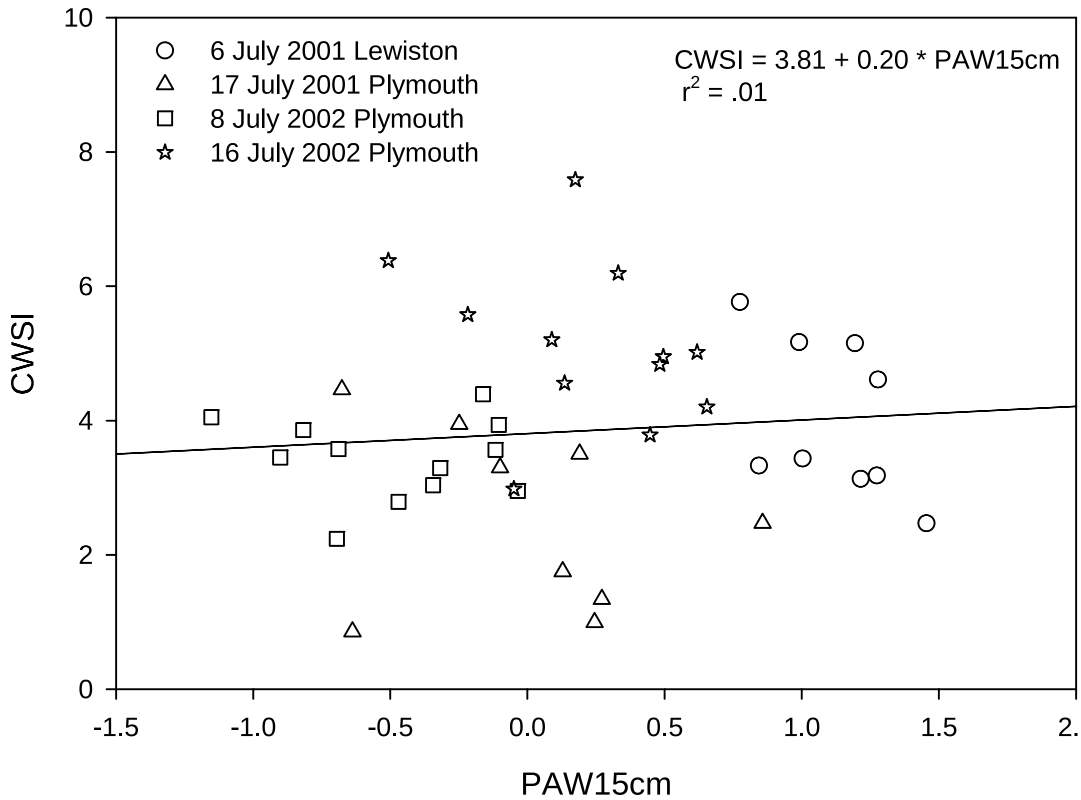

Figure 4.1. Linear regression of crop water stress index (CWSI) on plant available water per fifteen centimeters of soil depth (PAW15cm) at the 0- to 15-cm sampling depth at growth stage IV.

