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MAIZE EVAPOTRANSPIRATION, YIELD PRODUCTION FUNCTIONS, BIOMASS, GRAIN YIELD, HARVEST INDEX, AND YIELD RESPONSE FACTORS UNDER FULL AND LIMITED IRRIGATION

K. Djaman, S. Irmak, W. R. Rathje, D. L. Martin, D. E. Eisenhauer

ABSTRACT. South-central Nebraska is one of the most extensively irrigated areas in the U.S., with over 65,000 active irrigation wells, and maize is the major agronomical crop produced. Maize production in this region requires supplementary irrigation for maximum productivity. Effective on-farm implementation of full and limited irrigation practices for potential improvements of crop productivity requires knowledge of locally developed crop yield response to water functions. In this study, the effects of full and limited irrigation practices on maize (*Zea mays* L.) plant height, leaf area index (LAI), grain yield and biomass production, actual crop evapotranspiration (ET_a), yield production functions, yield response factors (K_y), and harvest index (HI) were investigated. Field experiments were conducted in 2009 and 2010 under center-pivot irrigation at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, Nebraska. Four irrigation regimes [fully irrigated treatment (FIT), 75% FIT, 60% FIT, and 50% FIT] and a rainfed treatment were evaluated each year. Maize ET_a , LAI, biomass production, grain yield, and HI were significantly affected by the irrigation regimes. Maize yields varied from 9.05 Mg ha⁻¹ for the rainfed treatment to 15.5 Mg ha⁻¹ for FIT in 2009 and from 11.7 to 15.5 Mg ha⁻¹ for the respective treatments in 2010. HI ranged between 0.49 for rainfed and 0.57 for FIT with an all-treatment average of 0.54. ET_a ranged from 481 mm for rainfed treatment to 620 mm for FIT in 2009 and from 579 to 634 mm for the same treatments in 2010. Strong yield vs. irrigation relationships ($R^2 \geq 0.98$ in both years) and yield vs. ET_a relationships ($R^2 = 0.94$ in 2009 and $R^2 = 0.97$ in 2010) were measured. There was a strong linear increase in ET_a with increasing irrigation amounts ($R^2 \geq 0.97$). The yield-irrigation and yield- ET_a relationships showed variation between the two years due to the impact of weather variability on these relationships, indicating the importance of accounting for weather variability impact on the slopes of crop yield production functions. Based on the slopes of the ET_a vs. grain yield relationships, 1.2 Mg ha⁻¹ (in 2009) and 1.7 Mg ha⁻¹ (in 2010) of grain yield was produced per 25.4 mm of ET_a beyond 280 mm (in 2009) and 403 mm (in 2010) of ET_a that was used by maize to start producing grain yield, which is also called the amount of ET_a required for establishing grain yield. Yield response factors varied between treatments and with year for the same treatment and averaged 1.65 in 2009 and 2.85 in 2010, with a two-year average of 1.82. No statistically significant difference ($p > 0.05$) in grain yield was found between 75% FIT and 100% FIT. In terms of crop response to water performance, the 75% FIT and 60% FIT treatments were very comparable to the fully irrigated treatment and are viable practices in increasing crop water productivity of maize with supplementary irrigation under these experimental, soil and crop management, and climatic conditions.

Keywords: Crop production function, Crop response factor, Evapotranspiration, Limited irrigation, Maize.

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Decline in availability of freshwater resources is one of the most critical challenges in food and fiber production in the Midwestern U.S., including Nebraska, and in many parts of the world. In many areas, freshwater for irrigation represents the largest water withdrawal. On a global average, the amount of water pumped for irrigation represents approximately 75% to 90% of the total surface and groundwater withdrawals (United Nations, 2003). Due to growing population and competition for water resources by many different water users (e.g., industries, environmental functions, municipalities and recreation, biofuel energy production, mining, etc.) as well as degradation of water quality, the quantity of water that can be used for irrigated production agriculture is decreasing throughout the world. In addition, climate change is having an impact on the

seasonal distribution and magnitude of precipitation and the recharge of the ground and surface water resources (Irmak et al., 2012). In some areas, distribution of rainfall during the growing season has shifted to the early or late growing season with an increase in extreme events (Irmak et al., 2012), making the rainfall less effective, in some cases, in meeting the plant water requirements in irrigated agriculture. In addition to well-organized water management practices for fully irrigated settings, best limited irrigation management practices have been developed and need to be improved and implemented at the farm level to ensure the sustainability of precious water resources and to enhance the productivity of irrigated agriculture. Robust irrigation management practices should be promoted to enhance the efficiency of agricultural production systems by reducing inputs while maintaining similar or improved yields. Within this context, limited irrigation has been proposed as a valuable strategy for arid and semiarid regions where water is one of the most limiting factors in crop production. Limited irrigation management practices could enhance crop productivity in semi-humid locations as well.

Maize (*Zea mays* L.) is a major irrigated and rainfed crop in the U.S. High Plains and Midwestern states, including Nebraska. Knowledge of a locally developed crop yield response to irrigation water is essential for effective on-farm implementation of limited irrigation practices. Locally developed crop response to water relationships, including crop production functions, yield response factors, and crop growth and yield parameters, can aid growers, crop consultants, irrigation districts, and water management agencies in understanding and quantifying the crop water productivity under various crop production systems and practices, including under limited and fully irrigated settings and rainfed conditions. Limited irrigation can result in substantially different productivity in various climates. For example, Howell et al. (1995) reported that limited irrigation of maize reduced yields by affecting both kernel weight and kernels per ear in the semi-arid region of Bushland, Texas. It has been shown that limited irrigation management practices enhance water use efficiency (WUE, also known as crop water productivity) of maize and other crops by reducing water use more sharply than the yield (Letey and Peters, 1957; Sinclair et al., 1975; Tanner and Sinclair, 1983; Eck, 1986; Howell et al., 1995; Howell and Tolk, 1998; Djaman, 1999; Stewart and Nielsen, 1990; Howell, 2001; Payero et al., 2006; Payero et al., 2009; Ko and Piccinini, 2009; Katerji and Mastrorilli, 2009; Liu et al., 2010; Kapanigowda et al., 2010; Djaman and Irmak, 2012). Payero et al. (2006) reported a linear increase in maize yield with increased seasonal irrigation, but the relationship varied from year to year. They found that actual crop evapotranspiration (ET_a) had the best correlation to grain yield as compared with seasonal total water, seasonal irrigation, and seasonal transpiration. In addition, they reported that the seasonal ET_a for different treatments was 37% to 79% in 2003 and 63% to 91% in 2004 as compared with the seasonal ET_a when water was not limited. Payero et al. (2008) evaluated eight irrigation treatments ranging from 53 to 356 mm of water application in 2005 and from 22 to 226 mm in 2006 in semiarid west central Nebraska. In both seasons, irrigation

significantly improved yields up to a point at which irrigation became excessive such that crop yield did not increase with increase in irrigation application. They found that irrigation significantly affected dry matter production and partitioning into the different plant components (grain, cob, and stover). On average, grain accounted for the majority of the above-ground plant dry mass ($\approx 59\%$), followed by stover ($\approx 33\%$) and cob ($\approx 8\%$), and dry mass of the plant and of each plant component tended to increase with seasonal ET_a . Payero et al. (2009) reported linear increases in yield and WUE with increasing ET_a and with the ratio of ET_a to ET_p ($ET_p = ET_a$ with no water stress).

The effect of water stress on maize ET_a had also been studied experimentally (Stewart and Hagan, 1973; Stewart et al., 1975; Stewart et al., 1983; Hanks, 1983; Vaux and Pruitt, 1983; Stewart and Nielsen, 1990; Howell et al., 1995; Howell, 2001; Ko and Piccinini, 2009; Djaman and Irmak, 2012). Klocke et al. (2004) reported that limited irrigation management practices in semi-arid southwest Nebraska resulted in only 16% yield reduction with about 40% less irrigation water application as compared with the fully irrigated practice. Bryant et al. (1992) and Earl and Davis (2003) indicated that water stress reduced yield, accumulated biomass, and harvest index (HI). Pandey et al. (2000) reported that when limited irrigation during the maize vegetative period was imposed, grain yield was reduced by 7% to 11% relative to the fully irrigated practice, and when water deficit occurred during the vegetative stage and early reproductive stage, significant yield reductions of 23% to 26% were observed.

Linear relationships between yield and ET_a of maize have been reported by Stewart et al. (1975), Hanks (1983), Howell et al. (1995), Irmak et al. (2000), Payero et al. (2006), Howell et al. (2006), Payero et al. (2009), Ko and Piccinini (2009), and Djaman and Irmak (2012). These relationships are valuable in understanding how the crop water productivity of the same crop shows variation under different conditions, and how the slopes of production functions might better represent the physiological WUE of grain than the irrigation water use efficiency (IWUE) ratios (Howell et al., 1995; Schneider and Howell, 1998; Djaman and Irmak, 2012). Crop water production functions have been analyzed in mechanistic terms (Tanner and Sinclair, 1983) and experimentally (Stewart and Hagan, 1973), with varying results for the same crop. The empirical models, in general, are of two types: one relating crop yield to ET_a (Hiler and Clark, 1971; Stewart and Hagan, 1973; Hanks, 1974), and the other one addressing crop yield response relative to ET_a in specific crop growth stages (Jensen, 1968; Howell and Hiler, 1975; Doorenbos and Kassam, 1979). Doorenbos and Kassam (1979) and Musick and Dusek (1980) related plant water deficit to yield as affected by relative ET_a , which is defined as the ratio of actual crop ET over maximum actual crop ET obtained from a fully irrigated crop (ET_a/ET_m). They expressed the relative yield decrease as a function of relative ET_a deficit and experimentally derived yield response factors (K_y). About 80% to 85% of the observed yield variability at different locations was explained by this relationship. The response factors were, therefore, recommended for planning, operation, and

evaluation of irrigation systems in limited and fully irrigated settings to understand plant response to water dynamics. In general, K_y is defined as a decrease in yield with respect to per unit decrease in ET_a and is the slope of the relationship of these variables, as described and expressed explicitly in the following equations (Doorenbos and Kassam, 1979):

$$\left[1 - \frac{Y_a}{Y_m}\right] = K_y \left[1 - \frac{ET_a}{ET_m}\right] \quad (1)$$

$$K_y = \left[1 - \frac{Y_a}{Y_m}\right] / \left[1 - \frac{ET_a}{ET_m}\right] \quad (2)$$

where Y_a is actual yield (kg ha^{-1}), Y_m is maximum yield (kg ha^{-1}), Y_a/Y_m is relative yield (relative to the yield from fully irrigated treatment), $1 - (Y_a/Y_m)$ is decrease in relative yield, ET_a is actual crop ET (mm), ET_m is maximum crop ET (mm) from fully irrigated crop, ET_a/ET_m is relative crop ET (relative to the fully irrigated crop ET), $1 - (ET_a/ET_m)$ is decrease in relative crop ET, and K_y is yield response factor. In this study, the crop yield response data from limited irrigation were fitted to equation 2 following FAO-33 (Doorenbos and Kassam, 1979). When $K_y < 1$, the decrease in yield is proportionally less with the decrease in water deficit; when $K_y > 1$, the decrease in yield is proportionally greater with the decrease in water deficit (for maize, $K_y = 1.25$ for the whole growing period). When $K_y = 1$, yield loss is equal to ET_a deficit.

A wide range of variability of K_y for maize related to environmental and management conditions and other factors has been reported in the literature. Kipkorir et al. (2002) reported a maize K_y value of 1.21 in Perkerra, Kenya, which is close to the 1.25 reported by Doorenbos and Kassam (1979). Andrioli and Sentelhas (2009) reported a maize K_y of 2.15 for the total growing season for drought-sensitive genotypes and 1.56 for drought-resistant genotypes in Brazil, and they related K_y to genotype sensitivity to water deficit. Payero et al. (2008) and Payero et al. (2009) reported K_y values of 1.58 and 1.50 in North Platte, Nebraska, which are the same as the value reported by Doorenbos and Kassam (1979) when water stress occurred during flowering stage. Dehghanisanij et al. (2009) reported K_y values in Iran ranging from 1.03 to 1.46. Igbadun et al. (2008) reported an average K_y value of 2.36 for a two-year study in Tanzania. Igbadun et al. (2007) obtained yield response factors of 0.21, 0.86, and 0.49, respectively, for the vegetative, flowering, and grain filling stages of maize in Tanzania, while Doorenbos and Kassam (1979) presented these values as 0.40, 1.50, and 0.50, respectively.

