CORN AND PALMER AMARANTH INTERACTIONS IN DRYLAND AND IRRIGATED ENVIRONMENTS

by

DWAIN MICHAEL RULE

B.S., Purdue University, 1997
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AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

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Department of Agronomy
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Abstract

Palmer amaranth is a competitive weed and has caused variable corn yield losses in diverse environments of Kansas. The objectives of this study were to 1) determine corn and Palmer amaranth growth, development, and grain (seed) production, 2) determine soil water content throughout the growing season, and 3) evaluate the performance of the modified ALMANAC model for simulating monoculture corn yield and corn yield loss from Palmer amaranth competition when corn and Palmer amaranth were grown alone or in competition under dryland and irrigated environments. For the first objective, field experiments were conducted in 2005 and 2006 with whole-plots of dryland and furrow irrigation arranged in a side-by-side design. Within each soil water environment, sub-plot treatments were monoculture Palmer amaranth at one plant m^{-1} of row, and corn with zero, one, and four Palmer amaranth plants m^{-1} of row. Corn height, leaf number, LAI, and total plant dry weight were reduced with increasing water stress and were reduced further in the presence of Palmer amaranth. Corn yield losses were similar with increasing Palmer amaranth density across soil water environments in each year, except for 2006 dryland corn. Palmer amaranth growth and development were negatively impacted by corn interference and weed density. For the second objective, Time Domain Reflectometry measurements documented seasonal trends of volumetric soil water content at the 0 to 15 and 0 to 30 cm soil profile depths for treatments in dryland and irrigated environments each year. The soil water depletion rate increased as water received prior to a drying period increased at the 0 to 30 cm soil depth in the dryland and irrigated environments.

For the third objective, the modified ALMANAC model was parameterized based on monoculture corn and Palmer amaranth growth data. The model underestimated monoculture corn yield but overestimated corn yield with Palmer amaranth competition. The model performance was not consistent when comparing simulation results to dryland and irrigated experiments conducted across Kansas. Overall, the experiment provided an improved understanding of corn yield loss risks associated with water management and Palmer amaranth competition.

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Dedication

To my wife, Kim, and two sons, Caden and Rylan, thank you for all your love, continuous support and encouragement, and sacrifice during this journey to complete my dreams. Kim, you're an amazing woman like no other that can give so much, which has and will continue to inspire me in the future.

INTRODUCTION

In the semiarid areas of the U.S. Great Plains region, water is the most limiting resource for crop production (Smika 1970). Crop yields in the region are impacted by highly variable precipitation, low soil water availability, and high evapotranspiration. Producers' management decisions to maximize potential yield and profitability are dependent on their ability to minimize yield losses. Weed interference with crops is one source of crop yield loss because weeds compete for solar radiation, nutrients, and water. The level of interference weeds have on crops for water availability depends on the weed species, density, time of emergence, and spatial distribution and duration of growth with crop with the environmental conditions limiting water availability (Patterson 1995). Weeds have adapted to water stress by possessing one or more mechanisms which include: 1) avoidance of stress, 2) conservation and efficient use of water, or 3) tolerance to water stress (Radosevich et al. 1997). The adaptations are based on the morphology and distribution of the root system, leaf characteristics, physiological mechanisms for maintaining high water use efficiency (WUE), stomatal control, and osmotic adjustment (Radosevich et al. 1997). The variations of these adaptations among species of crops and weeds will influence the rate, magnitude, duration of crop-weed water interference when water availability declines (Patterson 1995). In addition, weeds that are more effective competitors for soil water could cause more yield loss when soil water is limiting, but this is not always the case when crop potential yield is lowered due to water stress (Patterson 1995, Mortensen and Coble

1989). Thus, the competition between crops and weeds growing in variable environments is poorly understood (Mortensen and Coble 1989). Therefore, competitive mechanisms for crops and weeds need to be better understood and quantified to develop effective crop management solutions to minimize yield loss in water limited environments.

Improved understanding of the crop growth, development, and yield potential in association with sensitivity to seasonal water stress in water limited environments would aid crop managers in making profitable decisions for weed control. Variability in environmental conditions and implementation of crop management operations are the major factors influencing the dynamics of weed-crop interference relationships among sites and years (Lindquist et al. 1996). The interactions can be simulated with eco-physiological process-oriented crop and weed competition models, such as ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria). The ALMANAC model can provide a practical, easily adopted tool for simulating competition in mixed plant communities (Kiniry et al. 1992). The ALMANAC model contains detailed functions to simulate plant growth, water balance, and nutrient cycling, as in the EPIC (Erosion-Productivity-Impact Calculator or Environmental Policy Integrated Climate) model (Sharpley and Williams 1990, Williams et al. 1984, 1989), together with additional detail for light competition, population density effects, and vapor pressure deficit effects which enable it to simulate the growth and yield of two or more competing plant species in a wide range of environments (Kiniry et al. 1992, 1997, McDonald and Riha 1999 a, b, Stockle and Kiniry 1990). Simulation accuracy has been validated for corn and sorghum yields in irrigated and water-stressed dryland environments (Kiniry et al. 1997, Kiniry and Blockholt 1998, Yun et al. 2001). The most optimistic use of crop-weed simulation models can be to explore the within season and year-to-year variations in crop yield loss caused by water stress and/or weed interference.

The ALMANAC model was modified to improve plant competition relationships and incorporated into GAPS (General purpose simulation model of the Atmosphere-Plant-Soil system) (McDonald and Riha 1999a, b, Rossiter and Riha 1999). The modified ALMANAC model partitions radiation into a mixed plant leaf canopy by replacing the functions developed by Spitters and Aerts (1983) with the Wallace (1995) method. The radiation partitioning method can characterize a fuller range of competitive relationships among interacting crop and weed species, where a linear interpolation is used to calculate the fraction of light intercepted by species in canopies in which one species does not exert complete dominance over the other (McDonald and Riha 1999a). The modified ALMANAC model improved the impact environmental stress on plant growth over the original ALMANAC model, where the daily index of environmental stress is incorporated in the equations for canopy height and root expansion (McDonald and Riha 1999a). The modified ALMANAC was altered to make daily increases in leaf area index (LAI), height, and rooting depth attenuated on the basis of accumulated aboveground biomass and by environmental stress (McDonald and Riha 1999a). The linkage of morphological development to resource capture is important for accurately simulating the growth and impact of weeds on crops, especially with weed cohorts, growth in stressful environmental conditions, and crops tolerant to certain weed species. McDonald and Riha (1999a) used the modified ALMANAC model to simulate monoculture corn yields and corn:velvetleaf competition from a field study, and they concluded that the model was capable of distinguishing between environmental conditions that facilitate large and small corn yield loss caused by velvetleaf competition. Furthermore, corn and velvetleaf competition simulated over 30 years at a single site showed water stress and indicated the probability of years where large corn yield losses would result from velvetleaf competition (McDonald and Riha 1999b). The competition simulation with historical weather data suggested that moisture stress during corn's exponential growth phase changes the competitive balance between the crop and weed, in that higher levels of crop yield loss were associated with moisture-deficit years (McDonald and Riha 1999b). This evaluation illustrates the potential to use simulation plant growth models for crop-weed competition, and how simulated estimates of seasonal environmental variations can aid in predicting crop yield losses. Also, crop and weed simulation models can give insight as to why specific responses are evident in the field in only certain sites and years, while providing a useful tool for quantifying the long-term occurrences of specific crop and weed interactions (McDonald and Riha 1999a).

In the Great Plains of the United States, Palmer amaranth (*Amaranthus palmeri*) is one of the most aggressive *Amaranthus* species (Whitson et al. 2002). Palmer amaranth emerges in early May, grows rapidly, and produces prolific numbers of seed (200,000 to 600,000 seed per female plant) (Guo and Al-Khatib 2003, Horak 1997, Horak and Loughin 2000, Keeley et al. 1987, Sellers et al. 2003). Palmer amaranth, a native from the Sonoran Desert of North America, is a summer annual, dioecious plant that can grow up to 3 m in height (Horak 1997, Horak et al. 1994, Horak and Loughin 2000). Palmer amaranth control is possible with pre-emergence and post-emergence herbicides, however Palmer amaranth can escape management as a result of poor herbicide efficacy or herbicide-resistant biotypes. In the last 15 years, researchers have reported biotypes of Palmer amaranth resistant to the acetolactate synthase (Horak and Peterson

1995, Sprague et al. 1997), dinitroaniline (Gossett et al. 1992), triazine (Heap 2006), and glycine (Culpepper et al. 2006, Heap 2006) herbicide groups.

Palmer amaranth is considered one of the most troublesome weed problems in the Midwest region of the United States (Stoller et al. 1993) and has become a problematic weed in the Great Plains (Horak 1997). Palmer amaranth reduces yields of soybean (Bensch et al. 2003, Klingaman and Oliver 1994), cotton (Morgan et al. 2001, Rowland et al. 1999), grain sorghum (Moore et al. 2004), and corn (Liphadzi and Dille 2006, Massinga et al. 2001, 2003). Massinga et al. (2001) reported that Palmer amaranth emerging with irrigated corn reduced yield from 11 to 91% for densities from 0.5 to 8 plants m^{-1} of row in western Kansas. In eastern Kansas, Liphadzi and Dille (2006) reported dryland corn and irrigated corn yield loss was 6 to 60% and 5 to 38%, respectively, for Palmer amaranth densities of 0.25 to 6 plants m^{-1} of row. Corn yield loss was variable between site-years and water management across Kansas. Massinga et al. (2001, 2003) demonstrated that irrigated corn yield losses were a result of reduced potential light interception with Palmer amaranth due to a decrease in corn leaf area index with increasing Palmer amaranth density. Information is needed for dryland corn production because corn yield loss and competition for light could be different when soil water is limited.

The degree of competition for water between a crop and a weed is determined by the relative root volume occupied by each species (Aldrich 1984) and subsequently, the competition for water will be greatest when the crop and weed roots are in the same volume of soil. Davis et al. (1965) described the root moisture extraction profile for Palmer amaranth and other weeds. Palmer amaranth had a relatively narrow lateral root distribution and extensive vertical root distribution. Palmer amaranth extracted more water from the upper 0.3 m soil layer which suggests a higher density of roots near the soil surface, but it could also be more competitive because it can extract water from greater depths when soil moisture is limited. Palmer amaranth was observed to have rapid root expansion rates (Weise 1968), which would serve as a mechanism to compete for soil water (Davis et al. 1967). Also, Palmer amaranth tolerated moisture stress similar to grain sorghum and better than corn when dry matter production was compared for wet, intermediate, and dry soil moisture conditions (Weise and Vandiver 1970).

The overall objective of this research was to investigate Palmer amaranth interference with corn produced in dryland and irrigated environments in Kansas. The specific objectives were:

1) to determine corn and Palmer amaranth growth, development, and grain (seed) production when grown alone or in competition,
2) to determine soil water content throughout the growing season when corn and Palmer amaranth were grown alone or in competition, and
3) to evaluate the performance of the modified ALMANAC model for predicting monoculture corn yield and corn yield loss from Palmer amaranth competition in dryland and irrigated environments.

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CHAPTER 1 - Corn and Palmer Amaranth Interactions in Dryland and Irrigated Environments

ABSTRACT

Palmer amaranth is a competitive weed in corn fields in the Great Plains of the United States. Field experiments were conducted in 2005 and 2006 at the Department of Agronomy Ashland Bottoms Research Farm near Manhattan, KS. The objective was to determine corn and Palmer amaranth growth, development, and grain (seed) production when grown alone or in competition under dryland and irrigated environments. The experiment was arranged in a side by side design with whole plots being dryland and furrow irrigation. Within each soil water environment, sub-plot treatments were monoculture Palmer amaranth at one plant m^{-1} of row, and corn with zero, one, and four Palmer amaranth plants m^{-1} of row. Water stress occurred earlier and caused more drought-like conditions in 2006 than 2005. Corn height was impacted more by water stress than by Palmer amaranth presence. Corn leaf number, LAI, and dry weight were reduced with increasing water stress and were reduced further in the presence of Palmer amaranth. In both years, dryland monoculture corn yield was 50% less when compared to irrigated monoculture corn. Corn yield reductions were similar with increasing Palmer amaranth density across soil water environments in each year except for 2006 dryland corn. Palmer amaranth growth and development were negatively impacted more by corn interference and Palmer amaranth density than by water stress. Growth and development trends of corn and Palmer amaranth in dryland and irrigated environments were used to understand competition during the season and end of season corn yield loss. The information improved the understanding of corn and Palmer amaranth interference in well-watered and limited soil water environments.

Key words: competition, furrow irrigation, leaf area index, water stress, weed seed production, yield loss

INTRODUCTION

In the semi-arid region of the U.S. Great Plains, water is the most limiting resource for crop production (Smika 1970). Crop yields in the region are impacted by highly variable precipitation, low soil water availability, and high evapotranspiration. Corn grown under dryland conditions often encounter water stress during the growing season, which results in unpredictable corn yields and yield losses due to water deficits. The potential corn yield in a given year is impacted by soil water availability and crop management practices. Any crop management practice that reduces the availability of soil water for corn plants can result in water-stressed plants such as allowing weed competition to occur, which subsequently will limit and reduce corn yield potential. If improper weed management occurs, then weeds also compete with corn for solar radiation, and nutrients, in addition to available soil water. The level of interference weeds have on crops for soil water depends on the weed species, density, time of emergence relative to crop, and spatial distribution and duration of weed growth with crop, together with the environmental conditions that limit water availability (Patterson 1995). In addition, weeds that are more effective competitors for soil water could cause more yield loss when soil water is limiting, but this is not always the case when potential crop yield is also lowered due to water stress (Mortensen and Coble 1989, Patterson 1995). Thus, the extent of competition between crops and weeds growing in variable environments is poorly understood (Mortensen and Coble 1989). Effective crop and weed management solutions to minimize yield loss could be developed with an improved understanding of the crop growth, development, and yield potential in association with sensitivity to seasonal water stress in water-limited environments.

In the Great Plains of the United States from Kansas south to Texas, Palmer amaranth (*Amaranthus palmeri*) is one of the most aggressive *Amaranthus* species (Whitson et al. 2002). Palmer amaranth emerges in early May, grows rapidly, and produces prolific number of seed (200,000 to 600,000 seeds per female plant) (Guo and Al-Khatib 2003, Horak and Loughin 2000, Keeley et al. 1987, Sellers et al. 2003). Palmer amaranth, a native from the Sonoran Desert of North America, is a summer annual, dioecious plant that can grow up to 3 m in height (Horak et al. 1994, Horak and Loughin 2000). Palmer amaranth control is possible with pre-emergence and post-emergence herbicides, however this weed can escape management as a result of poor herbicide efficacy or herbicide-resistant biotypes. In the last 15 years, researchers have reported biotypes of Palmer amaranth resistant to the acetolactate synthase (Horak and Peterson 1995, Sprague et al. 1997), dinitroaniline (Gossett et al. 1992), triazine (Heap 2006), and glycine (Culpepper et al. 2006, Heap 2006) herbicide groups.

Palmer amaranth reduces yields of soybean (Bensch et al. 2003, Klingaman and Oliver 1994); cotton (Morgan et al. 2001, Rowland et al. 1999), grain sorghum (Moore et al. 2004), and corn (Liphadzi and Dille 2006, Massinga et al. 2001, 2003). Massinga et al. (2001) reported Palmer amaranth emerging with irrigated corn reduced yield from 11 to 91% for densities from 0.5 to 8 plants m^{-1} of row in western Kansas. In eastern Kansas, Liphadzi and Dille (2006) reported dryland corn and irrigated corn yield losses were 6 to 60% and 5 to 38%, respectively, for Palmer amaranth densities of 0.25 to 6 plants m^{-1} of row. Corn yield loss was variable between site-years and water management across Kansas. Massinga et al. (2001, 2003) demonstrated that irrigated corn yield losses were a result of reduced potential light interception with Palmer amaranth as measured by a decrease in corn leaf area index (LAI) with increasing Palmer amaranth density. Information is needed for dryland corn production because corn yield loss and competition for light could be different when soil water is limited.

A mechanistic approach to quantifying corn and Palmer amaranth growth and development throughout the growing season would provide information to explain the causes of corn yield loss in different soil water environments. The objective of this study was to determine corn and Palmer amaranth growth, development, and grain (seed) production when grown alone or in competition under dryland and irrigated environments.

MATERIALS AND METHODS

Field experiments were conducted in 2005 and 2006 at the Kansas State University Agronomy Department Ashland Bottoms Research Farm 8 km south of Manhattan, KS. In 2005, the experiment was established on Eudora silt loam soil (coarse-silty, mixed, superactive, mesic Fluventic Hapludoll) with a pH of 5.8 and 2.0 % OM. The previous crop was soybean. The field was fertilized with 224 kg N ha^{-1} using liquid urea-ammonium nitrate (28-0-0) and a dry blend of 45 kg ha^{-1} muriate of potash, 33.5 kg ha^{-1} sulfur (90%), 13.5 kg ha^{-1} zinc sulfate (31%), and 336 kg ha^{-1} pell-lime in spring, then incorporated by field cultivation. The field was set up for furrow irrigation one month prior to planting with ridged rows made with one pass planter furrow row units and a second pass with a furrow cultivation unit. In 2006, the experiment was established in a neighboring field where the soil was a Belvue silt loam (coarse-silty, mixed, superactive, nonacid, mesic Typic Udifluvents) with a pH of 5.6 and 1.1 % OM. The previous crop was soybean followed immediately with winter wheat, which was terminated in early April. The field was fertilized with 224 kg N ha^{-1} using liquid urea-ammonium nitrate (32-0-0) and a dry blend of 56 kg ha^{-1} muriate of potash, 33.5 kg ha^{-1} sulfur (90%), 13.5 kg ha^{-1} zinc sulfate (31%), and 336 kg ha^{-1} pell-lime. Ridged furrow irrigation rows were established with one pass planter furrow row units and two passes with a furrow cultivation unit one month prior to planting, which also incorporated the fertilizer. Corn hybrid 'DKC60-19RR' was planted at 76,600 seeds ha^{-1} at 0.76 m row spacing on May 6, 2005 and May 11, 2006 on the ridged rows.

Experiments were arranged in a split-plot design with two whole plot treatments being soil water environment (dryland and well watered furrow irrigation). Replication was restricted to within each soil water environment due to logistics of irrigation methods. Within each soil water environment, four sub-plot treatments were established including monoculture corn, monoculture Palmer amaranth at one plant m^{-1} of row, and two mixtures of corn with Palmer amaranth at one and four weeds m^{-1} of row. The weed densities were selected based on previous research results for Palmer amaranth competitiveness in dryland and irrigated environments (Blinka 2004, Liphadzi and Dille 2006, Massinga et al. 2001). Treatments (sub-plot) were replicated four times and arranged in a randomized complete block within each soil water environment. Each sub-plot was four corn rows wide and 17 m long to allow for up to 12 destructive plant harvests, yield estimation, and soil environment measurements. Immediately after planting, the plot layout was established and Palmer amaranth seeds were hand sown to all four rows of a plot and lightly raked to cover seed with soil. The Palmer amaranth seed was collected in fall (2004 and 2005) at the Ashland Bottoms Research Farm. All plots were furrow irrigated to establish corn and Palmer amaranth where two and one irrigation applications were made in 2005 and 2006, respectively. The irrigated plots were watered as needed by the crop with each application being approximately 50 mm. In 2005, irrigation applications were made June 27, July 14 and 28, and August 9, and in 2006, applied on June 9, 22, 30, July 19 and 27, and August 2 and 10.

After emergence, Palmer amaranth seedlings were hand thinned to treatment densities with plants located 10 cm of each corn row and corn was removed from monoculture Palmer amaranth plots. Plots were hand weeded to maintain treatment densities and to remove other weed species for the duration of the experiment. Destructive plant harvests started five days after crop and weed emergence (DAE) and sampling was repeated every four to nine days until corn tasseled and a final plant harvest was taken after plant physiological maturity (Table 1.1). At each harvest date, two corn and/or two Palmer amaranth plants were randomly selected from one row meter in the two center rows of the four row plots. In the field, plant growth stage and height data were measured. Corn plant height was determined from the soil surface near the plant to the tallest portion of the upper most developed leaf. Corn growth stage (leaf number) was determined based on Ritchie et al. (1996). Palmer amaranth plant height was determined from the soil surface to the top of the apical node at vegetative stages and to the top of inflorescence once reproductive structures were initiated. Plants were then cut at the soil surface, labeled, and taken to the Kansas State Weed Ecology laboratory for further processing. During plant processing, plants were separated into stem, leaf, and reproductive parts. Palmer amaranth leaves were cut from the plant without the petiole and total plant leaf number was recorded. Corn plants were partitioned into stem, leaf, and reproductive (ear and tassel) parts. Green corn leaf blades and Palmer amaranth leaves were used to determine leaf area per plant in cm^2 using a LI-COR Li-3100[1]. Partitioned plant parts were placed into individual paper sacks, dried at 66° C to constant weight, and final dry biomass was determined. At corn and Palmer amaranth physiological maturity, the plants were collected and processed as previously described, except no leaf number and leaf area measurements were determined. Palmer amaranth seed was sieved from the inflorescence and further cleaned with a seed air blower device[2]. Palmer amaranth seed was weighed and a 0.25 g sub-sample was counted to determine total seed production per plant. Corn grain yield was determined by harvesting two m from each of the two center rows in each sub-plot. Corn yield was adjusted to 15.5% moisture content.

Soil moisture was measured in the 0-15 and 0-30 cm depths to evaluate early season soil water availability. Soil moisture was measured within one treatment plot for one replication using Time Domain Reflectometry (TDR100[3]). Rainfall was measured using a tipping bucket rain gauge[4]. Rainfall data were recorded every 60 minutes to the data logger. The data acquisition and control system and rain gauge were installed after planting and soil moisture probes were installed after establishment of Palmer amaranth plant densities. Data were downloaded from the data logger[5] to a laptop computer at least once each week to monitor operation of the instruments and data quality.

Soil physical properties were determined for the two soil types used in the experiment. Percent sand, silt, and clay were determined to a 120 cm depth by the Soil Testing Laboratory at Kansas State University. Dry bulk density of the field soils were determined from soil cores taken to 30 cm. Soil water content was determined at -0.03 and -1.5 MPa soil water potential with a cellulose acetate membrane from soil samples taken at 0 to 20 cm depth (conducted by Dr. L. Stone and Brian Frank, Kansas State University).

Dates of planting, emergence, and plant harvests are presented in Table 1.1. Corn and Palmer amaranth plant destructive data (specifically leaf number, height, and total plant weight on a per plant basis), LAI, corn grain yield, and weed seed production were analyzed using the GLIMMIX procedure in SAS v9.1[6]. The analyses were conducted for each plant species response and sample date. The LAI was calculated for each species in the sub-plots. The PROC GLIMMIX procedure calculated the least-squared means and least-squared standard errors. The difference between the standard errors was used to determine the Least Significant Difference (LSD) at $\alpha = 0.05$ for both within each soil water environment for sub-plot treatments and between soil water environments to test for soil water environment (whole-plot) and sub-plot treatment differences.

Response of corn height at tassel to Palmer amaranth density and response of weed height to increasing weed density were described using a linear regression model for treatments within environments:

$$\text{Hgt} = y_0 + b\text{d} \qquad [1]$$

where Hgt is the height (cm), y_0 is the intercept, b is the slope of the line, and d is the weed density (plants m^{-1} of row). Corn and Palmer amaranth plant height data that showed no response to weed density were analyzed with the GLIMMIX procedure to determine if differences existed due to environment and treatments.

Cumulative thermal time from emergence was calculated using growing degree days (GDD):

$$\Sigma M = ([\{T_{max} + T_{min}\}/2] - T_B) \qquad [2]$$

where M is the degree days for a given day, T_{max} and T_{min} are daily maximum and minimum air temperatures (°C), respectively, and T_B is the base temperature set at 10°C. The weather data were compiled from the Kansas State Weather Data Library (M. Knapp, personal communication). Precipitation data sources were the Ashland Bottoms Research Farm and rain-gauge measurements from within the field. The reference evapotranspiration (ET_o) was calculated based on methods described by Allen et al. (1998). Monthly mean air temperatures and total precipitation data for the period from April through September in 2005 and 2006 along with 30-yr normal values are presented in Table 1.2.

RESULTS AND DISCUSSION

Growing season monthly mean temperatures were near 30-yr normal temperatures for 2005 and 2006 but the 2006 season was slightly warmer overall than 2005 (Table 1.2 and Figure 1.1). Total rainfall received from May 1 to August 31 was 496 mm and 366 mm for 2005 and 2006, respectively (Table 1.2 and Figure 1.1). In both years, the May rainfall was almost 90 mm less than 30-yr normal precipitation. In 2005, 53% of the growing season rainfall occurred in early June, while July received only 60 mm of rainfall and August precipitation was too late in the season to impact corn yield results. The June 2005 rainfall provided near optimum growing conditions for corn and Palmer amaranth but limited rainfall thereafter generated a moderate midsummer drought. In 2006, rainfall deficits from 30-yr normal continued from May through July to generate a severe midsummer drought since 57% of the May through August rainfall occurred in mid to late August. Therefore, dryland corn was under water-limited stress throughout most of the 2006 growing season.

The difference in extent of water stress between the two years was not limited to rainfall but the 2005 field soil (0.26 cm^3 cm^{-3}) had 1.5 times higher available water content than the 2006 field soil (0.18 cm^3 cm^{-3}) in the 30 cm profile depth. The soil texture characteristics of the 2005 soil were 30, 59, and 11 percent sand, silt, and clay, respectively, while the 2006 soil had 44, 47, and 8 percent sand, silt, and clay, respectively, at the 0 to 30 cm depth. The volumetric soil water content determined by the TDR showed the seasonal trends of soil water for dryland and irrigated environments, which highlighted dryland water stress periods in the 2005 and 2006 growing season (data not shown, see Chapter 2). The cumulative ET_o from emergence to corn physiological maturity was 480 mm and 510 mm in 2005 and 2006, respectively (Figure 1.2), which indicated that the environmental demand for water was higher in 2006 than 2005. The furrow irrigated environment received a total of 203 mm and 356 mm of water in 2005 and 2006, respectively, from emergence to the final plant harvest. The difference in applied irrigation was attributed to differences in cumulative ET_o and soil physical properties for the two years, where 2006 had higher demand for water. Cumulative thermal time from emergence to corn physiological maturity was 1,676 GDD in 2005 (September 12) and 1,556 GDD in 2006 (August

28) (Table 1.1 and Figure 1.2), which indicated that corn matured slightly earlier in 2006 than 2005, due to warmer temperatures.

Corn and Palmer amaranth emerged at the same time in 2005 and 2006 aided by the irrigation of both soil water environments immediately after planting. The available soil water was equal in both soil water environment plots at the time of crop and weed emergence, however after emergence, rainfall was the only source of water for the dryland environment plots. First subsequent irrigation was June 27 in 2005 and earlier in 2006 on June 9 due to limited soil water.

Corn: emergence to tassel

Corn growth and development responses from emergence to mid-season are presented in Figures 1.3 through 1.10 for 2005 and 2006. In 2005, corn height differences were inconsistent. By corn tassel stage (620 GDD), dryland monoculture corn was significantly taller than dryland corn with Palmer amaranth at one plant m^{-1} of row, but not different from dryland corn with four Palmer amaranth plants m^{-1} of row or any irrigated corn treatments (Figure 1.3A). Irrigated corn height was not affected by Palmer amaranth at any weed density. In 2006, significant differences in corn plant height were not observed until 402 GDD, where dryland corn height was reduced due to water stress and continued to be 80 cm shorter than irrigated corn at 643 GDD (Figure 1.3B). Irrigated corn heights were taller than 200 cm and dryland corn heights were shorter than 150 cm. Height of dryland corn (116 cm) with four Palmer amaranth plants m^{-1} of row was reduced 47% when compared to irrigated monoculture corn (220 cm). At tassel stage (643 GDD), corn height decreased with increasing Palmer amaranth density for dryland or irrigated environments with a slope of -7.16 and -4.26 cm $weed^{-1}$ m^{-1} of row, respectively (Figure

1.4). Liphadzi and Dille (2006) also observed dryland corn height reductions from Palmer amaranth interference with a slope of -1.58 cm weed^{-1} m^{-1} of row.

In 2005, corn leaf number per plant at 620 GDD ranged from 18 to 19 leaves with no differences among treatments (Figure 1.5A). Corn leaf number in 2006 was the same across treatments until after 309 GDD when water stress appeared to have delayed leaf appearance and reduced leaf number for subsequent harvest dates (Figure 1.5B). Corn had one and two more leaves per plant at 402 and 500 GDD, respectively, in the irrigated compared to the dryland environments. At 643 GDD, irrigated monoculture corn had 19 leaves and presence of Palmer amaranth did not reduce corn leaf number. Palmer amaranth at four plants m^{-1} of row reduced corn leaf number per plant by two leaves in the dryland environment. Corn had three, three, and five fewer leaves per plant with zero, one, and four Palmer amaranth plants m^{-1} of row, respectively, in the dryland environment compared to monoculture irrigated corn (Figure 1.5B).

Corn LAI has been documented to provide an early indication of the effect of weed competition (Hall et al. 1992, Knezevic et al. 1994, Massinga et al. 2001, 2003, Tollenaar et al. 1994). Palmer amaranth's competitive ability to reduce corn LAI in water limited and non-limited conditions demonstrated the potential to reduce biomass and yield. Massinga et al. (2001) reported that irrigated corn LAI at silking decreased as Palmer amaranth density increased. In contrast, the results of this study showed that irrigated corn LAI reductions from Palmer amaranth interference were non-significantly less than LAI reductions previously reported by Massinga et al. (2001) (Figure 1.6). Corn LAI increased developmentally in the irrigated environment for both years with maximum LAI occurring at corn tassel (Figures 1.6). Palmer amaranth interference did not significantly reduce LAI in irrigated plots in both years. At 620

GDD, LAI for dryland and irrigated monoculture corn was 20% larger than dryland corn with both Palmer amaranth densities. In 2006 early water-stress reduced LAI of dryland corn by 22 to 37% across Palmer amaranth densities when compared with irrigated monoculture corn at 402 GDD (Figure 1.6B). At 500 GDD, dryland corn LAI was 38% lower than all irrigated corn treatments. Leaf area index of dryland corn with 4 Palmer amaranth plants m^{-1} of row LAI was 27% lower than dryland monoculture corn (4.3 m^2 m^{-2}) at 643 GDD. The 2006 water-stressed dryland corn LAI reductions were similar to Massinga et al. (2001) previously reported irrigated corn LAI reductions, which indicated there were differences in hybrid selection and crop management, which can greatly influence corn LAI values regardless of weed presence. Corn LAI reductions of 23 and 27% in 2005 and 2006 for dryland corn with 4 Palmer amaranth plants m^{-1} of row, respectively, were similar to those reported by Blinka (2004) with LAI reduction of 23%. The results indicate that actively growing non-stressed corn can compete with Palmer amaranth at low densities but when corn is water-stressed and resulting plant growth slows, Palmer amaranth can significantly reduce corn LAI and thus out-compete corn for light.

Corn grown alone had total plant dry weights that were not different between dryland and irrigated environments at 620 GDD, however corn grown with one or four Palmer amaranth plants m^{-1} of row had 20% less corn dry weight within either soil moisture environment in 2005 (Figure 1.7A). In 2006, water stress began to reduce dryland corn dry weight compared to irrigated corn by 402 GDD (Figure 1.7B). The combination of water stress and Palmer amaranth interference further reduced corn dry weight. At 643 GDD, irrigated monoculture corn had the highest corn dry weight at 124 g $plant^{-1}$ and corn dry weight was reduced 22 and 41% with one and four Palmer amaranth plants m^{-1} of row, respectively. Dryland corn dry weight decreased 25 and 47% with one and four Palmer amaranth plants m^{-1} of row, respectively, similar to influence of Palmer amaranth on irrigated corn dry weight. Overall, dryland corn with zero, one, and four Palmer amaranth plants m^{-1} of row had 50, 62, and 74% less plant dry weights compared to irrigated monoculture corn.

Overall by corn tasselling, water stresses impacted corn height, leaf number, LAI, and total dry weight. The presence of Palmer amaranth further reduced these corn growth and developmental measures, especially in 2006 with the early season drought.