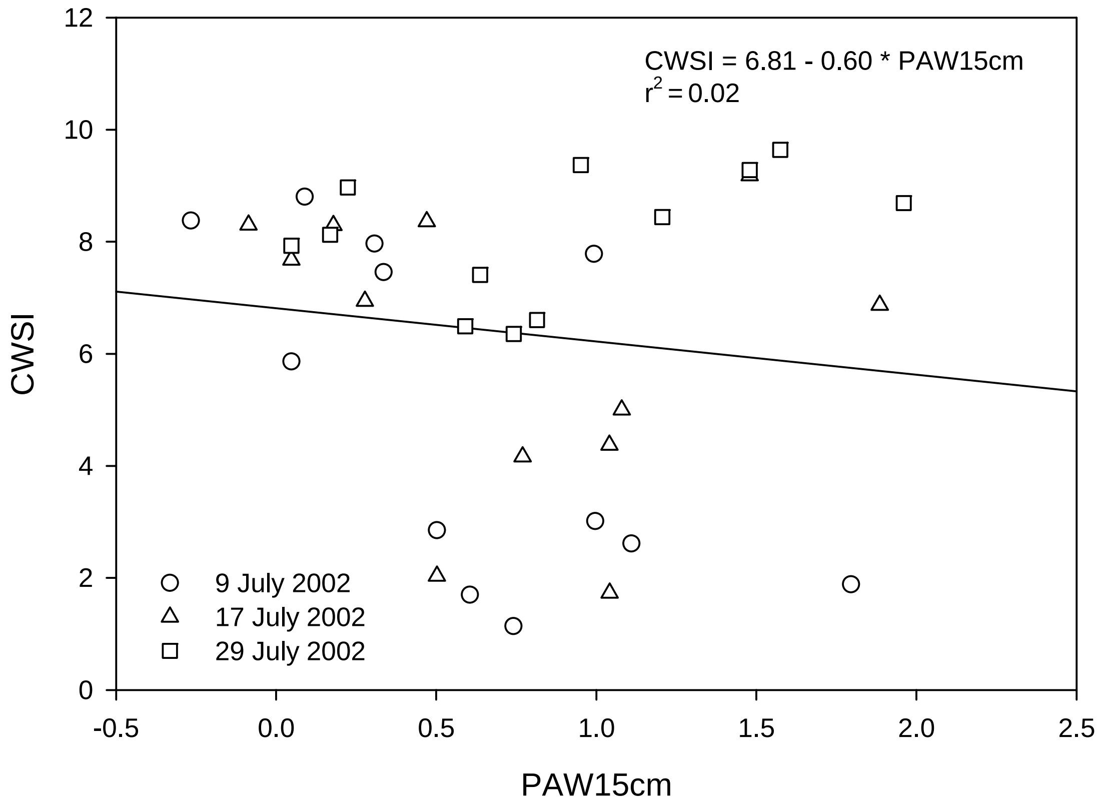

Figure 4.2. Linear regression of crop water stress index (CWSI) on plant available water per fifteen centimeters of soil depth (PAW15cm) at the 45- to 60-cm sampling depth at Lewiston in 2002.

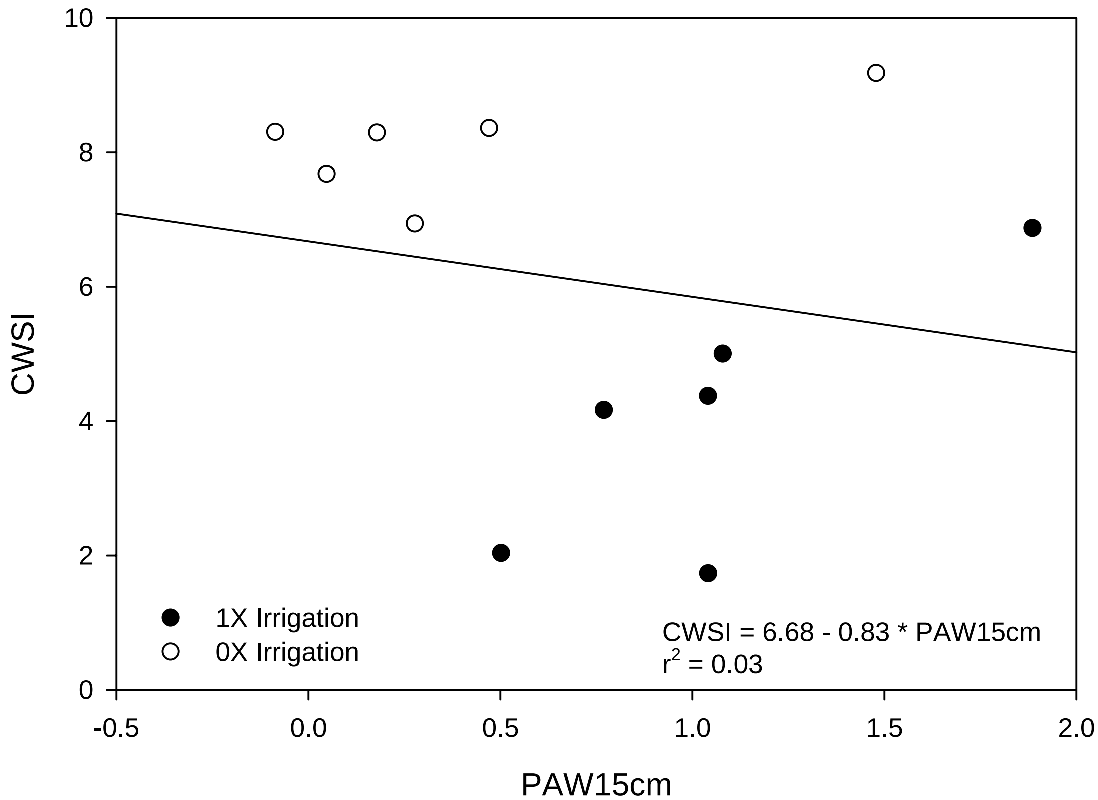

Figure 4.3. Linear regression of crop water stress index (CWSI) on plant available water per fifteen centimeters of soil depth (PAW15cm) at the 45- to 60-cm sampling depth at Lewiston on 17 July 2002.

