CORN AND WEED INTERACTIONS WITH NITROGEN IN DRYLAND AND IRRIGATED ENVIRONMENTS

by

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Abstract

Corn yield potential is limited by water deficit stress and limited soil nitrogen. Field and greenhouse experiments were conducted near Manhattan, KS in 2005 and 2006. The field experiment evaluated the influence of nitrogen (N) rate and increasing Palmer amaranth (PA) density grown alone and in competition with corn in two moisture environments. In 2006 the dryland environment was very drought stressed, while 2005 had more intermediate conditions. Weed-free corn yields were approximately half in dryland environments compared to the irrigated environment across years. Increasing PA density increased corn yield loss similarly in both 2005 environments and in 2006 dryland environment across all N rates. In the 2006 irrigated environment corn yield loss was increased by decreasing N rate and increasing PA density. Maximum predicted yield loss at high PA densities in both 2005 environments was 20-54% while in 2006 dryland environment, maximum yield loss was 95% and in the irrigated environment was 62%. In general, soil moisture environment was more critical than N rate or PA density when determining potential corn yield. In the greenhouse study a factorial arrangement of two irrigation methods and five crop-weed combinations (corn, PA, GF, corn/PA, and corn/GF) was established with two replications and three runs conducted. Two plants were grown in 25.4 cm diameter PVC pipe cut into 91.5 cm lengths. Irrigation application method included a surface and subsurface application. Plants were harvested at the V10 corn growth stage. No differences were detected between irrigation methods with respect to above- or belowground biomass production. Corn aboveground biomass was decreased by the presence of corn or PA but not GF. Belowground biomass information was presented as column totals because species could not be separated. There was no impact on root to shoot ratio, total belowground biomass, rooting depth, or root area across the crop-weed combinations except for the GF monoculture columns which were lower than all other crop-weed combinations. Future research needs to examine the light interception of corn and PA when grown at different N rates along with examining the influence of surface and subsurface irrigation practices on crop weed interactions and weed seed germination in a field setting.

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CHAPTER 1 - Literature Review

Water is an essential element to sustaining all life here on earth. We as humans use water everyday for washing our cars to washing the food we are going to eat to washing ourselves. You might be telling yourself, ‘water is all around us’, and that there is no reason to worry about a lack of water. In fact there is a need to worry, as 97.5 percent of the world’s water resources are saline water in the oceans and seas, making it virtually unusable for human consumption without a lengthy and expensive treatment. For the remaining 2.5%, 69% is stored in glaciers and is not readily available, 30% is stored as ground water, and less than one percent is located in rivers and lakes at any one point in time (Wood 2003). This leaves us with only 0.75% of the total water available as groundwater that can be used for irrigation purposes, as well as drinking water. Of the 0.75%, approximately 69% is used for irrigation to produce from 35 to 40% of the food crops of the world (Wood 2003). This brings to mind a much larger question that was posed by Thomas Malthus back in 1809. Malthus suggested in his book titled *An Essay on the Principle of Population as it Affects the Future Improvement of Society?* that the world would some day run out of fresh water to drink and use in foods.

Corn is a warm-season annual grass that is commonly grown across the Great Plains. The grain from this species contains starch, water, protein, fiber and oil. Corn grain may be broken down into these components and used to make many products we use daily such as adhesives, cleaners and detergents, ethanol fuel, chewing gum, antibiotics, aspirin, body lotion and moisturizer, soaps, and textiles. Corn grain and plant material are used as a food source for both humans as well as many domestic animals grown for meat (Magness et al. 1971).

In the Great Plains region, corn yield potential is commonly limited by water deficit stress and limited soil nitrogen. According to the National Agricultural Statistics Service, 1.4 million hectares of corn were harvested in 2005 followed in 2006 by 1.2 million hectares in Kansas alone with average yields of 9,083 kg ha^{-1}(135 bu acre^{-1}) and 7,728 kg ha^{-1}(115 bu ac^{-1}) in 2005 and 2006, respectively (NASS 2007). In the semi-arid region of Kansas, crops and weeds compete for plant growth resources including light, nutrients, and especially water (Zimdahl 1999). Weeds often extract more of each of these resources than necessary for their growth to the detriment of crop growth and production. Therefore, the presence of weeds in Kansas requires producers to pay special attention in order to achieve the maximum potential yield for corn production. Thus, managers often tend to over-irrigate and over-fertilize in order to feed both the crop and weeds.

With the increasing costs of nitrogen (N) and the depletion of the Ogallala Aquifer, however, alternative and more efficient methods and systems for corn production are necessary. In Kansas, water-deficit stress is the most variable factor that determines yield. Rainfall values vary from 400 mm in the western portion of the state to upwards of 1016 mm in the southeastern portion of the state with a state average of 690 mm (USDA 2007). Many producers attempt to manage this variability through irrigation where it is available. Irrigated hectares are supported by water from the Ogallala aquifer and corn is the dominant crop grown on those hectares (Norwood 2000). Over the years, various irrigation practices have been devised in order to maximize water use efficiency, beginning with flood or furrow irrigation, followed by overhead sprinkler irrigation, and, more recently, subsurface drip irrigation.

The Ogallala aquifer is part of the High Plains aquifer that underlies portions of eight states in the central United States (USGS 2006). Water levels have declined dramatically from this aquifer following the development of groundwater irrigation methods (USGS 2006). An estimated 165,000 wells currently pump from the aquifer and, in combination with the aquifer's slow to almost no ability to recharge over the past 40 years, the water level has declined to about 50% its original saturated thickness (Waskom et al. 2006). With this decline in the aquifer many corn producers are being forced to optimize their irrigation practices with less water. Muchow and Sinclair (1991) found that corn grain yield decreased dramatically with water deficit stress immediately following corn tasseling. Gordon et al. (1995) found that in north central Kansas, acceptable yields could be obtained with only one or two irrigations, as long as those irrigations were timed to meet high plant-water-use demands. Norwood (2000) found that a single irrigation at corn tasseling, combined with proper nitrogen, increased yield 29% from that of a rainfed (dryland) setting.