The aforementioned studies indicate that the crop yield production functions and crop growth parameters for the same crop, in general, exhibit substantial variation between different locations and under different management conditions. Knowledge of the sensitivity of maize to water and water stress over the whole growing season or during a specific growth stage is needed to develop limited irrigation management practices as well as to determine the yield response factors of maize under full irrigation. Furthermore, these functions should be determined for

multiple years to account for the impact of differences in climatic conditions on these functions in the same location. This study measured and evaluated crop response to several variables under full and limited irrigation and rainfed settings. The specific objectives of the study were to: (1) quantify crop yield response to irrigation and ET_a ; (2) quantify the effect of limited irrigation management practices on maize above-ground biomass production, yield, harvest index, and maize crop yield response factor; and (3) determine the irrigation level that results in maximum maize water productivity with less water in a transition zone between the sub-humid and semi-arid climatic region of south central Nebraska.

MATERIALS AND METHODS

SITE DESCRIPTION

Field experiments were conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory (SCAL) (40° 43' N and 98° 8' W at an elevation of 552 m above mean sea level) near Clay Center, Nebraska, during the 2009 and 2010 growing seasons. Clay Center is in a transition zone between the sub-humid and semi-arid zones, with strong winds. The long-term annual precipitation in the area is 680 mm, with significant annual and growing season variability in both magnitude and timing. For example, the annual rainfall at Clay Center in 1988 was only 420 mm, with growing season rainfall of 300 mm. The long-term average growing season (May 1 to September 30) precipitation is 468 mm, with 52% probability of exceeding occurrence. The site's greatest wind speeds usually occur from January to late June, with long-term average daily wind speed fluctuation from 2 m s^{-1} to over 8 m s^{-1} . The long-term average air temperature ranges from -5°C in January and December to 25°C in July. The soil at the site is a Hastings silt loam (fine, montmorillonitic, mesic Udic Argiustoll) with 0.5% slope, which is a well-drained soil on uplands, with a field capacity of $0.34 \text{ m}^3 \text{ m}^{-3}$, permanent wilting point of $0.14 \text{ m}^3 \text{ m}^{-3}$, and a saturation point of $0.53 \text{ m}^3 \text{ m}^{-3}$. The particle size distribution is 15% sand, 65% silt, and 20% clay, with 2.5% organic matter content in the topsoil (Irmak and Mutiibwa, 2009; Irmak, 2010).

EXPERIMENTAL DESIGN AND GENERAL SOIL AND CROP MANAGEMENT PRACTICES

Four irrigation treatments were evaluated in both growing seasons: fully irrigated treatment (FIT), 75% FIT, 60% FIT, 50% FIT, and rainfed treatment. The experimental design was a completely randomized design with three replications. Each replication plot was about 1 ha in size, and the sampling area (for harvest, LAI, plant height, and biomass) in each replication was eight rows wide and 15.2 m long with 0.76 m row spacing. The experimental field was maintained as ridge-till in both years. At planting, the top (center) of the ridge and associated crop residue were removed with a scraper and seed was planted into the center of the ridge. The ridge before clearing was typically 0.10 to 0.15 m higher than the furrow between the rows, which provided ample space to accommodate crop residue and loose soil moved

into the area between the rows. Only about one-third of the soil surface was disturbed by the ridge till practice at planting. Maize hybrid Mycogen 2V732 was planted on April 23, 2009, emerged on May 4-6, and was harvested on October 15, 2009. In 2010, the same maize hybrid was planted on April 28, emerged on May 15 (late emergence due to wet conditions in late April through mid-May), and was harvested on October 7, 2010. The planting population density was 73,000 plants ha⁻¹ in both years, and the planting depth was 0.05 m with a north-south planting direction (Irmak, 2010). All treatments were fertilized equally, and the nitrogen amount applied to the entire field was based on soil samples taken from several locations in the field and the University of Nebraska-Lincoln Extension nitrogen recommendation algorithms, which is based on the expected yield goal. The residual soil nitrogen was credited and subtracted from the final nitrogen amount needed. A total of 220 kg ha⁻¹ and 245 kg ha⁻¹ of nitrogen (28-0-0) were applied in the 2009 and 2010 growing seasons, respectively. Herbicide, insecticide, and fungicide applications were applied uniformly to the entire field when needed. The experimental field (16 ha) was irrigated using a four-span hydraulic and continuous-move center-pivot irrigation system (T-L Irrigation Co., Hastings, Neb.). Early in the season, the entire field received the same depth of water from snowmelt and/or rainfall, bringing the soil water content to field capacity for all treatments and providing adequate and uniform soil water for planting and crop germination.

MEASUREMENT OF SOIL WATER STATUS

Soil water status was monitored using two methods. Watermark Granular Matrix sensors (WGMS, Irrrometer, Co., Riverside, Cal.) were used to monitor soil matric potential (SMP) on an hourly basis. WGMSs are an indirect method of measuring SMP by directly measuring soil water tension. SMP measurements were converted to soil water content in percent volume using predetermined soil-water retention curves for the study field. The effective rooting depth for maize in the experimental site is 1.20 m, so WGMSs were installed every 0.30 m down to 1.20 m below the surface. The sensors were installed to measure resistance, which was related to soil water tension in two of the three replications of each treatment. The sensors were installed in the plant row, with each sensor installed between two healthy maize plants. The sensors were connected to a Watermark Monitor datalogger (Irrrometer Co., Riverside, Cal.), and measurements were recorded hourly throughout both growing seasons. In addition to WGMSs, the soil water content was measured using a neutron probe soil water meter (model 4302, Troxler Electronics Laboratories, Inc., Research Triangle Park, N.C.) at 0.30, 0.60, 0.90, 1.20, 1.50, and 1.80 m soil depths once or twice a week throughout the growing seasons. The neutron probe measurements were started on June 8, and the soil water content before that day and at planting was determined using gravimetric samplings. The neutron probe access tubes were installed between two plants in the plant row of representative experimental units (replication) of each treatment. The neutron probe measurements were used for soil water content dynamics analyses, and the WGMS data

were mainly used for determining irrigation timings. Irrigation timings were determined based on the WGMSs installed in the FIT. Under the FIT, the available soil water in the top 1.20 m profile was kept between approximately 90% of the field capacity and the maximum allowable depletion of 55% of total available water (TAW). Irrigations were initiated each time the soil water in the crop root zone in the FIT reference plot was depleted by about 40% to 45% below field capacity. The depletion criterion of 40% to 45% TAW was practiced to prevent the plants in the FIT from experiencing any water stress, as the center pivot requires two or three days to complete a full revolution. If the traditional 50% to 55% depletion was practiced, the plants in the FIT might have experienced water stress, and this would have jeopardized the project objectives. At each irrigation event, about 25, 19, 15, and 13 mm of irrigation water was applied to the FIT, 75% FIT, 60% FIT, and 50% FIT treatments, respectively. A total of seven irrigations were applied in the 2009 growing season on July 8, July 14, July 21, August 4, August 11, August 19, and August 27. In 2010, there were five irrigation applications (July 21, July 29, August 5, August 12, and August 19). The irrigation water was pumped from the Ogallala aquifer, and the depth to the water table was about 35 m in 2010.

SEASONAL EVAPOTRANSPIRATION CALCULATIONS USING SOIL-WATER BALANCE APPROACH

Seasonal ET_a (mm) was calculated using a general soil water balance equation:

$$P + I + U - RO - DP \pm \Delta W - ET_a = 0 \quad (3)$$

where P is rainfall (mm), I is the irrigation water applied (mm), U is the upward vertical soil water flux from below the root zone (mm, assumed zero), RO is the surface runoff (mm), DP is water lost through deep percolation, vertically downward from the root zone (mm), and ΔW is the change in soil water storage in the effective crop root zone (mm), which was negative in this study. The final equation that was solved for ET_a has the form:

$$ET_a = P + I - RO - DP - \Delta W \quad (4)$$

RUNOFF ESTIMATION

The surface runoff (RO) was estimated using the USDA Natural Resources Conservation Service (NRCS, previously known as the Soil Conservation Service, SCS) curve number procedure (USDA-SCS, 1972). The runoff was determined for each neutron probe soil moisture measurement days for the entire field rather than for individual replication plots; there was no visible runoff from the experimental plots nor runoff in the downgradient plots during the irrigation events (Djaman and Irmak, 2012). The SCS curve number method relates runoff curve number (CN) to runoff, accounting for initial abstraction losses and the soil infiltration rate. The following equation was used to estimate runoff from the experimental field:

$$RO = \frac{(P - I_a)^2}{(P - I_a) + S} \quad (5)$$

with the condition that $P > 0.2S$, I_a = initial abstraction (mm), and S = potential maximum watershed retention (mm), which is given by:

$$S = \frac{25400}{CN} - 254 \quad (6)$$

Initial abstraction (I_a) represents water losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. The I_a value is highly variable but is usually well correlated with soil and surface residue cover parameters. Through studies of many small agricultural watersheds (USDA-SCS, 1972), I_a is approximated by the following empirical equation:

$$I_a = 0.2S \quad (7)$$

The curve number is based on the site's hydrologic soil group, land use, treatment, and hydrologic condition. A value of $CN = 75$ was obtained from the USDA-NRCS (1985) and USDA-SCS (1972) tables based on the silt-loam soil of the experimental site, land use, and slope with conservation tillage characteristics. Since runoff is affected by soil water before a precipitation event, or the antecedent moisture condition (AMC), prior to estimating precipitation excess for a storm and/or irrigation event, the curve number was adjusted based on the five-day antecedent precipitation. The curve number, as determined above, may also be termed as AMC II or CN_{II} , or average soil moisture. The other moisture conditions are dry (AMC I or CN_I) and moist (AMC III or CN_{III}). The curve number can be adjusted by CN_{II} factors, where CN_I factors are less than 1 (reducing CN and potential runoff) and CN_{III} factors are greater than 1 (increasing CN and potential runoff).

By removing I_a as an independent parameter, this approximation allows the use of the combination of S and P to estimate the runoff amount. After substitution:

$$RO = \begin{cases} \frac{(P - 0.2S)^2}{(P + 0.8S)} & \text{if } P > 0.2S \\ RO = 0 & \text{if } P \leq 0.2S \end{cases} \quad (8)$$

ESTIMATION OF DEEP PERCOLATION

At the planting date, soil water depletion was zero. Daily soil water balance and ET_a were estimated with a computer program (Payero et al., 2009; Bryant et al., 1992). The inputs to the program were daily weather data (rainfall, air temperature, solar radiation, wind speed, relative humidity), irrigation date and amounts, soil physical parameters, and maximum crop rooting depth. The program calculated daily ET_a and the water balance in the crop root zone using the two-step approach from grass-reference evapotranspiration and grass-reference crop coefficient. Reference ET was calculated using the weather data as input to the Penman-Monteith equation (Monteith, 1965; Monteith and Unsworth, 1990) with a fixed canopy resistance (Irmak et al., 2012), and the crop coefficient was used to adjust the estimated reference ET at different growth stages. The daily water balance approach was used to estimate deep

percolation (mm) (Djaman and Irmak, 2012):

$$DP_j = \max(P_j - RO_j + I_j - ET_{aj} - CD_{j-1}, 0) \quad (9)$$

where DP_j is deep percolation on day j , P_j is precipitation on day j (mm), RO_j is irrigation runoff from the soil surface on day j (mm), I_j is irrigation depth on day j (mm), ET_{aj} is crop evapotranspiration on day j (mm), and CD_{j-1} is root zone cumulative depletion depth at the end of day $j-1$ (mm).

PLANT HEIGHT, LEAF AREA INDEX, AND ABOVE-GROUND BIOMASS MEASUREMENTS

Plant height was measured on a weekly basis on ten randomly selected plants per replication for each treatment. Plant height was determined by measuring the distance between the soil surface and the tip of the longest leaf that was held up in case it was hanging down, and to the top of the tassel at or after tasseling stage. A total of 13 and 11 plant height measurements were taken from each treatment on selected days in 2009 and 2010, respectively. From maize emergence until physiological maturity, six plants from each replication were selected randomly to quantify the biomass production over time. Samples were taken every two weeks and dried at 70°C until they reached a constant weight. Leaf area index (LAI) was measured every ten days using a leaf canopy analyzer (model Li-Cor-2000, LICOR Biosciences, Lincoln, Neb.). Twelve LAI measurements were taken from two replications of each treatment on selected days in both years. Daily treatment-mean LAI was calculated from the twelve measurements for each treatment. At harvest, the center two rows over 15.24 m of each plot were hand-harvested for grain yield. Grain yield was determined from shelled ears and was adjusted to 15.5% moisture content. The weight of 1000 kernels was measured for each treatment and adjusted to 15.5% moisture content. Harvest index (HI) was calculated by dividing the grain dry matter mass by total above-ground dry matter mass.