Corn: final plant harvest and grain yield

Corn dry weight accumulation and grain production from emergence to physiological maturity are represented by final harvest results (Table 1.3). Corn that experiences stress during the flowering and grain fill period can severely limit potential yield (Runge 1968, Shaw 1988). The experimental fields received 66 and 51 mm of rainfall from silking to dent corn growth stage in 2005 and 2006, respectively (Figure 1.1). The low rainfall amounts resulted in moderate drought stress in the dryland corn in 2005 but the 2006 field soil had lower soil water retention properties and therefore resulted in severely water-stressed dryland corn. The irrigated corn needed additional water application in 2006 compared to the 2005 growing season.

Corn plant dry weight at final harvest was impacted by the cumulative effects of leaf, stem, and reproductive tissue maintenance and growth with the major component being corn ear and grain development. These were further impacted by water-limited stress and presence of Palmer amaranth. Irrigated monoculture corn had the largest plant dry weight at 398 and 379 g $plant^{-1}$ in 2005 and 2006, respectively (Table 1.3). Dryland monoculture corn dry weight was

36% less than irrigated monoculture corn, which was similar to irrigated corn with Palmer amaranth. In 2005, irrigated corn with one and four Palmer amaranth m^{-1} of row had total plant dry weights that were 36 and 42% less than irrigated monoculture corn, respectively, although not different from each other. Plant dry weights for dryland corn with one and four Palmer amaranth plants m^{-1} of row were 34 and 53% lower, respectively, than dryland monoculture corn and 58 and 70% lower than irrigated monoculture corn at the same respective Palmer amaranth densities. These results indicate that moderate late season water stress can reduce dryland corn dry weight similar to irrigated corn with one and four Palmer amaranth plants m^{-1} of row. In 2006, all irrigated corn plant dry weights were greater than dryland corn with or without Palmer amaranth. Plant dry weights for irrigated corn with one and four Palmer amaranth plants m^{-1} of row were reduced 35 and 51%, respectively, due to the presence of Palmer amaranth interference, but they were not different (Table 1.3). Dryland corn plant dry weights were reduced 62 and 80% when in competition with one and four Palmer amaranth plants m^{-1}, respectively, than corn grown alone (180 g $plant^{-1}$). Water stress alone caused 52% reduction in dry weight and water-weed stress in combination reduced dryland corn dry weights by 82 and 90% with one and four Palmer amaranth plants m^{-1} of row, respectively, relative to irrigated monoculture corn.

Dryland corn with one and four Palmer amaranth plants m^{-1} of row had little biomass accumulation from corn tassel stage to physiological maturity, which resulted from poor corn ear development. Thus in both years corn plant dry weight was reduced with increasing water stress and further reduced with increasing Palmer amaranth density. Dryland corn dry weights were impacted more by water stress in 2006 than 2005 because the stress started earlier in the growing season and the soil had less water retention properties.

In 2005, corn grain yield had comparable reductions from Palmer amaranth and water stress as plant dry weight (Table 1.3). Dryland and irrigated monoculture corn grain yields were 7,005 and 15,435 kg ha^{-1}, respectively, and irrigated monoculture corn grain yield had the largest yield. Palmer amaranth at one and four plants m^{-1} of row reduced irrigated corn yield 35 and 43% while those populations reduced dryland corn yield 31 and 45%, respectively. Dryland corn yield was reduced 55, 69, and 75% with zero, one, and four Palmer amaranth plants m^{-1} of row when compared to irrigated monoculture corn, respectively. In 2006, irrigated monoculture corn grain yield was 16,108 kg ha^{-1} and greater than corn yields with water and Palmer amaranth stresses (Table 1.3). Irrigated corn yield loss with one and four Palmer amaranth plants m^{-1} of row was 39 and 52%, respectively. Dryland monoculture corn yield was 53% less than irrigated monoculture corn and Palmer amaranth at one and four plants m^{-1} of row reduced dryland corn yield 87 and 99% (1,013 and 98 kg ha^{-1}), respectively. The high dryland corn yield loss from Palmer amaranth presence and water stress was supported by the plant dry weight results, previously described. Potential yield of dryland corn was greatly reduced by the termination of crop growth and development caused by severe water stress combined with increasing Palmer amaranth density.

Percent corn yield losses were similar with increasing Palmer amaranth density between soil environments in each year, except for 2006 dryland corn, which corresponds to dry weights. The 2005 and 2006 irrigated environments provided optimum water and nutrients for corn, and corn yield losses still ranged from 35 to 39% and 42 to 52% for corn with one and four Palmer amaranth plants m^{-1} of row, respectively. Two different water-stress environments were studied across years; 2005 had mid-season drought while 2006 had an early season severe drought. Dryland corn yield loss with one and four Palmer amaranth plants m^{-1} of row was 31 and 45% in 2005 and 87 and 99% in 2006, respectively to weed density. Massinga et al. (2001) also observed irrigated corn yield losses from Palmer amaranth emerging with corn to be between 24 to 47% with one Palmer amaranth plant m^{-1} of row and 50 to 86% with four Palmer amaranth plants m^{-1} of row across four site-years in southwestern Kansas. Liphadzi and Dille (2006) reported much lower irrigated corn yield losses of 16 and 34% for corn with one and four Palmer amaranth plants m^{-1} of row, respectively, from one site-year in northeastern Kansas. The dryland corn yield losses reported by Liphadzi and Dille (2006) were 21 and 51% with one and four Palmer amaranth plants m^{-1} of row, respectively at two site-years. Blinka (2004) had 52% dryland corn yield loss from four Palmer amaranth plants m^{-1} of row. These previously reported dryland corn yield loss results were very similar to the 2005 corn yield reductions. There are occasions, however, when dryland corn does not produce any grain with or without weeds because of severe drought after tasselling (Blinka 2004, Liphadzi and Dille 2006). This demonstrates the challenge in predicting corn yield loss in water-stressed environments, and difficulties in making economical weed control decisions.

Palmer amaranth: emergence to final plant harvest

Palmer amaranth growth and development responses from emergence to mid-season (corn tassel stage) are presented in Figure 1.8 (height), Figure 1.9 (LAI), and Figure 1.10 (total plant weight) with final plant harvest results presented in Table 1.4 for 2005 and 2006. Overall, the growth and biomass accumulation of Palmer amaranth was greater in 2006 than 2005.

In 2005, dryland and irrigated Palmer amaranth heights at both densities with corn were taller (137 to 149) than monoculture Palmer amaranth (122 cm) from 445 GDD through 620 GDD in both environments (Figure 1.8). In 2006 by 643 GDD, irrigated Palmer amaranth was taller than dryland Palmer amaranth. Palmer amaranth in 2006 had earlier gains in height that could be attributed to warmer temperatures and the soil was not excessively wet, unlike early June 2005. Three weeks after emergence (~ 300 GDD), Palmer amaranth was more than two times taller in 2006 than in 2005 for respective treatments. In both years, corn interference with Palmer amaranth had little impact on weed height but four Palmer amaranth plants m^{-1} of row with corn was taller than monoculture Palmer amaranth beginning 300 GDD but not always different. Palmer amaranth height doubled every 60 GDD from emergence to 445 or 402 GDD in 2005 and 2006, respectively.

At final plant harvest Palmer amaranth height ranged from 256 to 305 cm in 2005 and from 264 to 243 in 2006 (Table 1.4). In 2005, Palmer amaranth height was not impacted by mid-to-late season low soil moisture, however in 2006, heights of dryland monoculture Palmer amaranth and dryland Palmer amaranth with corn were reduced 15 to 20% at tassel and maturity when compared to irrigated Palmer amaranth grown alone. This indicated that water stress negatively impacted Palmer amaranth with and without corn interference. Height measurements included any terminal inflorescence, and thus Palmer amaranth heights were taller than those previously reported for monoculture Palmer amaranth height by Horak and Loughin (2000) and Sellers et al. (2003).

Palmer amaranth at four plants m^{-1} of row with corn had the highest LAI in dryland and irrigated environments for both years from emergence through 300 GDD (Figure 1.9). After 300 GDD, Palmer amaranth growth increased exponentially resulting in rapidly increasing LAI across all treatments. By 620 GDD in 2005, LAI for monoculture Palmer amaranth was 1.48 and 2.29 m^2 m^{-2} for dryland and irrigated environments, respectively (Figure 1.9A). This was more than 6.5 and 2 times greater than LAI for one and four Palmer amaranth plants m^{-1} of row with corn, respectively. In 2006 by 643 GDD, one Palmer amaranth plant m^{-1} of row with corn had less LAI than one Palmer amaranth plant m^{-1} of row in monoculture or at four Palmer amaranth plants m^{-1} of row with corn. Palmer amaranth at one and four plants m^{-1} of row with corn in the dryland environment had the greatest increase in LAI from 500 to 643 GDD because the corn was water-stressed and, as a result, corn interfered less with Palmer amaranth growth. Our LAI values were similar to those reported by Massinga (2000) for the same Palmer amaranth densities with irrigated corn. Also, Palmer amaranth LAI increased with the addition of Palmer amaranth plants with corn, which agrees with Massinga et al. (2003).

Palmer amaranth dry weight per plant was reduced due to corn interference beginning at 378 and 302 GDD in 2005 and 2006, respectively (Figure 1.10). In 2005, dryland and irrigated monoculture Palmer amaranth dry weights were 171 and 199 g $plant^{-1}$ at 620 GDD and were 1,121 and 1,176 g $plant^{-1}$ by 1,676 GDD, respectively (Figure 1.10A and Table 1.4). Corn interference correspondingly caused over 55 and 65% reduction in Palmer amaranth dry weight at 620 and 1,676 GDD, respectively with no difference between dryland and irrigated environments. Palmer amaranth dry weight was greater in 2006 than 2005, which corresponds to taller plants with more leaf area (Figure 1.8 and 1.9). In 2006, Palmer amaranth had rapid early season growth which was over five times greater than 2005. In 2006 at 500 GDD, dryland Palmer amaranth dry weight was significantly reduced due to corn interference with increasing Palmer amaranth density compared to the irrigated Palmer amaranth treatments. At 643 GDD, however, dryland and irrigated monoculture Palmer amaranth dry weights were not different at 376 and 428 g plant^{-1}, respectively. Dryland Palmer amaranth at four plant m^{-1} of row with corn and irrigated Palmer amaranth at one and four plants m^{-1} of row with corn had the lowest plant dry weights at 105, 115, and 88 g plant^{-1}, respectively. The dry weight of irrigated Palmer amaranth with corn decreased from 500 to 643 GDD. This indicated that irrigated corn reduced Palmer amaranth biomass accumulation, while the weed was repartitioning growth for reproductive development and light interception. This means Palmer amaranth was senescing lower leaves (-0.32 g leaf dry weight plant^{-1}) in the canopy in an effort to develop stem (+0.21 g stem dry weight plant^{-1}), leaves, and inflorescence higher in the canopy, but corn competition limited this development due to its rapid growth during this period. During the same period, however dry weight of dryland Palmer amaranth at one plant m^{-1} of row with corn increased at 0.93 g plant $^{-1}$ GDD^{-1}, which was similar to dryland and irrigated monoculture Palmer amaranth at 1.12 and 1.18 g plant $^{-1}$ GDD^{-1}, respectively. The increase in dryland Palmer amaranth growth at one plant m^{-1} of row with corn at this time indicated that interference by water-stressed and corn was less than irrigated corn at the same weed density. Dry weight of dryland corn with one Palmer amaranth m^{-1} of row was 50% less than irrigated corn at the same weed density, which confirms the opportunity for Palmer amaranth growth. In 2006 at final harvest (1,556 GDD), irrigated monoculture Palmer amaranth plant dry weight (1,739 g plant^{-1}) was greater than all other Palmer amaranth water environment and density treatments with similar reductions in plant dry weight at 643 GDD (Figure 1.10). Dryland monoculture Palmer amaranth, dryland Palmer amaranth at one and four plants m^{-1} of row plant with corn, and irrigated Palmer amaranth at one and four plants m^{-1} of row plant with corn plant dry weight was reduced 26, 46, 79, 69, and 73 %, respectively when compared to irrigated monoculture Palmer amaranth. The 2006 Palmer amaranth dry weight was reduced with increasing water stress, corn interference, and Palmer amaranth density. In 2005 and 2006, Palmer amaranth plant dry weights were similar to those previously reported (Horak and Loughin 2000, Sellers et al. 2003). The 2006 monoculture Palmer amaranth plant dry weights from emergence to 400 GDD were similar to Horak and Loughin (2000) results with more rainfall, but the 2006 late season plant dry weight accumulations were greater than previously reported values.

Palmer amaranth seed production

Seed production by Palmer amaranth in both years was not different due to high variability among treatments, but positive trends with means were observed (Table 1.4). Seed production $plant^{-1}$ decreased with increasing Palmer amaranth density and the number of seeds m^{-2} increased with increasing weed density with corn, which agrees with previous studies (Bensch et al. 2003, Massinga et al. 2001). Liphadzi and Dille (2006) found no effect of Palmer amaranth density on seed production $plant^{-1}$ in adverse environmental conditions. In 2005, dryland and irrigated monoculture Palmer amaranth produced near 300,000 seeds m^{-2}. When Palmer amaranth was grown with corn, irrigated Palmer amaranth produced more seed m^{-2} than dryland Palmer amaranth. In 2006 less seeds m^{-2} were produced by dryland and irrigated monoculture Palmer amaranth with 147,000 and 111, 000 seeds m^{-2}. All of 2006 dryland Palmer amaranth with corn had higher seed production due to less corn interference and the ability to grow and develop opportunistically in water-stressed conditions. Fewer seeds produced in 2006 than 2005 could be attributed to high rainfall and high winds severely lodged Palmer amaranth plants in mid-August, which caused plants to abort or shatter seeds. Overall, seed production results may have been underestimated due to seed loss from shattering at harvest and seed separating procedures.

CONCLUSIONS

The results of this study showed that corn and Palmer amaranth growth, development, and grain (seed) production potential were dependent on which species had the competitive ability to capture a limiting resource (water and light). In this side-by-side comparison with different soil water environments, water stress negatively impacted corn more than Palmer amaranth and the magnitude of corn reductions depended on corn's ability to suppress Palmer amaranth. Lindquist et al. (1998) showed that high values of maximum corn LAI, rate of corn canopy closure, or corn height at which leaf area occurs vertically in the canopy can improve corn tolerance and suppressive ability of velvetleaf (*Abutilon theophrasti*). Our results showed that when Palmer amaranth had rapid early season growth, it was able to interfere more with corn and cause greater reductions in corn dry weight and LAI. Water-stressed dryland corn did not have the ability to suppress Palmer amaranth and subsequently Palmer amaranth significantly reduced corn growth and yield. The extent of dryland corn yield loss depended on the period of water stress and weed density, whereas irrigated corn yield losses were caused by Palmer amaranth interference. Massinga et al. (2003) showed that in an irrigated environment Palmer amaranth had a higher leaf area concentration in the upper canopy and able to intercept more solar radiation than corn.

Results of this research improve the understanding of interactions between corn and Palmer amaranth when soil water is both optimum and limited throughout the growing season. The information gained from this experiment has provided an improved understanding of corn yield loss risks associated with water management and Palmer amaranth competition. The research provided results to re-emphasize that corn management can be used as a tool to suppress weed competitiveness and ultimately minimize potential yield loss. Further research is needed to evaluate corn and Palmer amaranth interactions under limited irrigation systems to improve irrigation application profitability and environmental stewardship of water use. This future knowledge will improve crop-weed competition models and ultimately, optimize corn water use and weed management decisions in diverse environments.

SOURCES OF MATERIALS

[1] LI-3100 Leaf Area Meter. LI-COR Inc., 4421 Superior Street, Lincoln, NE 68504.

[2] Model 757 South Dakota Seed Blower. Seedburo Equipment Co. 1022 W. Jackson BLVD., Chicago, Ill 60607.

[3] TDR100 Time Domain Reflectometer (with PC-TDR software). Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[4] Sierra-Misco Model 2501. Nova Lynx Corporation, 431 Crown Point Circle, Suite G, Grass Valley, CA 95945.

[5] CR23X-4M Micrologger. Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[6] Statistical Analysis Systems, Version 9.1. 2003. Statistical Analysis Systems Institute Inc. 100 SAS Campus Drive, Cary, NC 27513-2414.

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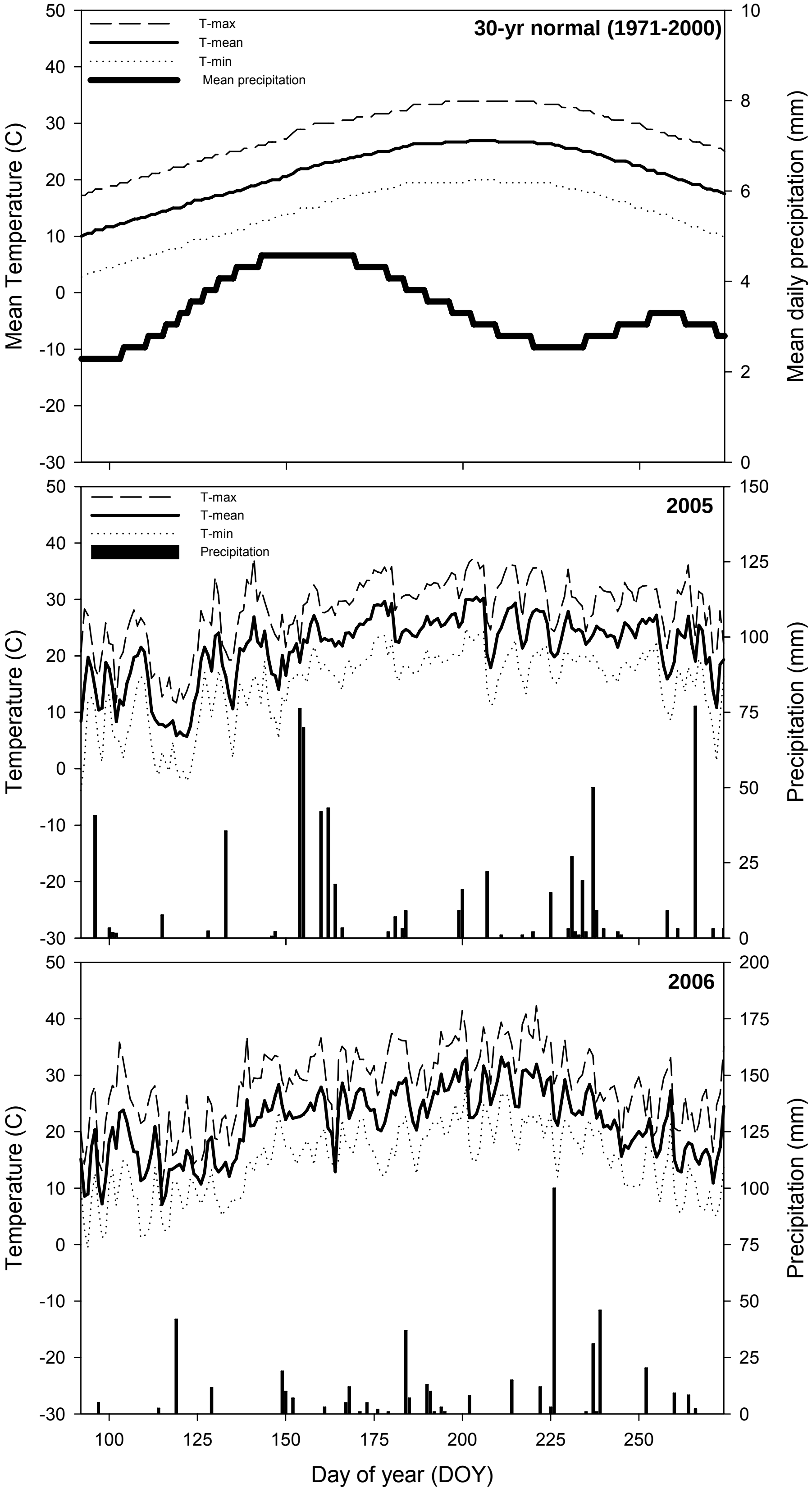
FIGURES AND TABLES

Figure 1.1 Air temperature and precipitation summary for 30-year normal, 2005, and 2006 at Manhattan, KS.

1971-2000 [normal daily maximum, mean, and minimum air temperature; mean daily precipitation]; 2005 and 2006 [daily maximum, mean, and minimum air temperature; daily precipitation].



T-max
T-mean
T-min
Mean precipitation
30-yr normal (1971-2000)
Mean Temperature (C)
Mean daily precipitation (mm)
50
40
30
20
10
0
-10
-20
-30
10
8
6
4
2
0
T-max
T-mean
T-min
Precipitation
2005
Temperature (C)
Precipitation (mm)
150
125
100
75
50
25
0
2006
Temperature (C)
Precipitation (mm)
200
175
150
125
100
75
50
25
0
100
125
150
175
200
225
250
Day of year (DOY)

Figure 1.2 Corn and Palmer amaranth emergence to final harvest cumulative thermal time (GDD) (A) and cumulative reference evapotranspiration (ET_O) (B) for 2005 and 2006 at Manhattan, KS.

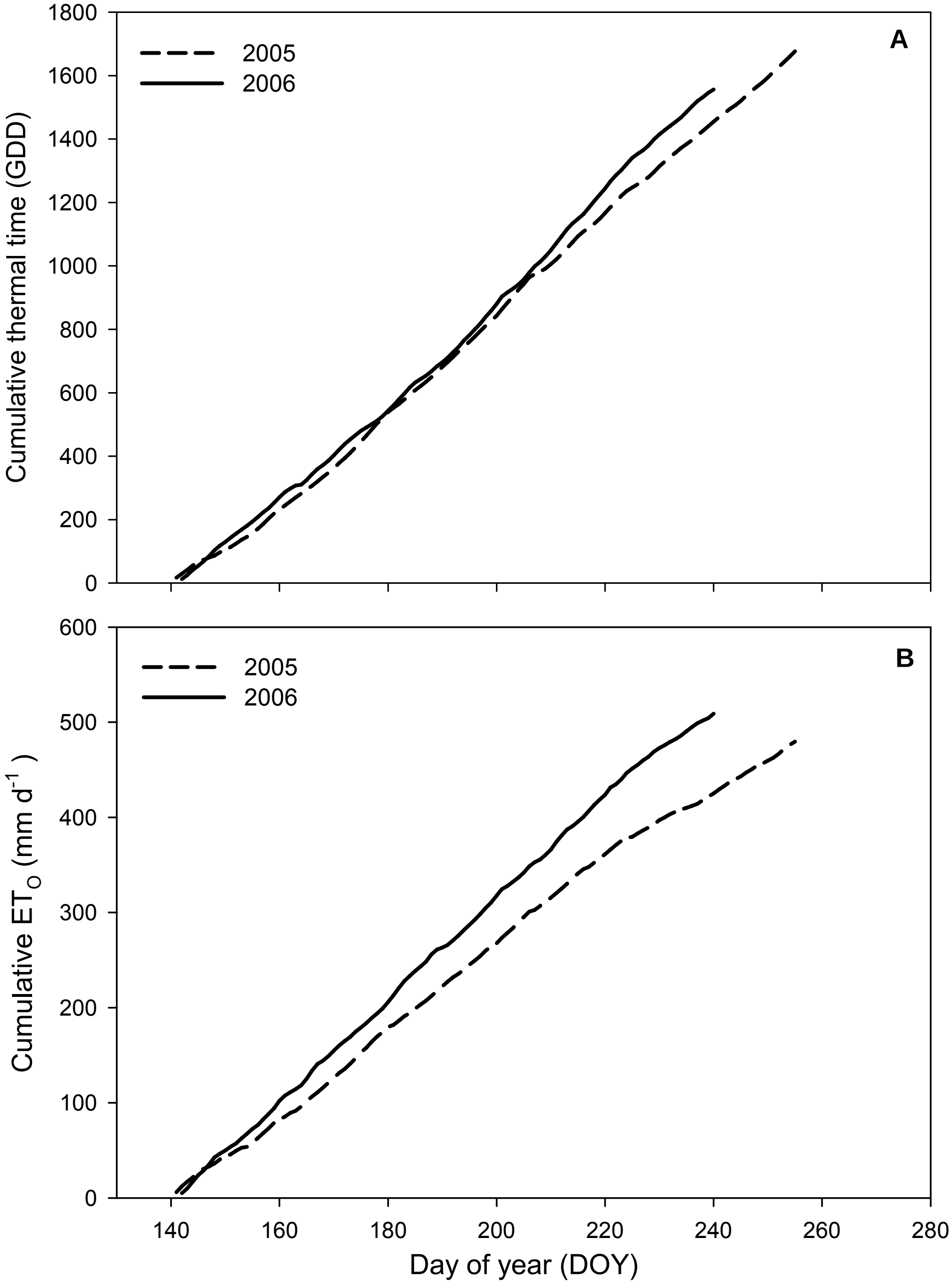
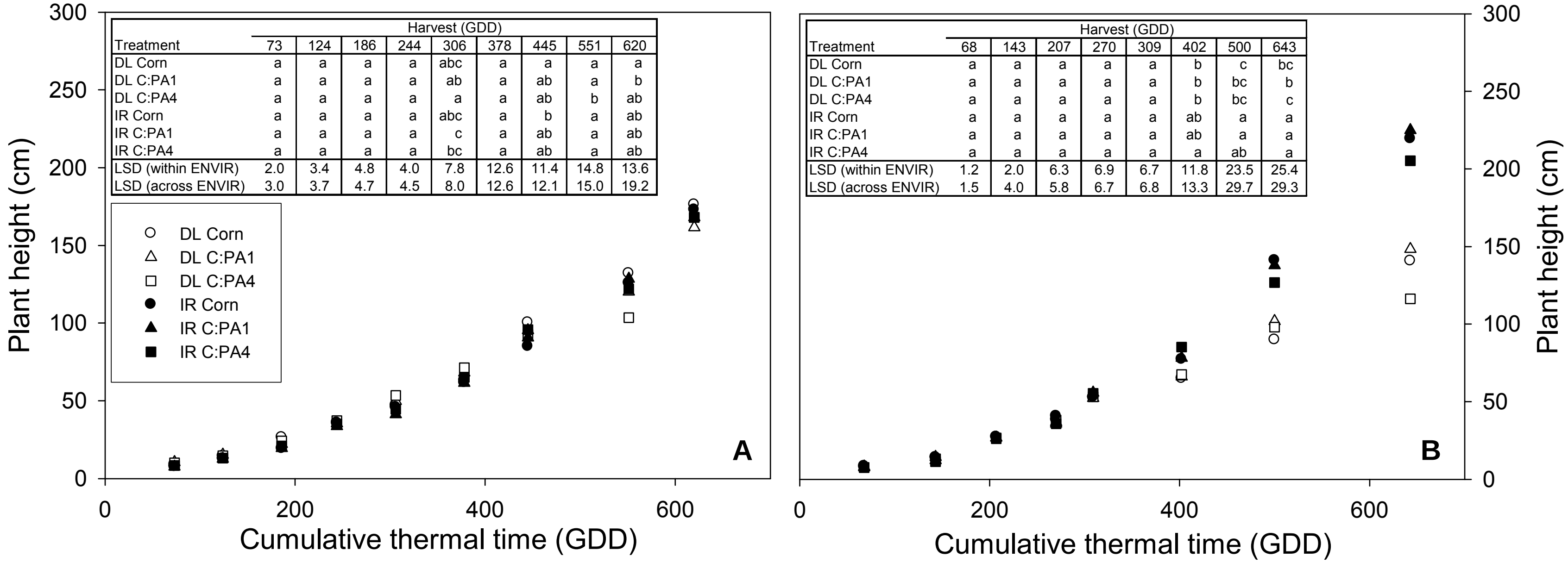


Figure 1.3 Corn plant height in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (Corn) and with one (C:PA1) or four (C:PA4) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B). Letter within columns by harvest date compare means using LSD (across ENVIR).



	Harvest (GDD)								
Treatment	73	124	186	244	306	378	445	551	620
DL Corn	a	a	a	a	abc	a	a	a	a
DL C:PA1	a	a	a	a	ab	a	ab	a	b
DL C:PA4	a	a	a	a	a	a	ab	b	ab
IR Corn	a	a	a	a	abc	a	b	a	ab
IR C:PA1	a	a	a	a	c	a	ab	a	ab
IR C:PA4	a	a	a	a	bc	a	ab	a	ab
LSD (within ENVIR)	2.0	3.4	4.8	4.0	7.8	12.6	11.4	14.8	13.6
LSD (across ENVIR)	3.0	3.7	4.7	4.5	8.0	12.6	12.1	15.0	19.2

	Harvest (GDD)							
Treatment	68	143	207	270	309	402	500	643
DL Corn	a	a	a	a	a	b	c	bc
DL C:PA1	a	a	a	a	a	b	bc	b
DL C:PA4	a	a	a	a	a	b	bc	c
IR Corn	a	a	a	a	a	ab	a	a
IR C:PA1	a	a	a	a	a	ab	a	a
IR C:PA4	a	a	a	a	a	a	ab	a
LSD (within ENVIR)	1.2	2.0	6.3	6.9	6.7	11.8	23.5	25.4
LSD (across ENVIR)	1.5	4.0	5.8	6.7	6.8	13.3	29.7	29.3

Figure 1.4 Corn plant height at tasseling in response to Palmer amaranth densities for 2006.

Dryland (DL-open symbols) and irrigated (IR-closed symbols) environments,

Regression lines were fitted using Equation 1: DL Corn, Hgt = 147 - 7.16d, R2 = 0.165, P = 0.0281; IR Corn, Hgt = 223 - 4.26, R2 = 0.244, P = 0.0083.