Based on this knowledge, it is essential for farmers and people in general to realize that a change in our practices is necessary. We are no longer able to carelessly manage our water use because if we continue at this rate, we will run out of fresh water to drink and much less water to irrigate our crops. This knowledge has sparked a large amount of research on water use and irrigation efficiency. A study performed in north-west Kansas found that irrigation water use for corn can be reduced by 35-55% when using SDI compared with more traditional forms such as furrow- or center-pivot irrigation (Lamm and Trooien 2000).

Furrow irrigation involves simply flooding a central furrow that runs between two crop rows with water and allowing that water to flow from one end of the field to the other. Furrow irrigation involves a pipe running along one side of the field with gates or holes allowing passing water to flow out and run down a furrow to the opposite end of the cornfield. This is a slower method of irrigating corn and allows for water to be applied to the surface and then allows it to soak into the ground and down to the roots of the plant. However, flood irrigation has some major disadvantages. For example; it is a very labor intensive process, requiring someone to check and change the water daily; water is allowed to evaporate as it is passing on down the ditch, and a great deal of water is allowed to run-off the end of the field without being used by the crop it is intended for.

Overhead sprinkler irrigation, more commonly called center pivot irrigation, involves a center point with wheeled-towers spreading outward from that point. These towers rotate around the center point and as they rotate water is sprinkled over the surface of the field applying a desired amount of water based on the speed at which the pivot is moving. Again sprinkler irrigation can be considered somewhat inefficient because it is spraying water into the air which falls onto the surface, allowing for multiple ways of evaporation. Sprinkler irrigation, however, does have a major advantage over that of furrow irrigation in the fact that it is much less labor intensive, and it allows for smaller amounts of water to be applied more uniformly over an area minimizing the loss of water from run-off.

Subsurface drip irrigation is a somewhat complex system as it relies more on pressure to release water and is also complex because after installation, we can no longer physically see what is going on as it is all belowground. SDI involves burying a main pipe (1-1.5 m deep) that delivers water along one end of the field; the main pipe is connected to plastic drip tape which is buried below the soil surface that has regularly spaced emitters or holes. The tape is connected to another smaller line on the opposite end of the field, creating a “closed” system. The drip tape is buried deep enough to avoid most tillage operations (usually around 0.5 m) and is positioned parallel to the row orientation, most commonly at a spacing of every other row (approximately 1.5-1.8 m apart). When the drip tape is filled with water and pressure is built up, water is then released by the emitters below the soil surface at the crop roots. By providing water to the crop roots, less water is lost directly to the atmosphere via evaporation and more water is available for use by the plants, therefore, increasing water use efficiency. The major drawback to SDI is the installation cost and the fact that because it is a newer technology, no one really knows how long the tape and the overall system will last.

Research at Kansas State University began in 1989 with the intent to determine how to effectively utilize SDI in corn production systems on the Great Plains (Lamm and Trooien 1998). Since this initial work several studies have been conducted to evaluate SDI based on water use (timing, frequency, and amount), drainage and percolation, dripline spacing, system uniformity, system life, economics, and nitrogen fertilization (Lamm and Trooien 2000).

Following water deficit stress, nitrogen stress is a close second. Nitrogen (N) is an essential element to plant growth and development, and is the most frequently deficient nutrient in crop production (Havlin et al. 2005). Nitrogen is an essential part of a large number of plant organic compounds including proteins, amino acids, nucleic acids and chlorophyll (Havlin et al. 2005). Many N sources are available for use in supplying N to crops. These sources range from inorganic fertilizer compounds, to organic forms of N in animal manures and other waste products, and from N fixation by legumes from the atmosphere. Nitrogen is a mobile nutrient in both the plant and the soil and is most commonly available to plants in the nitrate form. Transportation of N into the plant, along with several other nutrients, occurs with water by way of mass flow (Havlin et al. 2005). Movement of N with water is one more reason that supplying water to our crops is so important, because without water plants are not able to grow and produce nearly as much. However, because N is such a mobile nutrient in the soil and when you combine this with the over-application mentality that many producers have, we see elevated levels of N in ground and surface water (Shanahan et al. 2006).

In corn, the majority of N uptake occurs from early seedling development to 3 to 5 weeks after silking (Cathcart and Swanton 2004). All throughout this period an adequate amount of N needs to be available to the corn plant in order to achieve maximum dry matter production and yield. However, if inadequate amounts of water and N are available to the corn plant, yield will be reduced. Nitrogen deficiency can result in stunting or reduced growth of the crop, along with visual deficiency symptoms of a yellowish appearance for the entire plant with possible senescence of the lower or older leaves of the plant (Havlin et al. 2005). The reason for the older leaves to turn yellow and the younger leaves to remain green is the mobility of the N within the plant. When insufficient amounts of N are available to the plant, the plant is able to convert proteins in the older portion of the plant into soluble N and translocate it to the active meristematic tissues and then "reuse" the N for the synthesis of new proteins (Havlin et al. 2005).

In recent years, there has been more of a focus towards our nitrogen applications, and nitrogen use efficiency, as nitrogen is one of the greatest inputs for crop production. However, another concern that comes to mind concerning both water and N is that of groundwater pollution (Ephrath et al. 1996). More recently, many public officials along with the general public itself have become more and more aware of N fertilizers and NO_3- contamination in both the ground and surfacewater. This raised concern has sparked researchers to "reexamine" nitrogen management practices in attempts to increase efficiency (Teyker et al. 1991).