The growth of maize (LAI and plant height) was related to thermal units (TU) [or growing degree days (GDD)]. TU is the accumulation of the daily temperature, which is cumulative temperature above base temperature and is commonly expressed as:

$$TU = \sum_{i=1}^n \left(\frac{T_{max} + T_{min}}{2} - T_{base} \right) \quad (10)$$

where T_{max} is maximum air temperature, T_{min} is minimum air temperature, T_{base} is the base temperature threshold for maize (10°C), and n is the number of days. The base temperature for calculating growing degree days is the minimum threshold temperature at which plant growth resumes. In this study, maximum and minimum temperature thresholds of 30°C and 10°C, respectively, were used. All temperature values exceeding the upper threshold value were reduced to 30°C, and values below 10°C were taken as 10°C because limited or no growth occurs above the upper limit threshold or below the lower (base) threshold temperature. If the average daily

temperature, $[(T_{max} + T_{min})/2]$, was below the base temperature, the TU value was assumed to be equal to zero (Djaman and Irmak, 2012).

MAIZE YIELD RESPONSE FACTORS (K_y)

Seasonal values of K_y were determined for each year and for the two years pooled data. These values represented the relationship between relative maize yield reduction ($1 - Y_a/Y_m$) and relative evapotranspiration deficit ($1 - ET_a/ET_m$) (eqs. 1 and 2). In determining K_y values, the maximum maize yield (Y_m) and maximum maize evapotranspiration (ET_m) were obtained from the fully irrigated treatment (FIT). Actual yield (Y_a) and actual evapotranspiration (ET_a) values were obtained from the rainfed and limited irrigation treatments (50% FIT, 60% FIT, and 75% FIT).

STATISTICAL ANALYSES

Analysis of variance (ANOVA) was performed using the general linear model procedure in SAS (SAS, 2003). In addition, the regression procedure was used to perform stepwise multiple regression analysis, and means were separated using Fisher's protected least significance difference (LSD) test at the 95% level of probability to identify significant differences between the treatments for plant height, biomass production, grain yield, and 1000-kernel weight.

RESULTS AND DISCUSSION

WEATHER CONDITIONS DURING THE 2009 AND 2010 GROWING SEASONS

The 2010 growing season was warmer than 2009 with a mean air temperature in 2010 of 18.7°C, which is 2.5°C higher than the mean temperature of 16.2°C in 2009 (fig. 1). The highest monthly average temperature occurred in August. Warmer temperatures in 2010 caused differences in the cumulative TU from planting to harvest (fig. 2). Maize was harvested 163 days after planting (DAP) in 2010 and 177 DAP in 2009. TU at maturity was greater in 2010 than in 2009 (fig. 2). From emergence to harvest, TU was 1,477°C in 2009 and 1,726°C in 2010, and the long-term average value is 1,701°C. Thus, the TU at the end of the growing season were 13% less in 2009 and 2% greater in 2010 than the long-term average.

In figures 1a and 1b, growing season precipitation amounts were calculated from April 23 to October 13 in 2009 and from April 28 to October 6 in 2010. Thus, these long-term average precipitation amounts are specific to these two experimental years and are different from the long-term average value (468 mm) that was mentioned earlier for the average or typical growing season, which is from May 1 through September 30. Total growing season rainfall was greater in 2010 (563 mm) than in 2009 (426 mm) and greater than the long-term average (517 mm). Rainfall was more uniformly distributed in 2010 than in 2009. For example, in August 2009, there was a total of 100 mm of rainfall, but 83 mm (almost 20% of the seasonal total rainfall) occurred in one day. Cumulative precipitation was 9% greater in 2010 and 18% less in 2009

than the long-term average. More rainfall occurred in the early 2009 growing season than in the early part of the 2010 growing season. Growing season cumulative rainfall in 2010 was similar to the long-term average rainfall during the first 41 DAP, after which 2010 exceeded the long-term average cumulative rainfall. A dry period from June 24 to July 23 in 2009 (63 to 92 DAP) coincided with the tasseling stage and imposed water stress on the crops, which were in a drought-sensitive stage. In 2009, the first irrigation was initiated on July 8. Maize under limited irrigation and rainfed treatments began to experience different levels of water stress after this date. After adequate early growing season rainfall in 2010, there were only 17 mm of rainfall during the period from July 4 to August 3 (68 to 98 DAP), which corresponded to the maize silking stage. There was very high evaporative demand during this period, and the first irrigation was initiated on July 23, 2010. Average growing season relative humidity (RH) was similar in both years (73% in 2009 and 72% in 2010). Wind speed was 8% higher in 2010 than in 2009. The incoming shortwave radiation was, on average, 30% and 24% less than the long-term average in 2009 and 2010, respectively. The seasonal average incoming shortwave radiation in 2010 was 14% higher than the 2009 average.

EFFECT OF LIMITED IRRIGATION ON SOIL WATER DYNAMICS

Initial soil water contents were similar among treatments at the beginning of both growing seasons, indicating uniform soil water distributions in the field from winter and spring precipitation (figs. 3 and 4). Differences in soil water content appeared with irrigation events. In general, depletion of available soil water increased with the decrease in irrigation from FIT to the rainfed treatment. Under all treatments, the topsoil layer (0-0.30 m) showed the least water content throughout the growing season as a result of a greater rate of plant water uptake and soil water evaporation from the topsoil than from deeper soil layers, and the late-season increase in soil water status was due to late-season precipitation. The sharp increase between August 16 and September 12 in 2009 under all treatments was caused by a large rainfall event (50 mm) on August 23.

In both years, all treatments showed some level of soil water depletion in the deepest (1.50-1.80 m) soil layer (figs. 3 and 4), but the depletion level was more pronounced in the rainfed and 50% FIT (figs. 3a, 3b, 4a, and 4b), indicating that maize can extract soil water from the 1.80 m soil layer in an average year in these experimental conditions. For example, in 2009, the volumetric water content in the 1.50-1.80 m soil layer for the rainfed treatment decreased from about 31.5% vol in the beginning of the season to 26% vol at the end of the season. In 2010, the water content for the same treatment at the same layer (fig. 4a) decreased from 35% vol to 31% vol at the end of the season. In 2009, only the rainfed treatment had soil water depletion to below 55% TAW (fig. 3g). In 2010, rainfed and 50% FIT showed soil water depletion below 55% TAW in the top 1.20 m soil layer. The 55% TAW is equivalent to soil water content of approximately

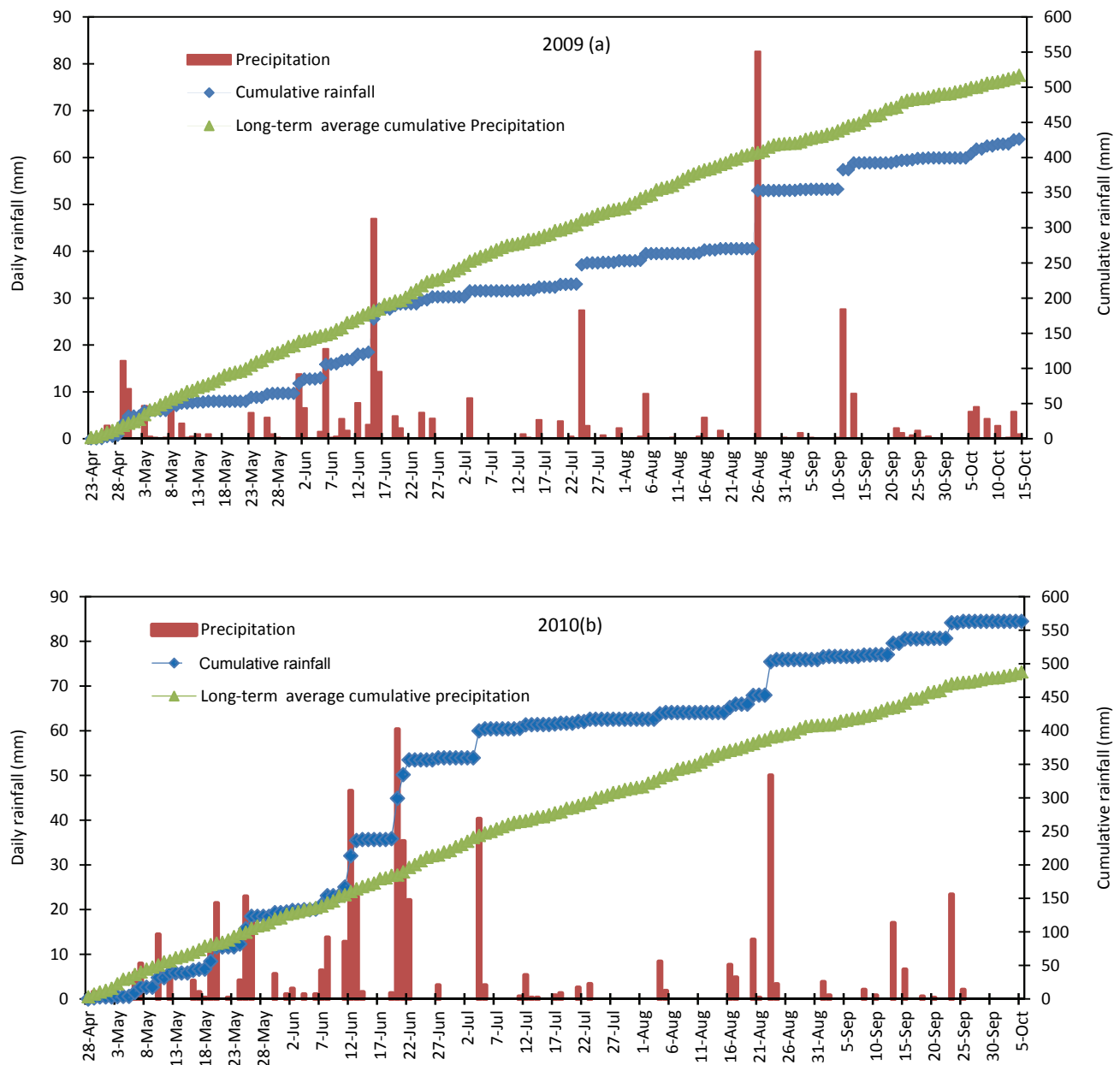


Figure 1. Daily and seasonal cumulative rainfall for (a) 2009 and (b) 2010, (c) air temperature, (d) relative humidity, (e) incoming shortwave radiation, and (f) wind speed in 2009 and 2010 measured using NEBFLUX (Irmak, 2010) BREBS near the experimental site.

0.25 cm³ cm⁻³ (figs. 4f and 4g). This indicates that crops in the rainfed treatment in 2009 (from tasseling to maturity) and rainfed and 50% FIT in 2010 (from silking to maturity) were under water stress. Under rainfed conditions, maize extracted water from the 0.30-1.20 m soil layer where the soil water content was near wilting point from August 15 (110 DAP) to the end of the growing season, corresponding to the milk, grain filling, and dent stages in 2010. In 2009, under rainfed conditions, soil water depletion values in the third and fourth layers of the soil profile were greater than 55% TAW after July 13, which corresponds to the period between the tasseling and physiological maturity stages. During both growing seasons under rainfed and 50% FIT,

crops extracted water from the deeper layers starting on August 10 in 2009 and August 23 in 2010, corresponding to the grain filling stage. In both years, plant water uptake in the 60% FIT treatment was mostly concentrated in the 0.60-0.90 m layer (figs. 3c and 4c). Soil water uptake under 75% FIT was mostly concentrated in 0.60-1.20 m soil layer. Very small soil water content variation was observed below 1.20 m (figs. 3d and 4d). Under FIT, water uptake was uniform from soil layers below 0.30 m. In this treatment, water uptake by ET_a was almost fully replaced by irrigation water, and the available soil water was always at the readily available water level. Plants under FIT did not experience visible signs of water stress (figs. 3e and 4e).