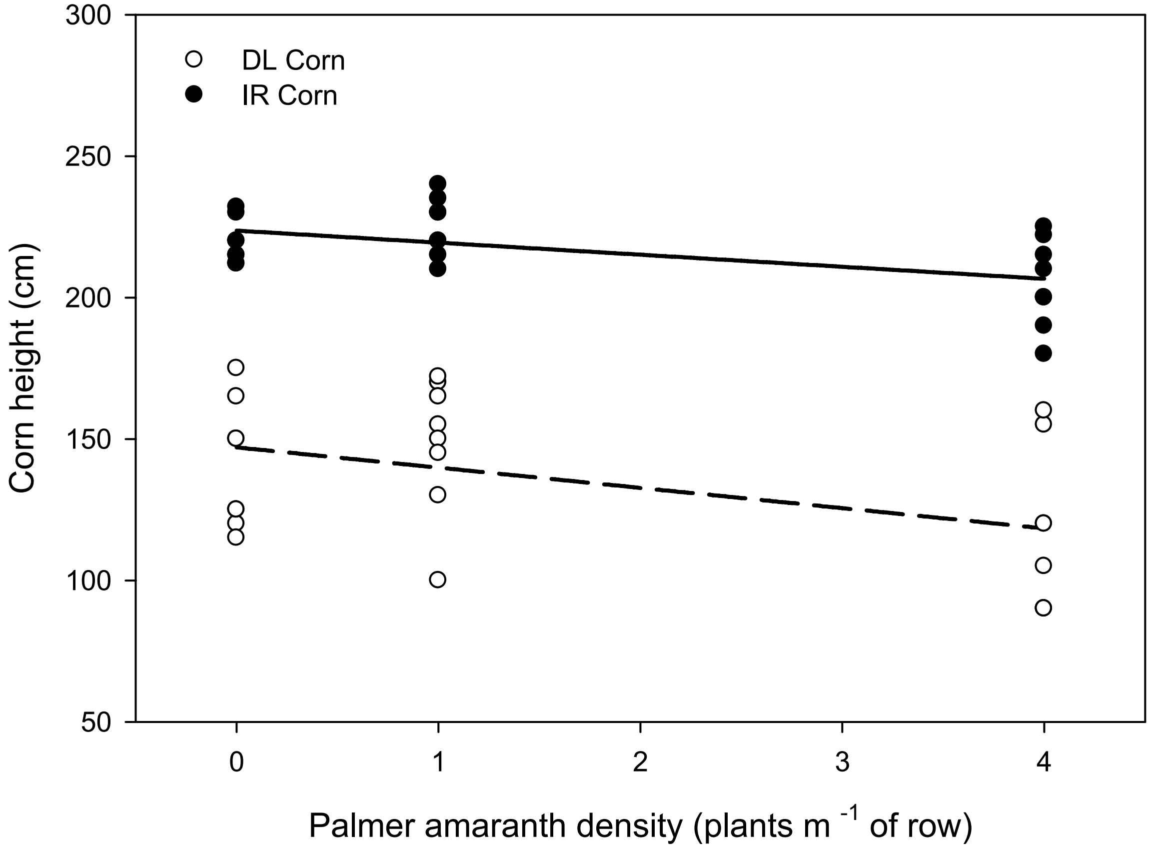
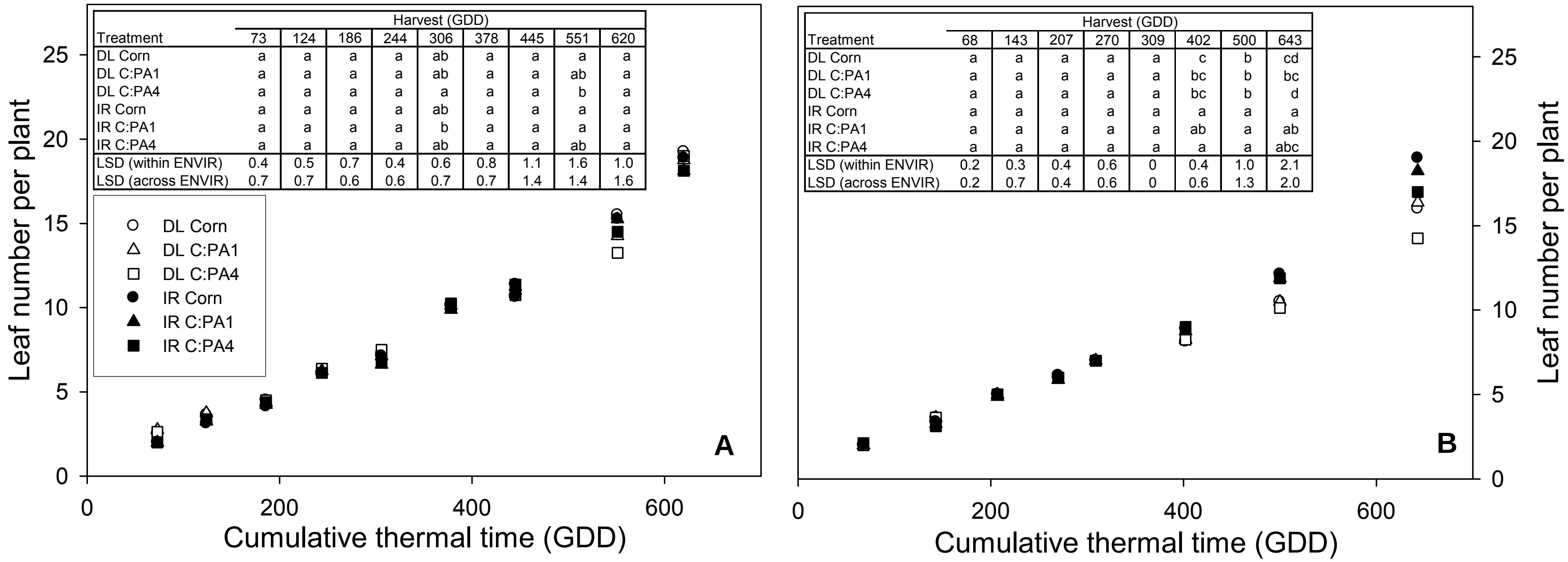


Figure 1.5 Corn leaf number per plant in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone and with one or four Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B). Letter within columns by harvest date compare means using LSD (across ENVIR).



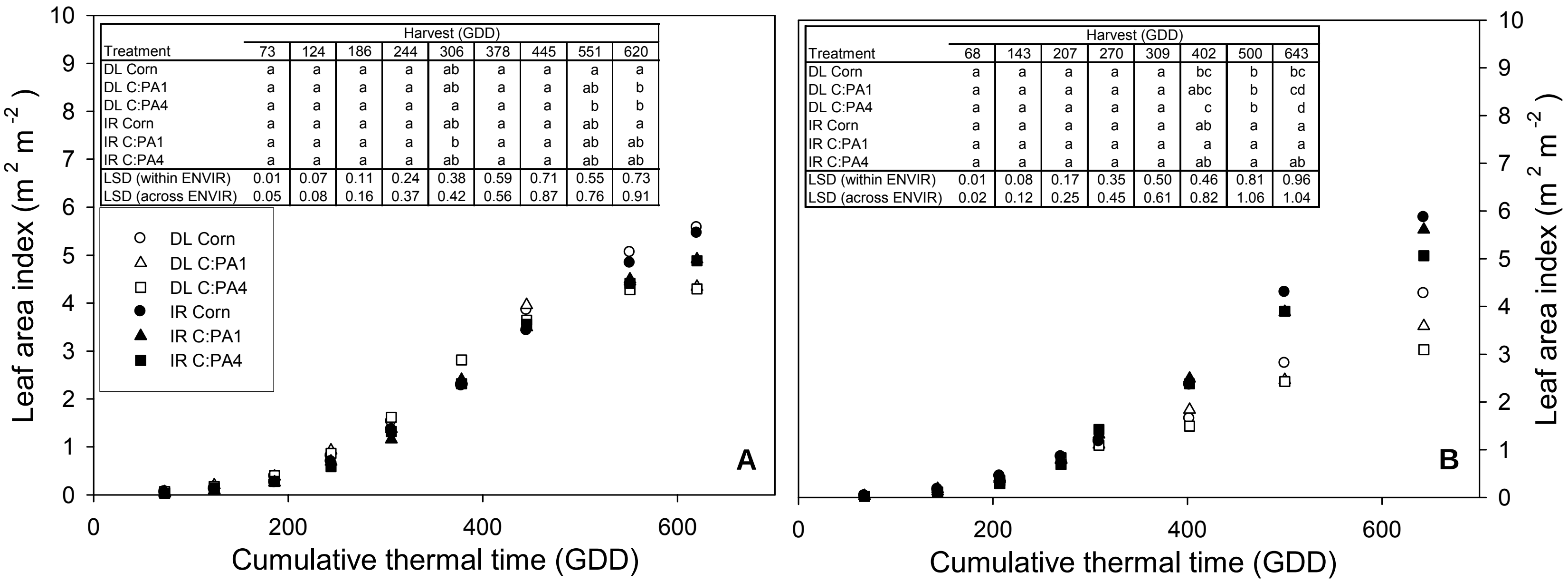
A

	Harvest (GDD)								
Treatment	73	124	186	244	306	378	445	551	620
DL Corn	a	a	a	a	ab	a	a	a	a
DL C:PA1	a	a	a	a	ab	a	a	ab	a
DL C:PA4	a	a	a	a	a	a	a	b	a
IR Corn	a	a	a	a	ab	a	a	a	a
IR C:PA1	a	a	a	a	b	a	a	a	a
IR C:PA4	a	a	a	a	ab	a	a	ab	a
LSD (within ENVIR)	0.4	0.5	0.7	0.4	0.6	0.8	1.1	1.6	1.0
LSD (across ENVIR)	0.7	0.7	0.6	0.6	0.7	0.7	1.4	1.4	1.6

B

	Harvest (GDD)							
Treatment	68	143	207	270	309	402	500	643
DL Corn	a	a	a	a	a	c	b	cd
DL C:PA1	a	a	a	a	a	bc	b	bc
DL C:PA4	a	a	a	a	a	bc	b	d
IR Corn	a	a	a	a	a	a	a	a
IR C:PA1	a	a	a	a	a	ab	a	ab
IR C:PA4	a	a	a	a	a	a	a	abc
LSD (within ENVIR)	0.2	0.3	0.4	0.6	0	0.4	1.0	2.1
LSD (across ENVIR)	0.2	0.7	0.4	0.6	0	0.6	1.3	2.0

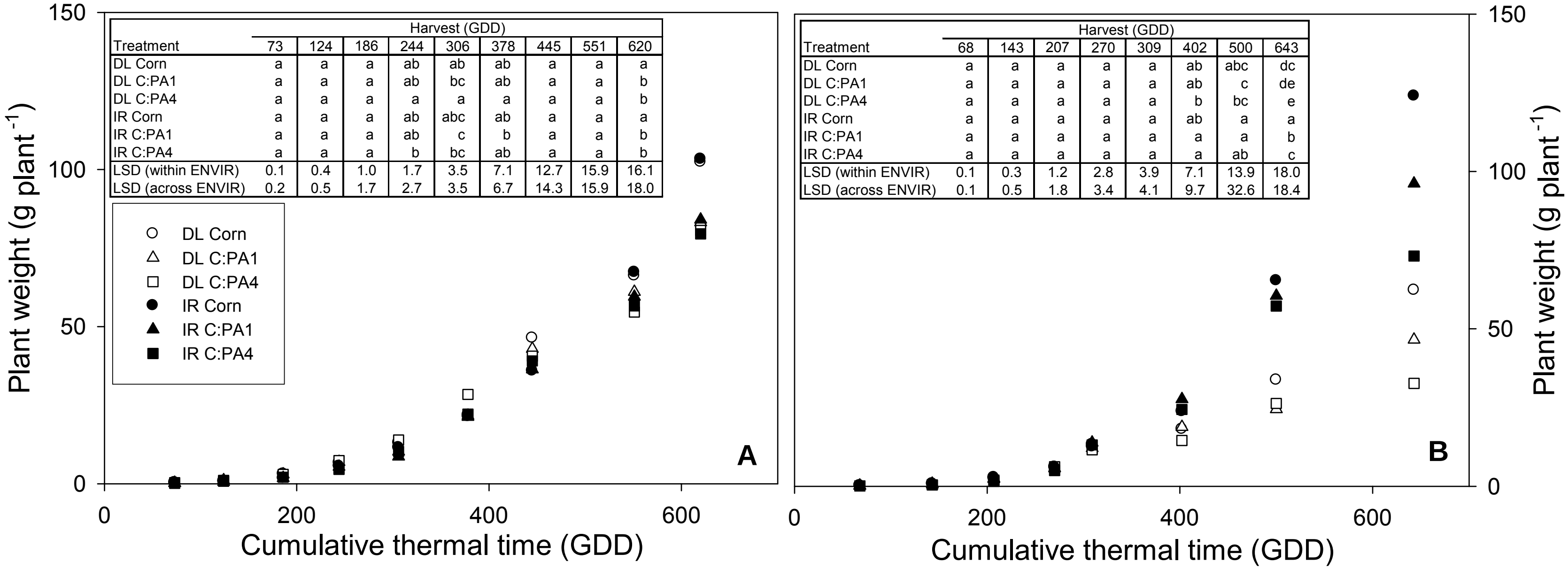
Figure 1.6 Corn plant leaf area index in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (Corn) and with one (C:PA1) or four (C:PA4) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B). Letter within columns by harvest date compare means using LSD (across ENVIR).



	Harvest (GDD)								
Treatment	73	124	186	244	306	378	445	551	620
DL Corn	a	a	a	a	ab	a	a	a	a
DL C:PA1	a	a	a	a	ab	a	a	ab	b
DL C:PA4	a	a	a	a	a	a	a	b	b
IR Corn	a	a	a	a	ab	a	a	ab	a
IR C:PA1	a	a	a	a	b	a	a	ab	ab
IR C:PA4	a	a	a	a	ab	a	a	ab	ab
LSD (within ENVIR)	0.01	0.07	0.11	0.24	0.38	0.59	0.71	0.55	0.73
LSD (across ENVIR)	0.05	0.08	0.16	0.37	0.42	0.56	0.87	0.76	0.91

	Harvest (GDD)							
Treatment	68	143	207	270	309	402	500	643
DL Corn	a	a	a	a	a	bc	b	bc
DL C:PA1	a	a	a	a	a	abc	b	cd
DL C:PA4	a	a	a	a	a	c	b	d
IR Corn	a	a	a	a	a	ab	a	a
IR C:PA1	a	a	a	a	a	a	a	a
IR C:PA4	a	a	a	a	a	ab	a	ab
LSD (within ENVIR)	0.01	0.08	0.17	0.35	0.50	0.46	0.81	0.96
LSD (across ENVIR)	0.02	0.12	0.25	0.45	0.61	0.82	1.06	1.04

Figure 1.7 Corn total dry weight (g plant^{-1}) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (Corn) and with one (C:PA1) or four (C:PA4) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B). Letter within columns by harvest date compare means using LSD (across ENVIR).

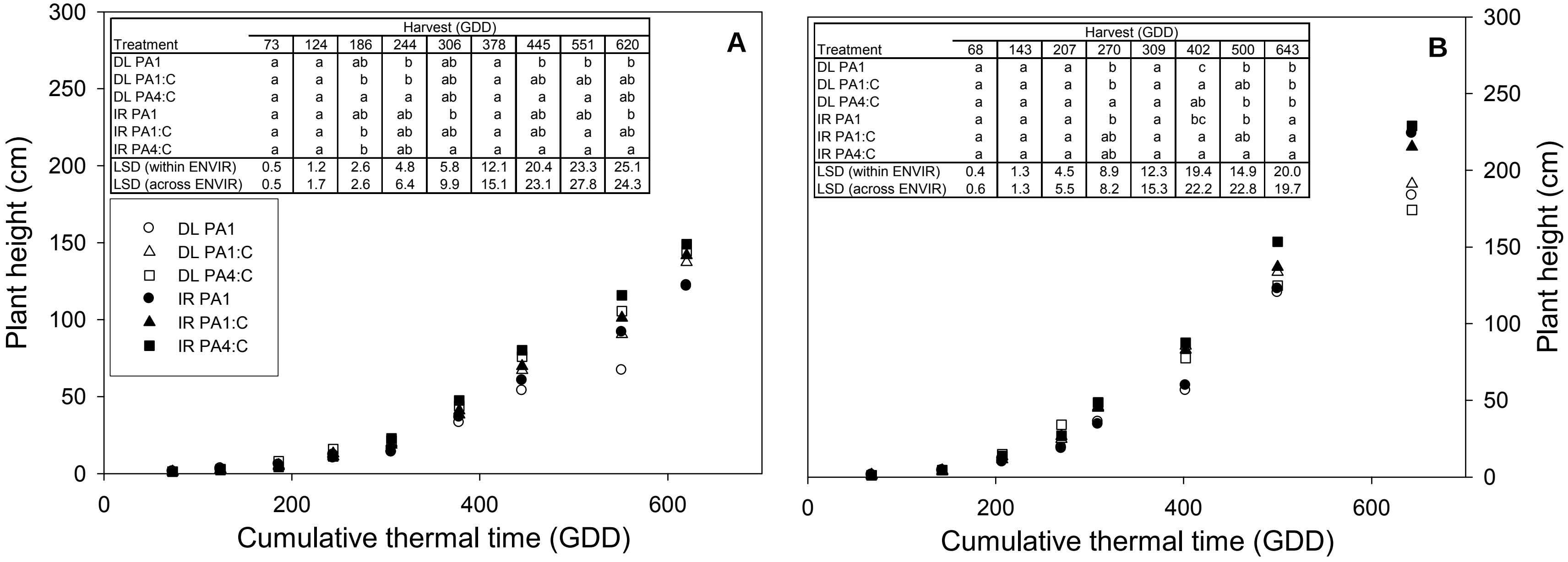


	Harvest (GDD)								
Treatment	73	124	186	244	306	378	445	551	620
DL Corn	a	a	a	ab	ab	ab	a	a	a
DL C:PA1	a	a	a	ab	bc	ab	a	a	b
DL C:PA4	a	a	a	a	a	a	a	a	b
IR Corn	a	a	a	ab	abc	ab	a	a	a
IR C:PA1	a	a	a	ab	c	b	a	a	b
IR C:PA4	a	a	a	b	bc	ab	a	a	b
LSD (within ENVIR)	0.1	0.4	1.0	1.7	3.5	7.1	12.7	15.9	16.1
LSD (across ENVIR)	0.2	0.5	1.7	2.7	3.5	6.7	14.3	15.9	18.0

	Harvest (GDD)							
Treatment	68	143	207	270	309	402	500	643
DL Corn	a	a	a	a	a	ab	abc	dc
DL C:PA1	a	a	a	a	a	ab	c	de
DL C:PA4	a	a	a	a	a	b	bc	e
IR Corn	a	a	a	a	a	ab	a	a
IR C:PA1	a	a	a	a	a	a	a	b
IR C:PA4	a	a	a	a	a	a	ab	c
LSD (within ENVIR)	0.1	0.3	1.2	2.8	3.9	7.1	13.9	18.0
LSD (across ENVIR)	0.1	0.5	1.8	3.4	4.1	9.7	32.6	18.4

Figure 1.8 Palmer amaranth plant height in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (PA1) at one Palmer amaranth plant m^{-1} of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).



A

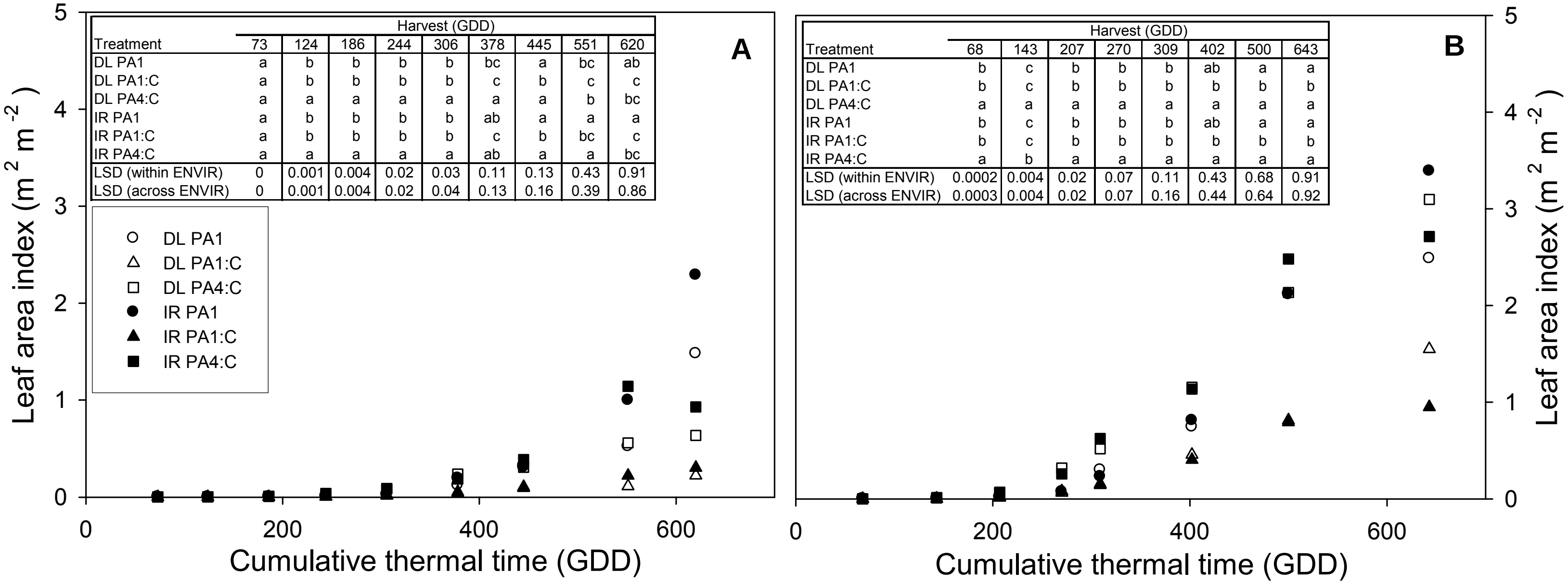
Treatment	Harvest (GDD) 73	124	186	244	306	378	445	551	620
DL PA1	a	a	ab	b	ab	a	b	b	b
DL PA1:C	a	a	b	b	ab	a	ab	ab	ab
DL PA4:C	a	a	a	a	ab	a	a	a	ab
IR PA1	a	a	ab	ab	b	a	ab	ab	b
IR PA1:C	a	a	b	ab	ab	a	ab	a	ab
IR PA4:C	a	a	b	ab	a	a	a	a	a
LSD (within ENVIR)	0.5	1.2	2.6	4.8	5.8	12.1	20.4	23.3	25.1
LSD (across ENVIR)	0.5	1.7	2.6	6.4	9.9	15.1	23.1	27.8	24.3

B

Treatment	Harvest (GDD) 68	143	207	270	309	402	500	643
DL PA1	a	a	a	b	a	c	b	b
DL PA1:C	a	a	a	b	a	a	ab	b
DL PA4:C	a	a	a	a	a	ab	b	b
IR PA1	a	a	a	b	a	bc	b	a
IR PA1:C	a	a	a	ab	a	a	ab	a
IR PA4:C	a	a	a	ab	a	a	a	a
LSD (within ENVIR)	0.4	1.3	4.5	8.9	12.3	19.4	14.9	20.0
LSD (across ENVIR)	0.6	1.3	5.5	8.2	15.3	22.2	22.8	19.7

Figure 1.9 Palmer amaranth leaf area index in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone at one Palmer amaranth plant m^{-1} of row and with corn at one or four Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).

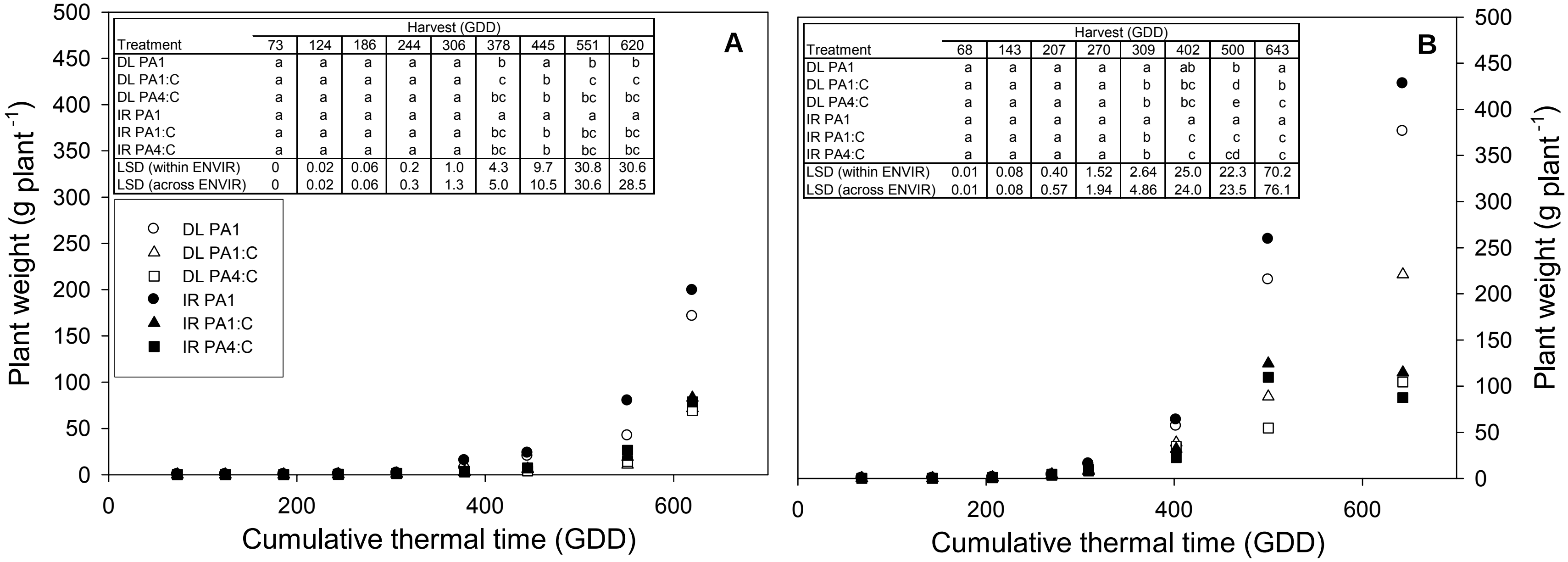


	Harvest (GDD)								
Treatment	73	124	186	244	306	378	445	551	620
DL PA1	a	b	b	b	b	bc	a	bc	ab
DL PA1:C	a	b	b	b	b	c	b	c	c
DL PA4:C	a	a	a	a	a	a	a	b	bc
IR PA1	a	b	b	b	b	ab	a	a	a
IR PA1:C	a	b	b	b	b	c	b	bc	c
IR PA4:C	a	a	a	a	a	ab	a	a	bc
LSD (within ENVIR)	0	0.001	0.004	0.02	0.03	0.11	0.13	0.43	0.91
LSD (across ENVIR)	0	0.001	0.004	0.02	0.04	0.13	0.16	0.39	0.86

	Harvest (GDD)							
Treatment	68	143	207	270	309	402	500	643
DL PA1	b	c	b	b	b	ab	a	a
DL PA1:C	b	c	b	b	b	b	b	b
DL PA4:C	a	a	a	a	a	a	a	a
IR PA1	b	c	b	b	b	ab	a	a
IR PA1:C	b	c	b	b	b	b	b	b
IR PA4:C	a	b	a	a	a	a	a	a
LSD (within ENVIR)	0.0002	0.004	0.02	0.07	0.11	0.43	0.68	0.91
LSD (across ENVIR)	0.0003	0.004	0.02	0.07	0.16	0.44	0.64	0.92

Figure 1.10 Palmer amaranth total dry weight (g plant^{-1}) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (PA1) at one Palmer amaranth plant m^{-1} of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).



A

	Harvest (GDD)								
Treatment	73	124	186	244	306	378	445	551	620
DL PA1	a	a	a	a	a	b	a	b	b
DL PA1:C	a	a	a	a	a	c	b	c	c
DL PA4:C	a	a	a	a	a	bc	b	bc	bc
IR PA1	a	a	a	a	a	a	a	a	a
IR PA1:C	a	a	a	a	a	bc	b	bc	bc
IR PA4:C	a	a	a	a	a	bc	b	bc	bc
LSD (within ENVIR)	0	0.02	0.06	0.2	1.0	4.3	9.7	30.8	30.6
LSD (across ENVIR)	0	0.02	0.06	0.3	1.3	5.0	10.5	30.6	28.5

B

	Harvest (GDD)							
Treatment	68	143	207	270	309	402	500	643
DL PA1	a	a	a	a	a	ab	b	a
DL PA1:C	a	a	a	a	b	bc	d	b
DL PA4:C	a	a	a	a	b	bc	e	c
IR PA1	a	a	a	a	a	a	a	a
IR PA1:C	a	a	a	a	b	c	c	c
IR PA4:C	a	a	a	a	b	c	cd	c
LSD (within ENVIR)	0.01	0.08	0.40	1.52	2.64	25.0	22.3	70.2
LSD (across ENVIR)	0.01	0.08	0.57	1.94	4.86	24.0	23.5	76.1

Table 1.1 Corn and Palmer amaranth planting, emergence, and harvest dates for 2005 and 2006.

Year	Event	Calender Date	DOY [1]	DAE [2]	Thermal time (GDD [3])
2005	Planting Date	May 5	126	0	—
	Emergence Date [4]	May 21	141	0	—
	Harvest 1	May 26	146	5	73
	Harvest 2	June 1	152	11	124
	Harvest 3	June 6	157	16	186
	Harvest 4	June 10	161	20	244
	Harvest 5	June 15	166	25	306
	Harvest 6	June 20	171	30	378
	Harvest 7	June 24	175	34	445
	Harvest 8	June 30	181	40	551
	Harvest 9	July 5	186	45	620
	Final Harvest	Sept. 12	255	113	1,676
2006	Planting Date	May 11	131	0	—
	Emergence Date [4]	May 22	142	0	—
	Harvest 1	May 26	146	4	68
	Harvest 2	May 31	151	9	143
	Harvest 3	June 5	156	14	207
	Harvest 4	June 9	160	19	270
	Harvest 5	June 13	164	22	309
	Harvest 6	June 19	170	28	402
	Harvest 7	June 26	177	35	500
	Harvest 8	July 5	186	44	643
	Final Harvest	Aug. 28	240	98	1,556

[1] DOY = Day of Year

[2] DAE = Days after emergence

[3] GDD = Growing degree days (Cumulative from emergence)

[4] Emergence Date = Corn and Palmer amaranth emerged on the same date

Table 1.2 Monthly mean air temperatures and total precipitation for 2005, 2006, and 30-year normal (1971-2000) at Manhattan, KS.

	Temperature (°C)			Precipitation (mm)		
Month	2005	2006	Normal	2005	2006	Normal
April	12.9	15.0	12.8	55	66	78
May	17.8	18.6	18.3	40	41	129
June	24.6	23.9	23.7	261	36	133
July	25.6	27.2	26.6	60	80	104
August	24.8	26.0	25.6	134	209	83
September	22.1	17.5	20.4	95	40	93
May to August[1]	23.2	23.9	23.6	496	366	449

[1] May to August = mean temperature and total precipitation from May to August

Table 1.3 Average final harvest total plant dry weights and grain yield of corn for 2005 and 2006 at Manhattan, KS.

Year	Soil water environment	Palmer amaranth density	Total plant dry weight		Grain yield	
		no. m^{-1} row	g plant^{-1}		kg ha^{-1}	
2005	Dryland	0	254	b[3]	7,005	c
	Dryland	1	167	c	4,849	d
	Dryland	4	120	d	3,886	d
	Irrigated	0	398	a	15,435	a
	Irrigated	1	253	b	9,976	b
	Irrigated	4	229	b	8,820	bc
	LSD (within ENVIR)[1]		44		1,569	
	LSD (across ENVIR)[2]		43		1,913	
2006	Dryland	0	183	c	7,665	b
	Dryland	1	70	d	1,013	c
	Dryland	4	38	d	98	c
	Irrigated	0	379	a	16,108	a
	Irrigated	1	246	b	9,829	b
	Irrigated	4	185	bc	7,699	b
	LSD (within ENVIR)[1]		62		2,383	
	LSD (across ENVIR)[2]		58		2,650	

[1] LSD (within ENVIR) = LSD (0.05) for comparing means within soil water environment

[2] LSD (across ENVIR) = LSD (0.05) for comparing means across soil water environment

[3] Means with the same letter within columns for each year are not different according to LSD (across ENVIR)

Table 1.4 Average Palmer amaranth final harvest height, total plant dry weight, and seed production for 2005 and 2006 at Manhattan, KS.

Year	environment	Corn density	Palmer amaranth density	Height		Total plant dry weight		Seed Production	
		——no. m^{-1} row——		cm		g $plant^{-1}$		seeds m^{-2}	
2005	Dryland	0	1	282	abc[3]	1,122	a	333,360	a
	Dryland	5.25	1	260	bc	206	b	61,600	a
	Dryland	5.25	4	256	c	162	b	197,450	a
	Irrigated	0	1	284	ab	1,176	a	296,100	a
	Irrigated	5.25	1	305	a	369	b	158,370	a
	Irrigated	5.25	4	284	ab	211	b	234,550	a
	LSD (within ENVIR)[1]			29		277		135,170	
	LSD (across ENVIR)[2]			27		247		137,500	
2006	Dryland	0	1	264	d	1,282	b	147,690	a
	Dryland	6	1	288	cd	936	b	95,090	a
	Dryland	6	4	289	bcd	364	c	157,230	a
	Irrigated	0	1	342	a	1,739	a	111,810	a
	Irrigated	6	1	338	ab	537	c	44,200	a
	Irrigated	6	4	335	abc	471	c	108,750	a
	LSD (within ENVIR)[1]			55		403		81,150	
	LSD (across ENVIR)[2]			50		382		76,640	

[1] LSD (within ENVIR) = LSD (0.05) for comparing means within soil water environment

[2] LSD (across ENVIR) = LSD (0.05) for comparing means across soil water environment

[3] Means with the same letter within columns for each year are not different according to LSD (across ENVIR)

CHAPTER 2 - Corn and Palmer Amaranth Soil Water Competition

ABSTRACT

Weeds that compete with crops for soil water can decrease the available soil water for the crop and increase the potential for water stress. Palmer amaranth is a competitive weed in corn fields in the Great Plains of the United States. An improved understanding of Palmer amaranth competitive interactions for soil water and the impact on soil water depletion in the root zone is necessary for predicting crop yield losses under different soil water conditions. Field experiments were conducted in 2005 and 2006 at the Department of Agronomy Ashland Bottoms Research Farm near Manhattan, KS. The objective was to determine soil water content throughout the growing season when corn and Palmer amaranth were grown alone or in competition under dryland and irrigated environments. The experiment was arranged in a side by side design with whole plots being dryland and furrow irrigation. Within each soil water environment, sub-plot treatments were monoculture Palmer amaranth at one plant m^{-1} of row, and corn with zero, one, and four Palmer amaranth plants m^{-1} of row. Soil water was measured within one treatment plot for one replication using Time Domain Reflectometry (TDR). The TDR measurements provided seasonal trends of volumetric soil water content for treatments in dryland and irrigated environments at the 0 to 15 and 0 to 30 cm soil profile depths each year.