Nitrogen rate research has increased over the past few years due to the increasing costs of nitrogen, along with the increased concerns of the people; however, a majority of the research investigating N rates deals only with application rates, timing and its resulting yield. Past research of N on corn has focused on the effect and role that N has on establishment and maintenance of photosynthetic activity and physiological sinks that ultimately contribute to grain yield (Cathcart and Swanton 2004). Few studies have examined the effect of N fertilizer rate on weed-crop competition. Most competition studies have used recommended N rates and focused on the effect of weed competition on crop yield (Cathcart and Swanton 2004; Lutman et al. 1996; Sibuga and Bandeen 1980). These studies, however, provide limited information on the interaction of N and weeds on weed-crop dynamics (Cathcart and Swanton 2004), when in fact altered soil fertility levels can markedly affect crop-weed competition (Blackshaw et al. 2003). The effects of this interaction are dependent on weed species and density along with the amount of alteration made to soil fertility. The increase in N fertilizer can increase the competitive ability of some weed species more than that of the crop, and therefore can negate any change in yield we would expect to see from the increased fertilizer (Carlson and Hill 1985). Therefore, producers need to focus their attention not only on applying enough N to support the crop but also to controlling any weed species that may also inhibit the uptake of N by that crop.

Weed management requires the combined use of all available tactics for reducing the impact of weeds on crops, including chemical, biological, mechanical, and cultural control tactics. One of the first steps a producer needs to take in developing a weed management program is to identify the critical period for weed control (CPWC) for the crop which he intends to grow (Evans et al. 2003b). The CPWC is the period in the crop growth cycle during which weeds must be controlled in order for that crop to achieve maximum yield. Knowledge of the CPWC, and all the parts that play a role in determining this growth period, allow producers to better manage their weed control program. Also, by understanding the biology and effect weeds have on corn, managers are better able to minimize the cost of their weed control decisions and management practices to reduce the overall impact weeds will have on crop production.

In a study conducted near Mead, NE, Evans et al. (2003a) confirmed that the supply of N available to a crop and weeds can significantly influence the crop-weed interference relationship. This study also utilized differences in the CPWC due to N application to highlight the importance of incorporating N management decisions into the timing of weed control. Researchers determined that a 50% reduction in N applied before crop establishment may not result in lower corn yields, but is likely that weed interference will have a more immediate and pronounced effect on yield potential, meaning that the reduction in N fertilizer before plating may create the need of a more intense weed control practice extended over a longer period of time (Evans et al. 2003a).

Palmer amaranth is a widespread annual broadleaf species that has incredible growth and reproductive characteristics. Palmer amaranth (*Amaranthus palmeri)* (PA) was the most aggressive *Amaranthus* species in terms of growth in Kansas when compared to common waterhemp (*Amaranthus rudis*), redroot pigweed (*Amaranthus retroflexus*), and tumble pigweed (*Amaranthus albus)* when grown under dryland conditions (Horak and Loughin 2000). Palmer amaranth has been known to cause corn yield losses up to 41% with only 1 plant m^{-1} row and ranges from 11 to 91% corn yield reduction with PA density from 0.5 to 8 plts m^{-1} row, respectively when grown under irrigated conditions (Massinga et al. 2001). At Ashland Bottoms in 2001, PA was estimated to cause 18% yield loss with only 1 plt m^{-1} row along with a 38% yield loss at 6 plts m^{-1} row under dryland conditions (Liphadzi and Dille 2006).

Giant foxtail (*Setaria faberi)* (GF) is a widespread annual grass species that is one of the most prevalent grass weeds in the Midwestern United States (Knake and Slife 1961). In more recent years, annual grass species have again became more prevalent in Kansas as producers are altering their tillage practices from conventional tillage to more of a minimum or no-till system. Giant foxtail can cause corn yield loss of 13-14% under dryland conditions (Fausey et al. 1997). Studies conducted in Illinois concluded that GF at high densities (200 plts m^{-1}) caused corn yield loss of 25% (Knake and Slife 1961).

The different weed species and types affect our corn crop differently, therefore it is important to study and analyze weed species and N fertilizer under different environments to get a better understanding of how corn will react under these conditions. It is also unknown how the change in placement of water will impact the competitive interactions between crops and weeds. Therefore research needs to be conducted to evaluate crop-weed competition under varied irrigation conditions as well as under varied N rates and weed densities to determine the effects these variables will have on corn growth, development, and production.

The objective of the field study was to determine the influence of increasing Palmer amaranth density on corn growth, specifically leaf and stem biomass at VT, and grain yield with nitrogen in irrigated and dryland environments. The objective of the greenhouse study was to deliver water via surface or subsurface means to evaluate root growth and development, along with aboveground growth, of corn, Palmer amaranth (PA), and giant foxtail (GF) grown alone or in 2-way mixtures of crop-weed in the greenhouse.

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CHAPTER 2 - Corn and Palmer amaranth Interactions with Nitrogen in Dryland and Irrigated Environments

Abstract

In the Great Plains region, corn yield potential is commonly limited by water deficit stress and limited soil nitrogen. Field experiments were conducted near Manhattan, KS in 2005 and 2006 to evaluate the influence of nitrogen (N) rate when applied at 0, 112, and 224 kg N ha^{-1} and the influence of Palmer amaranth (PA) densities of 0, 1, 4, and 8 plants m^{-1} row when grown in competition with corn in two moisture environments. Across the two years, 2006 depicted both the very drought stressed year in the dryland environment and a well watered irrigated environment, while both environments in 2005 were intermediate. Corn biomass at VT in 2005 was impacted separately by soil moisture environment, by N rate, and by PA density. In 2006 corn biomass at VT was impacted by N rate and PA density such that biomass decreased with increasing PA density and decreasing N rate. Monoculture PA biomass at corn VT was larger than PA grown with corn across all PA densities and N rates. Weed free corn yields were approximately half in dryland compared to irrigated environment across years. Palmer amaranth density impacted corn yield similarly in 2005 and 2006 dryland across all N rates while in the 2006 irrigated environment, corn yield loss was impacted by both N rate and PA density. Maximum yield loss in both 2005 environments was 42-54% while in 2006 dryland soil moisture environment maximum yield loss was 95% while in the irrigated environment the maximum yield loss was 62%. In general, soil moisture environment was more critical than N rate or PA

density when determining potential corn yield. Future research needs to be conducted to evaluate corn growth and yield with PA densities less than 1 plt m^{-1} at differing N rates.