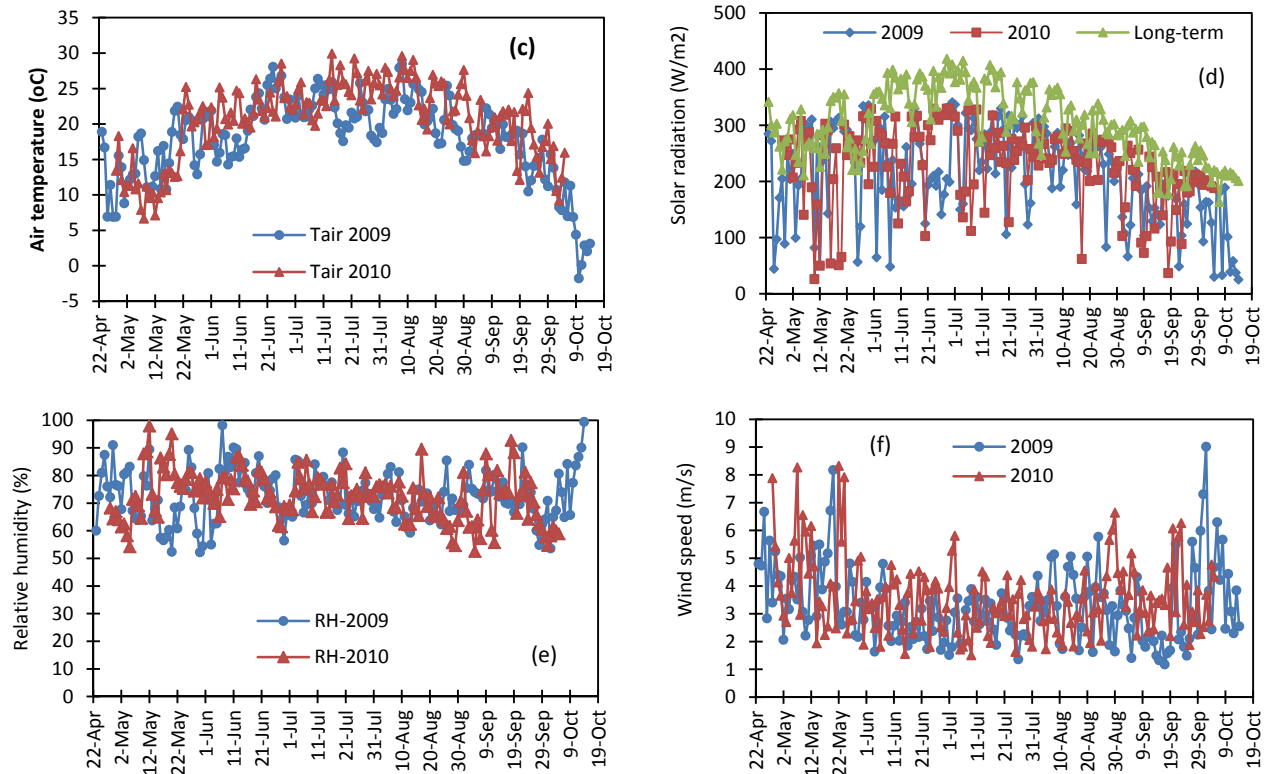


Figure 1 (continued). Daily and seasonal cumulative rainfall for (a) 2009 and (b) 2010, (c) air temperature, (d) relative humidity, (e) incoming shortwave radiation, and (f) wind speed in 2009 and 2010 measured using NEBFLUX (Irmak, 2010) BREBS near the experimental site.

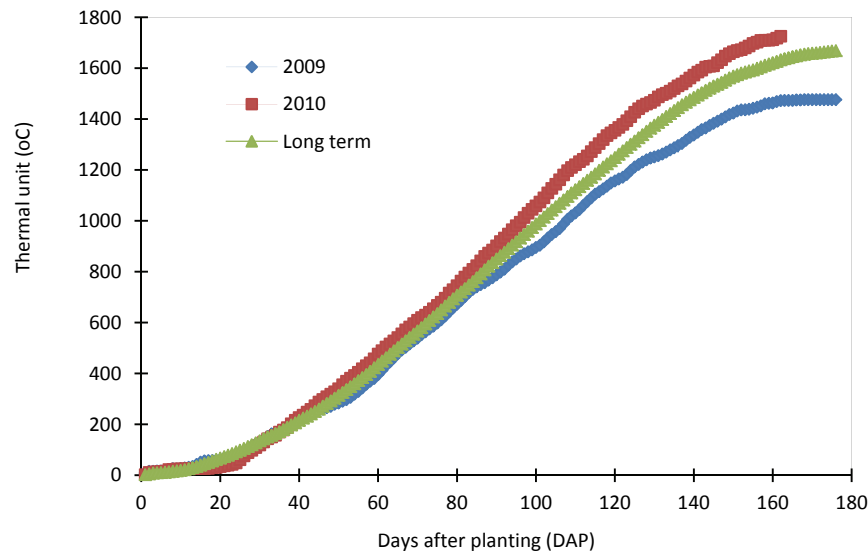


Figure 2. Cumulative thermal units (TU) (also known as growing degree days, GDD) during the 2009 and 2010 growing seasons and long-term average values in south central Nebraska.

EFFECT OF LIMITED IRRIGATION ON LAI AND PLANT HEIGHT AND THE RELATIONSHIP BETWEEN THE TWO VARIABLES

In both years, the progression of LAI was similar for all treatments from emergence to the first irrigation (fig. 5). Following the first irrigation, plants in the rainfed treatment had the lowest LAI, which declined most rapidly among all treatments starting after tasseling-silking stage. In 2010, plants reached the silking stage before water stress

occurred, but in 2009 water stress began before the full crop development stage, resulting in differences in peak LAI between the irrigation treatments. In 2009, the peak LAI under rainfed conditions occurred slightly earlier, 92 DAP (cumulative TU = 840°C), than under the irrigated treatments, which reached peak LAI at 102 DAP (cumulative TU = 950°C). In 2010, peak LAI occurred at 80 DAP (cumulative TU = 746°C) and 87 DAP (cumulative

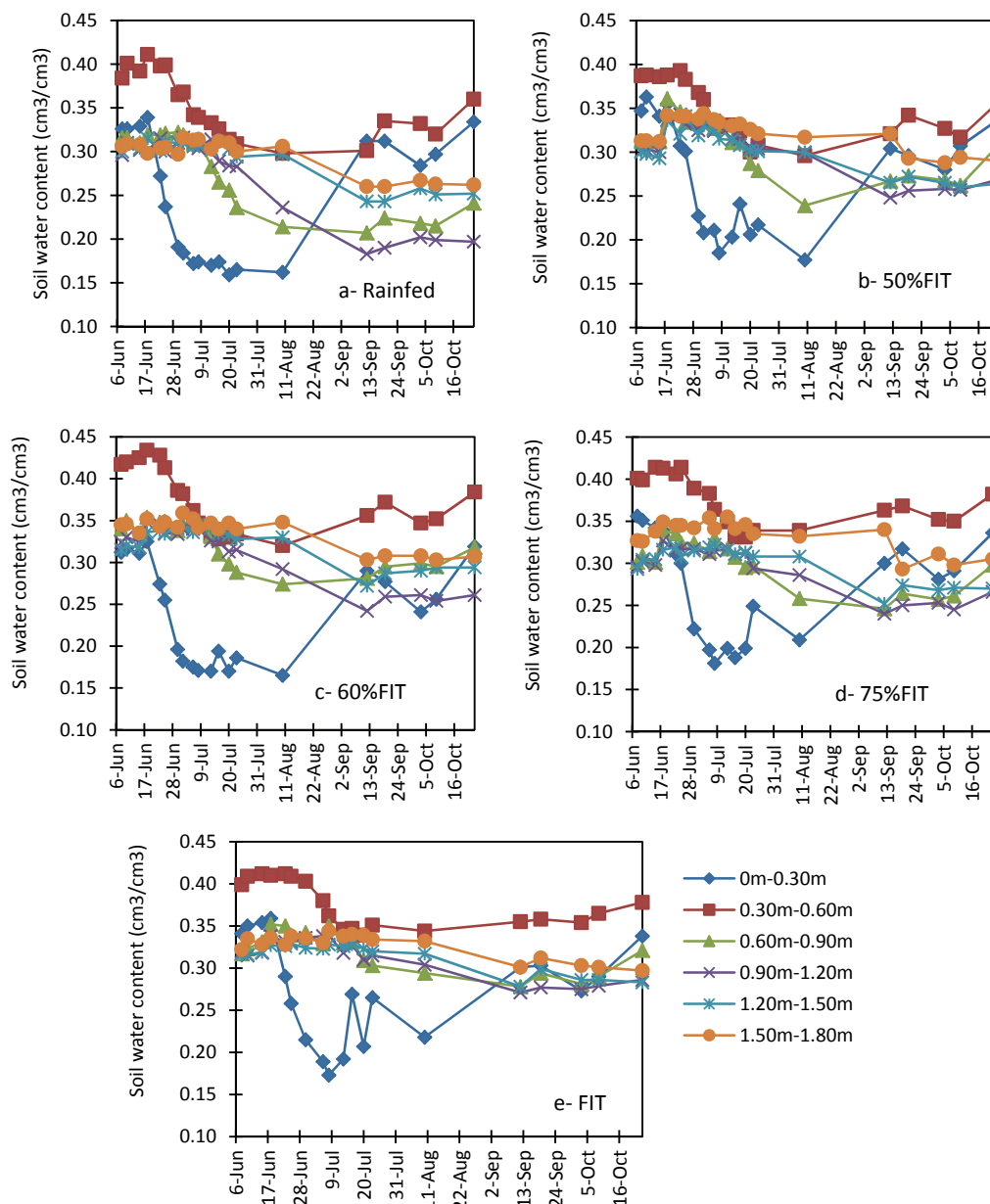


Figure 3. Volumetric soil water content in the 0-1.80 m soil profile for different irrigation treatments [(a) rainfed, (b) 50% FIT, (c) 60% FIT, (d) 75% FIT, and (e) FIT] as measured using a neutron probe, (f) average volumetric water content in the effective root zone (0-1.20 m) for the same treatments, and (g) total soil water in the crop root zone in 2009.

TU = 860°C) for rainfed and for all irrigated treatments, respectively (fig. 5). The relationship between LAI and TU for each treatment separately is presented in figure 6. There was no significant difference ($p > 0.05$) in plant height between any of the treatments in both years because the early-season soil water status was adequate for plant growth and development until the plants attained their maximum height before irrigations started (fig. 7). Maximum plant height varied from 2.7 to 2.9 m. A polynomial function was fitted to the relationship between plant height and TU for the pooled (2009 and 2010) data and is presented in figure 7.

A linear relationship exists between LAI and plant height for maize vegetative growth period under different irrigation treatments, as shown in figure 8 with R^2 values

ranging from 0.90 to 0.97. The slope of the function gradually increases from 1.82 for the rainfed treatment to 2.12 for the FIT. In practice, LAI is a more difficult variable to measure than plant height. However, it can be calculated with the least error using crop height as a single variable under different irrigation levels using the function presented in figure 7. One drawback of estimating LAI from plant height is that the linear relationship between the two variables only exists until the plants reach their maximum height and when leaf senescence starts. At that time, while the plant height remains relatively constant, the LAI decreases and the relationship between the two variables halts (Mutiibwa and Irmak, 2011).

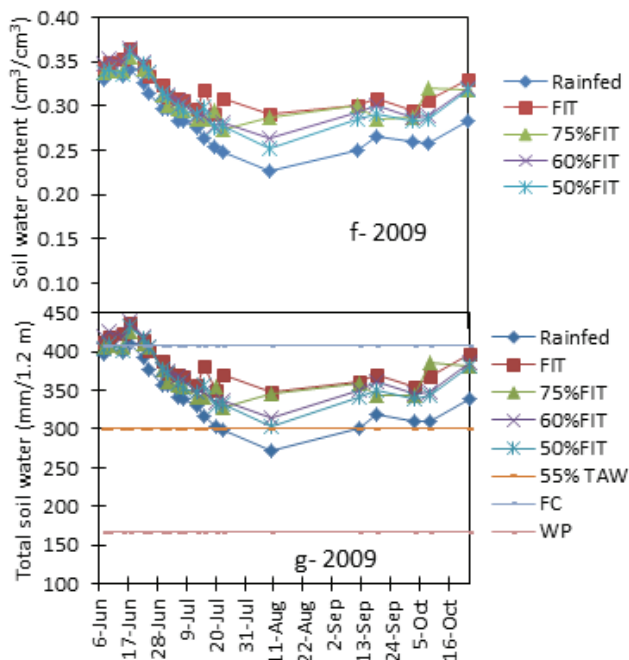


Figure 3 (continued). Volumetric soil water content in the 0-1.80 m soil profile for different irrigation treatments [(a) rainfed, (b) 50% FIT, (c) 60% FIT, (d) 75% FIT, and (e) FIT] as measured using a neutron probe, (f) average volumetric water content in the effective root zone (0-1.20 m) for the same treatments, and (g) total soil water in the crop root zone in 2009.

EFFECT OF IRRIGATION ON CROP EVAPOTRANSPIRATION

In 2009, ET_a ranged from 481 mm for the rainfed treatment to 620 mm for FIT (table 1). ET_a values for all treatments were higher in 2010 than in 2009 due to warmer temperatures, higher seasonal rainfall, and higher wind speeds (especially early and late in the growing season), which resulted in greater evaporative demand and losses. In 2010, there was a more uniform temporal distribution of rainfall as compared with 2009 (figs. 1a and 1b). As a result, there were fewer irrigation events (five) in 2010 than in 2009 (seven). ET_a in 2010 ranged from 579 mm for the rainfed treatment to 634 mm for FIT (table 1). There was a strong linear increase in ET_a with increasing irrigation amounts ($R^2 = 0.97$ for 2009; $R^2 = 0.98$ for 2010) among treatments, as presented in figure 9. For every 25.4 mm increase in irrigation application, ET_a increased by 20.4 mm in 2009 and 11.4 mm in 2010. The slope of the regression line between irrigation and ET_a in 2009 was much greater than the slope in 2010. The relationship between crop ET and irrigation amounts was explained by a curvilinear function in other studies. However, the data distribution does not plateau at the highest irrigation level in the results of this study. This indicates that there was no excessive irrigation applied to the fully irrigated treatment in both years. The curvilinear relationships between ET_a and irrigation amounts were reported by Payero et al. (2008) for their experiment in a drier location in North Platte, Nebraska. A steeper slope in the irrigation vs. ET_a line is expected in drier climates than in sub-humid locations because crop response to irrigation is stronger in drier conditions.