The soil water depletion rate per day increased as water received prior to a drying period increased at the 0 to 30 cm depth for soil drying periods in the dryland and irrigated environments. The loss of soil water during drying periods for corn and Palmer amaranth populations in both environments and years varied due to plant and atmosphere water demand.

Key words: crop and weed competition, root distribution, Time Domain Reflectrometry volumetric water content

INTRODUCTION

Corn grown under the semi-arid conditions of the U.S. Great Plains region are impacted by highly variable precipitation, low soil water availability, and high evapotranspiration. The state of Kansas lies in this water-limited region where it ranks tenth in total corn grain production in the U.S. (NASS 2005). In the last 15 years, total corn production acreage in Kansas has increased 56% and the production of irrigated and dryland acres have increased 32% and 74%, respectively (NASS 2005). The average harvested acreage (grain yield) from 2001 to 2005 was 589,680 ha (5,132 kg ha^{-1}) for dryland and 583,200 ha (11,055 kg ha^{-1}) for irrigated production. Therefore in recent years, the state land area has been equally managed for dryland and irrigated corn production but the irrigated corn grain yields were two times higher than dryland yields. This clearly shows that supplemental water must be applied to attain higher potential yields. Corn grown under dryland conditions often encounters seasonal water stress, which results in unstable corn yields and yield loss due to water deficit. Also, the potential corn yield for dryland and irrigated conditions are impacted by choice of crop management practices. Any crop management practice that reduces the availability of soil water for corn plants can result in water stressed plants, which subsequently will limit and reduce corn yield potential. One crop management practice that could reduce soil water availability is to allow weed competition for soil water. If improper weed management occurs and weeds are growing with the corn, then available stored soil water is depleted, thus increasing the risk of potential corn yield loss. Improved understanding of corn yield loss from weeds in association with sensitivity to seasonal water stress in water-limited environments would aid crop managers in making profitable decisions for weed control. Variability in environmental conditions and implementation of crop management operations are the major factors influencing the dynamics of weed-crop interference relationships among sites and years (Lindquist et al. 1996). The impact of a weed population on a crop however, is difficult to predict particularly in dryland crop production systems (Lindquist et al. 1996).

Palmer amaranth (*Amaranthus palmeri* S. Wats.) is considered one of the most serious weed problems in the Great Plains of the United States due to its ability to reduce crop yields and interfere with harvest (Horak et al. 1994). Palmer amaranth has been reported to compete aggressively and cause significant yield loss in irrigated soybean (Bensch et al. 2003, Klingaman and Oliver 1994), cotton (Morgan et al. 2001, Rowland et al. 1999), and grain sorghum (Moore et al. 2004). Even across Kansas, irrigated and dryland corn yields were impacted significantly by competition with low densities of Palmer amaranth (Liphadzi and Dille 2006, Massinga et al. 2001). Corn yield loss from Palmer amaranth among site-years and water management practices were variable in Kansas, therefore an improved understanding is needed to determine the extent to which Palmer amaranth reduces soil water to the detriment of corn.

The degree of competition for water between a crop and a weed is determined by the relative root volume occupied by each species and subsequently, the competition for water will be greatest when the roots of the crop and the weed are in the same volume of soil (Aldrich 1984). Davis et al. (1965) described the root moisture extraction profile for Palmer amaranth and other several weeds. Palmer amaranth had a relatively narrow lateral root distribution and an extensive vertical root distribution compared to other weeds. Palmer amaranth extracted more water from the upper 30 cm layer of soil than lower in the soil profile, which suggests a higher density of roots near the soil surface, but it could be more competitive because it can also extract water from greater depths when soil moisture is limited. Palmer amaranth was observed to have rapid root expansion rates (Weise 1968), which would be a mechanism for soil water competition (Davis et al. 1967). Also, Palmer amaranth tolerated moisture stress similar to grain sorghum and better than corn when dry matter production was compared for wet, intermediate, and dry soil moisture conditions (Weise and Vandiver 1970). Furthermore, corn, grain sorghum, and Palmer amaranth are C_4 plants and considered to have greater water use efficiencies than C_3 plants (Black et al. 1969).

Limited research has been conducted on the effects of soil moisture on Palmer amaranth's competitiveness with crops across different soil water environments. Palmer amaranth's competitive ability and increasing presence in crop fields has alerted researchers to investigate the mechanisms of Palmer amaranth interference with crops. Massinga et al. (2003) demonstrated the total water use and water use efficiency of irrigated corn in competition with a range of Palmer amaranth densities. Volumetric soil water content (VWC) was determined in the top 240 cm of the soil profile in 30 cm increments next to corn alone and corn with Palmer amaranth. The water use varied due to the evapotranspiration experienced between locations and years studied, however the maximum water use period for corn occurred from tasseling through pollination. Water use increased most as Palmer amaranth density increased up to two plants m^{-1} of row. Then as density increased to eight plants m^{-1} of row water use rate was slower (Massinga et al. 2003). It was suggested that the canopy cover provided by the increase from two to eight Palmer amaranth plants m^{-1} of row contributed to maximum water loss caused by evapotranspiration, but resulted in little change in water use because mutual shading was occurring between plants. The higher Palmer amaranth densities in corn shaded the soil surface and decreased soil water evaporation. Water use efficiency in production of corn grain yield decreased as Palmer amaranth density increased. Measured VWC was lowest in the upper 30 cm depth of the soil profile, indicating crop and weed roots were competing for extractable water in this zone of interference. Massinga et al. (2003) indicated that future work was needed at different levels of soil water availability to better understand the dynamics of water competition by these two species.

Soil water measurement methods, such as Time Domain Reflectrometry (TDR) have been developed to determine soil water content on a continuous automated basis. Time Domain Reflectrometry measurements can provide real-time soil water content based on a specified measurement time interval defined by the user. The depth of measured soil water content depends on probe length, installation depth, and position (vertical, horizontal, or angle). Continuously measuring the soil water content and its rate of decline over with time after a precipitation or irrigation event would improve the understanding of corn and Palmer amaranth competition for soil water. The objective of this study was to determine soil water content throughout the growing season when corn and Palmer amaranth were grown alone or in competition under dryland and irrigated environments.

MATERIALS AND METHODS

Field experiments were conducted in 2005 and 2006 at the Kansas State University Agronomy Department Ashland Bottoms Research Farm 8 km south of Manhattan, KS. In 2005, the experiment was established on Eudora silt loam soil (coarse-silty, mixed, superactive, mesic Fluventic Hapludoll). The previous crop was soybean. The field was spring fertilized with 224 kg N ha^{-1} using liquid urea-ammonium nitrate (28-0-0) and a dry blend of 45 kg ha^{-1} muriate of potash, 33.5 kg ha^{-1} sulfur (90%), 13.5 kg ha^{-1} zinc sulfate (31%), and 336 kg ha^{-1} pell-lime, then incorporated by field cultivation. Furrowed rows were made with one pass planter furrow row units and a second pass with a furrow cultivation unit one month prior to planting. In 2006, the field soil was a Belvue silt loam (coarse-silty, mixed, superactive, nonacid, mesic Typic Udifluvents). The previous crop was soybean, followed by that had fall planted winter wheat, which was terminated in early April. The field was fertilized with 224 kg N ha^{-1} using liquid urea-ammonium nitrate (32-0-0) and a dry blend of 56 kg ha^{-1} muriate of potash, 33.5 kg ha^{-1} sulfur (90%), 13.5 kg ha^{-1} zinc sulfate (31%), and 336 kg ha^{-1} pell-lime. Furrowed rows were made with one pass planter furrow row units and two passes with a furrow cultivation unit one month prior to planting, which also incorporated the fertilizer. Corn hybrid ‘DKC60-19RR’ was planted at 76,600 seeds ha^{-1} with a 0.76 m row spacing on May 6, 2005 and May 11, 2006.

Experiments were arranged in a split-plot design with the whole plot treatments being soil moisture environment which consisted of dryland and well-watered furrow irrigation. Replication was restricted to within each soil moisture environment due to logistics of irrigation methods. Within each soil moisture environment, four sub-plot treatments were established including monoculture corn, monoculture Palmer amaranth at one plant m^{-1} of row, and two mixtures of corn with Palmer amaranth at one and four weeds m^{-1} of row. The weed densities were selected based on previous research results for Palmer amaranth competitiveness in dryland and irrigated environments (Blinka 2004, Liphadzi and Dille 2006, Massinga et al. 2001). Treatments (sub-plot) were replicated four times and arranged in a randomized complete block within each soil moisture environment. Each sub-plot was four corn rows wide and 17 m long. Immediately after planting, the plot layout was established and Palmer amaranth seeds were hand sown to all four rows of a plot and lightly raked to cover seed with soil. The Palmer amaranth seed source was from the Ashland Bottoms Research Farm. All plots were furrow irrigated to establish corn and Palmer amaranth emergence at the same time. The well watered plots were furrow irrigated as needed by the crop. The plots were established in both years to maximize furrow irrigation effectiveness based on slope of land. A six meter buffer was established between irrigation pipe and start of the experimental plots. Irrigation water was applied to every row furrow.

After emergence, Palmer amaranth seedlings were hand thinned to treatment densities with plants located within 10 cm of each corn row and corn was removed from monoculture Palmer amaranth plots. Plots were hand weeded or hand hoed to maintain treatment densities and to remove other weed species for the duration of the experiment.

Soil moisture was measured within one treatment sub-plot for one replication using a TDR100[1] with sixteen TDR probes[2] and three coaxial multiplexers[3] (Labeled I, II, III). The TDR100 and coaxial multiplexer (I) were located in the data acquisition and control system (DACS) enclosure[4] located in the center of the field study area. Two coaxial multiplexers were located in smaller enclosures[5] within the dryland (II) and irrigated (III) environments. Coaxial multiplexer (I) was connected to coaxial multiplexers (II and III) with 6 m of RG8 coaxial cable[6]. Eight TDR probes were connected to each coaxial multiplexer (II and III) with cable of 9 m in length. Within the sub-plot, soil moisture was measured with one probe per treatment per environment at 0 to 15 and 0 to 30 cm depths. Four TDR probes were inserted into the soil at a 30° angle from the soil surface to acquire an integrated soil moisture measurement at the 0 to 15 cm. Four TDR probes were inserted perpendicular to the soil surface for an integrated soil moisture measurement over the 0 to 30 cm depth in each environment. The TDR probes were placed 5 cm from the center of the row next to separate monoculture plants or between corn and Palmer amaranth plants. The TDR measurements were taken every 60 minutes and then the data logger[7] recorded the VWC data. The VWC was determined from TDR measurements using the Topp et al. (1980) equation. Rainfall was measured using a tipping bucket rain gauge[8]. Rainfall data were recorded every 60 minutes and daily totals were recorded to the data logger. The DACS and rain gauge were installed after planting and TDR probes were installed after establishment of Palmer amaranth plant densities. The DACS was powered by a 12 Volt battery[9] equipped with a trickle solar charger[10]. Data were downloaded from the data logger to a laptop computer at least once a week to monitor instrumentation operation and data quality.

The 2005 TDR probes were installed later than intended because of the extremely wet early June, where a majority of the focus at that time was to establish Palmer amaranth treatment densities. The 2006 probes were installed the same week as corn and Palmer amaranth emergence when weed densities were established. The installation of TDR probes occurred without the ability to differentiate male and female Palmer amaranth plants. In both years at both depths, there was an equal member of male and female plants where TDR probes were installed. At this time, no research has shown water use or root pattern distribution differences between male and female Palmer amaranth during the growing season. Both female and male Palmer amaranth plants in this study were actively living until corn physiological maturity and assumed to have no differences in measured VWC.

Soil physical properties were determined for the two soil types used in the experiment. Percent sand, silt, and clay were determined to a 120 cm depth by the Soil Testing Laboratory at Kansas State University. Dry bulk density of the field soils were determined from soil cores taken to 30 cm. Soil water content was determined at -0.03 and -1.5 MPa soil water potential with a cellulose acetate membrane from disturbed soil samples taken at 0 to 20 cm depth (conducted by Dr. L. Stone, Brian Frank, and Ryan Cyr, Kansas State University). The soil water contents were used to calculate the VWC for the 0 to 15 and 15 to 30 cm soil depths with their respective bulk density values.

The weather data were compiled from the Kansas State Weather Data Library (M. Knapp, personal communication). Precipitation data sources were the Ashland Bottoms Agronomy Research Farm and within-experiment rain gauge measurements. The reference evapotranspiration (ET_o) and corn evapotransporation (ET_{Corn}) (single crop coefficient) were calculated based on methods described by Allen et al. (1998).

Root distributions of Monoculture corn and monoculture Palmer amaranth were determined in early October 2006. A tractor-mounted Giddings probe[11] with a 5 cm diameter core was used to take soil cores. Four corn and four female Palmer amaranth plants were randomly selected in an area of replication three of the experiment where plants had not been removed or disturbed in the dryland and irrigated environments. Four cores were taken 8 to 10 cm from the plants to a depth of 120 cm. The soil cores were hand broken at 15 cm intervals and visible roots were counted at each core break. The percent of visible roots by depth were determined from the total counted roots in each 120 cm core. An analysis of variance was conducted using SAS v9.1[12] PROC GLM for each environment and species and means of percent visible roots by soil depth were separated by Least Significant Difference (LSD) at $\alpha = 0.05$.

The VWC for each soil water environment (dryland and irrigated) and each depth (0 to 15 and 0 to 30 cm) was visually inspected for differences, since no statistical analyses could be performed with data obtained from only one replication by probe depth in each sub-plot. Soil water (mm) was calculated from VWC for each probe depth. The rate of soil water depletion was calculated by determining the change in soil water for the period of days after a precipitation or irrigation event to the day prior to the next soil wetting occurrence. The beginning of the drying period started one day after the VWC started to decrease and the loss of soil water was calculated daily to the last day of the drying period (next wetting event). The cumulative loss of soil water was calculated for each depth measured and then the rate was based on the number of days in the drying period. A drying period consisted of at least four days. The rate of water loss by ET_{Corn} was calculated with the same procedure as soil water loss for each drying period. The effective precipitation prior to a drying period was summed to show the amount of water gained and was estimated to be 80% of total rainfall received, if equal to or greater than 10 mm. When rainfall was less than 10 mm, then 100% of the total rainfall received was considered to be effective precipitation. The 10 mm rainfall threshold was based on observations that revealed that rainfall over 10 mm had 20% runoff from the furrowed ridges where the TDR probes were placed and did not add to the gain of soil water. Water applied as furrow irrigation was considered 100% effective because the experiment was bermed on all sides of both environments and resulted in no runoff from the study.

RESULTS AND DISCUSSION

The impact on VWC by corn and Palmer amaranth can be best understood from 1) the precipitation and irrigation patterns, 2) soil properties, 3) ET_{Corn}, 4) plant root distribution, and 5) soil water depletion rates. The total rainfall received from May 1 to August 31 was 496 mm and 366 mm for 2005 and 2006, respectively. In 2005, the May rainfall was almost 90 mm less than the 30-yr normal amount of precipitation (Figure 2.1). In June 2005, precipitation was 128 mm above the 30-yr normal and 53% of the growing season rainfall occurred in early June. In July 2005, there was only 60 mm of rainfall and this was 44 mm below the normal monthly precipitation. August precipitation was received too late in the season to impact plant growth requirements because corn and Palmer amaranth were near physiological maturity. The June 2005 rainfall provided near optimum growing conditions for corn and Palmer amaranth but limited rainfall thereafter generated a moderate midsummer drought. The 2006 growing season was much drier than 2005. In May 2006, rainfall was almost 90 mm less than the 30-yr normal precipitation (Figure 2.1). Opposite to 2005, June 2006 precipitation was near 100 mm below the 30-yr normal. Rainfall deficits from the 30-yr normal continued from May through July in

2006 to generate a severe midsummer drought since 57% of the May through August rainfall occurred in mid to late August. Therefore, dryland corn was under water-limited stress throughout most of the 2006 growing season.

Field soil properties differed across the two years that further impacted the extent of water-limiting stress that occurred (Table 2.1). The 2005 field soil was an Eudora silt loam that had an average 30, 59, and 11 percent sand, silt, and clay content, respectively, while the 2006 Belvue silt loam soil had 44, 47, and 8 percent sand, silt, and clay content, respectively at the 0 to 30 cm depth. The Eudora soil had 2.0% organic matter whereas the Belvue soil had only 1.1%. The Eudora soil in 2005 having a higher silt and less sand content in addition to more organic matter than the Belvue soil in 2006 provided ~1.4 times more plant available VWC (PAW) in the upper 30 cm of the soil profile (PAW: Eudora soil = 0.268 cm^3 cm^{-3}, Belvue soil = 0.187 cm^3 cm^{-3}). So in addition to limited precipitation, the soil physical properties limited the 2006 soil from holding sufficient soil water available for corn and Palmer amaranth growth.

The cumulative ET_{Corn} from emergence to corn physiological maturity was 400 mm and 440 mm in 2005 and 2006, respectively, which indicated that the environmental demand for water was higher in 2006 than 2005. In 2005 and 2006, the irrigated environment received a total of 203 mm and 356 mm of irrigation water, respectively, from emergence to the final plant harvest. Corn and Palmer amaranth emerged at the same time in both years aided by irrigating both soil water environments immediately after planting. After emergence, rainfall was the only source of water for the dryland environment plots. The next irrigation in 2006 was June 9 and was earlier than first irrigation in 2005 since June rainfall was above normal. The difference in total irrigation amounts was attributed to differences in water requirements during crop development, precipitation patterns, evapotranspiration, and soil physical properties for the two years, where in the 2006 crop had higher demand for water.

The measured water content peaks and depletion periods at both depths each year followed precipitation and irrigation patterns that occurred. The 0 to 15 cm probe depth (Figure 2.2) and 0 to 30 cm probe depth (Figure 2.3) in 2005 along with the 0 to 15 cm probe depth (Figure 2.4) and 0 to 30 cm probe depth (Figure 2.5) in 2006 resulted in similar trends of soil water content in each year indicating both depths captured the change in VWC through the growing season and that there was little difference in VWC between treatments. In both years, the 0 to 15 cm depth had less soil water overall and exhibited more rapid rise and fall in water content than the 0 to 30 cm depth. This was expected based on water storage with increasing depth. The monoculture Palmer amaranth treatment had highest soil water content in the irrigated environment at both depths in 2005 (Figures 2.2 and 2.3). Treatments of corn with one and four Palmer amaranth plants m^{-1} of row consistently had the lowest soil water content throughout the growing season at both depths in the dryland environment in 2005. Growth and development of corn in 2005 with and without the presence of Palmer amaranth had few differences. Both dryland and irrigated plots showed no visible plant water stress up to corn tassel stage (DOY 186) where the 0 to 30 cm depth water contents were above 50% of field capacity (0.19 cm^3 cm^{-3}) (refer to Chapter 1). Dryland corn development thereafter, however, exhibited physical water stress symptoms of leaf rolling at the late phase of individual drying periods, for example on DOY 194 and 206 (personal observation). Dryland corn with Palmer amaranth during grain fill had measured soil water contents of 0.13 cm^3 cm^{-3} at the 0 to 30 cm depth (DOY 202 to 206 and DOY 211 to 221), and this was near the wilting point of 0.115 cm^3

cm^{-3}. Even though the Eudora soil was capable of holding adequate moisture for the corn, the limited dryland precipitation resulted in water stress conditions that reduced monoculture corn yield 50% when compared to the irrigated monoculture corn at physiological maturity (refer to Chapter 1). Even though the corn had roots that were expected to be below 30 cm, it appeared that available soil water was limited and could not meet the demand of the crop from corn tasselling through the grain fill period (DOY 186 to 221). Monoculture corn and corn with Palmer amaranth in the irrigated environment resulted in similar soil water content trends at the 0 to 15 cm and 0 to 30 cm depths. Plants could have competed for soil water at greater soil depths but this was not measured.

In 2006, water stress started at the early vegetative stage of corn due to the limited rainfall in May and June, and soil water content was 20% below field capacity (DOY 159) (Figure 2.5). This stress was likely a combination of heat and water stress but visible leaf rolling started at the 6-leaf stage, so irrigation was applied (personal observation). The dryland plots continued to decrease in soil water content to 0.10 cm^3 cm^{-3}, equal to 60% below field capacity, just prior to corn tassel (DOY 180) at both depths. Precipitation that occurred during pollination (DOY 188 to 190) protected dryland corn yield to some degree and allowed it to escape premature death. During ear development and grain fill, however corn with and without Palmer amaranth present encountered severe water stress at both depths. During this period, monoculture Palmer amaranth had approximately 10% more soil water at the 0 to 30 cm depth in the dryland environment than any of the corn plots. This indicated that monoculture Palmer amaranth required less soil water to meet its water needs or it was capable of extracting soil water from deeper depths. One Palmer amaranth plant m^{-1} of row with dryland corn grew and developed with little water stress and had near equal biomass compared to dryland monoculture Palmer amaranth (refer to Chapter 1).

The distribution patterns of monoculture corn and Palmer amaranth roots over depth was determined in 2006 (Figure 2.6). The percentage of roots at each depth was calculated from the number of total visible roots and used to describe the distribution pattern with depth using a soil “core break-count” method. Dryland and irrigated Palmer amaranth had 70% of the roots in the upper 0 to 30 cm soil depth with the remaining proportion of roots gradually tapering off to the 120 cm depth (Figure 2.6). Palmer amaranth root distribution results agree with Davis et al. (1965), where Palmer amaranth was reported to have extracted more water from the upper 30 cm soil layer which suggests a higher density of roots near the soil surface. Davis et al. (1965) also reported that Palmer amaranth had a relatively narrow lateral root distribution and an extensive vertical root distribution. In this study dryland Palmer amaranth had more roots below 75 cm in the soil profile than irrigated Palmer amaranth, which indicated that the dryland plants had the ability to extract more soil water at greater depth in the profile when soil water was limited in the upper soil profile, which agree with Davis et al. (1965).

Dryland and irrigated corn had 60 to 70% of its roots concentrated in the upper 30 cm of the soil profile (Figure 2.6). This agrees with Follet et al. (1974) where corn roots were concentrated in the upper 40 cm of the soil profile. Irrigated corn had more visible roots at the 30, 45, and 60 cm depths than dryland. The dryland corn was severely water stressed and probably did not have the ability to produce roots to meet its water demand but it did have similar percent visible roots as irrigated corn below 75 cm in the soil profile.

Both corn and Palmer amaranth appear to have the majority of their roots in the upper 30 cm of the soil profile when planted on top of a ridge designed for furrow irrigation. This indicated that the 0 to 30 cm profile depth would provide adequate estimates of water depletion rates if soil water was extractable by roots in this zone. Roots below the 30 cm depths likely contributed to meeting the dryland corn and Palmer amaranth water requirements but water content was not measured at those depths. Therefore, only 0 to 30 cm depth soil water depletion rates are presented and discussed.

The effective precipitation or effective precipitation plus irrigation prior to the drying periods, the daily loss of water from ET_{Corn}, and the soil water depletion rate per day at the 0 to 30 cm depth for soil drying periods in the dryland and irrigated environments in 2005 and 2006 are shown in Figures 2.7 to 2.10. The ET_{Corn} shows the estimated loss of water to meet the environmental demand from monoculture corn with respect to climatic conditions. The water prior to the drying period shows the amount of water that could have been extracted by plant roots, lost by soil evaporation, or drained through the upper 30 cm soil profile.

In 2005, four drying periods were identified and resulted in the dryland environment using less water (Figure 2.7) than the irrigated environment (Figure 2.8). The treatments in the irrigated environment depleted the soil water at a greater rate than treatments in the dryland environment, likely due to more water at the beginning of the periods from irrigation applications. Dryland depletion rates were lower due to less effective precipitation with no irrigation prior to the drying period and less available for plant uptake in the 0 to 30 cm depth. Thus soil water was extracted from below 30 cm in the soil profile because roots were deeper than 30 cm in the soil profile. Irrigated corn alone and with Palmer amaranth had the higher depletion rates than monoculture Palmer amaranth for all drying periods (Figure 2.8). In the last two drying periods during corn grain fill (202 – 206, 211 – 221), depletion rates were almost two times greater for corn treatments than Palmer amaranth alone. In the same periods, monoculture corn had the highest depletion rates. In all drying periods, ET_{Corn} was greater than any species alone or in mixture for each environment, which indicated that water loss from ET_{Corn} appeared to be extracted from depths greater than 30 cm.

In 2006, seven drying periods were used to calculate soil water depletion rates. The rate of soil water depletion in the dryland environment corresponded to the amount of precipitation received prior to the drying event (Figure 2.9). When available soil water was high then depletion rates were high and vice versa. In the first three drying periods, the depletion rates were similar across dryland plant populations. In the four later drying periods, dryland monoculture Palmer amaranth and corn with one Palmer amaranth plant m^{-1} of row had the highest depletion rates when rainfall was received prior soil drying. This indicated that the Palmer amaranth was growing actively and continued to extract more soil water in the upper 30 cm profile where it had a greater proportion of roots compared to lower soil depths.

The rate of soil water depletion from the irrigated environment (Figure 2.10) was greater than dryland because more water was available in the upper 30 cm soil profile and corresponded to the amount of water received prior to the drying period. In the first three drying periods irrigated monoculture corn had similar rates to corn with one or four Palmer amaranth m^{-1} of row, but greater than irrigated monoculture Palmer amaranth. During the last four drying periods, irrigated monoculture corn had the lowest depletion rates compared to corn with Palmer amaranth, where the highest Palmer amaranth density with corn had the greatest soil water depletion rates. Also during the last four drying periods, irrigated monoculture Palmer amaranth depleted soil water at greater rates than earlier in the growing season, mainly due to the plants were larger and had greater demand for soil moisture. The depletion rates were greater than ET_{Corn} likely due to soil water drainage through the profile, more plant water use, or an underestimation of ET_{Corn}. The irrigated corn depletion rates agree with Massinga et al. (2003) where irrigated corn with Palmer amaranth water use increased as Palmer amaranth density increased.

The soil water depletion rates during drying periods were higher when total added precipitation with and without irrigation to the soil system and plant population water demand were greater. Plant populations that were large in size and had higher total biomass depleted soil water at higher rates. Palmer amaranth with corn can deplete the soil water more than monoculture corn when plants are not water stressed. Severe water stressed dryland corn with Palmer amaranth have lower soil water depletion rates than monoculture Palmer amaranth.

Investigations were made to estimate the treatments' evapotranspiration using water balance methodology, but the number of assumptions and estimates of soil drainage resulted in unacceptable calculations and conclusions. The soil profile water content was needed to measure the total change in soil water content for the entire root depth. The root depth distribution data showed that monoculture corn and Palmer amaranth roots were below 30 cm in the soil profile. The results presented were for the upper 30 cm and readers need to recognize that profile soil water competition did occur, but not determined. Future work is needed to determine the soil water extraction in the soil profile through the growing season along with the root distributions of corn with Palmer amaranth in different soil water availability regimes. The information would improve the understanding of competition for soil water between corn and Palmer amaranth, which would ultimately improve water use modules in crop:weed competition models.

Time Domain Reflectrometry method was useful to determine the soil water content at the 0 to 15 cm and 0 to 30 cm on a continuous basis. Once the equipment was setup and programmed to read and record data, the system was very reliable. The TDR instrumentation was new to the Kansas State Weed Ecology group and required one growing season (2004) to fully operate and understand the process and data collection. Researchers with experience in soil water measurement would not likely require the same time to establish an operating system. The major limitation was probe length offered by the manufacture, but users can construct and calibrate probes to measure water content at greater depths (Long et al. 2002). This study lacked profile soil water measurements and could not account for soil water extracted below the 30 cm long TDR probes. The TDR probes can be buried at greater depths to measure profile water content, but other instruments can also be used to determine profile soil water. Dalley et al. (2006) and Massinga et al. (2003) demonstrated the water use of crop and weed population using incremental measurements in the soil profile. Although this study only had a single replication of soil water content measurements at two depths in the upper 30 cm, the information was insightful for the temporal change in VWC and soil water depletion rates when soil water was available where 60% of the roots were concentrated. The single replication limited the ability to identify the treatments with the highest and lowest soil water content due to the high degree of variability of spatial arrangement of mixed species and all probe placements on the row ridges. The slight difference in land slope and furrowed ridge affected the water content measurements with probe installation, perhaps more than plant spacing. The probes were installed next to plants based on their spatial arrangement, not on ridge height or geometry. The probe installation procedure resulted in measuring unequal increases in soil water more after irrigation than rainfall events. This observation can be seen with all the irrigated treatments at both depths (Figures 2.2 to 2.5). Since the VWC was determined from the soil in contact with the probe rods, there were equal differences in depletion of soil water when compared to the gain after precipitation or irrigation events. Therefore, the ability to determine the depletion or loss of soil water during a drying period after a wetting event was possible. Regardless of the challenges in differentiating temporal changes in soil water content among individual treatments, trends were observed that matched corn and Palmer amaranth growth and development and the soil's water holding capabilities. Future research investigating soil water competition will need replication for the treatments and for individual plants of interest, along with full profile measurements for soil water content change with increasing depth of the root zone.

SOURCES OF MATERIALS

[1] TDR100 Time Domain Reflectometer (with PC-TDR software). Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[2] CS605 (3-rod TDR Probe with RG58 coaxial cable). Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[3] SDMX50 (50 Ohm Multiplexer). Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[4] ENCTDR100 40.6 x 45.7 cm Enclosure, NEMA Type 4, single door. Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[5] 25.4 x 30.5 cm Enclosure, NEMA Type 4, single door. Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[6] COAXTDR (RG8 coaxial cable). Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[7] CR23X-4M Micrologger. Campbell Scientific, Inc., 815 W. 1800 N., Logan, UT 84321-1784.

[8] Sierra-Misco Model 2501. Nova Lynx Corporation, 431 Crown Point Circle, Suite G, Grass Valley, CA 95945.

[9] Die Hard, Deep Cycle Marine Battery. Sears Auto Center, 103 Manhattan Town Center, Manhattan, KS 66502.

[10] American Hunter 12-Volt Solar Panel. Cabela's, 400 E. Ave. A, Oshkosh, NE 69190.

[11] Giddings probe Model GSRTS. Giddings Machine Company Inc., Ft. Collins, CO.

[12] Statistical Analysis Systems, Version 9.1. 2003. Statistical Analysis Systems Institute Inc. 100 SAS Campus Drive, Cary, NC 27513-2414.

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FIGURES AND TABLES

Figure 2.1 Monthly precipitation deviation from 30-yr normal for 2005 and 2006 at Manhattan, KS.