Introduction

In the Great Plains region, corn yield potential is commonly limited by water deficit stress and limited soil nitrogen. According to the National Agricultural Statistics Service (NASS), 1.4 million hectares of corn were harvested in 2005 followed by 1.2 million hectares in 2006 in Kansas alone with average yields of 9,083 kg ha^{-1}(135 bu $acre^{-1}$) and 7,728 kg ha^{-1}(115 bu ac^{-1}) in 2005 and 2006, respectively (NASS 2007). In the semi-arid region of Kansas, crops and weeds compete for plant growth resources including light, nutrients, and especially water (Zimdahl 1999). Weeds are often considered luxury consumers because they extract more of each of these resources than necessary for growth to the detriment of crop growth and production (Zimdahl 1999). Therefore, the presence of weeds in Kansas requires producers to pay special attention in order to achieve the maximum potential yield for corn production.

With the increasing costs of nitrogen (N) and the depletion of the Ogallala Aquifer, however, alternative and more efficient methods and systems for corn production are necessary. In Kansas, water-deficit stress is the most variable factor that determines yield. Rainfall values vary from 400 mm in the western portion of the state to upwards of 1016 mm in the southeastern portion of the state with a state average of 690 mm (USDA 2007). Many producers attempt to manage this variability through irrigation where available. Irrigated hectares are supported by water from the Ogallala aquifer and corn is the dominant crop grown on those hectares (Norwood 2000). Over the years, various irrigation practices have been devised in order to maximize water use efficiency, such as flood or furrow irrigation, overhead sprinkler irrigation, and, more recently, subsurface drip irrigation. The Ogallala aquifer is part of the High Plains aquifer that underlies portions of eight states in the central United States (USGS 2006). Water levels in this aquifer have declined dramatically after the development of groundwater-based irrigation methods (USGS 2006). An estimated 165,000 wells currently pump from the aquifer, and in combination with the aquifer's slow to almost no ability to recharge over the past 40 years, the water level has declined to about 50% its original saturated thickness (Waskom et al. 2006). With this decline in the aquifer many corn producers are being forced to optimize their irrigation practices with less water. Muchow and Sinclair (1991) found that corn grain yield decreased dramatically with water-deficit stress immediately following corn tasseling. Gordon et al. (1995) found that in north central Kansas, acceptable yields could be obtained with only one or two irrigations, as long as those irrigations were timed to meet high plant-water-use demands. Norwood (2000) found that a single irrigation at corn tasseling, combined with proper nitrogen, increased yield 29% from that of a rainfed or dryland setting.

Nitrogen is an essential element for plant growth and development and is the most frequently deficient nutrient in crop production (Havlin et al. 2005). Nitrogen is required in a large number of plant organic compounds including proteins, amino acids, nucleic acids, and chlorophyll. Nitrogen fertilizer was applied to 96% of the corn planted across 19 states with an average application rate of 155 kg N ha^{-1} in 2005 (NASS 2006). Many N sources are available including inorganic fertilizer compounds, organic forms of N in animal manures and other waste products, and N-fixation from the atmosphere by legumes. Nitrogen is a mobile nutrient in both the plant and the soil, therefore transportation of N into the plant, along with several other nutrients, occurs with water by way of mass flow (Havlin et al. 2005). The movement of N with water also raises the concern of elevated levels of N in ground and surface waters (Shanahan et al. 2006).

Few studies have examined the effect of N fertilizer rate on weed-crop competition and of those studies, most were unable to determine the mechanism of competition (Tilman 1990; Zimdahl 2004). Most competition studies have used recommended N rates and focused on the general effect of weed competition on crop yield (Cathcart and Swanton 2004; Lutman et al. 1996; Sibuga and Bandeen 1980). These studies provide limited information on the interaction of N and weeds on weed-crop dynamics when in fact altered soil fertility levels can markedly affect both the shoot and root growth of crops and weeds when grown alone or in competition (Blackshaw et al. 2003). The effects of this N-weed interaction were dependent on weed species and weed density along with the amount of alteration made to soil fertility. The increase in N fertilizer can increase the competitive ability of some weed species more than that of the crop and therefore can negate any change in yield we would expect to see from the increased amount of fertilizer (Carlson and Hill 1985). Research has shown that 140 kg N ha^{-1} can replace the common application rate of 250 kg N ha^{-1} used under irrigated conditions in northeast Colorado without reducing yield (Al-Kaisi and Yin 2003). Another study conducted in Nebraska suggested that a 50% reduction in N supply to both the crops and weeds before establishment may not result in lower corn yields, but weed interference would have a more immediate and direct reduction on yield potential (Evans et al. 2003b). This study also showed that the addition of 120 kg N ha^{-1} delayed or lengthened the critical period for weed control for all site years as compared to the 0 kg N ha^{-1} (Evans et al. 2003a). Evans et al. indicated that the addition of N made corn more competitive than corn that had no additional N added.