EFFECT OF IRRIGATION ON YIELD, YIELD COMPONENTS, AND ABOVE-GROUND BIOMASS

In both years, yield increased with irrigation amounts (table 1, figs. 10 and 11). All irrigated treatments had significantly greater ($p < 0.05$) yields than the rainfed treatment at the 5% significance level, except 50% FIT in 2010. The fully irrigated treatment had the greatest numerical yield but was not significantly different ($p > 0.05$) from the 75% FIT yield in either year. Irrigation impact on grain yield, as compared with the rainfed treatment, lead to an increase in grain yield of 58%, 65%, 66%, and 72% for 50% FIT, 60% FIT, 75% FIT, and FIT, respectively, in 2009, and 14%, 21%, 26%, and 31% for the respective treatments in 2010 (fig. 11b). The relationship between irrigation amount and yield was similar in both years, and it appears that the grain yield starts being relatively stable at approximately 175 mm of irrigation (fig. 11b), indicating that irrigation beyond 175 mm can result in excessive application that would not contribute to the yield (diminishing return) under these experimental conditions in 2009 and 2010. The relationship between yield and irrigation amount, excluding the rainfed treatment, had very strong correlation (fig. 11c).

The above-ground biomass was significantly impacted by the irrigation amounts (table 1 and fig. 10). The increases in the above-ground biomass relative to the rainfed treatment were 24%, 24%, 26%, and 46% for 50% FIT, 60% FIT, 75% FIT, and FIT, respectively, in 2009, and 4%, 5%, 13%, and 20% for the respective treatments in 2010, which are very similar to the findings of Eck (1986), Bryant et al. (1992), Payero et al. (2008), and Payero et al. (2009). Water stress can reduce crop yield by reducing CO_2 assimilation area, leaf number and total leaf area, net assimilation rate, and yield components such as ear size, number of kernels per ear, and kernel weight (Eck, 1986; Singh and Singh, 1995; Earl and Davis, 2003), resulting in reduction in biomass production. There was a strong linear correlation between irrigation amount and biomass, as shown in figure 11e. The 1000-kernel weight was also linearly related to seasonal irrigation (fig. 11g). There were significant difference between rainfed and all irrigated treatments for 1000-kernel weights. The 1000-kernel weight differences among 50% FIT, 60% FIT, 75% FIT, and FIT were not significant ($p > 0.05$). Linear relationships between maize yield and above-ground biomass and the seasonal irrigation under limited irrigation were reported by Irmak et al. (2000), Farré and Faci (2006), Payero et al. (2006), and Igbadun et al. (2008). In contrast, a curvilinear relationship between maize yield and seasonal irrigation was reported by Payero et al. (2008) and Farré and Faci (2009). The inconsistency in the form of the relationships can be expected, as they are impacted by climate, soil properties, irrigation practices, experimental procedures, soil and crop management practices, differences in hybrid genetics, and other factors.

The grain yield and above-ground biomass increased linearly with ET_a in both years (figs. 11a and 11d). Similar linear relationships between grain yield, biomass, and crop evapotranspiration were reported by Eck (1986), Payero et

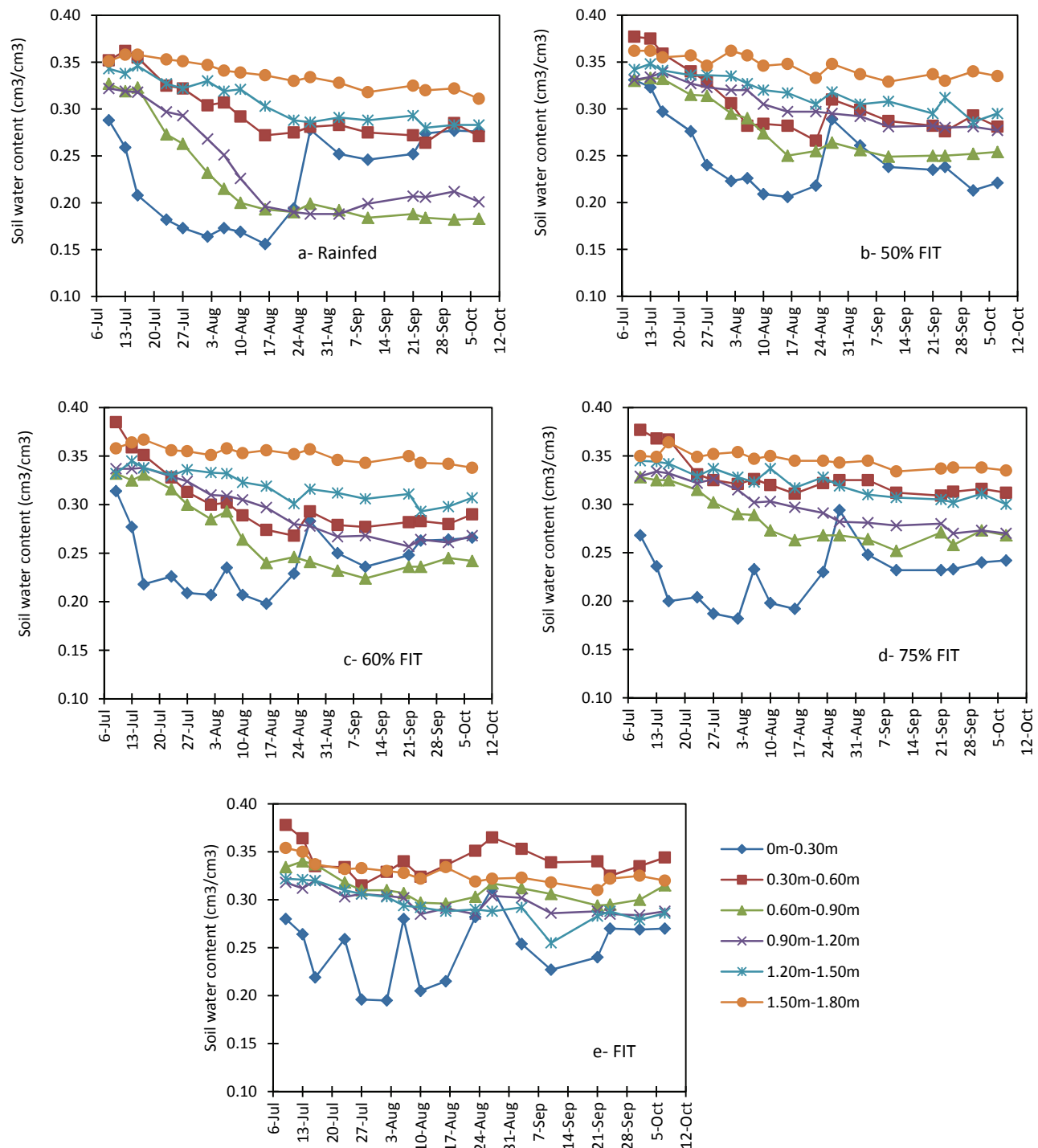


Figure 4. Volumetric soil water content in the 0-1.80 m soil profile for different irrigation treatments [(a) rainfed, (b) 50% FIT, (c) 60% FIT, (d) 75% FIT, and (e) FIT] as measured using a neutron probe, (f) average volumetric water content in the effective root zone (0-1.20 m) for the same treatments, and (g) the total soil water between the early and late season in the crop root zone in 2010.

al. (2008), Payero et al. (2009), and Kapanigowda et al. (2010). While most researchers found strong linear relationships between yield and/or biomass and seasonal ET_a or irrigation, the slope of the line varied considerably between studies due to differences in seasonal precipitation amounts and temporal distributions, soil and crop characteristics, and other climatic and management conditions. Quantitatively, from the fitted linear regression

equations in figure 11e, deficits of 1 mm of irrigation water reduced the above-ground biomass by 1.48 kg ha^{-1} in both years, while similar irrigation deficits had different impacts on 1000-kernel weight that varied with year and irrigation treatment (fig. 11g). Withholding irrigation application at certain stages impacted the above-ground biomass and its components more in 2009 than in 2010 due to the lesser amount of rainfall in 2009.

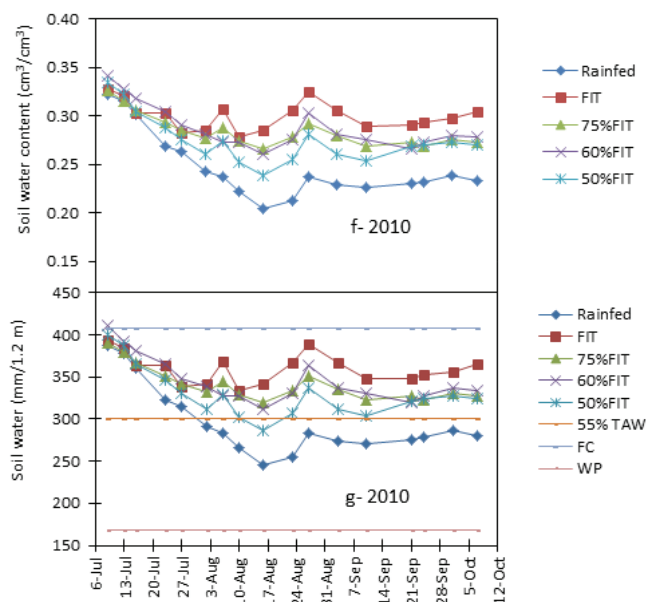


Figure 4 (continued). Volumetric soil water content in the 0-1.80 m soil profile for different irrigation treatments [(a) rainfed, (b) 50% FIT, (c) 60% FIT, (d) 75% FIT, and (e) FIT] as measured using a neutron probe, (f) average volumetric water content in the effective root zone (0-1.20 m) for the same treatments, and (g) the total soil water between the early and late season in the crop root zone in 2010.

EFFECT OF LIMITED IRRIGATION ON MAIZE HARVEST INDEX

The 2009 maize HI was not estimated because of the loss of the senesced leaves at the physiological maturity stage due to a strong wind gust. The 2010 HI ranged between 0.49 for the rainfed treatment and 0.57 for 60% FIT with an average of 0.54 (table 1). The HI had a quadratic relationship with the seasonal ET_a and irrigation amount (fig. 12). Payero et al. (2009) reported a linear relationship between HI and seasonal evapotranspiration. In this study, HI increased moderately with the seasonal irrigation, reached its maximum of 0.57 when the irrigation amount was 76 mm, and decreased to 0.50. The 60% FIT had the highest HI. The 75% FIT also had greater HI than the fully irrigated treatment. Beyond 60% FIT, it is assumed that the additional transpiration contributed more to biomass production than to grain yield. In both cases (HI vs. ET_a and HI vs. irrigation amount), the HI in the rainfed treatment was impacted the most by water stress, but again, even though the HI increased with ET_a and irrigation, the HI for the rainfed treatment (0.5) was only about 20% lower than the HI measured for the fully irrigated treatment (HI = 0.54), indicating that the water stress in 2010 was not severe enough to substantially reduce the HI for the rainfed treatment relative to the FIT. Our results are in agreement with those reported by Kiniry and Bockholt (1998), Xie et al. (2001), Kiniry and Echarte (2005), Farré and Faci

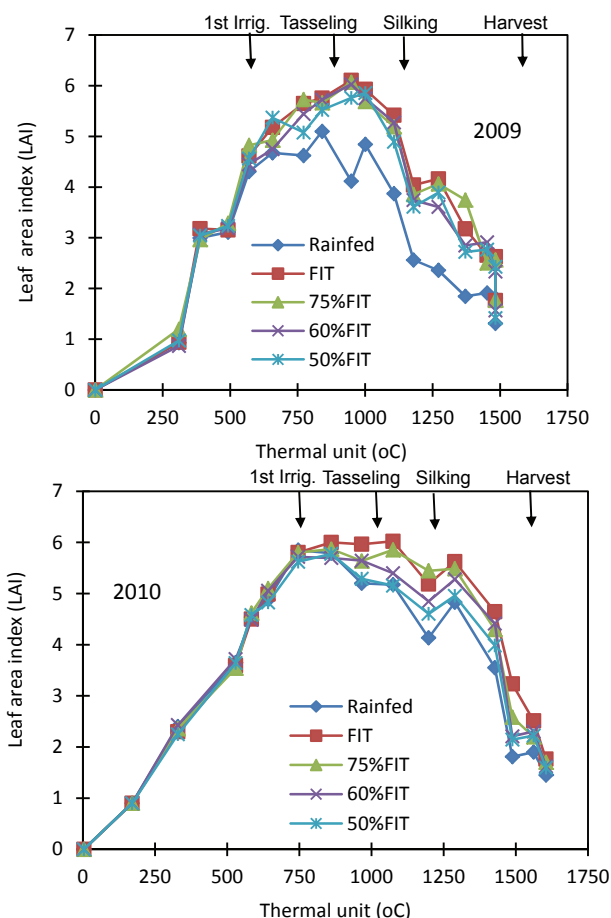


Figure 5. Distribution of maize leaf area index (LAI) as a function of thermal unit (TU) for different irrigation treatments during the 2009 and 2010 growing seasons. Each data point represents an average of twelve LAI measurements. Approximate dates of the first irrigation, tasseling and silking stages, and harvest are indicated by arrows.