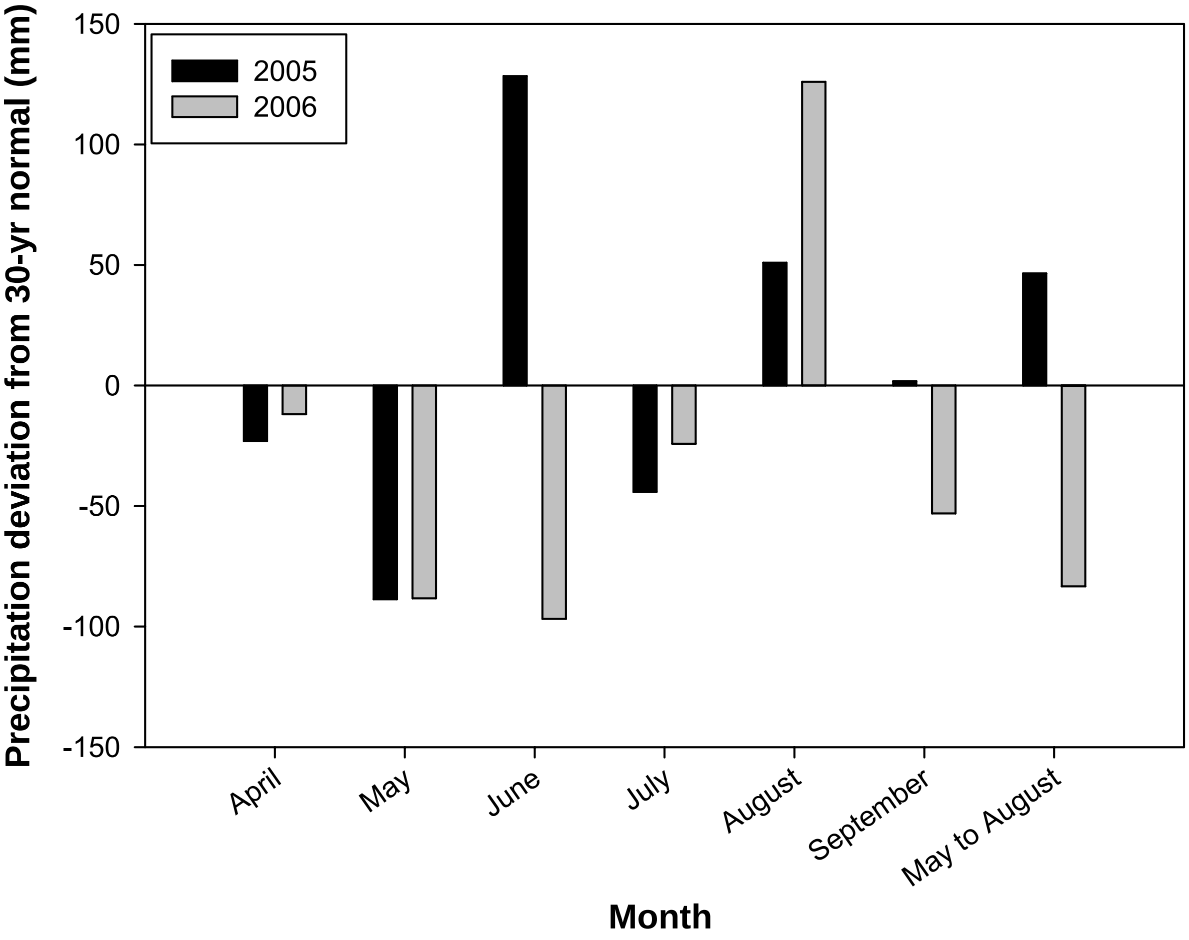

Figure 2.2 Soil water content at 0 to 15 cm depth, precipitation, and irrigation for the 2005 growing season. Dryland (DL-open symbols) and irrigated (IR-closed symbols) environments with monoculture corn (Corn), monoculture Palmer amaranth at one plant m^{-1} of row (PA1), and corn with one or four Palmer amaranth plants m^{-1} of row (C:PA1 or C:PA4).

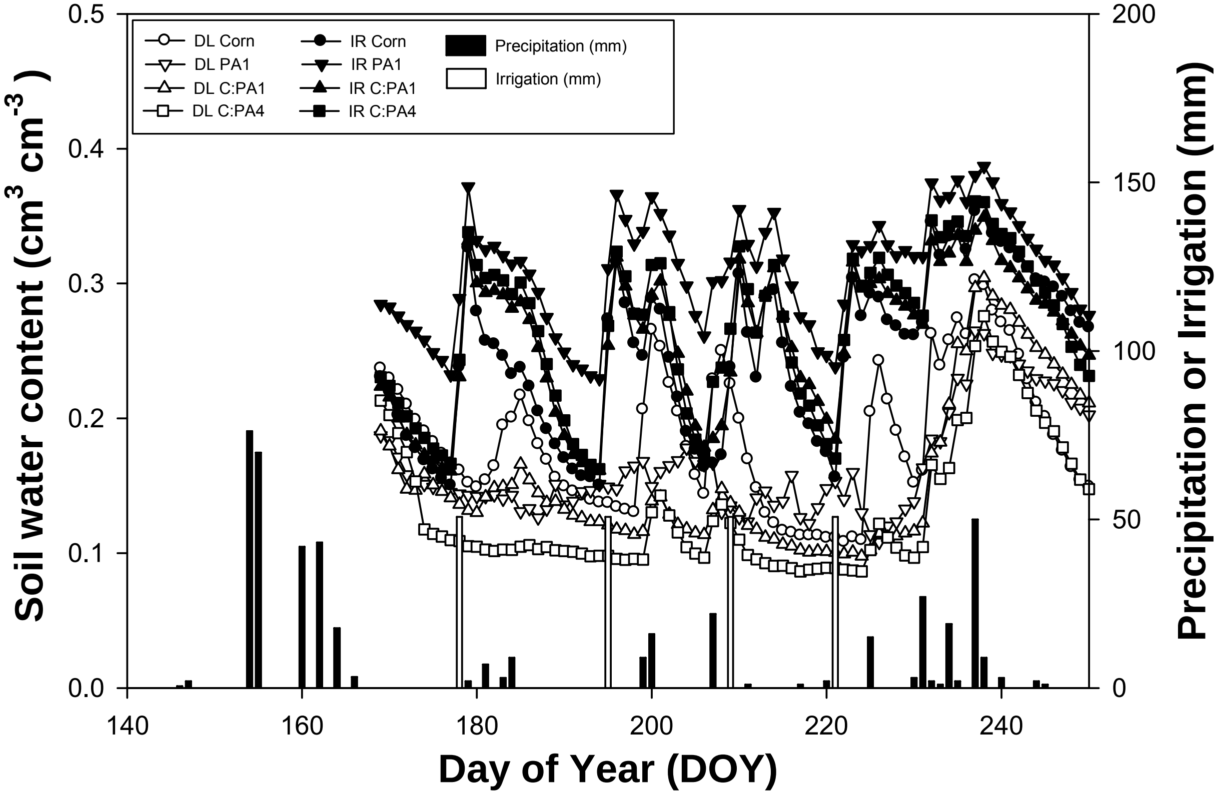

Figure 2.3 Soil water content at 0 to 30 cm depth, precipitation, and irrigation for the 2005 growing season. Dryland (DL-open symbols) and irrigated (IR-closed symbols) environments with monoculture corn (Corn), monoculture Palmer amaranth at one plant m^{-1} of row (PA1), and corn with one or four Palmer amaranth plants m^{-1} of row (C:PA1 or C:PA4).

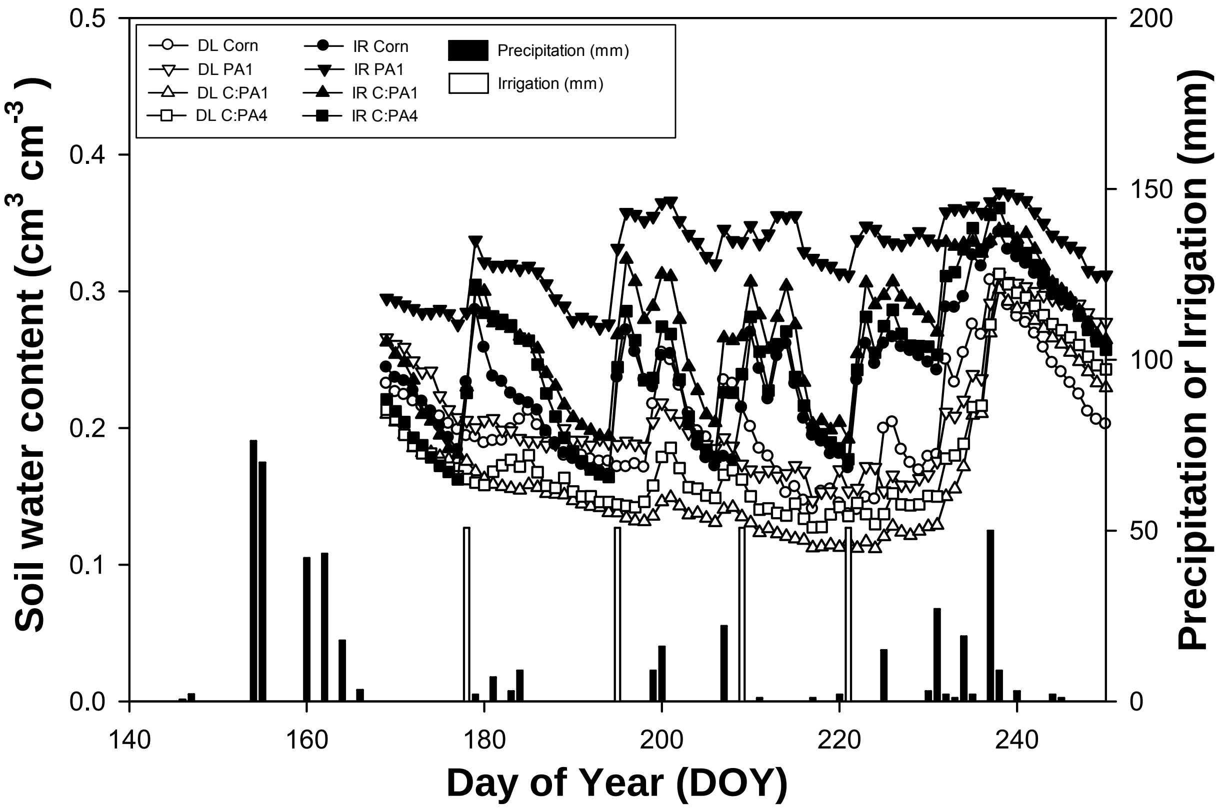

Figure 2.4 Soil water content at 0 to 15 cm depth, precipitation, and irrigation for the 2006 growing season. Dryland (DL-open symbols) and irrigated (IR-closed symbols) environments with monoculture corn (Corn), monoculture Palmer amaranth at one plant m^{-1} of row (PA1), and corn with one or four Palmer amaranth plants m^{-1} of row (C:PA1 or C:PA4).

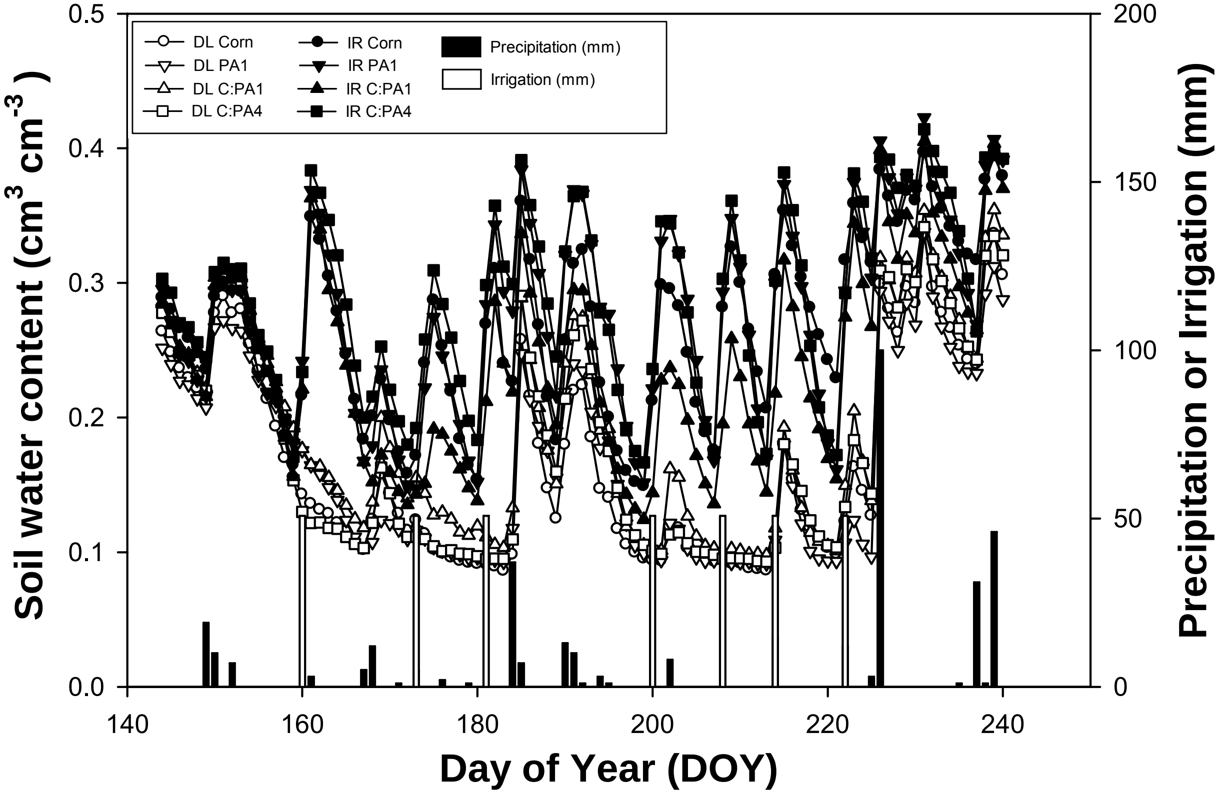

Figure 2.5 Soil water content at 0 to 30 cm depth, precipitation, and irrigation for the 2006 growing season. Dryland (DL-open symbols) and irrigated (IR-closed symbols) environments with monoculture corn (Corn), monoculture Palmer amaranth at one plant m^{-1} of row (PA1), and corn with one or four Palmer amaranth plants m^{-1} of row (C:PA1 or C:PA4).

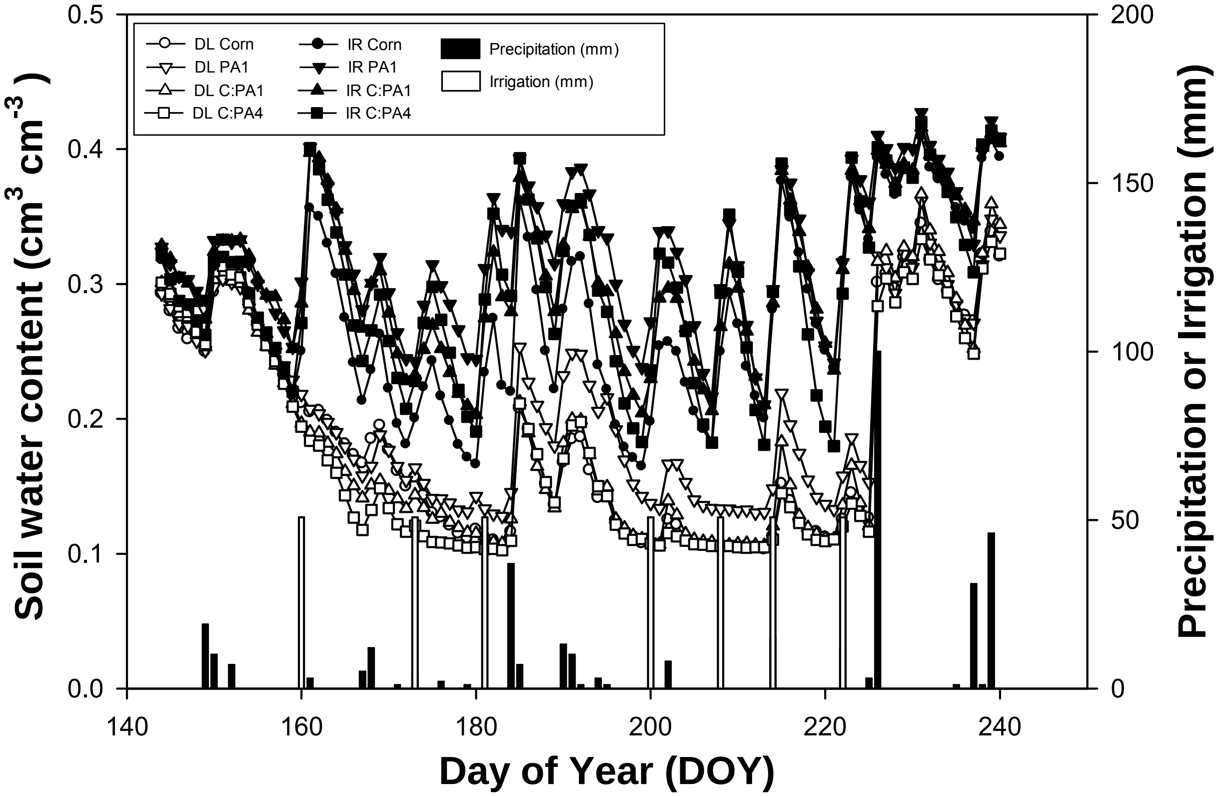

Figure 2.6 Monoculture corn and Palmer amaranth percent visible roots by soil depth for dryland and irrigated environments at the end of the growing season in 2006. Horizontal bars represent mean ± standard error. A) Palmer amaranth at one plant m^{-1} of row [LSD (0.05): DL = 4.08, IR = 3.91] and B) corn at six plants m^{-1} of row [LSD (0.05): DL = 3.40, IR = 2.73].

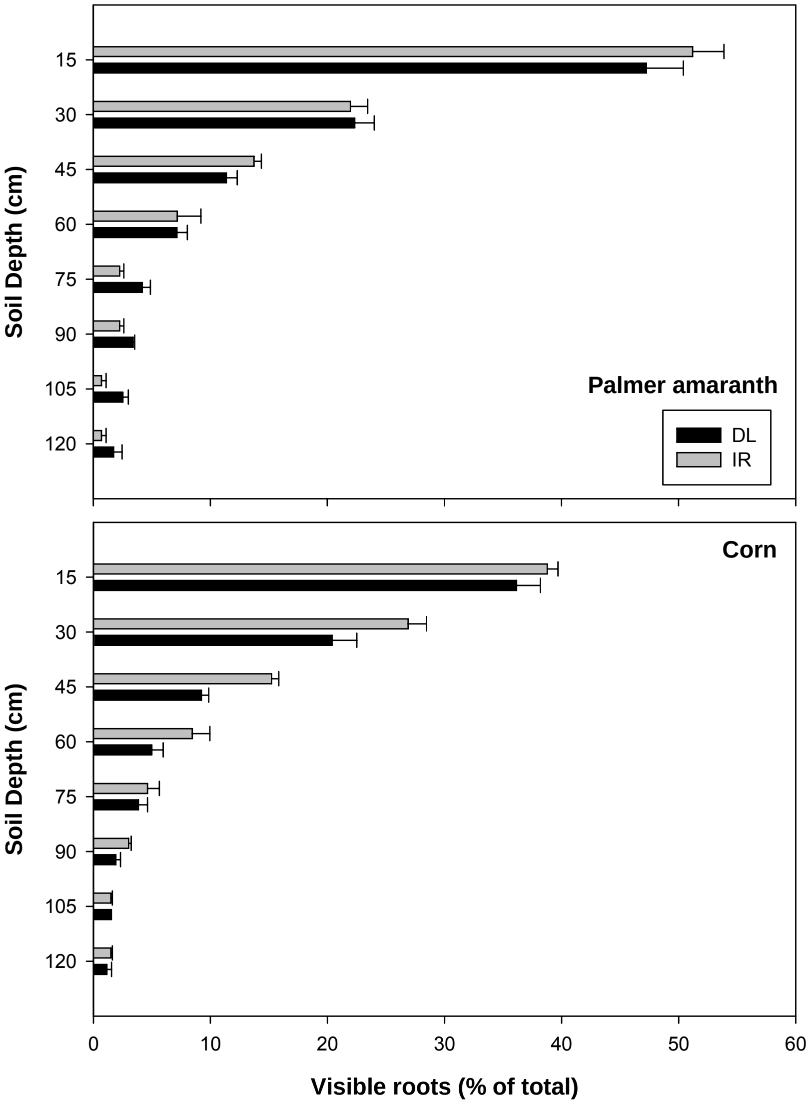

Figure 2.7 Effective precipitation prior to soil drying period (A), rate of soil water depletion and corn evapotranspiration (B) for each drying period in the 0 to 30 cm depth in the dryland environment in 2005.

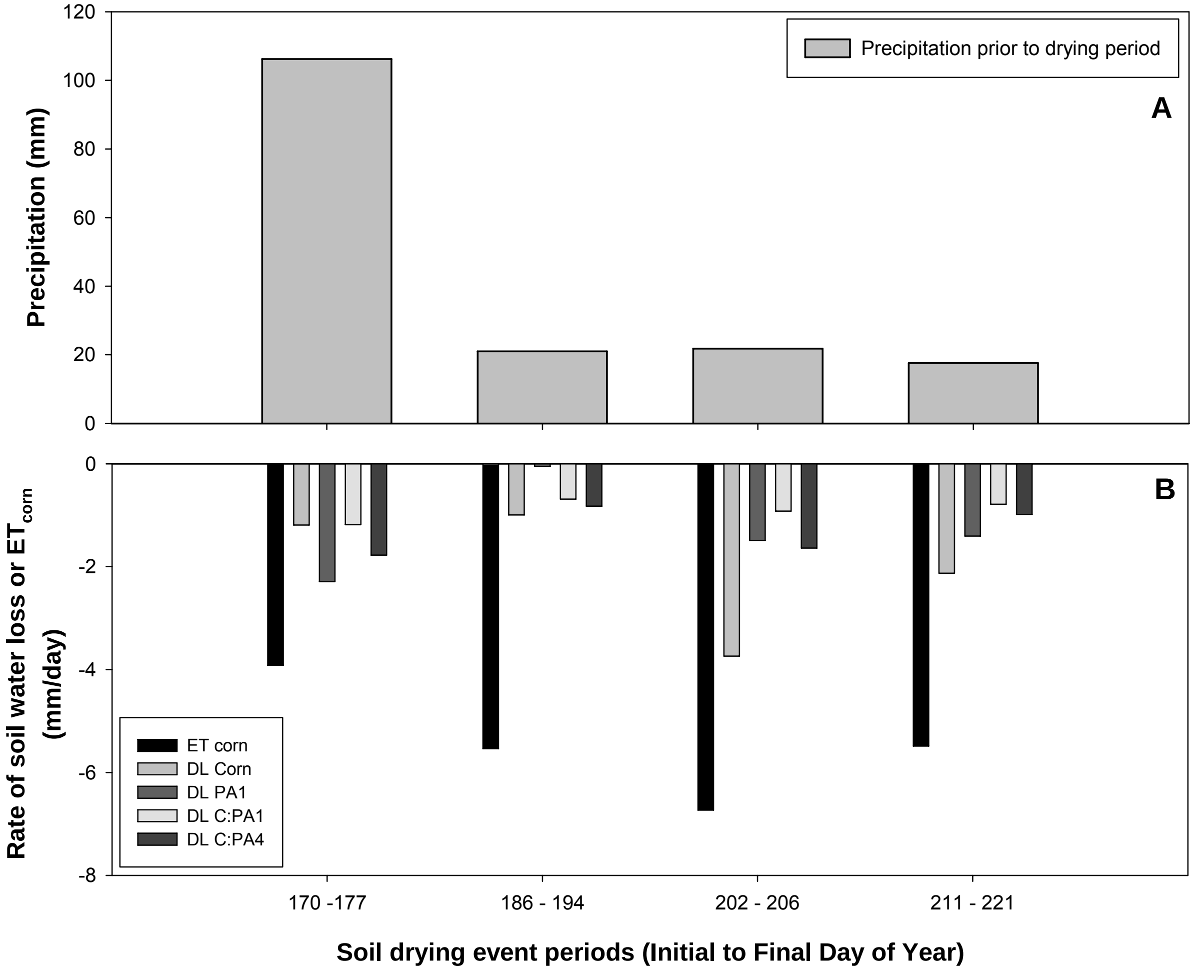

Figure 2.8 Effective precipitation + irrigation prior to soil drying period (A), rate of soil water depletion and corn evapotranspiration (B) for each drying period in the 0 to 30 cm depth in the irrigated environment in 2005.

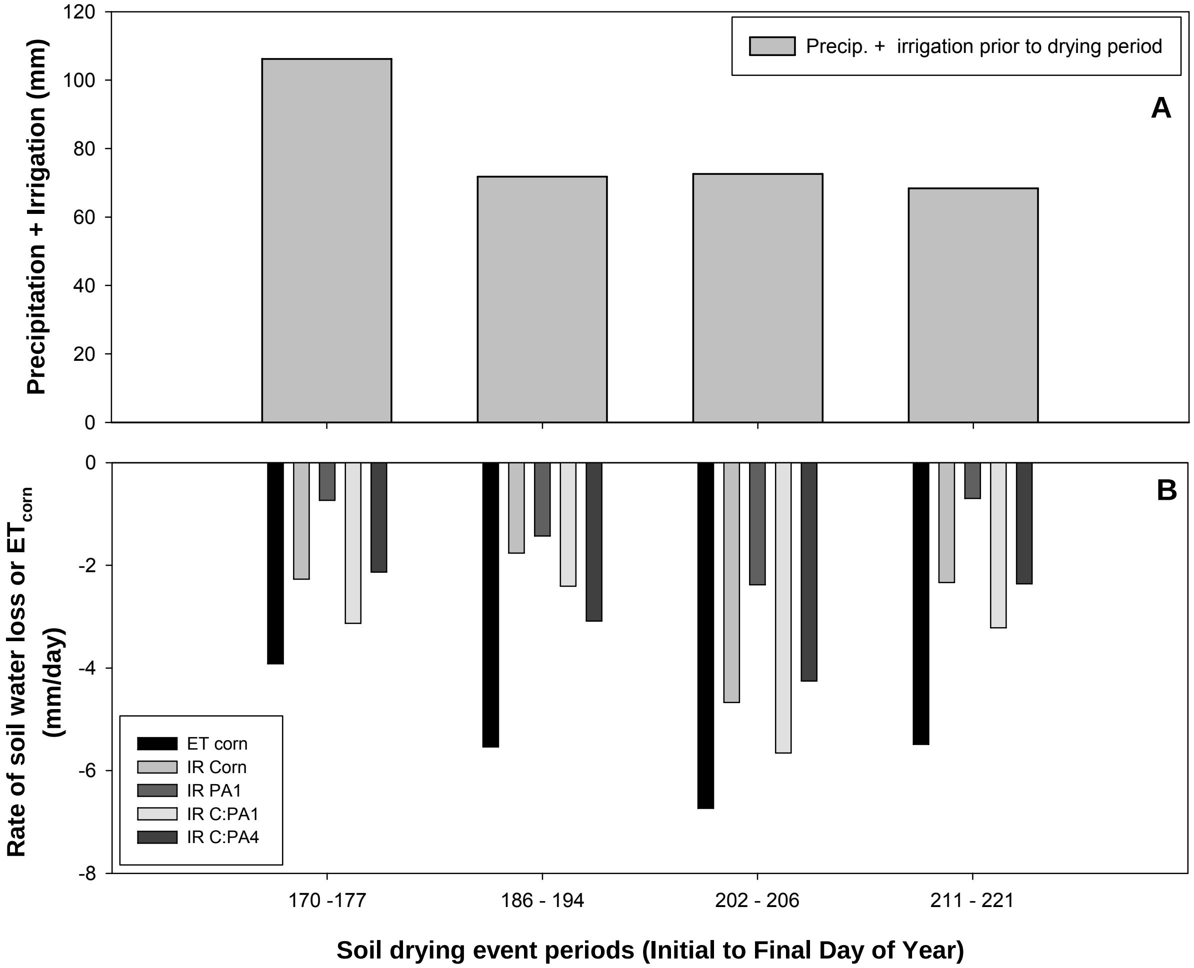

Figure 2.9 Effective precipitation prior to soil drying period (A), rate of soil water depletion and corn evapotranspiration (B) for each drying period in the 0 to 30 cm depth in the dryland environment in 2006.

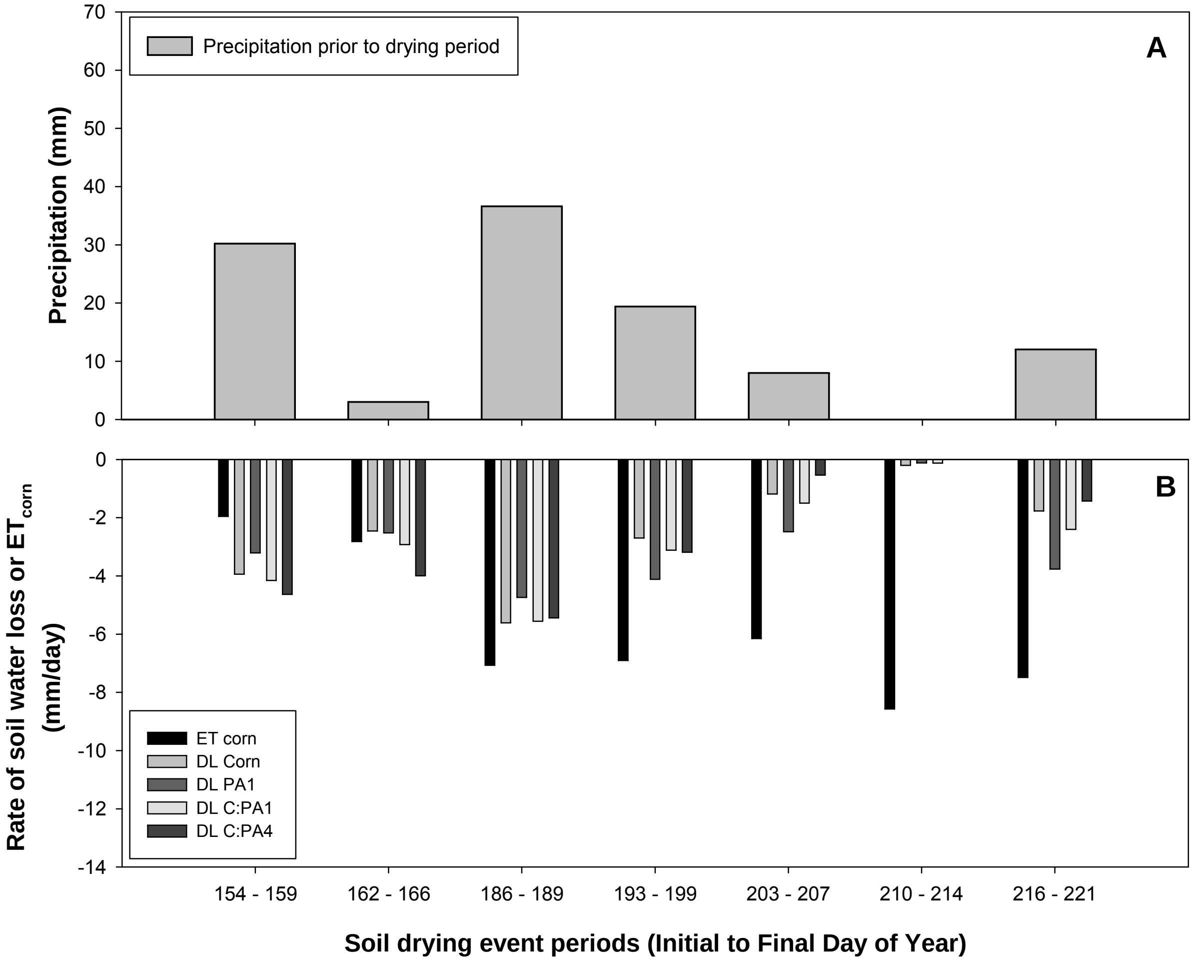

Figure 2.10 Effective precipitation + irrigation prior to soil drying period (A), rate of soil water depletion and corn evapotranspiration (B) for each drying period in the 0 to 30 cm depth in the irrigated environment in 2006.