Palmer amaranth (*Amaranthus palmeri)* (PA) was the most aggressive of four *Amaranthus* species in terms of growth in Kansas when compared to common waterhemp (*Amaranthus rudis*), redroot pigweed (*Amaranthus retroflexus*), and tumble pigweed (*Amaranthus albus)* (Horak and Loughin 2000). At Garden City, KS, Palmer amaranth has caused corn yield losses up to 41% with only 1 plt m^{-1} row and caused from 11 to 91% corn yield reduction with PA densities ranging from 0.5 to 8 plts m^{-1} row, respectively, under irrigated conditions (Massinga et al. 2001). At Manhattan, KS in 2001, PA was estimated to cause 18% yield loss with only 1 plt m^{-1} row along with a 38% yield loss at 6 plts m^{-1} row under dryland conditions (Liphadzi and Dille 2006).

By gaining a better understanding of competition between corn and Palmer amaranth at different nitrogen application rates in two soil moisture environments, improved management decisions dealing with the costly inputs of nitrogen fertilizer, weed control, and irrigation can be made. This information will allow producers to optimize inputs and possibly minimize the overall cost of corn production in Kansas. The objective of this study was to determine the influence of increasing Palmer amaranth density on corn growth, specifically leaf and stem biomass at VT, and grain yield with nitrogen in irrigated and dryland environments.

Materials and Methods

Field experiments were conducted in 2005 and 2006 at the Kansas State University Department of Agronomy Ashland Bottoms Research Farm approximately 8 km south of Manhattan, KS. The soil type in 2005 was a Eudora silt loam (2.0% OM, pH 5.8) and in 2006 a Bellvue silt loam (1.1% OM, pH 5.6). Plots were established as a split-split plot design with two soil moisture environments (dryland and irrigated) established side-by-side as main plots.

Within each soil moisture environment sub-plots were three nitrogen rates of 0, 112, and 224 kg N ha^{-1}. Sub-sub plots were five populations including corn monoculture, PA monoculture at 1 plant m^{-1} row, and corn with 1, 4, and 8 PA plants m^{-1} row. The treatments had four replications within each soil moisture environment. Urea ammonium nitrate solution (32%) was broadcast applied to the appropriate sub-plots two weeks prior to planting. DeKalb (DKC) 60-19 RR corn was planted on May 6, 2005 and May 11, 2006 at a seeding rate of 76,600 seeds ha^{-1} in 0.76 m rows that were 10 m long. Plots consisted of three rows in 2005 and four rows in 2006. Immediately after the corn was planted, PA seed was over-seeded and hand raked into the appropriate plots. Following planting the entire study was furrow irrigated to ensure even emergence for both species. Corn was removed from the PA monoculture plots and PA was hand thinned to the desired densities by 20 days after emergence. Plots were hand weeded thereafter to maintain densities and remove any additional weeds. Irrigation management was determined using Time Domain Reflectrometry[1] (TDR) probes with approximately 50 mm of water being applied for each irrigation event when field capacity was below 50%.

At corn tasseling (VT) two plants of each species in each treatment were harvested. Plant height was measured from the soil surface to the top of the corn tassel and to the top of the PA inflorescence. Corn growth stage was recorded as described by Ritchie et al. (1997). Palmer amaranth growth staging was determined using leaf number. Leaves, stems, and reproductive material were separated and green leaf tissue was measured for leaf area using a leaf area meter[2]. Dry biomass was determined using the partitioned leaf, stem, and reproductive parts being placed into separate bags and dried at 66°C until constant weight. For this study, biomass dry weights at VT included only the leaf and stem biomass since corn tasseling occurred at different times across the different N rates. Tasseling in the high N rate (224 kg N ha^{-1}) occurred early followed by the 112 kg N ha^{-1} rate and then the low (0 kg N ha^{-1}) rate, approximately 7 to 10 days later than the high rate and resulted in variable reproductive biomass.

At corn physiological maturity, final yield was determined by hand-harvesting ears from 4 m of row. Ears were shelled, grain dried and weighed to determine final yield. Yield measures of grain weight, grain moisture, test weight, temperature, and 100-kernel dry weights were taken with final grain yield being adjusted to 15.5% moisture. Palmer amaranth seed were harvested from two female plants from each plot. The inflorescence was stripped off the stem, placed into bags and dried at 66°C for 48 hrs. The inflorescence was then sieved and separated using an air seed blower[3] to obtain pure seed. Total seed was weighed and seed number in 0.25 g was determined to estimate total seed production and seed number per plant.

Aboveground corn or PA leaf and stem biomass at VT, corn yield, PA biomass and seed production were analyzed using PROC Mixed in SAS[4] with soil moisture environment, N rate, and PA density as main effects with all interactions tested. Year and replication were random effects in the mixed model. The relationship between corn leaf and stem biomass at VT and PA density was analyzed by fitting a rectangular hyperbola model or linear model to each data set separately by year and soil moisture environment and N rate. The relationship for the corn biomass as a function of PA density was determined using Equation 1:

$$\mathrm{B} = B_{\mathrm{wf}}\left[1-\left\{\frac{I\mathrm{w}}{100\left(1+\left(\frac{I\mathrm{w}}{A}\right)\right)}\right\}\right] \qquad [1]$$

where B is the measured corn biomass (g plant^{-1}), B_{wf} is the estimated weed-free corn biomass, w is PA density (plants m^{-1} row), I is the slope of the line as PA density approaches zero, w is the PA density, and A is the parameter estimate of the line as PA density approaches infinity. If the test for lack of fit was accepted, then a liner relationship for corn biomass as a function of PA density was determined using Equation 2:

$$\mathrm{B} = m\mathrm{w} + b \qquad [2]$$

where B is the measured corn biomass, *m* is the slope of the line, w is the PA density, and *b* is the y-intercept (biomass weed-free).