(2006), and Kapanigowda et al. (2010). Farré and Faci (2009) reported a significant effect of limited irrigation on HI, which ranged from 0.31 to 0.55. Yazar et al. (1999) reported harvest index values of 0.51, 0.53, 0.54, 0.55, 0.57 and 0.57 for 0%, 20%, 40%, 60%, 80%, and 100% replenishment of soil water depletions, respectively; therefore, the HI was not significantly affected by irrigation treatments. Earl and Davis (2003) reported HI of 0.52, 0.28, and 0.17 in the first year and 0.58, 0.57, and 0.52 in the second year of their experiments for unstressed, mildly stressed, and severely stressed maize treatments, respectively. Zhang et al. (2004) reported HI of 0.40 and 0.43 in 2000 and HI of 0.50 and 0.49 in 2001 for irrigated and rainfed treatments, respectively, with no impact of irrigation regimes on HI. Hay and Gilbert (2001) showed that HI of tropical maize varies considerably and seems to depend on variety, crop management, growing season, and other factors.

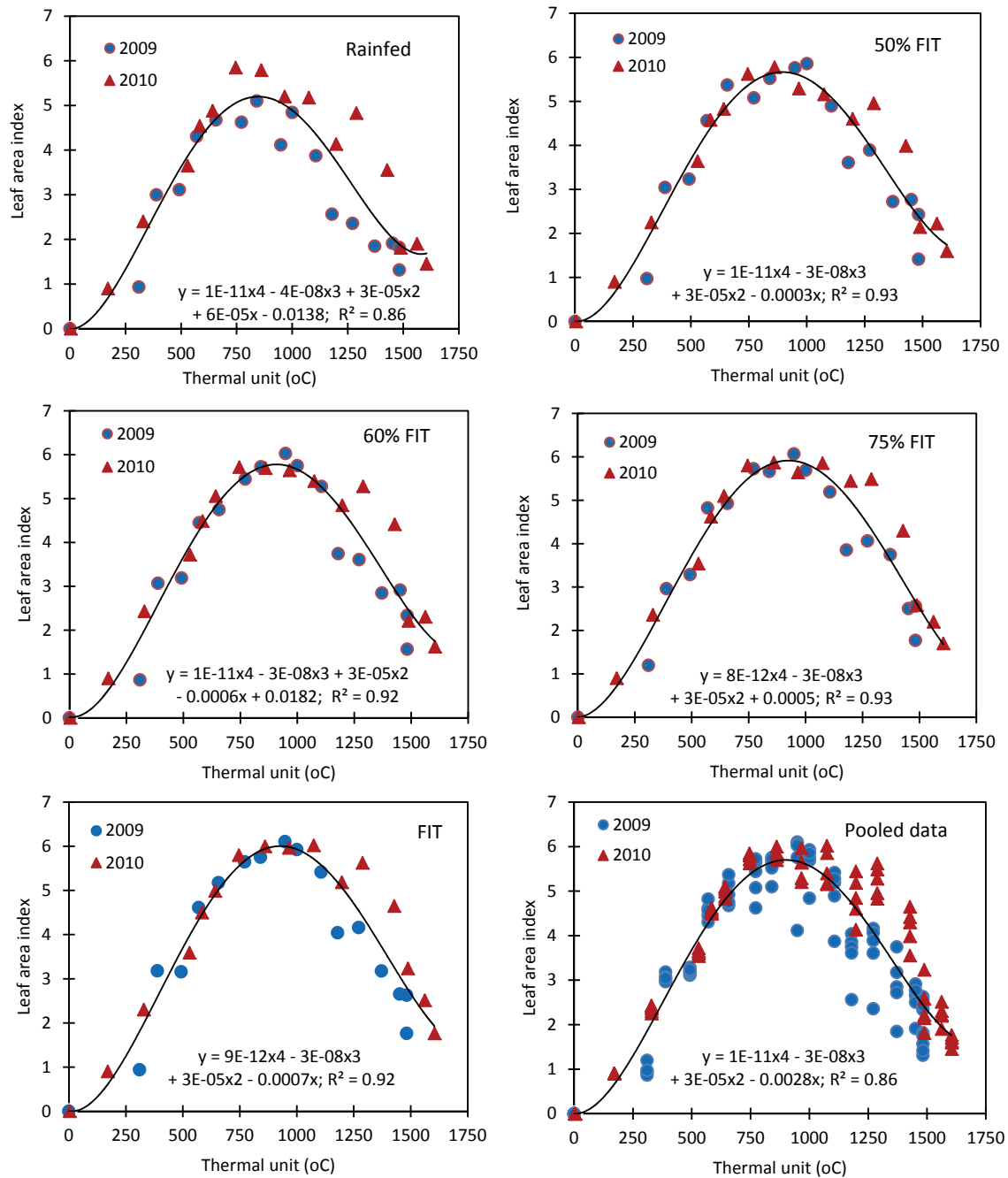


Figure 6. Leaf area index (LAI) as a function of thermal unit (TU) for different irrigation treatments. Data from 2009 and 2010 are combined for each treatment. Each data point represents an average of twelve LAI measurements.

YIELD RESPONSE FACTORS

In general, relative yield decreased linearly with increasing relative evapotranspiration deficit (fig. 13a). K_y values varied with irrigation, and the values were 1.9, 0.9, 0.6, and 1.4 in 2009 and 2.8, 3.1, 2.9, and 4.2 in 2010 for rainfed, 50% FIT, 60% FIT, and 75% FIT, respectively. In limited irrigation and rainfed conditions, the water stress effect on plants was observed visually, as the water stress caused wilting and/or senescence of the leaves, as shown in figure 14 (the pictures were taken on September 13, 2009; 134 DAP). The impact of water stress on maize (fig. 14) varied gradually with the stress level, and plant senescence increased as the stress level increased from FIT to the

rainfed treatment. The 2009 seasonal average K_y was 1.65 (fig. 13b) and is consistent with the value observed by Payero et al. (2008) for North Platte, Nebraska. In 2010, irrigation applications began at silking stage, and the seasonal K_y value of 2.85 (fig. 13b) is greater than those reported by Doorenbos and Kassam (1979), indicating that the water stress imposed was severe enough to decrease the grain yield three times proportionally higher than the relative evapotranspiration deficits ($1 - ET/ET_m$). Maize response factor, as an indicator of maize sensitivity to water stress, over the two growing seasons was averaged as 1.82 (fig. 13c), which is close to the value reported by Doorenbos and Kassam (1979, 1994) and Andrioli and

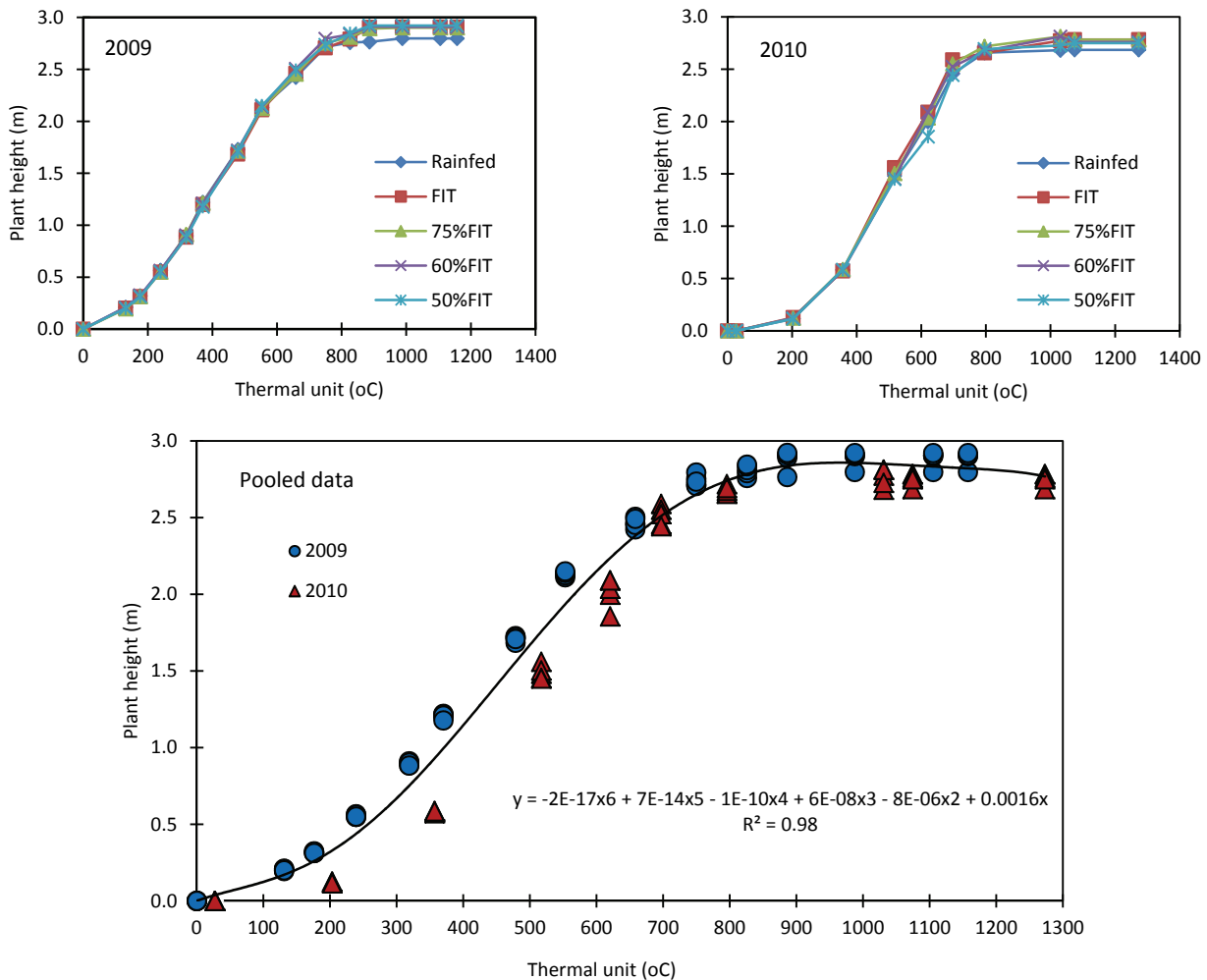


Figure 7. Seasonal distribution of maize plant height for all treatments during the 2009 and 2010 growing seasons as a function of thermal unit (TU) (pooled data). Each data point represents an average of twenty plant height measurements.

Sentelhas (2009), who observed that the general K_y for the total growing season was 2.15 for drought-sensitive genotypes and 1.56 for drought-resistant genotypes. There is also similarity of the value observed in this study with the value of 1.90 reported by Igbadun et al. (2008). In fact, in 2009, drought stress began occurring just before flowering, and it occurred during silking and grain formation in 2010, so the K_y value (1.82) of this study is within the range of 1.50 to 2.30 reported by Doorenbos and Kassam (1979). When water stress occurred during flowering, Igbadun et al. (2008) reported a K_y value as high as 2.36 for their two-year study. The two-season combined K_y value of 1.82 is higher than the value of 1.58 found by Payero et al. (2008) for their 2005-2006 experiment and the value of 1.50 observed by Payero et al. (2009). Overall, the high K_y value of 1.82 for the two-year average data could be an indication of severe water stresses or low water stress resistance of the variety of maize hybrid used. This implies that the rate of relative yield decrease resulting from water stress is proportionally higher than the relative evapotranspiration deficit. In addition, the large worldwide diversity of K_y may result from dependency of K_y on maize genotype, the climatic conditions, the period of occurrence

of the water stress during the growing season and associated difference in crop response, the severity of the water stress, root growth and distribution, and local soil and crop management practices, emphasizing the importance of locally developed values.