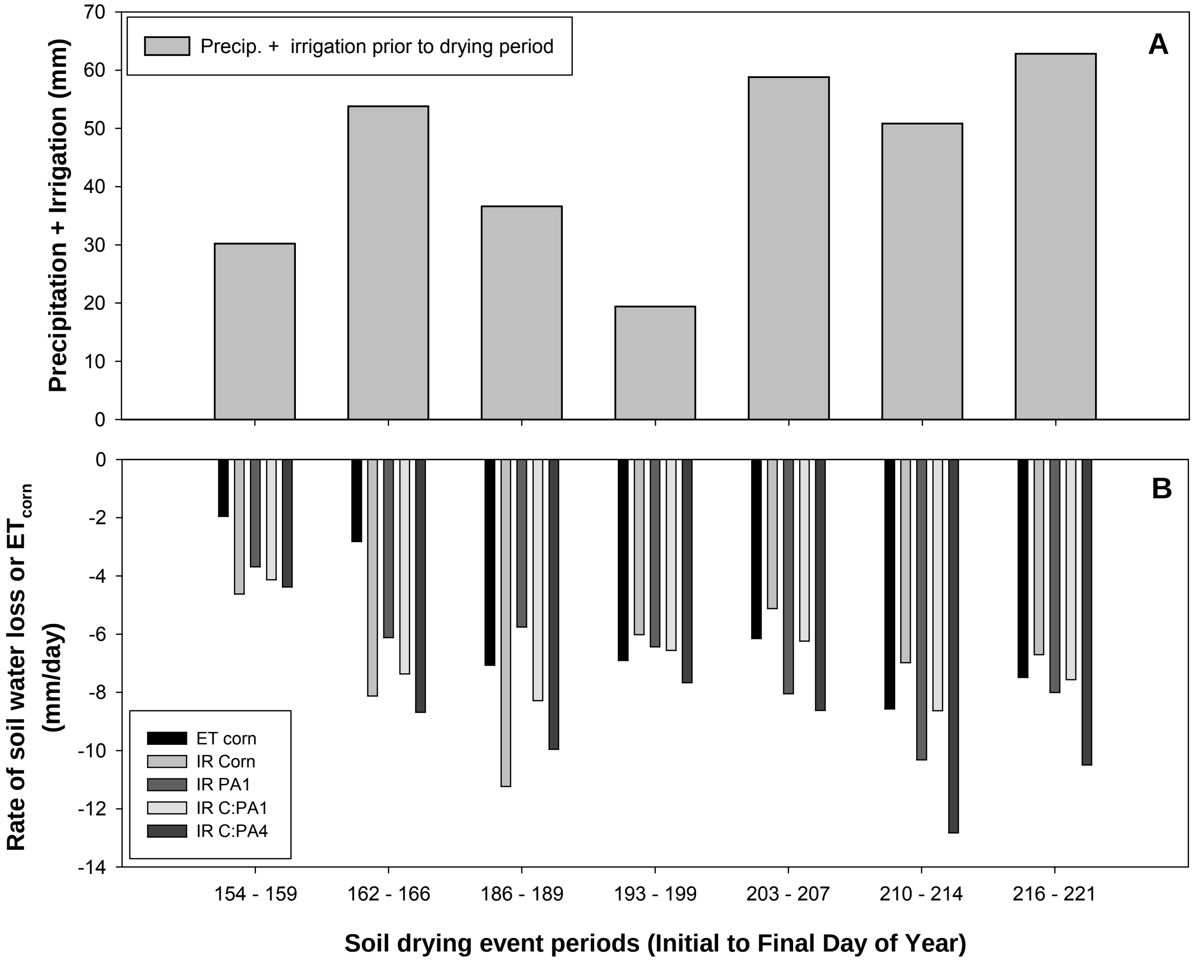

Table 2.1 Selected properties of the Eudora (2005) and Belvue (2006) field experiment soils at Manhattan, KS.

Eudora silt loam (2005)

	Particle size distribution					Cation		Volumetric water content	
	Sand	Silt	Clay	Organic		exchange	Bulk	Soil water potential	
Depth	(0.05–2 mm)	(0.05–0.002 mm)	(<0.002 mm)	matter	pH	capacity	density	(-0.030 MPa)	(-1.50 MPa)
cm	%					meq/100g	g/cm^3	cm^3 cm^{-3}	
0 – 15	28	58	14	2.0	5.8	14.7	1.38	0.380	0.113
15 – 30	32	60	8	1.6	6.1	11.0	1.40	0.385	0.115
30 – 45	42	54	4	1.3					
45 – 60	46	48	6	0.6					
60 – 75	42	51	7	0.6					
75 – 90	52	44	4	0.5					
90 – 105	59	37	4	0.5					
105 – 120	55	41	4	0.5					

Belvue silt loam (2006)

	Particle size distribution					Cation		Volumetric water content	
	Sand	Silt	Clay	Organic		exchange	Bulk	Soil water potential	
Depth	(0.05–2 mm)	(0.05–0.002 mm)	(<0.002 mm)	matter	pH	capacity	density	(-0.030 MPa)	(-1.50 MPa)
cm	%					meq/100g	g/cm^3	cm^3 cm^{-3}	
0 – 15	44	48	8	1.1	5.6	7.0	1.45	0.249	0.062
15 – 30	44	46	10	1.0	5.8	6.8	1.45	0.249	0.062
30 – 45	42	46	12	0.8	6.5				
45 – 60	40	46	14	0.6	6.7				
60 – 75	42	46	12	0.6	6.9				
75 – 90	56	36	8	0.5	7.1				
90 – 105	60	34	6	0.5	7.3				
105 – 120	52	42	6	0.5	7.4				

CHAPTER 3 - Corn and Palmer Amaranth Competition Simulated by a Crop:Weed Growth Model

ABSTRACT

An improved understanding of plant interactions for resources of limiting solar radiation, water, and nutrients, and their impact on growth is necessary for predicting crop yield losses under different environmental conditions. These interactions can be simulated with mechanistic crop-weed competition models. The modified ALMANAC model was parameterized to simulate both monoculture corn and corn with Palmer amaranth competition for dryland and irrigated conditions in Kansas. Correlation coefficients between simulated and measured corn grain yields for monoculture corn and for corn with one and four Palmer amaranth plants m^{-1} of row were 0.55, 0.55, and 0.13, respectively. The model underestimated monoculture corn yield but overestimated corn yield with Palmer amaranth competition. Overall, the model was unable to sufficiently simulate corn yield loss for ten site-years in Kansas. Based on these preliminary validation simulations, the modified ALMANAC model was not able to consistently simulate corn and Palmer amaranth competition in dryland and irrigated environments in Kansas but it was capable of distinguishing dryland and irrigated yield potential and causing an increase in yield loss with the addition of Palmer amaranth plants. The model could be improved by partitioning water stress between plant populations and modifying the light interception module to account for vertical leaf area distribution of each plant population’s canopy.

Key words: crop and weed competition, modified ALMANAC, simulation models, yield loss

INTRODUCTION

Crop yields in the U.S. Great Plains region are impacted by highly variable precipitation, low soil water availability, and high evapotranspiration. Producers' management decisions to maximize potential yield and profitability are dependent on their ability to minimize yield losses. Heiniger et al. (1991) stated that, "the ability to raise a profitable crop is tied to the ability to predict the conditions under which that crop will be grown and then to manage that crop and its immediate environment to best take advantage of those conditions. As the costs of crop inputs (fertilizer, seed, and pesticides) have increased over the years, so has the need for predictable yields in order to optimize economic gain. Unfortunately many agricultural areas, particularly in the Great Plains region of the United States, have climates that are variable and unpredictable." The ability to predict and minimize yield loss in a crop's environment is very complicated because of biotic and abiotic interactions. Weed interference with crops is one source of crop yield loss because weeds compete for solar radiation, nutrients, and water.

Improved understanding of crop yield loss from weeds in association with sensitivity to seasonal water stress in water-limited environments would aid crop managers in making profitable decisions for weed control. Variability in environmental conditions and implementation of crop management operations are the major factors influencing the dynamics of weed-crop interference relationships among sites and years (Lindquist et al. 1996). The impact of a weed population on a crop, however, is difficult to predict particularly in non-irrigated crop production systems (Lindquist et al. 1996).

Interactions among crop, weed, and environment can be simulated with eco-physiological process-oriented competition models such as ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) (Kiniry et al. 1992). The ALMANAC model provides a practical, easily adopted tool for simulating competition in mixed plant communities (Kiniry et al. 1992). The model requires a relatively small number of species-specific plant parameters and is considered of intermediate complexity (Debaeke et al. 1997). The ALMANAC model contains detailed functions to simulate plant growth, water balance, and nutrient cycling as in the EPIC (Erosion-Productivity-Impact Calculator or Environmental Policy Integrated Climate) model (Sharpley and Williams 1990, Williams et al. 1984, 1989), together with additional detail for light competition, population density effects, and vapor pressure deficit effects, which enable it to simulate the growth and yield of two or more competing plant species in a wide range of environments (Kiniry et al. 1992, 1997, Stockle and Kiniry 1990). The ALMANAC model simulates grain yield based on harvest index (HI), which is grain yield as a fraction of total above-ground biomass at maturity. Simulation accuracy has been validated for monoculture corn and grain sorghum yields in irrigated and water-stressed dryland environments (Kiniry et al. 1997, Kiniry and Blockholt 1998, Yun et al. 2001).

The ALMANAC model was modified to improve plant competition relationships and incorporated into GAPS (General purpose simulation model of the Atmosphere-Plant-Soil system) (McDonald and Riha 1999a, b, Rossiter and Riha 1999). The modified ALMANAC model partitions radiation into a mixed plant leaf canopy by replacing the functions developed by

Spitters and Aerts (1983) with the Wallace (1995) method. The radiation partitioning method can characterize a fuller range of competitive relationships among interacting crop and weed species, where a linear interpolation is used to calculate the fraction of light intercepted by species in canopies in which one species does not exert complete dominance over the other (McDonald and Riha 1999a). In the original ALMANAC model four environmental stress factors, i.e. nutrient, aeration, temperature, and water stress, can limit daily biomass accumulation, leaf area development, and reduce HI, where the lowest valued factor among the four stress indices is considered the limitation for daily index of environmental stress. In the modified ALMANAC model, environmental stress is set equal to the daily water stress index and it does not consider stress effects from aeration or nutrients (McDonald and Riha 1999a). Water stress is determined by the ratio of actual to potential transpiration (T-ratio) calculated on a daily time-step (McDonald and Riha 1999a). Also, the modified ALMANAC model does not simulate the influence of vapor pressure deficit on plant radiation use efficiency as in ALMANAC (McDonald and Riha 1999a). The modified ALMANAC model improved the environmental stress impact on plant growth over the original ALMANAC model, where the daily index of environmental stress (T-ratio) was incorporated into the equations for canopy height and root expansion (McDonald and Riha 1999a). This is important for simulating competition when water stress occurs, so that impacts of environmental stress simulation impacts are not limited to biomass accumulation, leaf area development, and HI. McDonald and Riha (1999a) recognized that the original ALMANAC model's morphological development was driven by cumulative thermal units from establishment and was not influenced by resource capture (rate of carbon assimilation). Therefore, the modified ALMANAC model was altered to make daily increases in leaf area index (LAI), height, and rooting depth attenuated on the basis of accumulated aboveground biomass and by environmental stress (McDonald and Riha 1999a). The linkage of morphological development to resource capture was important for accurately simulating the growth and impact of weeds on crops, especially with weed cohorts, growth in stressful environmental conditions, or crops not impacted by certain weed species.

McDonald and Riha (1999a) used the modified ALMANAC model to simulate monoculture corn yields and corn competing with velvetleaf from a field study. They concluded that the model was capable of distinguishing between environmental conditions that facilitate large and small corn yield losses caused by velvetleaf competition. Furthermore, corn and velvetleaf competition simulated over 30 years at a single site with water stress determined the probability of years that large corn yield losses would result from velvetleaf competition (McDonald and Riha 1999b). The simulation of competition with historical weather data suggested that water stress during corn's exponential growth phase changed the competitive balance between the crop and weed, in that higher levels of crop yield loss were associated with moisture deficit years, and corn competing with velvetleaf could have greater than 20% yield reductions two out of ten years (McDonald and Riha 1999b). This evaluation illustrated the potential to use simulation plant growth models for crop-weed competition and how simulated estimates of seasonal environmental variations can aid in predicting crop yield losses. Also, crop and weed simulation models give insight as to why specific responses were evident in the field in only certain sites and years, while providing a useful tool for quantifying the long-term occurrences of specific crop and weed combinations (McDonald and Riha 1999a).

The ability to improve and maximize corn yield involves development of corn genetics and optimizing crop management practices to obtain potential crop yields in a given environment. To profitably produce corn, growers require information and tools to predict and minimize yield loss while balancing the cost of crop inputs to crop value. Yield loss due to weeds is important, but more crucial is understanding or determining the mechanisms that cause yield loss. Research conducted to understand the mechanisms of yield loss caused by weeds would improve the development of potential weed management strategies. Also, an improved understanding of the crop-weed interference environment (ie. soil water, light, and nutrients) would provide information to develop management strategies for environmental resources. The quantification of weed and crop growth during competition can be used to simulate crop yield loss with crop-weed competition models in different environments and management conditions (Kiniry et al. 1992, McDonald and Riha 1999a, b).

Palmer amaranth (*Amaranthus palmeri*) is considered one of the most serious weed problems in the Great Plains of the United States due to its ability to reduce crop yields and interfere with harvest (Horak et al. 1994). Palmer amaranth has been reported to compete aggressively with corn in Kansas (Liphadzi and Dille 2006, Massinga et al. 2001, 2003). Massinga et al. (2001) reported Palmer amaranth emerging with irrigated corn reduced yield from 11 to 91% for densities from 0.5 to 8 plants m^{-1} of row in western Kansas. In eastern Kansas, Liphadzi and Dille (2006) reported dryland corn and irrigated corn yield losses were 6 to 60% and 5 to 38%, respectively, for Palmer amaranth densities of 0.25 to 6 plants m^{-1}. Corn yield loss from Palmer amaranth between site-years and water management were variable in Kansas and competition models can be a tool to improve the mechanistic understanding of this interaction. Corn and Palmer amaranth competition studies provided an opportunity to test the performance of the modified ALMANAC model for predicting the effect of weed interference on corn yield in diverse environments. The objective was to evaluate the performance of the modified ALMANAC model for predicting monoculture corn yield and corn yield loss from Palmer amaranth competition in dryland and irrigated environments in Kansas.

MATERIALS AND METHODS

The modified ALMANAC model was parameterized with specific plant parameters for corn and Palmer amaranth that were estimated, adopted, or developed for optimum growth conditions in Kansas. Monoculture corn parameter values came from previously reported studies (Kiniry et al. 1992, McDonald and Riha 1999a) and from Manhattan, KS field experiments (Rule unpublished data) (Table 3.1). Palmer amaranth data from both monocultues and in competition with corn were used to estimate parameter values because limited data exists for monoculture Palmer amaranth over a wide range of plant densities (Massinga 2000, Rule unpublished data, see Chapter 1).

The output from the parameterized modified ALMANAC model was evaluated against yield data of monoculture corn and corn with Palmer amaranth from field experiments in Kansas (Table 3.2). The experimental locations included Garden City, Manhattan, and Rossville. Garden City is located in southwest Kansas where irrigated corn production predominates. The field experiment was conducted in 1996 to 1998 for optimum corn and Palmer amaranth growing conditions in all four site-years. Manhattan and Rossville are located in northeast Kansas where corn production occurs in both dryland and irrigated environments. The northeast Kansas data set includes four dryland and four irrigated site-years. The 2001 Manhattan and 2002 Rossville were managed for normal production practices and 2004 to 2006 Manhattan site-years were managed for optimum growing conditions. The data sets provided a wide range of environment and management conditions to evaluate the model.

The parameterized modified ALMANAC model was used for all simulations. A description of the modified ALMANAC model and its input parameters was documented by McDonald and Riha (1999a), while the original model was described by Kiniry et al. (1992). The methods for soil water uptake and flow processes in original ALMANAC model were used for all simulations. Daily potential evapotranspiration was estimated using the Penman-Monteith equation. Both temperature and water stress functions were included in the simulations. Model simulations were conducted based on input data for soil, climate, location, and management for each site-year (Table 3.2). The climate data input files were developed for each evaluation site-year from weather data compiled from the Kansas State Weather Data Library (M. Knapp, personal communication). Climate variables used in the simulations included maximum and minimum temperature, solar radiation, precipitation, humidity, and wind speed. Soil input parameters were obtained and estimated on a horizon basis from soil survey data and experimentally-determined field data. The soil series for each site-year are shown in Table 3.2. The soil input data included bulk density, initial water content, field capacity, wilting point, percent clay, and percent silt with all other parameters set to default values. The location and sequence input parameters were developed based on site-year experimental information. The location input parameters included information for irrigation where actual data were used when possible.

The modified ALMANAC model performance or predictive ability was evaluated by comparing measured and simulated monoculture corn yield, corn yield with Palmer amaranth competition, and percent corn yield loss using correlation coefficients and estimates of bias and root mean squared error (RMSE). Bias was calculated as the average of the differences between measured and simulated values and indicated whether the simulation was, on average, higher or lower than the measured values:

$$\text{Bias} = \frac{1}{N}\sum_{i=1}^{n}(\text{simulated}_i \text{ - measured}_i) \qquad [1]$$

Root mean squared error was an estimate of the overall differences between measured and simulated values:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(\text{simulated}_i \text{ - measured}_i)^2} \qquad [2]$$

where N was the total number of measured values. A relatively small value for RMSE indicated good simulation values compared to measured values.

RESULTS

The modified ALMANAC model simulated corn yield accurately for monoculture corn and corn with one Palmer amaranth m^{-1} of row but poorly for corn yield with four Palmer amaranth m^{-1} of row (Figure 3.1). Monoculture corn yield was simulated with a relative average ability ($r = 0.55$, $p = 0.0658$) and was less than measured yield (bias = -1.66, RMSE = 1.99). A visual inspection of Figure 3.1A indicated that the model simulated dryland corn at Manhattan and irrigated corn at Garden City more accurately than irrigated corn at Manhattan (2005, 2006) and Rossville (2002). The correlation of measured corn yield with one Palmer amaranth plant m^{-1} of row to simulated yield was $r = 0.55$ ($p = 0.0993$) (Figure 3.1B), but corn yield with four Palmer amaranth plant m^{-1} of row ($r = 0.13$, $p = 0.7114$) was poorly simulated (Figure 3.1C). Corn yield was overestimated when competing with one and four Palmer amaranth plants m^{-1} of row (bias = 0.19, RMSE = 1.71 and bias = 0.93, RMSE = 1.64, respectively to one and four Palmer amaranth plants m^{-1} of row). A visual inspection of simulated corn yields with one and four Palmer amaranth plants m^{-1} of row indicated that the model consistently underestimated irrigated corn yield at Manhattan (2005, 2006) and Rossville (2002). Simulated corn yields with one and four Palmer amaranth plants m^{-1} of row dryland Manhattan 2006 were overestimated by 4.5 Mg ha^{-1}. Measured corn yields dryland Manhattan 2006 were very low due to early season water stress that continued throughout the growing season, this greatly reduced corn growth, while Palmer amaranth continued to grow well, while resulted in more interference and additional impact on corn growth and yield.

Measured and simulated corn yield losses with one Palmer amaranth plant m^{-1} of row were poorly correlated ($r = 0.07$) and overall simulated yield loss was underestimated (bias = -10.71, RMSE = 3.90) (Figure 3.2A). The range of measured corn yield losses for corn with one Palmer amaranth plant m^{-1} of row was 15 to 87% and for simulated corn yield losses was 21 to 35%. The simulated corn yield loss for 2006 dryland Manhattan resulted in an outlier for the model evaluation because the model failed to simulate corn yield with both weed pressure and severe water stress Likewise, the model also underestimated corn yield loss with four Palmer amaranth plants m^{-1} of row (bias = -13.88, RMSE = 5.08) but the correlation between measured and simulated corn yield loss did improve (r = 0.28) (Figure 3.2B). Again, the model poorly simulated 2006 Manhattan dryland corn yield loss but it also failed to simulate corn yield loss from the 1996 irrigated Garden City site.

The model's performance was improved when the data of the outlier site-year of 2006 Manhattan dryland was removed for corn yield loss from one Palmer amaranth plant m^{-1} of row (r = 0.41, bias = -5.24, RMSE = 3.77). When 2006 Manhattan dryland and 1996 Garden City irrigated data were removed from the data set, the correlation coefficient slightly decreased (r = 0.27) and the bias and RMSE values improved to -4.38 and 5.76, respectively (Data not shown).

DISCUSSION

Numerous corn-weed competition experiments conducted by the Kansas State Weed Ecology research group has resulted in crop failures because of drought and high temperatures leading to premature crop death or barren corn plants. These simulation results reflect a preliminary investigation of a crop-weed competition model to simulate corn yield with and without weed competition with a water-stress module.

Overall, the modified ALMANAC model did not simulate corn yields and yield loss as expected when compared to results of previous studies by McDonald and Riha (1999a, b). Their simulations adequately captured (average) monoculture corn grain yield and yield variation among years in the state of New York. Their model was also able to simulate corn yield loss from velvetleaf competition and segregate years when velvetleaf had a large impact on corn yield from years with little velvetleaf impact on corn yield, regardless of weed infestation density.

The results indicate that the modified ALMANAC model inadequately simulated monoculture corn yield in Kansas from the data sets used. When corn was competing with one Palmer amaranth plant m^{-1} of row, the model simulated Kansas dryland and irrigated yields with an average performance. The model was unable to simulate actual yield for corn with a moderate Palmer amaranth density, or capture the corn yield loss from Palmer amaranth among site-years, regardless of water management or weed density.

A number of observations/parameterizations highlighted the gaps, shortfalls, and limitations of the modified ALMANAC model to simulate corn yields in Kansas with very dynamic water environments, when competing with Palmer amaranth known to have very dynamic growth characteristics, and inadequate water uptake and light partitioning aspects of the model. Palmer amaranth growth was very plastic in order for it to compete aggressively with crops in diverse environments (Bensch et al. 2003, Klingaman and Oliver 1994, Liphadzi and Dille 2006, Massinga et al. 2001, Moore et al. 2004, Morgan et al. 2001, Rowland et al. 1999). When dryland corn was water stressed during the growing season, the Palmer amaranth continued to grow and overtop corn, thereby reducing light interception by corn. Palmer amaranth appeared to be less susceptible to water stress and was capable of maintaining growth when in competition with corn, thus increasing its competitiveness and causing more yield loss to already stressed corn. The modified ALMANAC model was not able to simulate crop and weed competition when soil water was limited, because plant available soil water was not partitioned adequately for those competing plants, as was described by McDonald and Riha (1999a). The model allows the first-established plant population (corn) to meet its daily transpirational demand, then the plant population established next (Palmer amaranth) is allowed to extract the remaining available soil water from the root zone. McDonald and Riha (1999a) implied that this method biases the impact of water storage against plant populations established after the first. They suggested future modifications to the model so it would partition available soil water to multiple competing plant populations based on root length density in a given soil layer, as described by Ball and Shaffer (1993). If this approach would be incorporated into the modified ALMANAC model, then model simulations would be improved to account for those weed populations capable of tolerating water stress when the crop is under water stress. This would provide much more realistic yield loss predictions in our semi-arid environments of Kansas.

The modified ALMANAC model was used because it incorporated a radiation-partitioning method described by Wallace (1995), which was an improvement over the original ALMANAC model because one specie's canopy does not exert complete dominance over the other specie's canopy. This simple method assumes, however that leaf area distribution is uniform over each plant population's canopy height. Massinga et al. (2003) reported that irrigated corn and Palmer amaranth in competition resulted in a corn leaf area distribution pattern that was similar across 0.5 to 8 Palmer amaranth plants m^{-1} densities, where 70 to 75% the total corn leaf area occurred 0.5 to 1.5 m above the ground. In contrast, Palmer amaranth intercepted 60 to 80% of the light 1 m above the ground, where 80% of the weed leaf area was concentrated.

Corn and Palmer amaranth do not have uniform vertical leaf area distribution, which is supported by Massinga et al. (2003) data. Also, our field observations revealed that Palmer amaranth competing with non-stressed corn distributes over 70% of its leaf area into the upper 20% of the canopy (Personnel observations). These plants produce fewer larger leaves slightly above the corn canopy, when compared to monoculture Palmer amaranth at low densities. Therefore, the model's solar radiation partitioning method could be improved to account for the vertical leaf area distribution of each plant population's canopy.

Overall, the modified ALMANAC model was a simple mechanistic plant competition model that simulated canopy level interactions over large areas, thus more generalized than models that simulate individual plant-to-plant interactions. Also, the modified ALMANAC model required fewer species-specific parameters allowing for simulations with limited data. The modified ALMANAC model distinguished dryland and irrigated corn yield thus appropriate for predicting yields in different environments. Improvements are needed however to partition water stress more appropriately across competing plant populations. Future modifications to the model need to maintain the simple parameterization utility as intended by the original ALMANAC model.

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FIGURES AND TABLES

Figure 3.1 Simulated corn yield across 10-12 site-years in Kansas using modified ALMANAC.

A) weed free corn yield; B) corn with one Palmer amaranth m^{-1} of row; C) corn with four Palmer amaranth m^{-1} of row. Simulations evaluated using: r = correlation coefficient; RMSE = root mean squared error (Mg ha^{-1}); and Bias = simulated minus measured (Mg ha^{-1}).

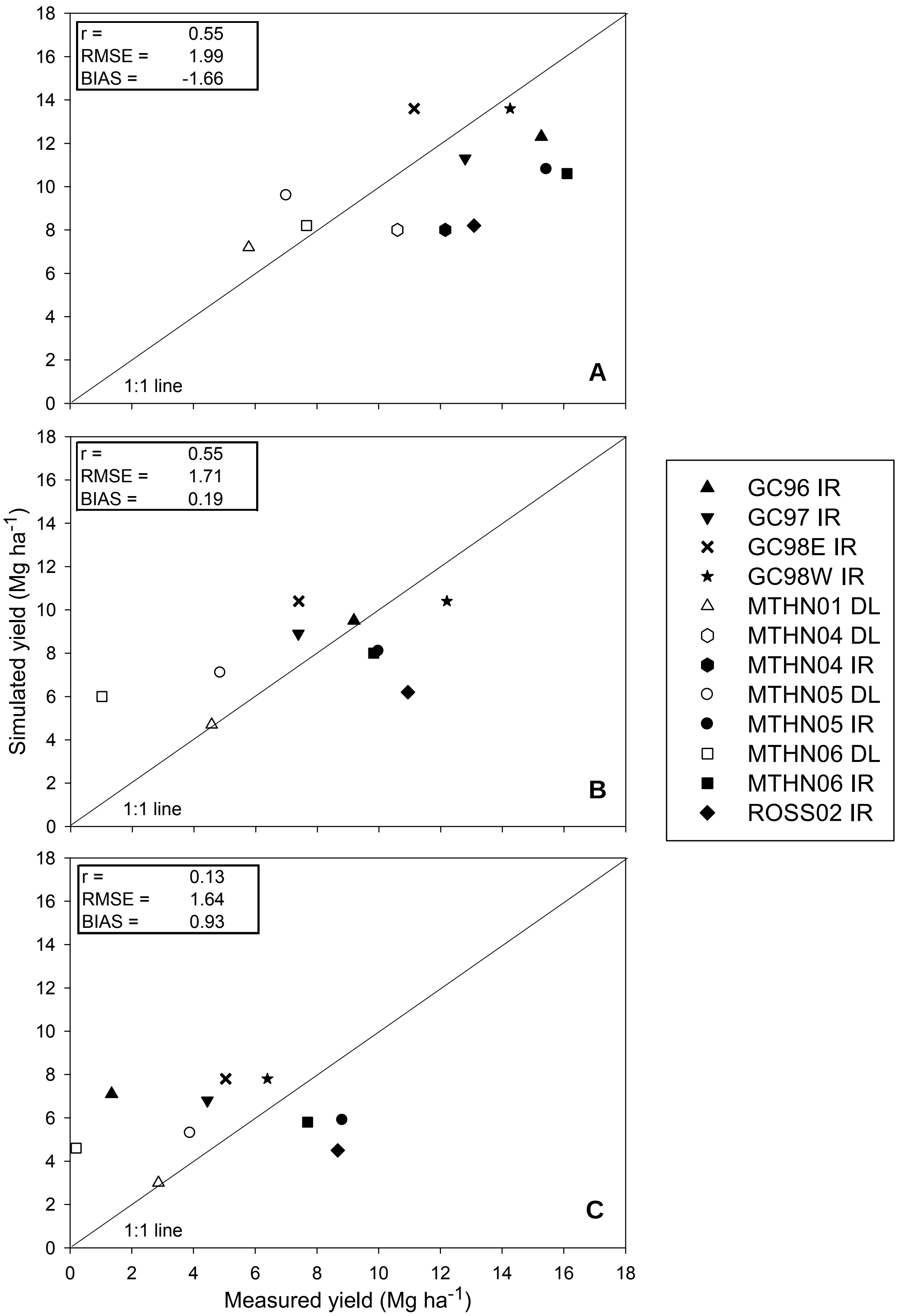
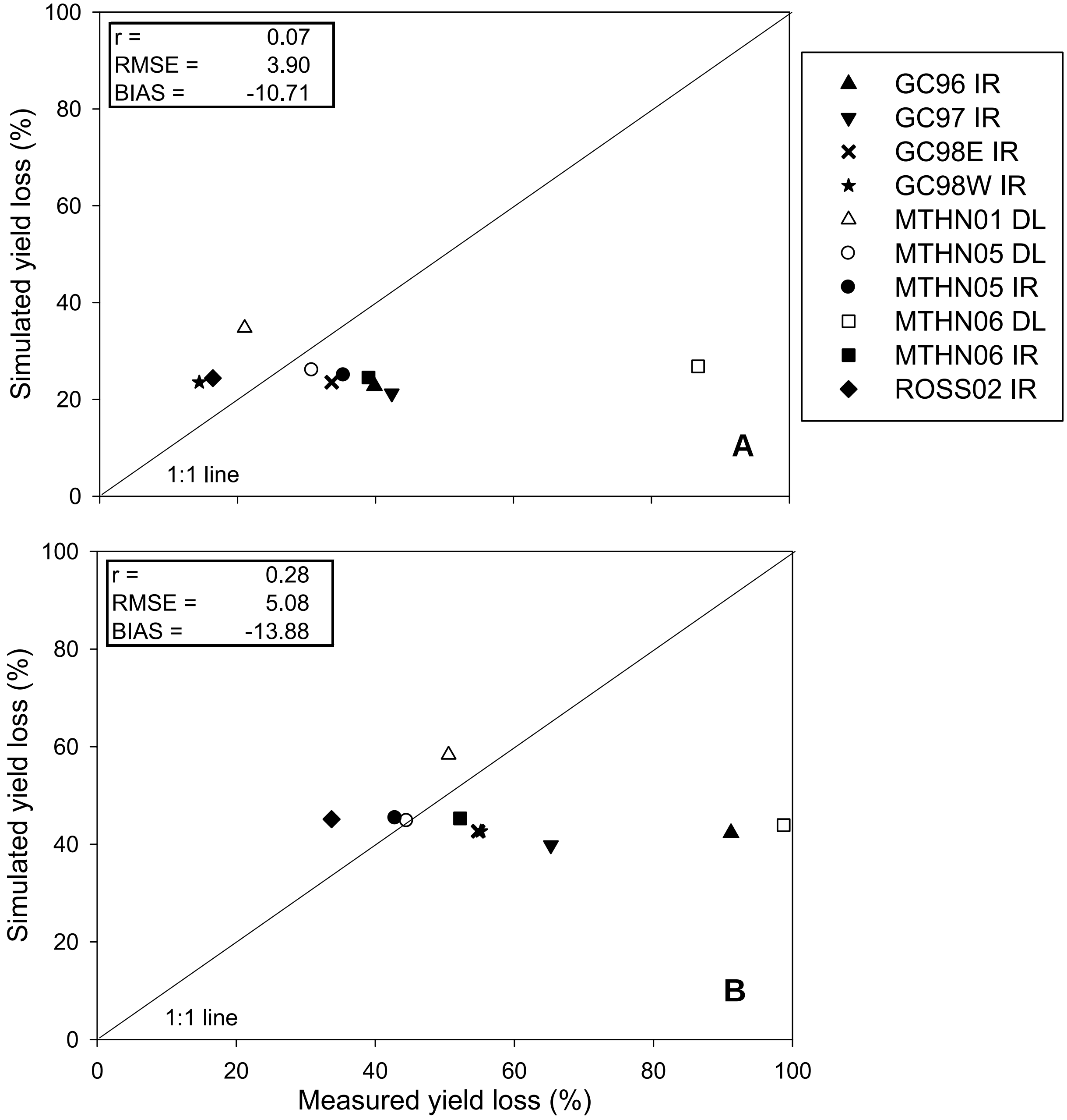

r = 0.55
RMSE = 1.99
BIAS = -1.66
A
1:1 line
r = 0.55
RMSE = 1.71
BIAS = 0.19
B
1:1 line
r = 0.13
RMSE = 1.64
BIAS = 0.93
C
1:1 line
Simulated yield (Mg ha-1)
Measured yield (Mg ha-1)
0
2
4
6
8
10
12
14
16
18
▲ GC96 IR
▼ GC97 IR
× GC98E IR
★ GC98W IR
△ MTHN01 DL
⬡ MTHN04 DL
⬢ MTHN04 IR
○ MTHN05 DL
● MTHN05 IR
□ MTHN06 DL
■ MTHN06 IR
◆ ROSS02 IR

Figure 3.2 Simulated corn yield loss across 10 site-years in Kansas using modified ALMANAC.