The relationship of corn grain yield with varying PA densities was analyzed by fitting the crop yield model described by Cousens (1985a) to each data set separately by year, soil water environment, and N rate:

$$\mathrm{Y} = Y_{w\mathrm{f}}\left[1 - \left\{\frac{Iw}{100\left(1 + \left(\frac{Iw}{A}\right)\right)}\right\}\right] \qquad [3]$$

where Y is the observed corn yield (kg ha^{-1}), Y_{wf}, *I*, and *A* are model parameters estimated from the data, and w is the PA density (plants m^{-1} row). Parameter Y_{wf} is the weed-free yield; *I* is the percent yield loss associated with the addition of the first PA per unit of density as density approaches zero; and *A* is the maximum percent yield loss as the PA density approaches infinity. Parameter estimates were determined for Equation 1 and 3 using nonlinear regression techniques (Sigma Plot V.10[5]).

A test for lack of fit of Equation 1 and 3 was performed by partitioning the nonlinear sums of squares into the error for lack of fit and pure experimental error (Draper and Smith 1981). If an *F*-test value for lack of fit sums of squares was not significant at the 5% level, Equations 1 and 3 were deemed appropriate for that soil moisture environment and N rate (Deines et al. 2004; Dieleman et al. 1995; Draper and Smith 1981).

Parameter estimates of Equations 1 and 3 were compared among soil moisture environments, N rates, and year using the method proposed by Chism et al. (1992). This was accomplished by using binary variables for each soil moisture environment, N rate, and year to calculate differences between parameter estimates ("S" parameters). For example, in comparing the regression fit for high N rate in dryland corn between 2005 and 2006 (S_0= (Y_{wf} in 2005)-(Y_{wf} in 2006)), S_1= (I in 2005)-(I in 2006), S_2=(A in 2005)-(A in 2006). Significant differences existed ($P< 0.05$) when the upper and lower confidence intervals for the S parameters did not contain zero (Chism et al. 1992). If the parameter estimate for Y_{wf} was different among soil moisture environments, N rates, and/or years, yield loss values were calculated for each plot in a given soil moisture environment and N rate for each year:

$$Y_L = \left(\frac{Y_{wf} - Y}{Y_{wf}}\right)100 \qquad [4]$$

where Y_L is the calculated observed corn yield loss (%), Y_{wf} is the parameter estimate from Equation 3, and Y is the observed yield (kg ha^{-1}) from each plot.

The stability of parameter estimates I and A across soil moisture environments, N rates, and years were then evaluated using the extra sum of squares principle for nonlinear regression analysis (Ratkowsky 1983) as described by Lindquist et al. (1996). The Residual Sums of Squares were determined for each data set and for the pooled data set of all N rates and PA densities, an F-test ($P< 0.05$) was conducted to determine if in fact I or A varied individually:

$$F = \frac{\left(\frac{\mathrm{RSS}_i - \sum \mathrm{RSS}}{\mathrm{df}_i - \sum \mathrm{df}}\right)}{\frac{\sum \mathrm{RSS}}{\sum \mathrm{df}}} \qquad [5]$$

where F is the variance ratio, RSS_i represents the pooled RSS obtained after setting the *I* or *A* value and RSS is the individual RSS obtained from each data set, df_i is degrees of freedom for the pooled data and df is the individual degrees of freedom for each data set. This tested the null hypothesis that *I* and *A* coefficients do not vary among years, soil moisture environments, and N rates. Rejection of the null hypothesis indicated that *I* and/or *A* were different across data sets but does not indicate if *I* alone varies, if *A* alone varies, or if both *I* and *A* vary. If it was deemed that *I* and/or *A* varied for a data set, Equation 4 was fit to each data set separately, setting the *I* coefficient equal to the value obtained from the pooled data. If *I* and *A* do not differ for a given soil moisture environment, across N rates and for years, data were pooled and Equation 4 fit to a pooled data set:

$$\hat{Y}_L = \left(\frac{Iw}{1+\left(\frac{Iw}{A}\right)}\right) \qquad [6]$$

where $\hat{Y}_L$ is predicted corn yield loss (%) and other parameters are as described for Equation 3.

Results and Discussion

Total precipitation and timing of precipitation differed for the two years, however temperatures were not different from year to year or from the 30-year average (Table 2.1). Total precipitation in 2005 was 660 mm of water and it was 600 mm in 2006, however the timing of the precipitation in 2006 was different which caused greater yield losses in 2006. In 2005, significant precipitation in May inhibited drought conditions in the dryland soil moisture environment and therefore when compared to irrigated soil moisture environment differences were not observed. In 2006, however, 47% of the total precipitation was received in August therefore drought conditions were apparent in the dryland soil moisture environment.

Differences in soil characteristics between the two years played a role in the amount of water-deficit stress observed in 2006 compared to 2005. In 2005, the field soil had a much higher available water content (0.26 cm^3-cm^{-3}) than that of the soil in 2006 (0.18 cm^3-cm^{-3}) in the 30 cm profile depth (Rule 2007). Soil texture characteristics for 2005 were 30, 59, and 11% sand, silt, and clay, respectively, while in 2006 the soil texture characteristics were 44, 47, and 8 percent sand, silt, and clay, respectively at the 0 to 30 cm depth (Table 2.2). Thus, very droughty conditions were experienced in the 2006 dryland soil moisture environment with low actual water content and little rainfall between May and August 2006.