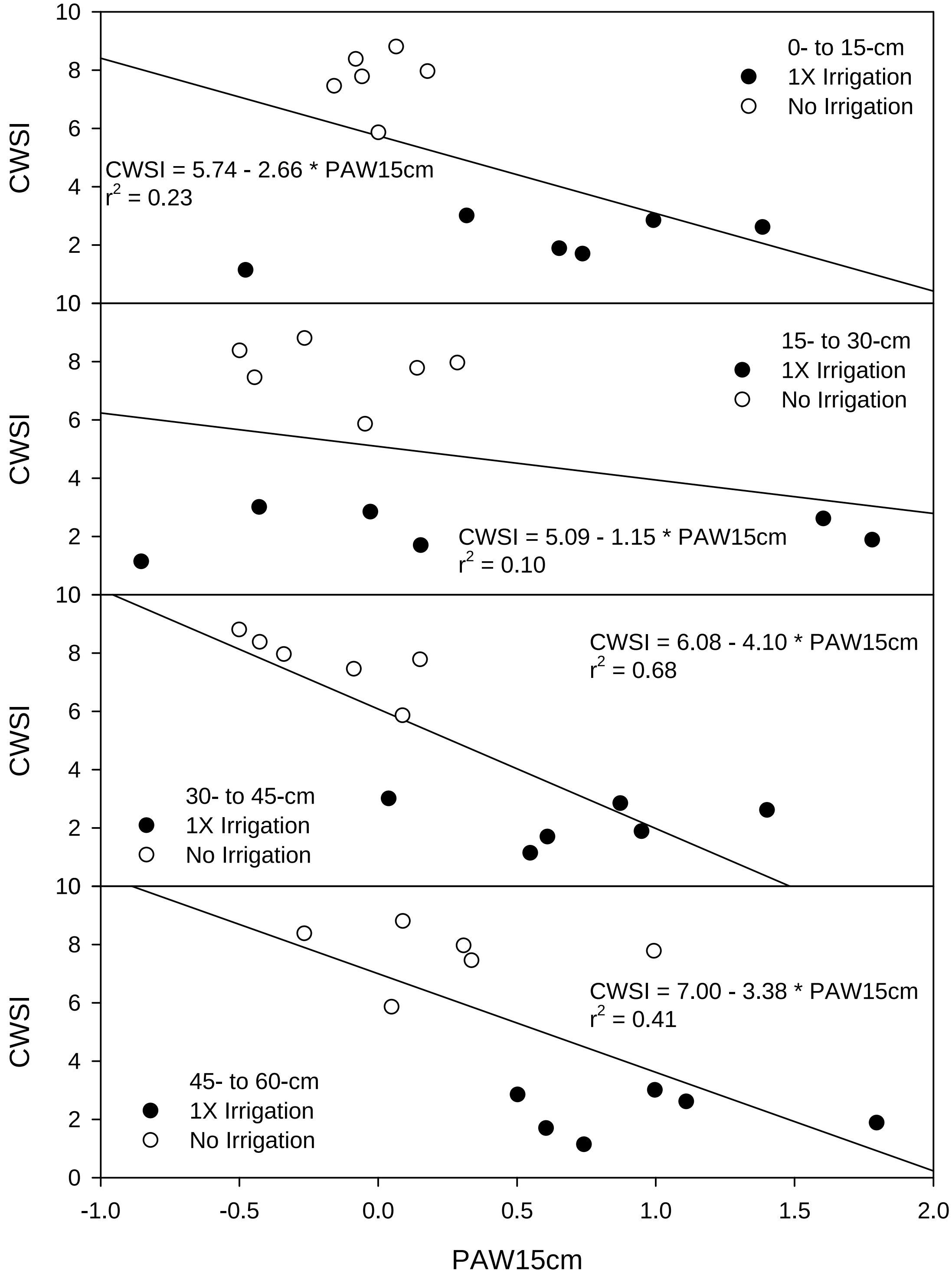

Figure 4.4. Linear regression of crop water stress index (CWSI) on plant available water per fifteen centimeters of soil depth (PAW15cm) at Lewiston on 9 July 2002.