A) corn with one Palmer amaranth m^{-1} of row and B) corn with four Palmer amaranth m^{-1} of row. Simulations evaluated using: r = correlation coefficient; RMSE = root mean squared error (%); and Bias = simulated minus measured (%).



r = 0.07
RMSE = 3.90
BIAS = -10.71
A
1:1 line
r = 0.28
RMSE = 5.08
BIAS = -13.88
B
1:1 line
Simulated yield loss (%)
Simulated yield loss (%)
Measured yield loss (%)
0
20
40
60
80
100
▲ GC96 IR
▼ GC97 IR
× GC98E IR
★ GC98W IR
△ MTHN01 DL
○ MTHN05 DL
● MTHN05 IR
□ MTHN06 DL
■ MTHN06 IR
◆ ROSS02 IR

Table 3.1 Corn and Palmer amaranth plant input parameters used in modified ALMANAC.

Parameter	Units	Corn	Palmer amaranth
PHU (thermal units to maturity)	°C	1600	1600
RUE (radiation use efficiency)	kg MJ $^{-1}$	40	50
T_b (base temperature for development)	°C	10	10
k (light extinction coefficient)	—	0.65	0.95
HI (harvest index)	kg kg $^{-1}$	0.56	0.10
MaxHeight (maximum canopy height)	m	2.0	3.0
HeightPoint 1 (first point, height vs. heat unit curve)	X = proportion of PHU	0.1687	0.1687
	Y = proportion of MaxHeight	0.163	0.08
HeightPoint 2 (second point, height vs. heat unit curve)	X = proportion of PHU	0.3125	0.3125
	Y = proportion of MaxHeight	0.564	0.44
MaxLAI (maximum potential LAI)	m m $^{-2}$	6.0	4.5
LAIPoint 1 (first point, LAI vs. heat unit curve)	x = proportion of PHU	0.1687	0.1687
	y = proportion of potential LAI	0.0731	0.02
LAIPoint 2 (second point, LAI vs. heat unit curve)	x = proportion of PHU	0.3125	0.3125
	y = proportion of potential LAI	0.7164	0.53
LAI-Pop 1 (first point, LAI vs. plant density curve)	x = density (plant m $^{-2}$)	5.0	1.0
	y = proportion of MaxLAI	0.66	0.45
LAI-Pop 2 (second point, LAI vs. plant density curve)	x = density (plant m $^{-2}$)	6.5	10.5
	y = proportion of MaxLAI	0.83	0.95

Table 3.2 Sources of year-site data for validation of model.

Year	Site	Water management	Code[4]	Corn density Plants m^{-2}	Soil series
1996	Garden City[3]	Furrow irrigated	GC96 IR	7.5	Ritchfield silt loam
1997	Garden City[3]	Furrow irrigated	GC97 IR	7.5	Ritchfield silt loam
1998E	Garden City[3]	Furrow irrigated	GC98E IR	7.5	Ritchfield silt loam
1998W	Garden City[3]	Furrow irrigated	GC98W IR	7.5	Ritchfield silt loam
2001	Manhattan[1]	Dryland	MTHN01 DL	5.5	Reading silt loam
2004	Manhattan[2]	Dryland	MTHN04 DL	5.5	Bismarckgrove silt loam
2004	Manhattan[2]	Furrow irrigated	MTHN04 IR	5.5	Bismarckgrove silt loam
2005	Manhattan[2]	Dryland	MTHN05 DL	6.8	Eudora silt loam
2005	Manhattan[2]	Furrow irrigated	MTHN05 IR	6.8	Eudora silt loam
2006	Manhattan[2]	Dryland	MTHN06 DL	7.8	Belvue silt loam
2006	Manhattan[2]	Furrow irrigated	MTHN06 IR	7.8	Belvue silt loam
2002	Rossville[1]	Sprinkler irrigated	ROSS02 IR	7.4	Eudora silt loam

[1] Site data source: Liphadzi 2004; Liphadzi and Dille 2006

[2] Site data source: 2004 Rule unpublished data; 2005 and 2006 Rule 2007 Chapter 1

[3] Site data source: Massinga 2000; Massinga et al. 2001; Massinga et al. 2003

[4] Code represents site, year, and water management for year-site figure legends

CONCLUSIONS

This research investigated Palmer amaranth interference with corn across dryland and irrigated environments in the same site-year and location. Previous research had conducted corn and Palmer amaranth interference studies in dryland and irrigated environments, but not in the same site, year or/and under similar management. This field study improved the understanding of corn and Palmer amaranth growth and development throughout the growing season when grown alone and in competition. It also provided information to explain the causes of corn yield loss from Palmer amaranth competition in different soil water available environments (Chapters 1 and 2). The crop model research evaluated the performance of the modified ALMANAC model to simulate corn yield and corn yield loss from Palmer amaranth competition in Kansas (Chapter 3). The information obtained provided a better understanding of corn yield loss from Palmer amaranth competition to maximize corn yield potential.

Chapter 1

The results of this study showed that corn and Palmer amaranth growth, development, and grain (seed) production potential were dependent on which species had the competitive ability to capture a limiting resource (water and light). In this side-by-side comparison with different soil water environments, water stress negatively impacted corn more than Palmer amaranth and the magnitude of reductions depended on corn's ability to suppress Palmer amaranth. Our results showed that when Palmer amaranth had rapid early season growth, it was able to interfere more with corn and cause greater reductions in dry weight and LAI. Water-stressed dryland corn did not have the ability to suppress Palmer amaranth and subsequently Palmer amaranth significantly reduced corn growth and yield. The extent of dryland corn yield loss depended on the period of water stress and weed density, whereas irrigated corn yield losses were caused by a decrease in light interception from Palmer amaranth interference. When water stress was mid-late season, dryland corn yield loss with increasing Palmer amaranth density was similar to irrigated corn yield loss. In 2006, early season water stress limited dryland corn yield potential and was further reduced with the presence of Palmer amaranth and water stress during grain fill. Palmer amaranth seed production plant^{-1} decreased with increasing Palmer amaranth density and the number of seeds m^{-2} increased with increasing density with corn.

Chapter 2

The soil VWC measurements demonstrated the seasonal trends of soil water with respect to precipitation and irrigation, soil physical properties, root distributions, ET_{Corn}, and soil water depletion rates in the 0 to 30 cm depth of the soil profile. The 2005 soil had higher plant available soil water content than the 2006 soil, which subsequently generated more water stress with less precipitation in the dryland environment. The soil VWC measurements in the field experiment provided an estimate of soil water in the 0 to 15 cm and 0 to 30 cm depth, where over 60% of the roots were found in monoculture corn and Palmer amaranth. Reductions in corn growth and development from water stress depended on the water requirement of corn with respect to stage of development, available soil water, and the extent of Palmer amaranth interference. Soil water depletion rates during drying periods were higher when total added precipitation with and without irrigation was high and plant population water demand was high.

Palmer amaranth with corn can deplete the soil water more than monoculture corn when plants were not water stressed. Severe water-stressed dryland corn with Palmer amaranth had lower soil water depletion rates than monoculture Palmer amaranth. The research results presented were for the upper 30 cm and future research is needed to determine the soil water extraction in the soil profile throughout the growing season along with the root distributions of corn with Palmer amaranth in different soil water availability regimes. Also, future research investigating soil water competition should have replication for the treatments and for individual plants of interest, along with profile measurement for soil water content change with increasing depth to the root zone.

Chapter 3

Overall, the modified ALMANAC model did not simulate corn yields and yield loss as expected, when compared to results of previously reported simulations. The results indicated that the modified ALMANAC model inadequately simulated monoculture corn yield in Kansas from the data sets used. When corn was competing with one Palmer amaranth plant m^{-1} of row, the model simulated Kansas dryland and irrigated yields with an average performance. The model was unable to simulate actual yield for corn with a moderate Palmer amaranth density, or to capture the corn yield loss from Palmer amaranth among site-years, regardless of water management or weed density. The model underestimated monoculture corn yield but overestimated corn yield with Palmer amaranth competition. The model performance was not consistent when comparing simulation results to dryland and irrigated experiments conducted across Kansas.

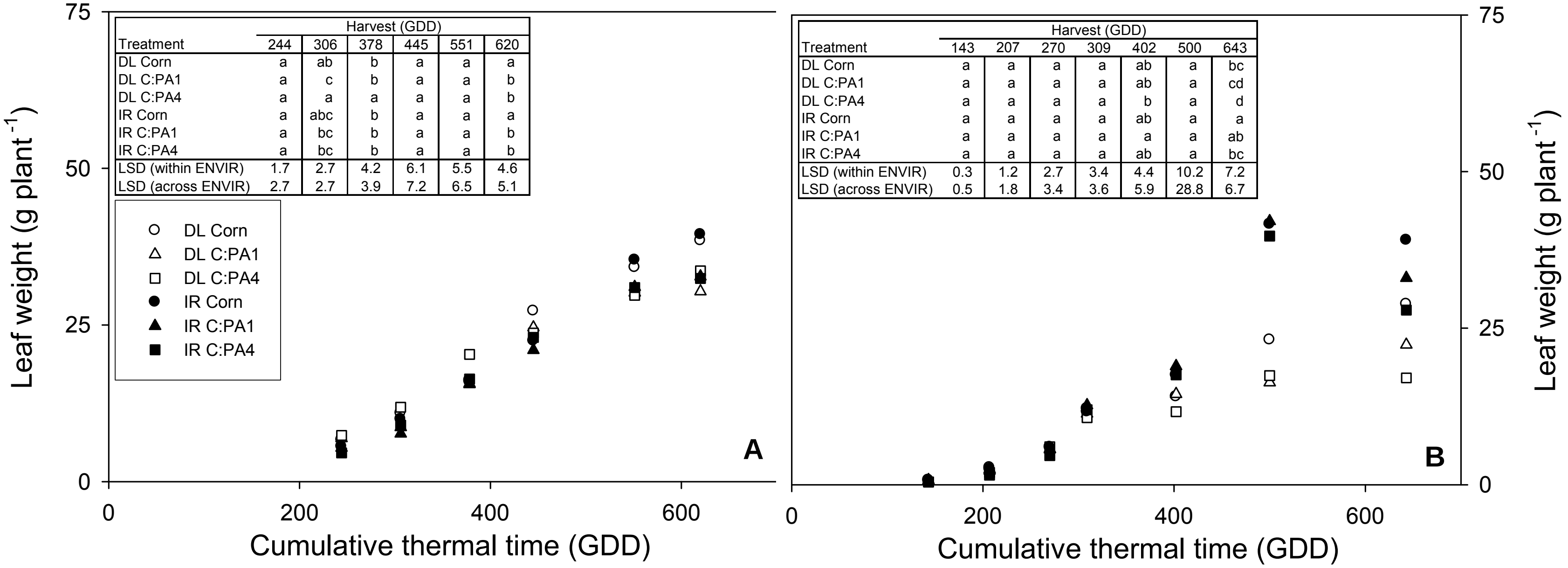
A number of observations/parameterizations highlighted the gaps, shortfalls, and limitations of the modified ALMANAC model to simulate corn yields in Kansas with very dynamic water environments, when competing with Palmer amaranth known to have very dynamic growth characteristics, and inadequate water uptake and light partitioning aspects of the model. The modified ALMANAC model was not able to capture the plastic growth of Palmer amaranth and subsequently, could not simulate Palmer amaranth competition with corn. When dryland corn was water stressed during the growing season, the Palmer amaranth continued to grow and overtop corn, thereby reducing light interception by corn. Palmer amaranth appears to be less susceptible to water stress and is capable of maintaining growth when in competition with corn, thus increasing its competitiveness and causing more yield loss to already stressed corn. The modified ALMANAC model was not able to simulate crop and weed competition when soil water was limited because plant-available soil water was not partitioned adequately for the competing plants. The modified ALMANAC model distinguished dryland and irrigated corn yield, thus it was appropriate for predicting yields in different environments. Improvements are needed to partition water stress more appropriately across competing plant populations, which would add value for the modified ALMANAC model to be used as a tool to improve corn and Palmer amaranth competition in diverse environments and management practices.

Overall summary

Results of this research improved the understanding of interactions between corn and Palmer amaranth when soil water was both optimum and limited throughout the growing season. The information gained from this experiment has provided an improved understanding of corn yield loss risks associated with water management and Palmer amaranth competition. The research provided results to re-emphasize that corn management can be used as a tool to suppress weed competitiveness and ultimately minimize potential yield loss. When improvements to the modified ALMANAC model for soil water and light partitions are made, then future simulations can be conducted to explore and evaluate corn and Palmer amaranth interactions under limited irrigation systems to improve irrigation application profitability and environmental stewardship of water use. This future knowledge will improve crop-weed competition models and ultimately, optimize corn water use and weed management decisions in diverse environments.

Appendix A - Chapter 1

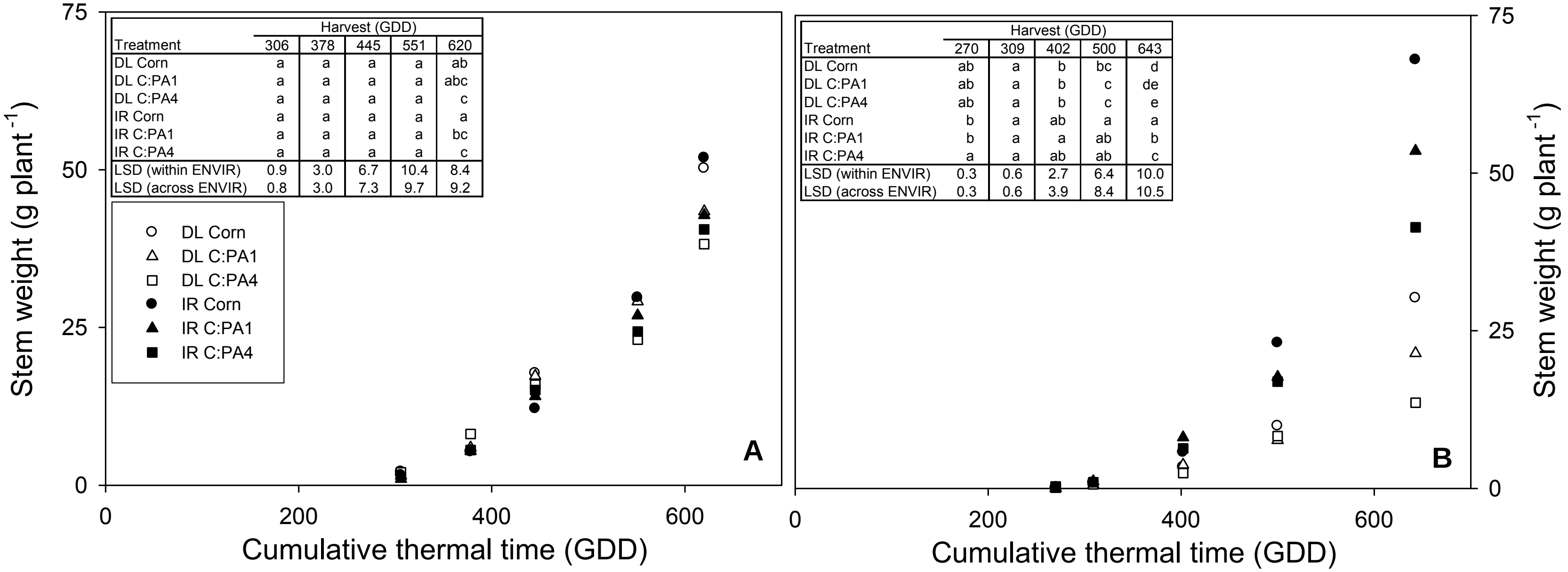
Figure A.1 Corn leaf dry weight (g plant^{-1}) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (Corn) and with one (C:PA1) or four (C:PA4) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B). Letter within columns by harvest date compare means using LSD (across ENVIR).



	Harvest (GDD)					
Treatment	244	306	378	445	551	620
DL Corn	a	ab	b	a	a	a
DL C:PA1	a	c	b	a	a	b
DL C:PA4	a	a	a	a	a	b
IR Corn	a	abc	b	a	a	a
IR C:PA1	a	bc	b	a	a	b
IR C:PA4	a	bc	b	a	a	b
LSD (within ENVIR)	1.7	2.7	4.2	6.1	5.5	4.6
LSD (across ENVIR)	2.7	2.7	3.9	7.2	6.5	5.1

	Harvest (GDD)						
Treatment	143	207	270	309	402	500	643
DL Corn	a	a	a	a	ab	a	bc
DL C:PA1	a	a	a	a	ab	a	cd
DL C:PA4	a	a	a	a	b	a	d
IR Corn	a	a	a	a	ab	a	a
IR C:PA1	a	a	a	a	a	a	ab
IR C:PA4	a	a	a	a	ab	a	bc
LSD (within ENVIR)	0.3	1.2	2.7	3.4	4.4	10.2	7.2
LSD (across ENVIR)	0.5	1.8	3.4	3.6	5.9	28.8	6.7

Figure A.2 Corn stem dry weight (g plant^{-1}) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (Corn) and with one (C:PA1) or four (C:PA4) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B). Letter within columns by harvest date compare means using LSD (across ENVIR).

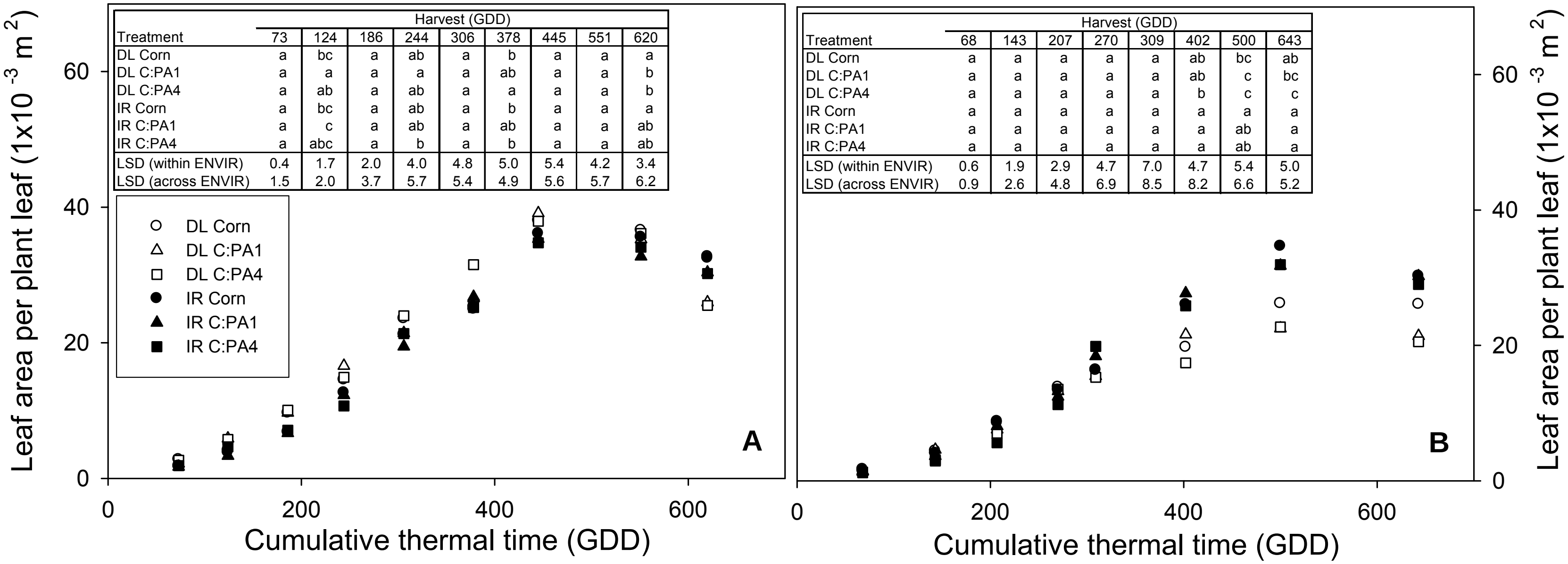


Treatment	Harvest (GDD)				
	306	378	445	551	620
DL Corn	a	a	a	a	ab
DL C:PA1	a	a	a	a	abc
DL C:PA4	a	a	a	a	c
IR Corn	a	a	a	a	a
IR C:PA1	a	a	a	a	bc
IR C:PA4	a	a	a	a	c
LSD (within ENVIR)	0.9	3.0	6.7	10.4	8.4
LSD (across ENVIR)	0.8	3.0	7.3	9.7	9.2

Treatment	Harvest (GDD)				
	270	309	402	500	643
DL Corn	ab	a	b	bc	d
DL C:PA1	ab	a	b	c	de
DL C:PA4	ab	a	b	c	e
IR Corn	b	a	ab	a	a
IR C:PA1	b	a	a	ab	b
IR C:PA4	a	a	ab	ab	c
LSD (within ENVIR)	0.3	0.6	2.7	6.4	10.0
LSD (across ENVIR)	0.3	0.6	3.9	8.4	10.5

Figure A.3 Corn leaf area per plant leaf (1 x 10^{-3} m^2) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (Corn) and with one (C:PA1) or four (C:PA4) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).

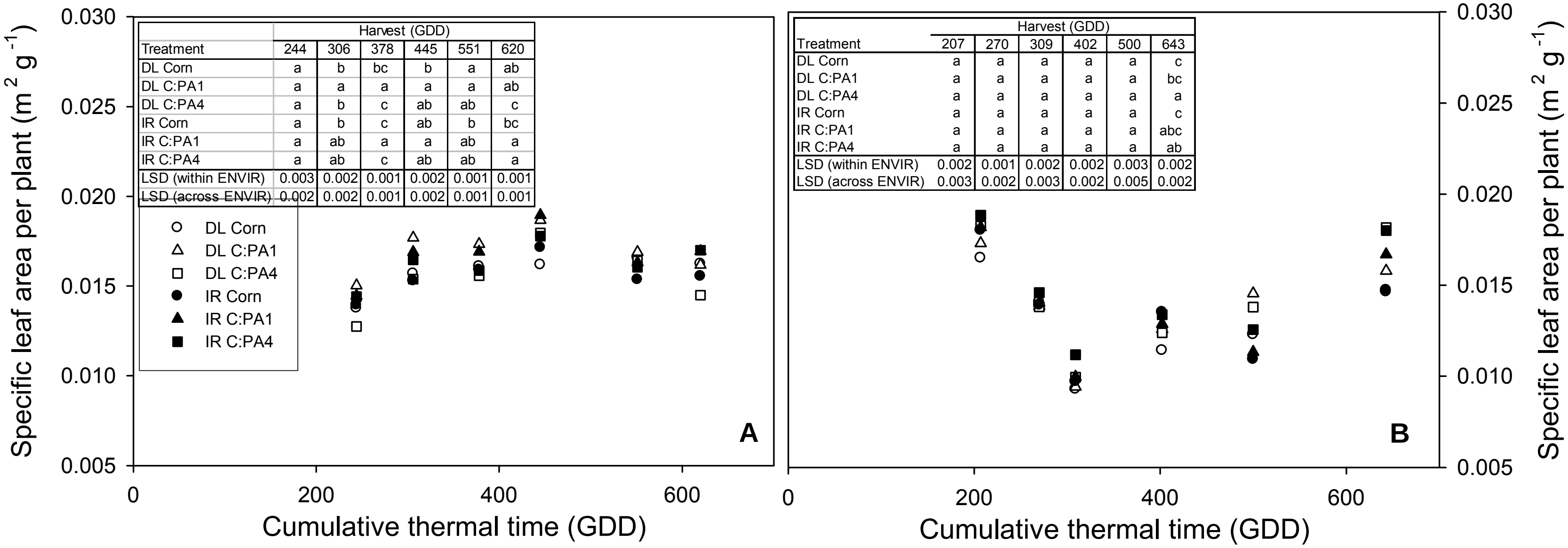


Treatment	Harvest (GDD) 73	124	186	244	306	378	445	551	620
DL Corn	a	bc	a	ab	a	b	a	a	a
DL C:PA1	a	a	a	a	a	ab	a	a	b
DL C:PA4	a	ab	a	ab	a	a	a	a	b
IR Corn	a	bc	a	ab	a	b	a	a	a
IR C:PA1	a	c	a	ab	a	ab	a	a	ab
IR C:PA4	a	abc	a	b	a	b	a	a	ab
LSD (within ENVIR)	0.4	1.7	2.0	4.0	4.8	5.0	5.4	4.2	3.4
LSD (across ENVIR)	1.5	2.0	3.7	5.7	5.4	4.9	5.6	5.7	6.2

Treatment	Harvest (GDD) 68	143	207	270	309	402	500	643
DL Corn	a	a	a	a	a	ab	bc	ab
DL C:PA1	a	a	a	a	a	ab	c	bc
DL C:PA4	a	a	a	a	a	b	c	c
IR Corn	a	a	a	a	a	a	a	a
IR C:PA1	a	a	a	a	a	a	ab	a
IR C:PA4	a	a	a	a	a	a	ab	a
LSD (within ENVIR)	0.6	1.9	2.9	4.7	7.0	4.7	5.4	5.0
LSD (across ENVIR)	0.9	2.6	4.8	6.9	8.5	8.2	6.6	5.2

Figure A.4 Corn specific leaf area per plant leaf (m^2 g^{-1}) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (Corn) and with one (C:PA1) or four (C:PA4) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).

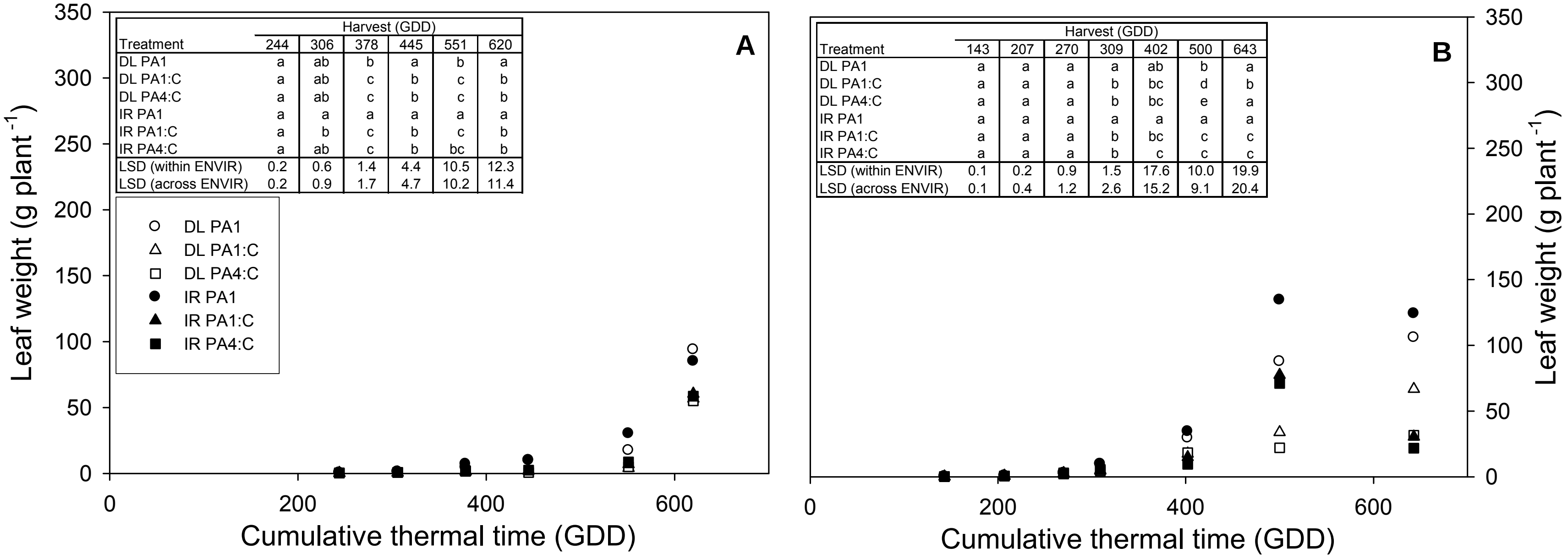


	Harvest (GDD)					
Treatment	244	306	378	445	551	620
DL Corn	a	b	bc	b	a	ab
DL C:PA1	a	a	a	a	a	ab
DL C:PA4	a	b	c	ab	ab	c
IR Corn	a	b	c	ab	b	bc
IR C:PA1	a	ab	a	a	ab	a
IR C:PA4	a	ab	c	ab	ab	a
LSD (within ENVIR)	0.003	0.002	0.001	0.002	0.001	0.001
LSD (across ENVIR)	0.002	0.002	0.001	0.002	0.001	0.001

	Harvest (GDD)					
Treatment	207	270	309	402	500	643
DL Corn	a	a	a	a	a	c
DL C:PA1	a	a	a	a	a	bc
DL C:PA4	a	a	a	a	a	a
IR Corn	a	a	a	a	a	c
IR C:PA1	a	a	a	a	a	abc
IR C:PA4	a	a	a	a	a	ab
LSD (within ENVIR)	0.002	0.001	0.002	0.002	0.003	0.002
LSD (across ENVIR)	0.003	0.002	0.003	0.002	0.005	0.002

Figure A.5 Palmer amaranth leaf dry weight (g plant^{-1}) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (PA1) at one Palmer amaranth plant m^{-1} of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).

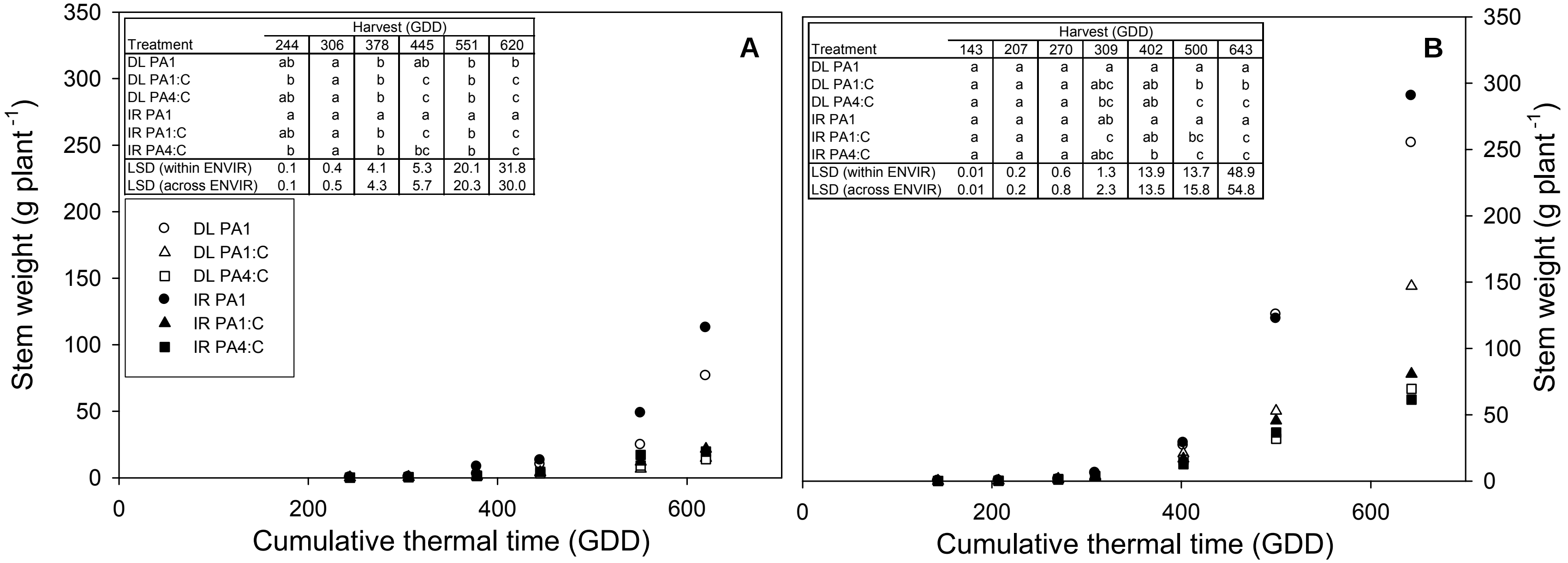


	Harvest (GDD)					
Treatment	244	306	378	445	551	620
DL PA1	a	ab	b	a	b	a
DL PA1:C	a	ab	c	b	c	b
DL PA4:C	a	ab	c	b	c	b
IR PA1	a	a	a	a	a	a
IR PA1:C	a	b	c	b	c	b
IR PA4:C	a	ab	c	b	bc	b
LSD (within ENVIR)	0.2	0.6	1.4	4.4	10.5	12.3
LSD (across ENVIR)	0.2	0.9	1.7	4.7	10.2	11.4

	Harvest (GDD)						
Treatment	143	207	270	309	402	500	643
DL PA1	a	a	a	a	ab	b	a
DL PA1:C	a	a	a	b	bc	d	b
DL PA4:C	a	a	a	b	bc	e	a
IR PA1	a	a	a	a	a	a	a
IR PA1:C	a	a	a	b	bc	c	c
IR PA4:C	a	a	a	b	c	c	c
LSD (within ENVIR)	0.1	0.2	0.9	1.5	17.6	10.0	19.9
LSD (across ENVIR)	0.1	0.4	1.2	2.6	15.2	9.1	20.4

Figure A.6 Palmer amaranth stem dry weight (g plant^{-1}) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (PA1) at one Palmer amaranth plant m^{-1} of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).