Corn Biomass at VT

Corn leaf and stem biomass at VT were significantly impacted by the main effects of N rate and PA density when year and rep were random effects. When years and soil moisture environment were analyzed, the impacts on corn biomass were explored separately, in explanation, was a change in corn biomass at VT observed as PA density increases. The dryland environment in 2006 showed a linear relationship for each N rate while the irrigated environment in 2006 had a non-linear relationship (Figure 2.1). In 2005, corn biomass at VT showed no response to increasing PA density, so main effects of soil moisture environment, N rate or PA density were summarized (Table 2.3).

In 2005, corn leaf and stem biomass at VT was higher in the irrigated environment at 82 g plt^{-1} versus dryland at 75 g plt^{-1} when compared across N rates and PA density (Table 2.3). Corn biomass was larger with additional N as compared to no N applied. Corn with no PA produced 100.6 g plt^{-1}of leaf and stem biomass compared to only 70 to 72 g plt^{-1} in the presence of PA. In 2006, corn biomass at VT in the dryland environment declined as PA density increased. In the dryland environment with no PA, corn biomass at the 112 N rate was 60 g plt^{-1} whereas the corn biomass with 8 PA plts m^{-1} at the 112 N rate was 20 g plt^{-1}. In the irrigated environment, however corn biomass with no PA at the 112 N rate was 87 g plt^{-1} whereas the corn biomass with 8 PA plts m^{-1} row was 69 g plt^{-1}.

Palmer amaranth Biomass at corn VT

Palmer amaranth leaf and stem bimass at corn VT was influenced by the interaction of PA density and N rates when years and replications were considered random effects. When years were examined separately, interactions of PA density with N rate and with soil moisture environment were significant for PA leaf and stem biomass at corn VT (Table 2.4).

In 2005 at 0 kg N ha^{-1}, monoculture PA biomass at corn VT was much larger (48.5 g plt^{-1}) than that of the PA biomass when grown in competition with corn (14.7 g plt^{-1}) (Table 2.4). Also, when comparing within a PA density but across N rates, the 224 kg N ha^{-1} biomass (184 g plt^{-1}) was 3.7 times larger than that of the 0 kg N ha^{-1}(49 g plt^{-1}). Differences were not observed however between the dryland and irrigated soil moisture environments when comparing PA biomass for monoculture, 1, 4, or 8 plt m^{-1} treatments.

In 2006, monoculture PA biomass at corn VT with 224 kg N was at least twice as heavy (404.2 g plt^{-1}) as that of the PA biomass at 8 plt m^{-1} (70.9 g plt^{-1}) when grown in competition with corn (Table 2.4). Monoculture PA biomass increased with N rate, from 111.9 g plt^{-1} in the

0 kg N ha^{-1}plots, 126.4 g plt^{-1} for the 112 kg N ha^{-1} rate, and 404.2 g plt^{-1} for the 224 kg N ha^{-1} rate. Differences were observed between the dryland and irrigated soil moisture environments when comparing PA biomass for monoculture treatments and 1 plt m^{-1} row, however per plant PA biomass was not different at densities of 4 and 8 plt m^{-1} row.

Corn Yield

Corn grain yield varied with soil moisture environment and N rate when years and replication were random effects in the mixed model. Observed weed-free corn yields ranged from 4,091 kg ha^{-1} in the dryland 0 kg N ha^{-1} plots to 16,108 kg ha^{-1} in the irrigated 224 kg N ha^{-1} plots (Table 2.5).

Equation 3 was fit to the data within each year by soil moisture environment and N rate (Table 2.5). A test for lack of fit indicated that Equation 3 provided a satisfactory fit to all harvested corn yield data sets (data not shown). Parameter estimates from Equation 3, Y_{wf}, I, and A were compared between soil moisture environments within years and N rate, between years within soil moisture environment and N rates, and between N rates within year and soil moisture environment (Table 2.6).

Estimated weed-free yields (Y_{wf}) were different across soil moisture environments within each year across N rates because water-deficit stress, a major factor when determining corn yield was minimized with the addition of water. Parameters I and A were not different except in 2006 between dryland (100.0 ± 12.4) and irrigated (62.5 ± 3.0) soil moisture environments at the 224 kg N ha^{-1} rate. This difference may be due to the additional water available in both the irrigated environment and the dryland environment in 2005, allowing corn to take up the water and additional N in the high N plots whereas there was no water to aid in the uptake of N in the dryland environment.

When parameter estimates at different levels of N were compared across year and soil moisture environments, weed-free yield (Y_{wf}), initial yield loss (I), and maximum yield loss (A) were not different in the dryland soil moisture environment except maximum yield loss at high PA densities with high N (224 kg N ha^{-1}). Therefore with additional N (112 or 224 kg ha^{-1}) but potentially limited water, maximum expected yield loss at high weed densities was different between 2005 and 2006 (48.5% and 100%, respectively). In 2005, corn in the dryland soil moisture environment had enough water to use the additional N and be more competitive with the weeds, therefore producing some yield, whereas 2006, was a much drier year and the corn did not have enough water to take up the additional N and was not able to compete with the PA. In the irrigated soil moisture environment, Y_{wf} at 112 kg N ha^{-1} was different between years with 11,165 kg ha^{-1} produced in 2005 and 13,899 kg ha^{-1} in 2006. Maximum yield loss at high densities (A) was different for two N rates, 112 and 224 kg N ha^{-1} between 2005 and 2006 (Table 2.6). With unlimited water, maximum yield loss at high weed density had a varying impact on corn yield across different N rates, just as Evans et al. (2003b) described.

Parameter estimates of Y_{wf} were different when comparing across N rates within years and soil moisture environments, however, I and A estimates were not different due to the variability that surrounded these estimates (Table 2.6). Nitrogen rates were causing differences in yield loss within years and soil moisture environments. In 2005, only Y_{wf} estimates were different in the irrigated environment between 112 and 224 kg N ha^{-1} (11,165 and 15,436 kg ha^{-1}, respectively) and between 0 and 224 kg N ha^{-1} (9,974 and 15,436 kg ha^{-1}, respectively). Therefore there was a yield response to increased N rates under irrigation with no PA. In the 2006 dryland environment, only Y_{wf} estimates were different with 0 and 224 kg N ha^{-1} (4,093 and

7,664 kg ha^{-1}, respectively) and among all N rate comparisons in the irrigated soil moisture environment.