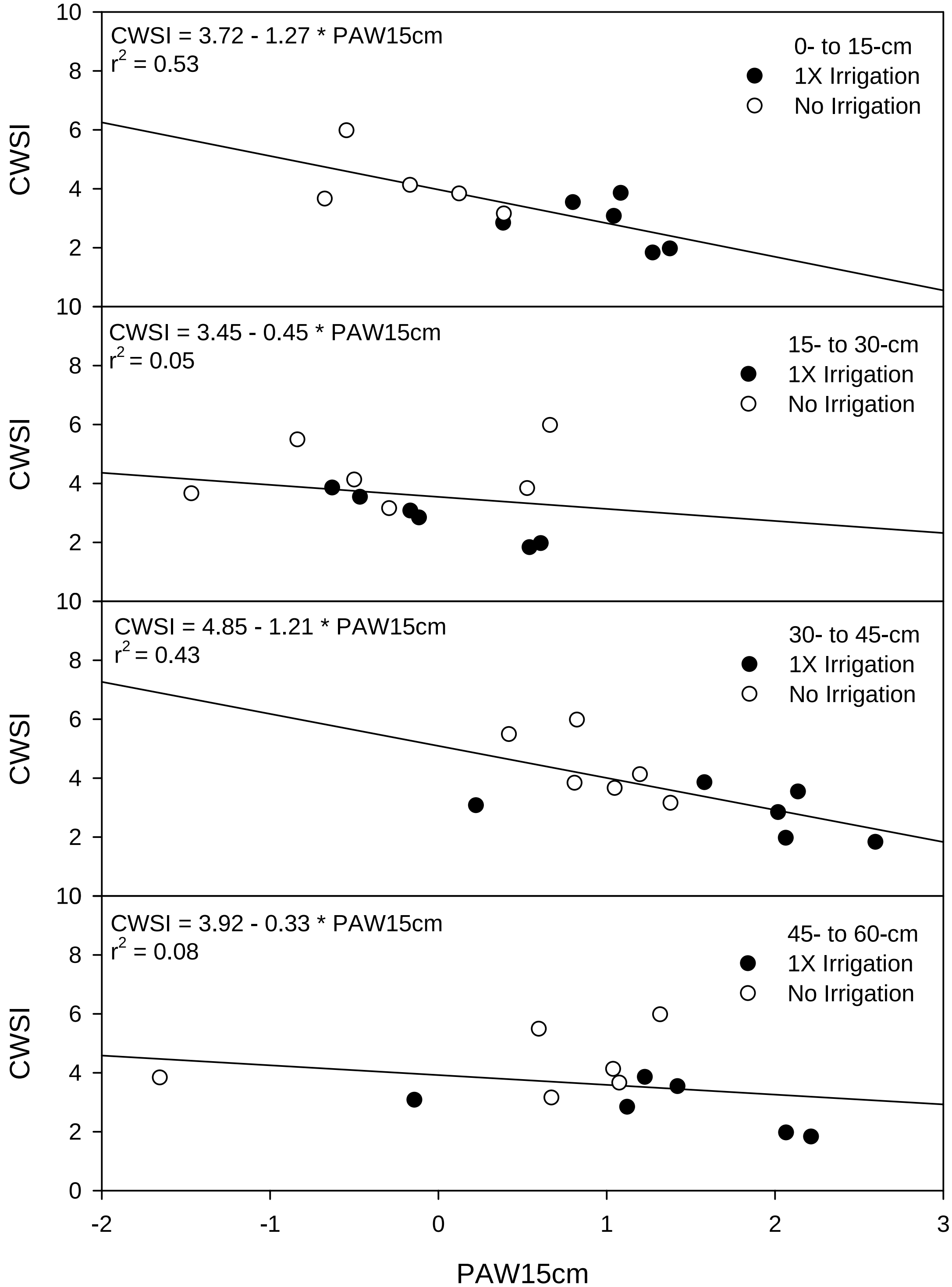

Figure 4.5. Linear regression of crop water stress index (CWSI) on plant available water per fifteen centimeters of soil depth (PAW15cm) at Plymouth on 3 July 2002.