SUMMARY AND CONCLUSIONS

A field study was conducted to evaluate the effect of limited and full irrigation management practices as well as rainfed conditions on plant growth, leaf area index (LAI), plant height, actual crop evapotranspiration (ET_a), above-ground biomass production, grain yield, harvest index (HI), yield production functions, and maize yield response factors (K_y) during 2009 and 2010 in south central Nebraska. Maize ET_a , LAI, biomass production, and grain yield were significantly affected by the irrigation levels. In both years, maize yield and above-ground biomass were linearly related to the irrigation depths. Actual crop evapotranspiration increased with irrigation amounts and ranged from 480 mm for the rainfed treatment to 620 mm for FIT in 2009 and from 579 mm to 634 mm in 2010 for

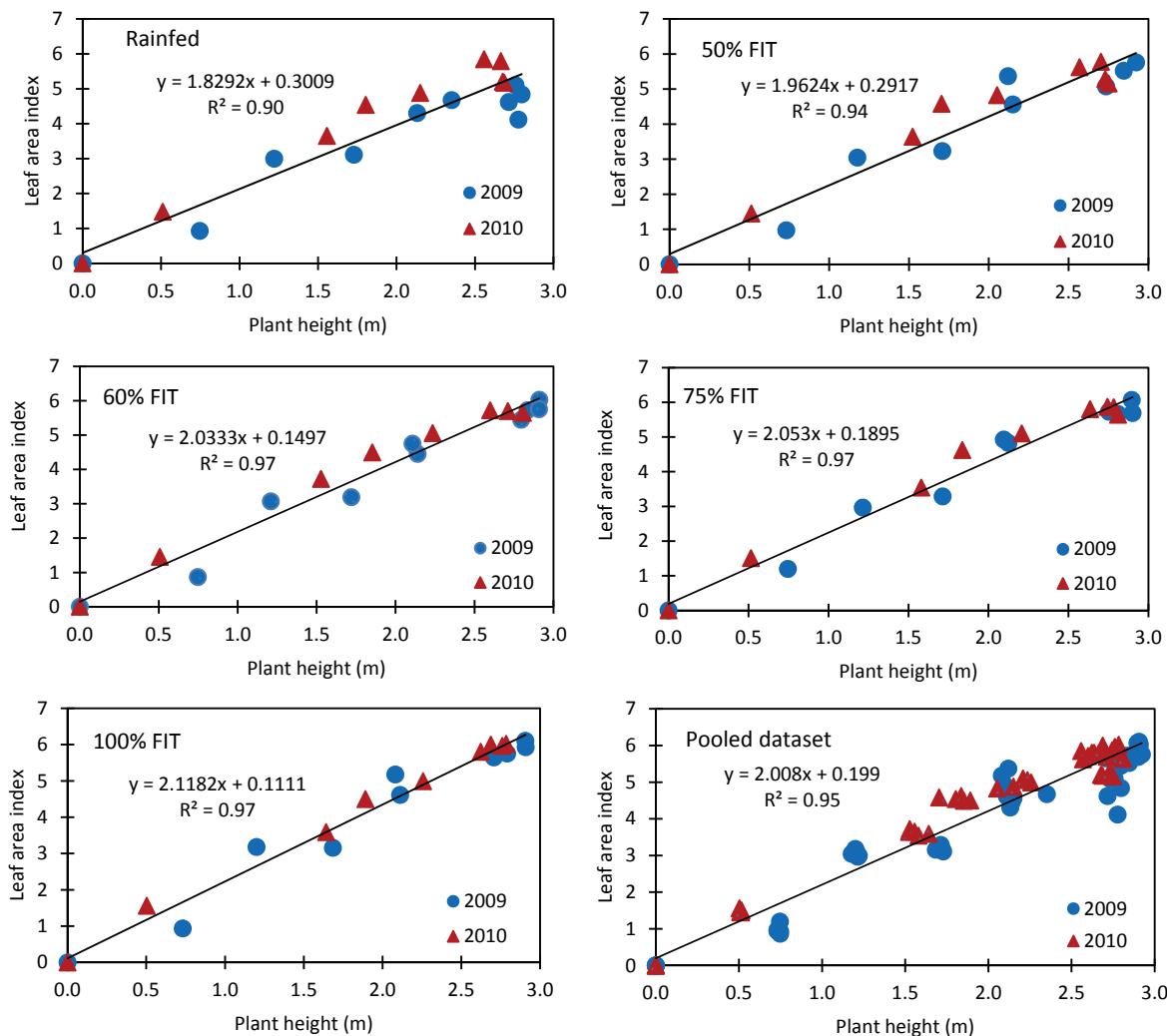


Figure 8. Relationship between plant height and leaf area index (LAI) from plant emergence to period when plants attained maximum height under various irrigation levels and rainfed condition. Each graph represents pooled data from the 2009 and 2010 growing seasons, and each data point represents an average of twenty plant height and twelve LAI measurements.

the same treatments. Maize yields varied from 9.05 Mg ha⁻¹ for the rainfed treatment to 15.5 Mg ha⁻¹ for FIT in 2009 and from 11.7 to 15.5 Mg ha⁻¹ for the same treatments in 2010. There was no statistically significant difference ($p > 0.05$) between 75% FIT and FIT in terms of grain yield, indicating that similar productivity as the fully irrigated maize can be achieved by practicing 75% FIT with 25% less irrigation water withdrawal and less energy use. The observed differences in yield resulted mainly from differences in ET_a that translated into differences in plant biomass production. For every 25 mm increase in irrigation application, ET_a increased by 20.4 mm in 2009 and 11.4 mm in 2010. Based on the slopes of the ET_a vs. grain yield relationships, about 1.2 Mg ha⁻¹ (in 2009) and 1.7 Mg ha⁻¹ (in 2010) of grain yield was produced per 25.4 mm of ET_a beyond 280 mm and 403 mm of ET_a that was used by maize to start producing grain yield, which is also called the amount of ET_a required for establishing grain yield. The regression lines for 2009 and 2010 intersect the x-axis at 280 and 403 mm, respectively. Deficits of 25 mm of irrigation water reduced the above-ground biomass by 37 kg ha⁻¹ in both years, while similar irrigation deficits

had different impacts on 1000-kernel weight that varied with year and irrigation treatment. Strong relationships for maize yield vs. irrigation amount ($R^2 = 0.99$ in 2009; $R^2 = 0.98$ in 2010) and maize yield vs. ET_a ($R^2 = 0.94$ in 2009; $R^2 = 0.99$ in 2010) measured in this study may be used for predicting yield target and associated water use and crop productivity indices for full and limited irrigation practices, as well as rainfed settings, in locations that have climate, soil, and crop production management conditions and practices similar to those of south central Nebraska. The variation shown in these relationships between the two years is due to the weather impact on these relationships. Therefore, it is important to account for the impact of climate variability on the slopes of these relationships. Yield response factor was determined as 1.65 in 2009 and 2.85 in 2010, with a two-year average of 1.82. In terms of crop response to water performance, the 75% FIT and 60% FIT treatments were very comparable to the fully irrigated treatment and are viable limited irrigation practices in increasing crop water productivity of maize with supplementary irrigation under these experimental, soil and crop management, and climatic conditions.

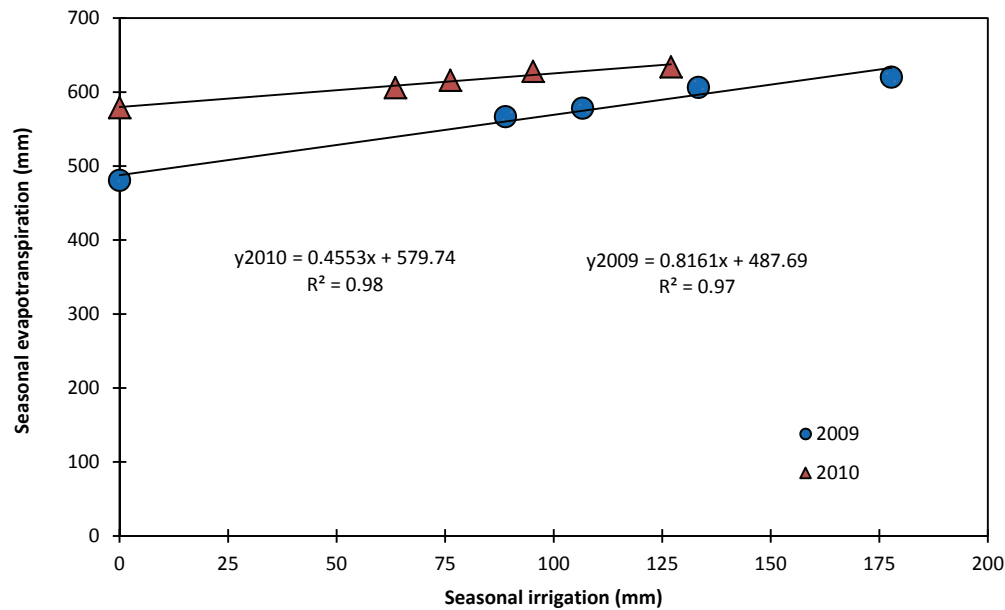


Figure 9. Relationship between total irrigation and seasonal crop evapotranspiration (ET_a) during 2009 and 2010 for all treatments.

Table 1. Seasonal irrigation, rainfall, surface runoff, deep percolation (DP), change in total soil water in the root zone in the early and late season (ΔTSW), seasonal total actual crop evapotranspiration (ET_a), seasonal average daily ET_a , biomass production, grain yield, harvest index (HI), and 1000-kernel weight for maize in the 2009 and 2010 growing seasons (CV = coefficient of variation).^[a]

Year	Treatment	Irrigation (mm)	Rainfall (mm)	Runoff (mm)	DP (mm)	ΔTSW (mm)	Seasonal ET_a (mm)	Daily ET_a (mm d ⁻¹)	Biomass (Mg ha ⁻¹)	Grain Yield (Mg ha ⁻¹)	CV (yield)	HI	1000-Kernel Weight (g)
2009	FIT	178	426	10	25	51	620	3.5	22.3 a	15.5 a	1.1	-	352.3 a
	75% FIT	133	426	10	26	82	606	3.4	19.4 b	15.0 ab	1.7	-	342.5 a
	60% FIT	107	426	10	25	80	578	3.3	18.9 b	14.9 b	1.8	-	333.8 a
	50% FIT	89	426	10	25	87	566	3.2	19.0 b	14.3 b	2.9	-	324.5 a
	Rainfed	0	426	10	27	93	480	2.7	15.3 c	9.1 c	13.1	-	248.1 b
2010	FIT	127	563	20.9	111	79	634	3.9	28.6 a	15.5 a	3.7	0.54	343.2 a
	75% FIT	95	563	20.9	111	101	628	3.9	27.0 b	14.8 a	4.2	0.55	343.7 a
	60% FIT	76	563	20.9	111	102	616	3.8	25.0 c	14.2 b	3.2	0.57	326.3 a
	50% FIT	65	563	20.9	111	112	606	3.7	24.9 c	13.4 b	11.4	0.54	315.7 a
	Rainfed	0	563	20.9	111	148	579	3.6	23.9 c	11.8 c	5.9	0.49	296.1 b

^[a] Within each year, values for biomass, grain yield, and 1000-kernel weight followed by the same letter are not significantly different at the 5% level.

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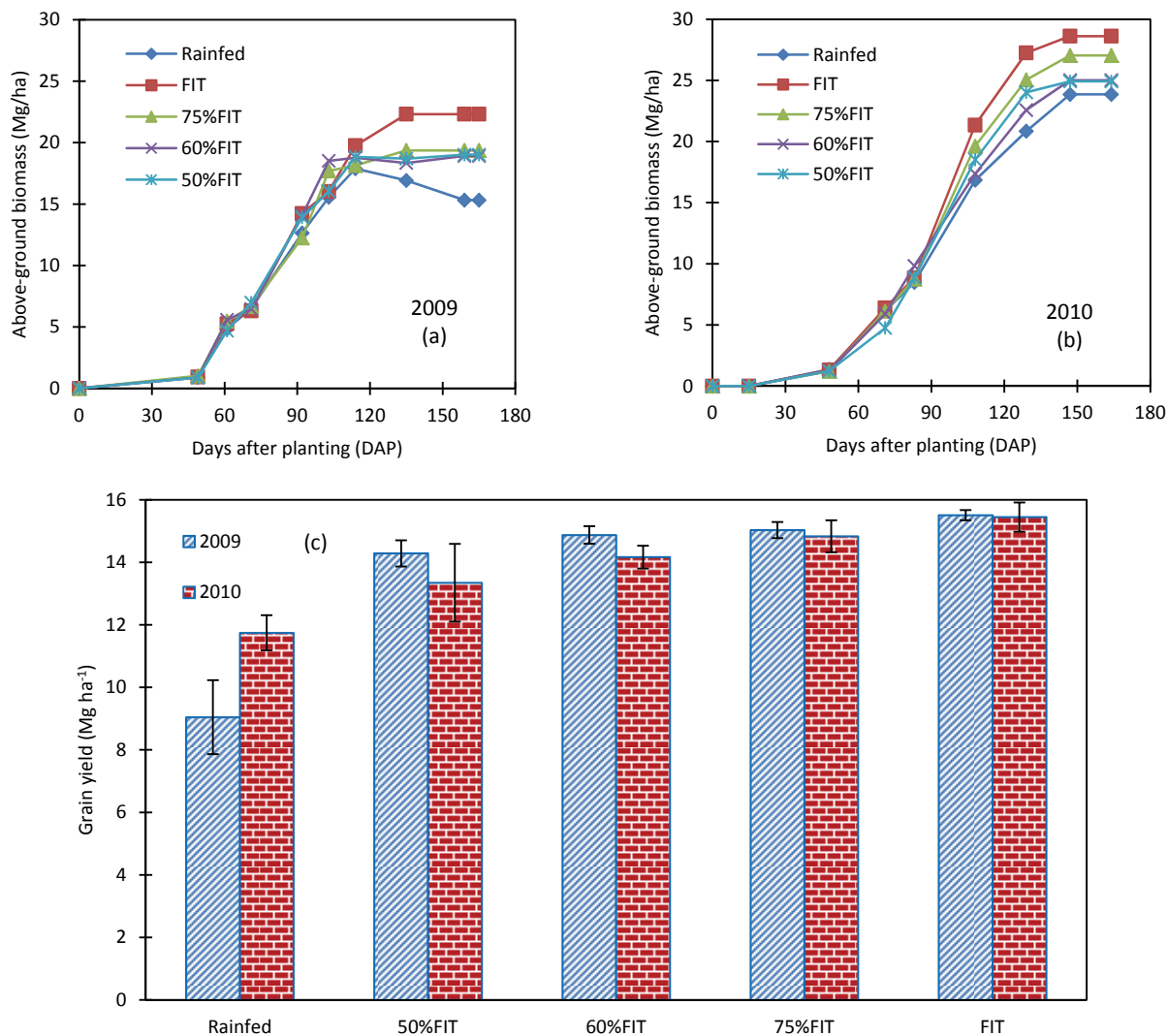


Figure 10. Measured above-ground biomass in (a) 2009 and (b) 2010, and (c) maize grain yield for five treatments. Vertical bars indicate standard deviations.