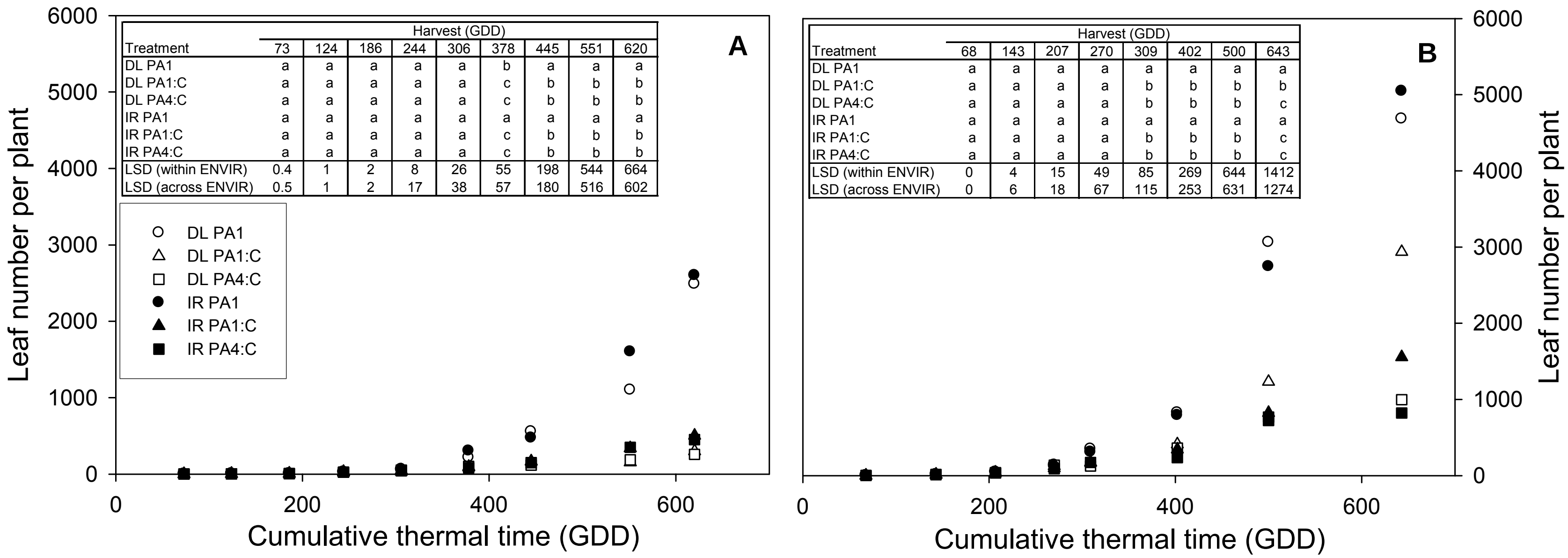


	Harvest (GDD)					
Treatment	244	306	378	445	551	620
DL PA1	ab	a	b	ab	b	b
DL PA1:C	b	a	b	c	b	c
DL PA4:C	ab	a	b	c	b	c
IR PA1	a	a	a	a	a	a
IR PA1:C	ab	a	b	c	b	c
IR PA4:C	b	a	b	bc	b	c
LSD (within ENVIR)	0.1	0.4	4.1	5.3	20.1	31.8
LSD (across ENVIR)	0.1	0.5	4.3	5.7	20.3	30.0

	Harvest (GDD)						
Treatment	143	207	270	309	402	500	643
DL PA1	a	a	a	a	a	a	a
DL PA1:C	a	a	a	abc	ab	b	b
DL PA4:C	a	a	a	bc	ab	c	c
IR PA1	a	a	a	ab	a	a	a
IR PA1:C	a	a	a	c	ab	bc	c
IR PA4:C	a	a	a	abc	b	c	c
LSD (within ENVIR)	0.01	0.2	0.6	1.3	13.9	13.7	48.9
LSD (across ENVIR)	0.01	0.2	0.8	2.3	13.5	15.8	54.8

Figure A.7 Palmer amaranth leaf number per plant in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (PA1) at one Palmer amaranth plant m^{-1} of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).

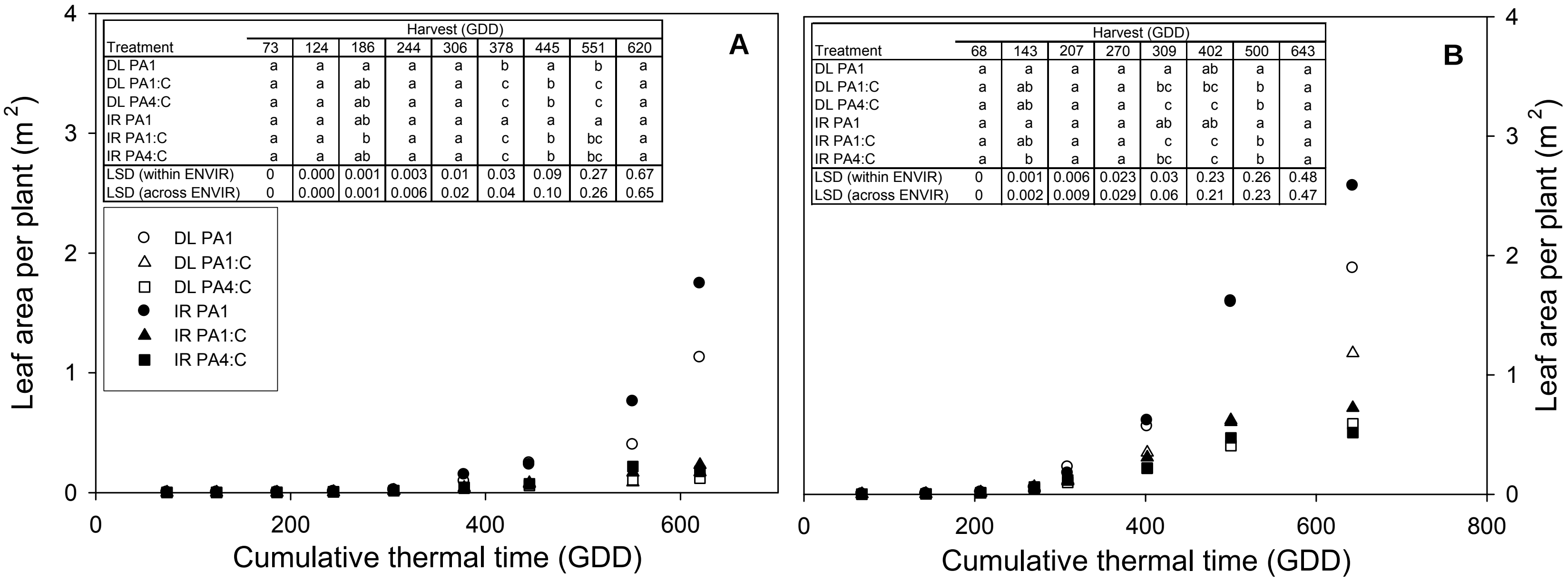


	Harvest (GDD)								
Treatment	73	124	186	244	306	378	445	551	620
DL PA1	a	a	a	a	a	b	a	a	a
DL PA1:C	a	a	a	a	a	c	b	b	b
DL PA4:C	a	a	a	a	a	c	b	b	b
IR PA1	a	a	a	a	a	a	a	a	a
IR PA1:C	a	a	a	a	a	c	b	b	b
IR PA4:C	a	a	a	a	a	c	b	b	b
LSD (within ENVIR)	0.4	1	2	8	26	55	198	544	664
LSD (across ENVIR)	0.5	1	2	17	38	57	180	516	602

	Harvest (GDD)							
Treatment	68	143	207	270	309	402	500	643
DL PA1	a	a	a	a	a	a	a	a
DL PA1:C	a	a	a	a	b	b	b	b
DL PA4:C	a	a	a	a	b	b	b	c
IR PA1	a	a	a	a	a	a	a	a
IR PA1:C	a	a	a	a	b	b	b	c
IR PA4:C	a	a	a	a	b	b	b	c
LSD (within ENVIR)	0	4	15	49	85	269	644	1412
LSD (across ENVIR)	0	6	18	67	115	253	631	1274

Figure A.8 Palmer amaranth leaf area per plant (m^2) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (PA1) at one Palmer amaranth plant m^{-1} of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).



A

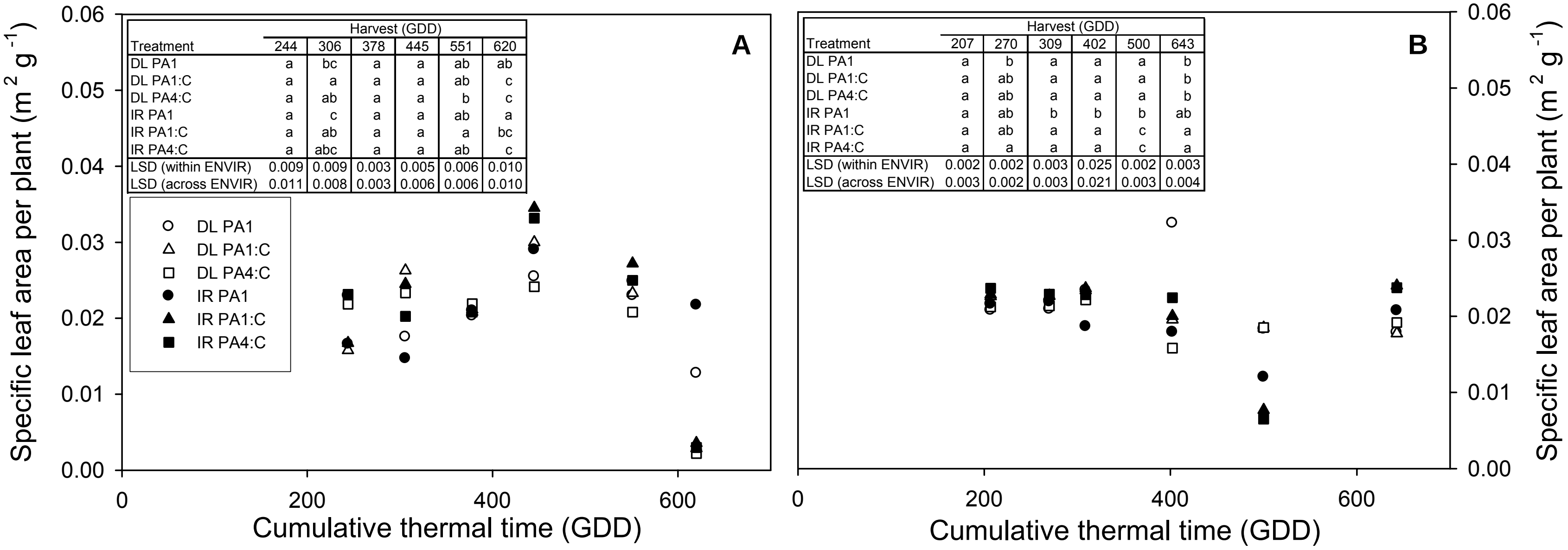
	Harvest (GDD)								
Treatment	73	124	186	244	306	378	445	551	620
DL PA1	a	a	a	a	a	b	a	b	a
DL PA1:C	a	a	ab	a	a	c	b	c	a
DL PA4:C	a	a	ab	a	a	c	b	c	a
IR PA1	a	a	ab	a	a	a	a	a	a
IR PA1:C	a	a	b	a	a	c	b	bc	a
IR PA4:C	a	a	ab	a	a	c	b	bc	a
LSD (within ENVIR)	0	0.000	0.001	0.003	0.01	0.03	0.09	0.27	0.67
LSD (across ENVIR)	0	0.000	0.001	0.006	0.02	0.04	0.10	0.26	0.65

B

	Harvest (GDD)							
Treatment	68	143	207	270	309	402	500	643
DL PA1	a	a	a	a	a	ab	a	a
DL PA1:C	a	ab	a	a	bc	bc	b	a
DL PA4:C	a	ab	a	a	c	c	b	a
IR PA1	a	a	a	a	ab	ab	a	a
IR PA1:C	a	ab	a	a	c	c	b	a
IR PA4:C	a	b	a	a	bc	c	b	a
LSD (within ENVIR)	0	0.001	0.006	0.023	0.03	0.23	0.26	0.48
LSD (across ENVIR)	0	0.002	0.009	0.029	0.06	0.21	0.23	0.47

Figure A.9 Palmer amaranth specific leaf area per plant (m^2 g^{-1}) in dryland (DL-open symbols) and irrigated (IR-closed symbols) environments grown alone (PA1) at one Palmer amaranth plant m^{-1} of row and with corn at one (PA1:C) or four (PA4:C) Palmer amaranth plants m^{-1} of row in 2005 (A) and 2006 (B).

Letter within columns by harvest date compare means using LSD (across ENVIR).



	Harvest (GDD)					
Treatment	244	306	378	445	551	620
DL PA1	a	bc	a	a	ab	ab
DL PA1:C	a	a	a	a	ab	c
DL PA4:C	a	ab	a	a	b	c
IR PA1	a	c	a	a	ab	a
IR PA1:C	a	ab	a	a	a	bc
IR PA4:C	a	abc	a	a	ab	c
LSD (within ENVIR)	0.009	0.009	0.003	0.005	0.006	0.010
LSD (across ENVIR)	0.011	0.008	0.003	0.006	0.006	0.010

	Harvest (GDD)					
Treatment	207	270	309	402	500	643
DL PA1	a	b	a	a	a	b
DL PA1:C	a	ab	a	a	a	b
DL PA4:C	a	ab	a	a	a	b
IR PA1	a	ab	b	b	b	ab
IR PA1:C	a	ab	a	a	c	a
IR PA4:C	a	a	a	a	c	a
LSD (within ENVIR)	0.002	0.002	0.003	0.025	0.002	0.003
LSD (across ENVIR)	0.003	0.002	0.003	0.021	0.003	0.004

Table A.1 Field experiment irrigation applications for 2005 and 2006.

Year	Calender Date	DOY[1]	Thermal time (GDD[2])	Soil water environment Dryland	Soil water environment Irrigated
				mm	mm
2005	May 12	132	—	50.8	50.8
	May 20	140	—	50.8	50.8
	June 27	178	503	—	50.8
	July 14	195	760	—	50.8
	July 28	209	991	—	50.8
	Aug. 9	221	1,184	—	50.8
2006	May 15	135	—	50.8	50.8
	June 9	160	271	—	50.8
	June 22	173	452	—	50.8
	June 30	181	560	—	50.8
	July 19	200	880	—	50.8
	July 27	208	1,013	—	50.8
	Aug. 2	214	1,134	—	50.8
	Aug. 10	222	1,285	—	50.8

[1] DOY = Day of Year

[2] GDD = Growing degree days (Cumulative GDD from emergence)

Appendix B - Chapter 3

Figure B.1 Effective precipitation prior to soil drying period (A), rate of soil water depletion and corn evapotranspiration (B) for each drying period in the 0 to 15 cm depth in the dryland environment in 2005.

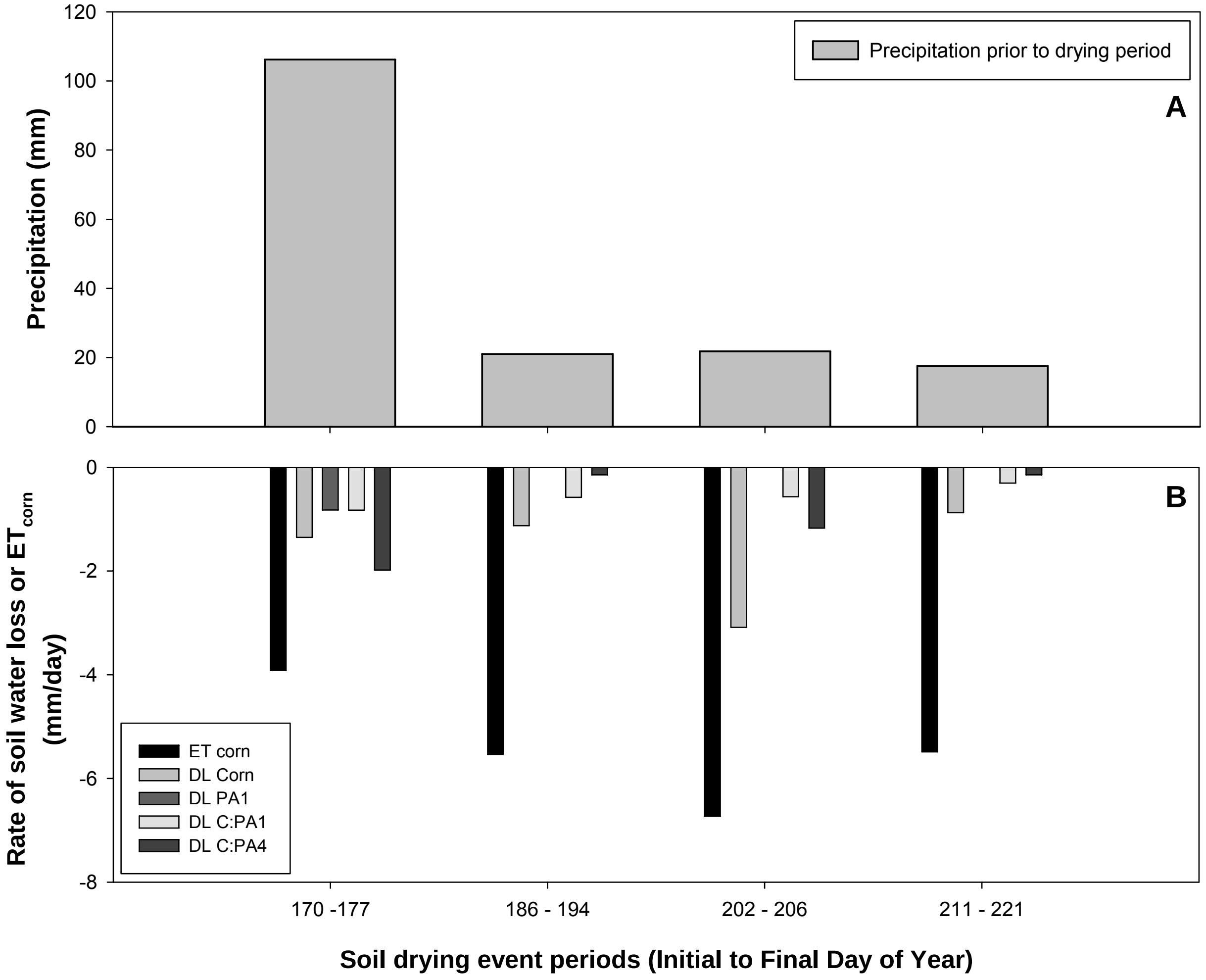


Figure B.2 Effective precipitation + irrigation prior to soil drying period (A), rate of soil water depletion and corn evapotranspiration (B) for each drying period in the 0 to 15 cm depth in the irrigated environment in 2005.

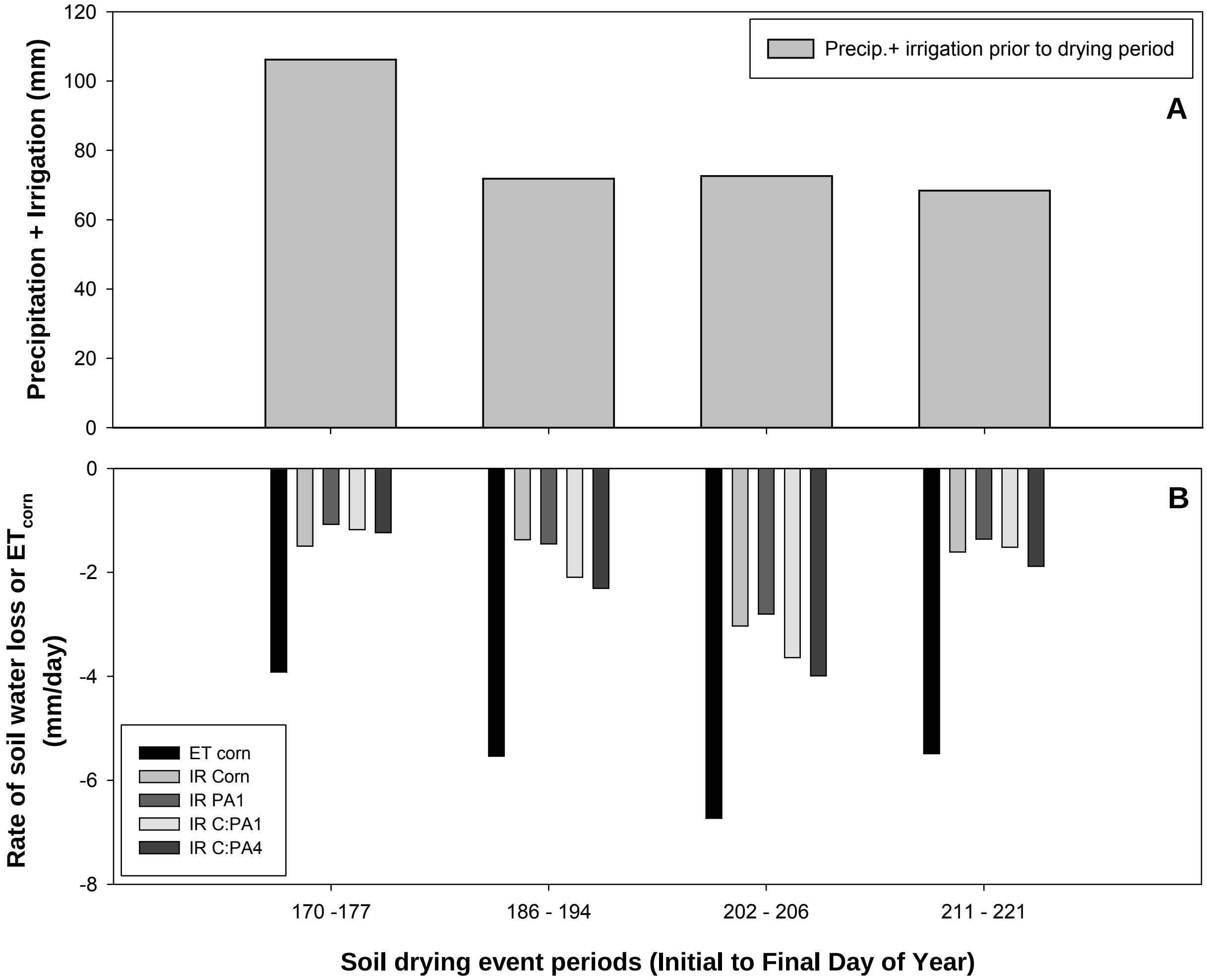


Figure B.3 Effective precipitation prior to soil drying period (A), rate of soil water depletion and corn evapotranspiration (B) for each drying period in the 0 to 15 cm depth in the dryland environment in 2006.

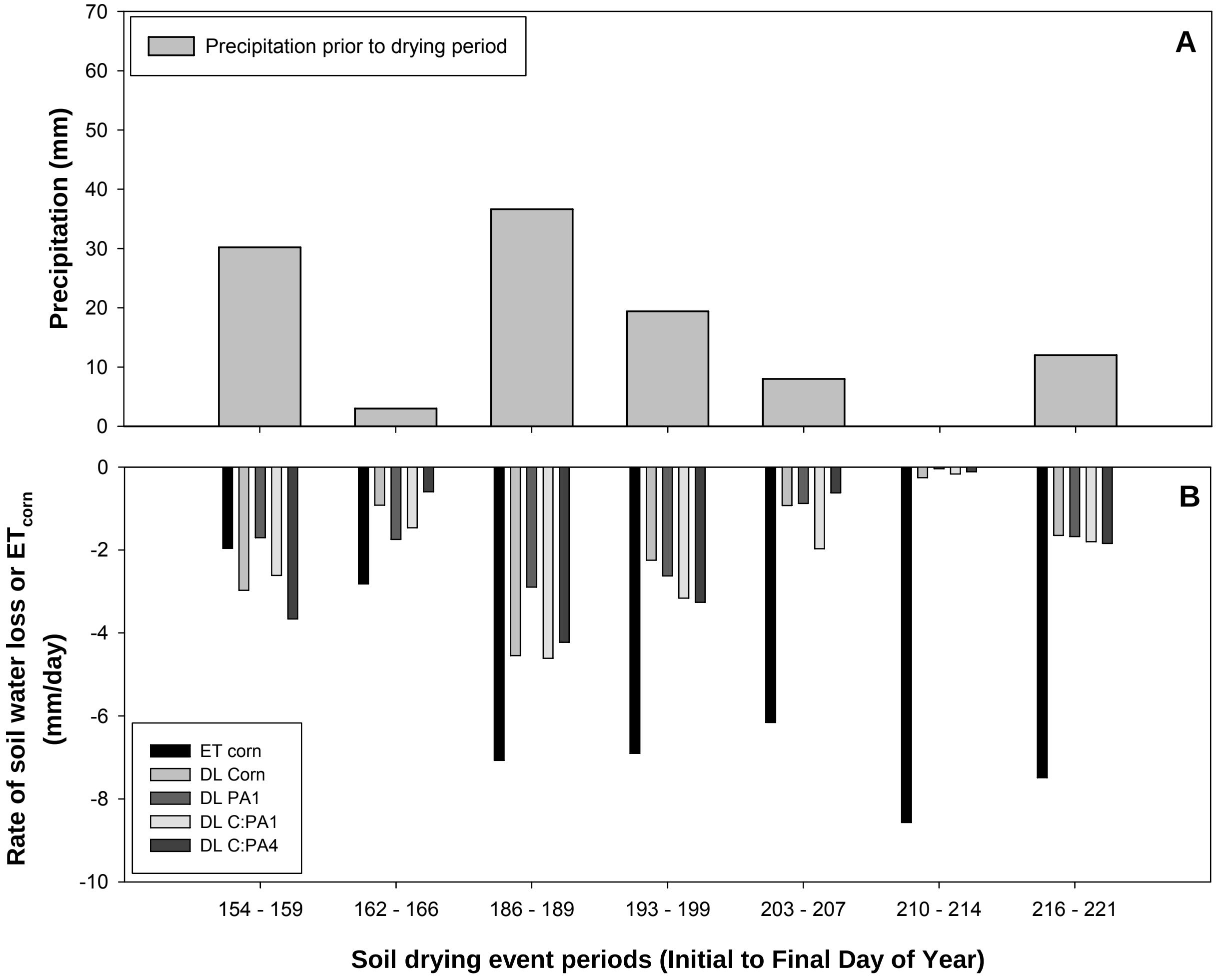


Figure B.4 Effective precipitation + irrigation prior to soil drying period (A), rate of soil water depletion and corn evapotranspiration (B) for each drying period in the 0 to 15 cm depth in the irrigated environment in 2006.

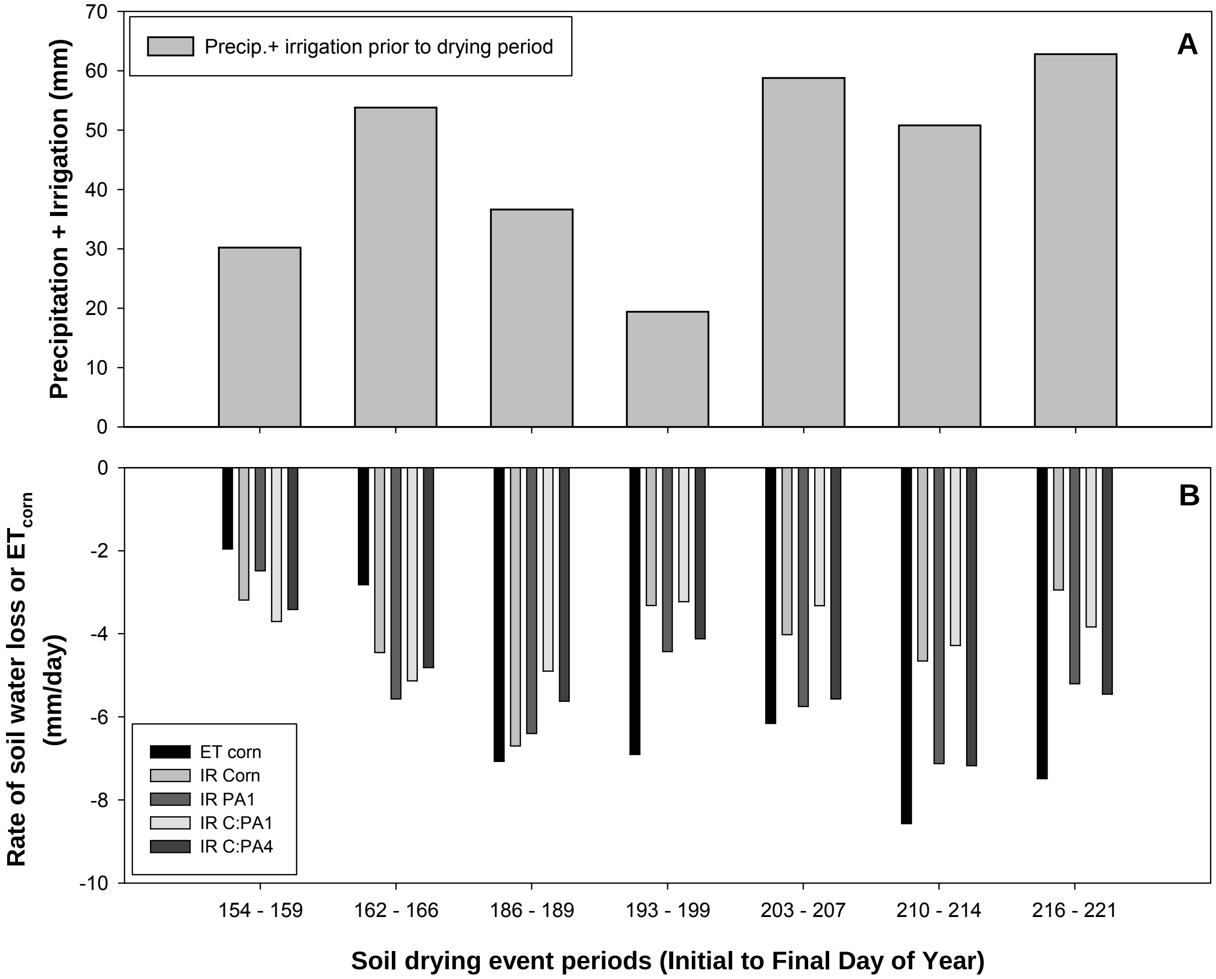


Table B.1 Soil water content at selected soil water potentials of the Eudora (2005) and Belvue (2006) field experiment soils at Manhattan, KS.

Eudora silt loam (2005)

	Water content				
	Soil water potential				
Sample analyses[1]	(-0.010 MPa)	(-0.020 MPa)	(-0.030 MPa)	(-0.040 MPa)	(-1.50 MPa)
	$g\ g^{-1}$				
Mean	0.390	0.330	0.275	0.230	0.082
Standard deviation	0.0116	0.0199	0.0142	0.0115	0.0005
Coefficient of Variability %	2.96	6.05	5.17	4.99	0.61

Belvue silt loam (2006)

	Water content				
	Soil water potential				
Sample analyses[1]	(-0.010 MPa)	(-0.020 MPa)	(-0.030 MPa)	(-0.040 MPa)	(-1.50 MPa)
	$g\ g^{-1}$				
Mean	0.308	0.204	0.172	0.148	0.043
Standard deviation	0.0158	0.0157	0.0150	0.0161	0.0004
Coefficient of Variability %	5.13	7.67	8.69	10.88	0.86

[1] Soil sample from 0 to 20 cm depth and mean, standard deviation, and coefficient of variability mass weight water content determined from four replications at each potential