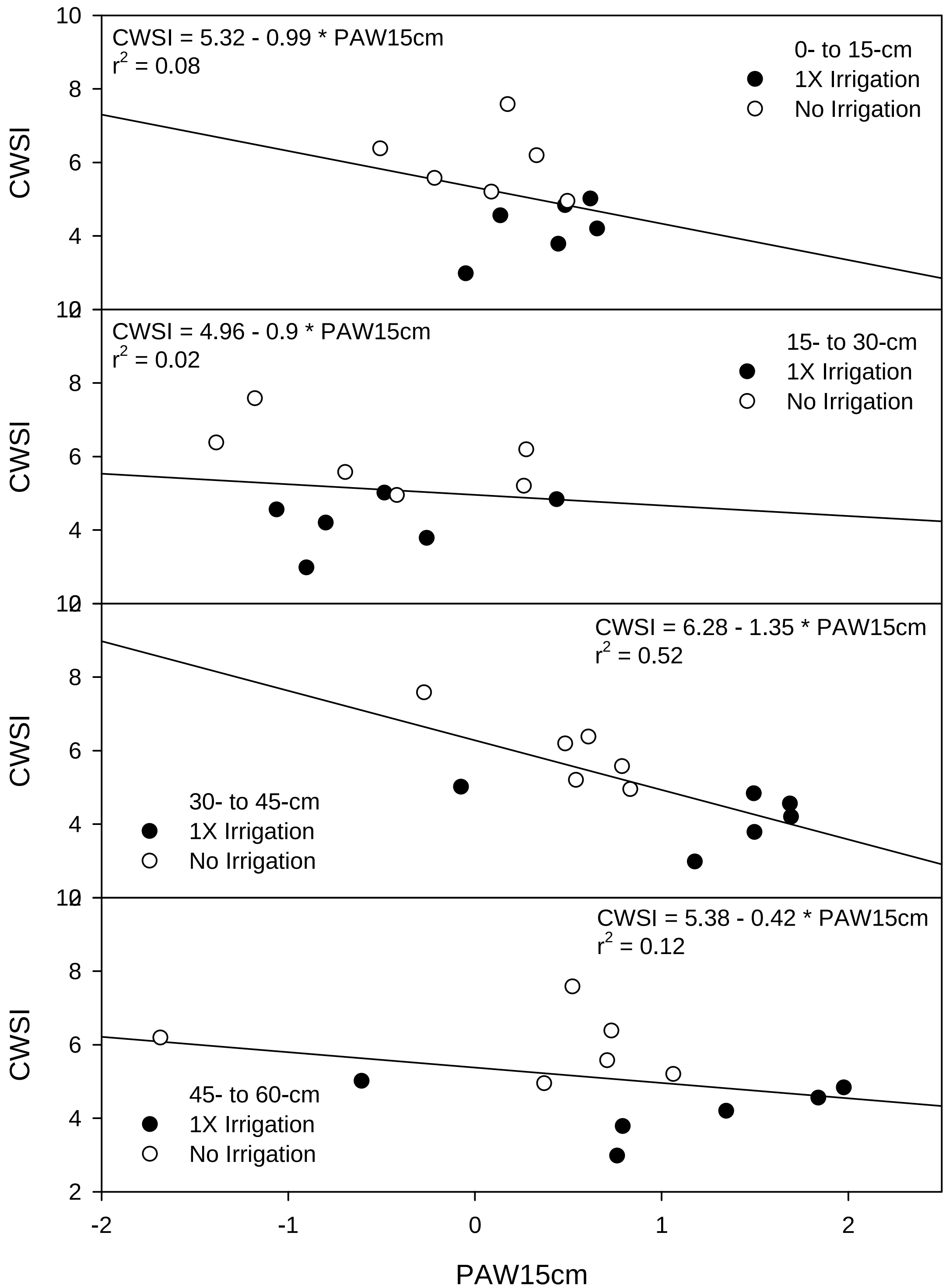

Figure 4.6. Linear regression of crop water stress index (CWSI) on plant available water per fifteen centimeters of soil depth (PAW15cm) at Plymouth on 16 July 2002.