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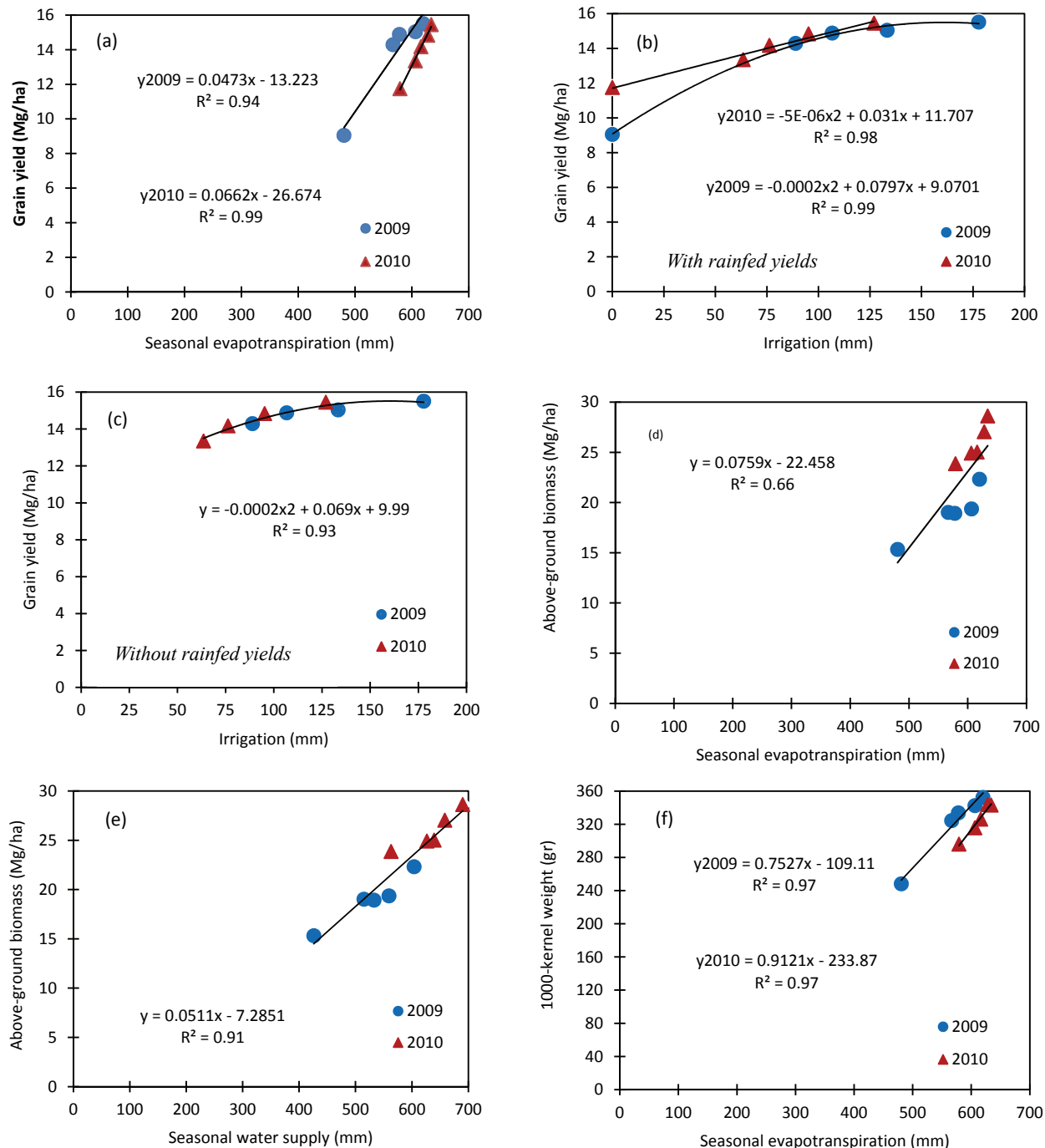


Figure 11. Relationship between: (a) seasonal actual crop evapotranspiration (ET_a) vs. grain yield, (b) seasonal irrigation amount vs. grain yield, (c) pooled seasonal irrigation amount vs. grain yield excluding rainfed treatment, (d) above-ground biomass and seasonal ET_a , (e) above-ground biomass and seasonal water supply (irrigation + rainfall + available soil water), (f) seasonal ET_a vs. 1000-kernel (seed) weight, and (g) seasonal irrigation vs. 1000-kernel weight measured for different irrigation treatments in the 2009 and 2010 growing seasons.

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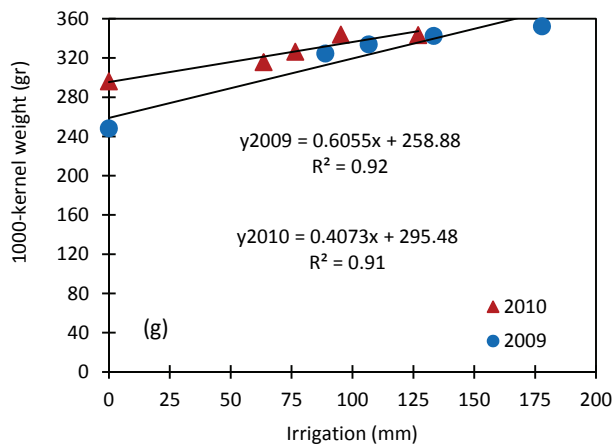


Figure 11 (continued). Relationship between: (a) seasonal actual crop evapotranspiration (ET_a) vs. grain yield, (b) seasonal irrigation amount vs. grain yield, (c) pooled seasonal irrigation amount vs. grain yield excluding rainfed treatment, (d) above-ground biomass and seasonal ET_a , (e) above-ground biomass and seasonal water supply (irrigation + rainfall + available soil water), (f) seasonal ET_a vs. 1000-kernel (seed) weight, and (g) seasonal irrigation vs. 1000-kernel weight measured for different irrigation treatments in the 2009 and 2010 growing seasons.

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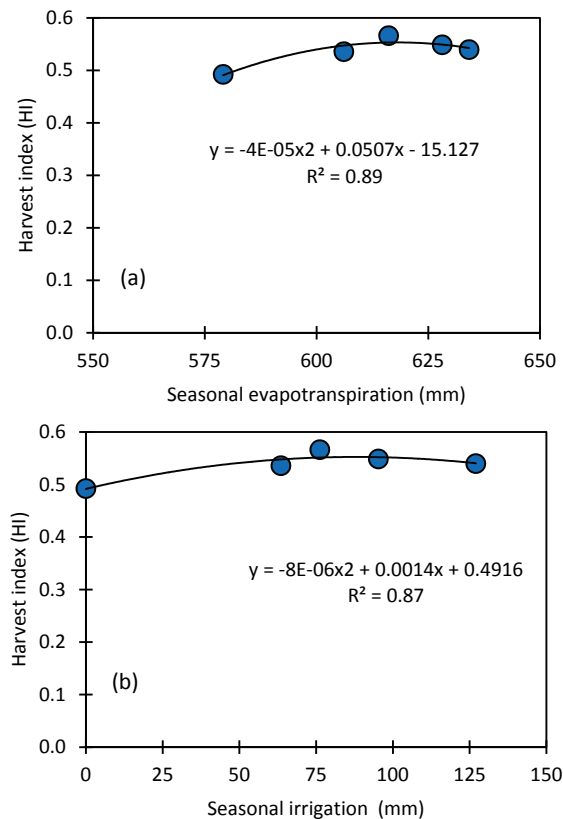


Figure 12. Relationship between harvest index (HI) and (a) seasonal evapotranspiration (ET_a) and (b) seasonal irrigation amount in the 2010 growing season.

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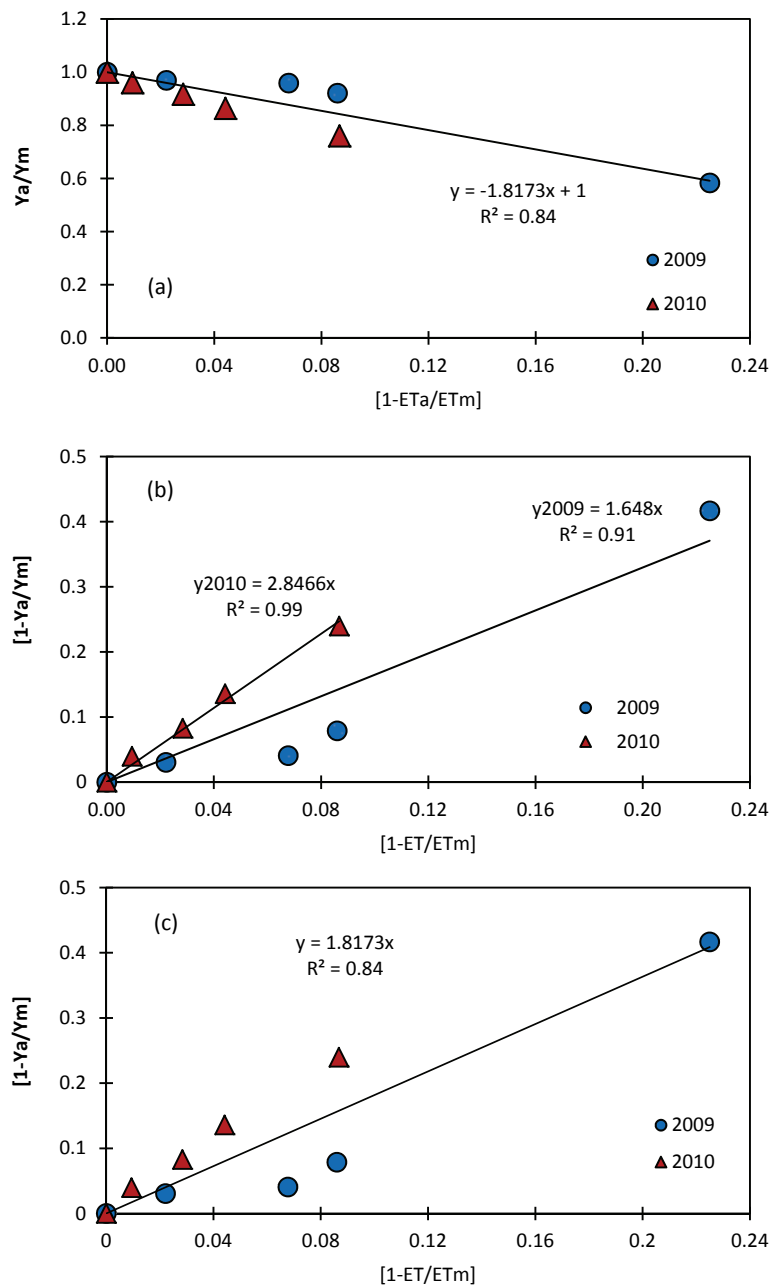


Figure 13. Relationship between (a) relative evapotranspiration deficit and relative yield in 2009 and 2010, (b) relative evapotranspiration deficit and relative yield deficit in 2009 and 2010, and (c) relative evapotranspiration deficit and relative yield deficit for pooled data.

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Rainfed



50% FIT



60% FIT



75% FIT



100% FIT

Figure 14. Appearance of maize plants experiencing water stress under different irrigation treatments at 134 DAP (September 13, 2009).