Appendices

Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at growth stage I with plant available water per fifteen centimeters of soil depth (PAW15cm) as a covariate.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Water Regime	1.2915	0.6553	1.7487	0.5565	1.3423	0.6476	0.8303	0.7572
PAW15cm	0.1195	0.8446	0.9039	0.5844	0.0014	0.9829	0.0293	0.9228

† = Mean Square Error

Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at growth stage II with plant available water per fifteen centimeters of soil depth (PAW15cm) as a covariate.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Water Regime	1.6525	0.6832	1.2959	0.7381	3.2957	0.5187	6.1296	0.2442
PAW15cm	4.2484	0.3509	4.2651	0.3498	2.3823	0.4944	8.1506	0.1734

† = Mean Square Error

Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at growth stage III with plant available water per fifteen centimeters of soil depth (PAW15cm) as a covariate.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Year	2.7861	0.1267	10.7153	0.0048	5.3250	0.0359	11.6525	0.0034
Water Regime	1.1989	0.3573	2.8995	0.0964	2.4307	0.1273	3.0457	0.0856
Year X Water Regime	1.3573	0.2809	1.8094	0.2176	1.4714	0.2558	2.0260	0.1916
PAW15cm	1.1413	0.3219	0.1530	0.7164	1.3379	0.2780	0.3129	0.6029

† = Mean Square Error

Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at growth stage V with plant available water per fifteen centimeters of soil depth (PAW15cm) as a covariate.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Location	1.5640	0.1259	14.2666	0.0002	5.2546	0.0126	12.3817	0.0004
Water Regime	51.5937	<0.0001	60.7117	<0.0001	40.5142	<0.0001	52.8201	<0.0001
Location X Water Regime	27.3998	<0.0001	24.4378	<0.0001	32.2187	<0.0001	31.8588	<0.0001
PAW15cm	0.1036	0.6843	0.1811	0.6167	0.3059	0.5143	0.5191	0.3936

† = Mean Square Error

Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at Lewiston in 2001.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Water Regime	1.9879	0.1783	0.8311	0.6323	0.7459	0.6569	0.9953	0.5884
PAW15cm	4.3446	0.0673	0.0893	0.8253	0.1993	0.7408	0.0445	0.8763

† = Mean Square Error

Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at Plymouth in 2001.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Date	2.9865	0.2920	6.2773	0.0553	4.7974	0.1317	4.7287	0.1353
Water Regime	5.6194	0.1055	8.6781	0.0312	7.7356	0.0532	7.6511	0.0544
Date X Water Regime	0.2834	0.9920	0.5136	0.9588	0.1940	0.9973	0.2491	0.9947
PAW15cm	1.7319	0.3906	4.4301	0.1641	0.5299	0.6368	0.6295	0.6066

† = Mean Square Error

Analysis of covariance (ANCOVA) of crop water stress index (CWSI) at Plymouth in 2002.

	Sampling depth							
	0- to 15-cm		15- to 30-cm		30- to 45-cm		45- to 60-cm	
	MSE†	p-value	MSE	p-value	MSE	p-value	MSE	p-value
Date	6.8238	<0.0001	14.0370	<0.0001	19.8975	<0.0001	19.3014	<0.0001
Water Regime	8.2502	0.0009	16.3536	<0.0001	9.0047	0.0009	16.1947	<0.0001
Date X Water Regime	0.9599	0.2315	1.1115	0.2034	1.1427	0.1893	1.1409	0.1859
PAW15cm	0.3349	0.4799	0.0851	0.7321	0.2955	0.5231	0.6355	0.3478

† = Mean Square Error

Correlation coefficients for relevance between CWSI (crop water stress index) and PAW15cm (plant available water per fifteen centimeters of soil depth) on one measurement date at Lewiston in 2001.

		Date		
Location and Year	Sampling depth	11 June	18 June	6 July
Lewiston 2001	0- to 15-cm	NA	NA	-0.50
	15- to 30-cm	NA	NA	0.27
	30- to 45-cm	NA	NA	0.31
	45- to 60-cm	NA	NA	0.19

NA = Data to calculate CWSI was not complete for these dates.

Correlation coefficients for relevance between CWSI (crop water stress index) and PAW15cm (plant available water per fifteen centimeters of soil depth) on four measurement dates at Plymouth in 2001.

		Date			
Location and Year	Sampling depth	19 June	27 June	6 July	17 July
Plymouth 2001	0- to 15-cm	0.20	-0.44	-0.45	-0.25
	15- to 30-cm	0.18	0.46	-0.56	0.11
	30- to 45-cm	0.16	0.13	-0.04	-0.14
	45- to 60-cm	0.29	-0.14	0.47	-0.28