Since Y_{wf} varied among many comparisons, observed yield losses (Y_L) were calculated for each year, soil moisture environment, and N rate using Equation 4. Tests for parameter estimate stability of N rates within a given year and soil moisture environment were conducted. Results indicated that neither parameter estimate for I or A varied in 2005 dryland or irrigated or in 2006 dryland (data not shown). In the 2006 irrigated environment, both parameter estimates I and A varied. Thus, the yield loss model (Equation 6) was fit to the observed yield loss data pooled across N rates of each year and soil moisture environment. For the yield loss data from 2006 irrigated environment, separate models were fit for each N rate (Figure 2.2).

Parameter estimates for the 2005 dryland pooled model were 77% and 54% for I and A, respectively, whereas the 2005 irrigated pooled model resulted in much larger estimates of 227% and 45% for I and A, respectively. In 2006, estimates for the dryland pooled data set were 326% and 95% for I and A, respectively. Individual models were fit for each N rate in the 2006 irrigated environment (Figure 2.5). The large parameter estimates of I indicate that the corn yield loss observed was due to the addition of the first PA plant.

Palmer amaranth seed production was based on harvesting two female plants from each plot. Seed production amounts were highly variable due in part with harvesting time and time of seed rain. In 2005 dryland, PA seed numbers ranged from 16,863 (± 9,203) seeds in the 8 PA plant m^{-1}row plots to 126,727 (± 9,203) seeds $plant^{-1}$ in the monoculture PA plots when averaged across N rates. Under irrigated conditions in 2005, seed numbers were slightly lower ranging from 18,227 (± 14,397) seeds plt^{-1} in the 8 PA plants m^{-1}row plots to 122,879 (± 14,397) seeds plt^{-1} in the monoculture PA plots. In 2006 dryland seed numbers ranging from 92,409 (± 24,710) seeds plt^{-1} in the 8 PA plt m^{-1} row plot to 280,248 (± 24,710) seeds plt^{-1} in the monoculture PA plots. Under irrigated conditions in 2006, seed numbers were lower ranging from 50,755 (± 22,927) seeds plt^{-1} to 140,338 (± 22,927) seeds plt^{-1} in the 8 PA plt m^{-1} row plots.

In this study, soil moisture environment played a major role in determining both corn and PA growth characteristics along with seed yield for both species. Across N rates, the impact of PA varied however, results indicate that as PA density increases from 1 to 8 plt m^{-1}, there was little increased effect on corn yield and that most of the yield loss suffered by corn from PA, across N rates, was due to the first PA plant m^{-1} row.

Sources of Materials

[1] Time Domain Reflectrometer (TDR100). Campbell Scintific 815 West 1800 North, Logan, Utah 84321-1784

[2] LI-Cor, LI 3100. LI-Cor Biosciences, 4647 Superior Street Lincoln, NE 68504-0425.

[3] Seed Blower Model #757. Seedburo Equipment Company, 1022 W. Jackson Blvd, Chicago, IL 60607.

[4] SAS Version 9.1 SAS Institute Inc. Cary NC 27513.

[5] Sigma Plot V 10.0 Systat Software Inc. 501 Canal Boulevard Suite E, Richmond, CA 94804

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Tables and Figures

Table 2.1 Monthly maximum and minimum temperatures, precipitation during the 2005 and 2006 growing seasons and the 30 year average for Manhattan, KS.

Month	Temperature						Precipitation		
	2005		2006		Average		2005	2006	Average
	Max	Min	Max	Min	Max	Min			
	------------------------------------°C-------------------------------------						-------------mm-------------		
April	20	6	23	7	20	6	40	70	78
May	25	10	31	17	25	11	302	29	129
June	31	19	34	21	31	17	51	29	133
July	32	29	34	21	34	20	51	94	104
August	31	19	33	20	33	18	142	283	83
September	29	15	24	11	28	13	91	51	93
Total							663	602	620

Table 2.2 Soil nutrient and texture analysis for 2005 and 2006 soils at Manhattan, KS.

Year	Soil Type	NO_3	P	K	OM	Sand	Silt	Clay	pH
		----------ppm----------			-------------------%-------------------				OH^-
2005	Eudora	25.4	50	362	2.0	30	59	11	5.8
2006	Bellvue	2.3	29	156	1.1	44	47	8	5.6

Table 2.3 Mean corn leaf and stem biomass at VT averaged over main effects in 2005.

Main Effect	Treatment	Mean (±SE)
		g plt^{-1}
Soil Moisture Environment	Dryland	74.8 (2.3)B[*]
	Irrigated	81.7 (2.3)A
N Rate (kg N ha^{-1})	0	65.4 (2.3)B
	112	89.5 (2.9)A
	224	79.8 (2.9)A
PA Density (plts m^{-1} row)	0	100.6 (3.3)A
	1	70.5 (3.3)B
	4	71.9 (3.3)B
	8	69.8 (3.3)B

[*] Means followed by the same letter within a main effect are not different at the $P<0.05$ level.

Table 2.4 Palmer amaranth biomass at corn VT growth stage.

Year		Treatment	Monoculture	Density with corn		
			(1 plt m^{-1} row)	1 plt m^{-1} row	4 plt m^{-1} row	8 plt m^{-1} row
			--	g plt^{-1}	-------------------------------	
2005	N rate	0	48.5 (5.7) C[*]	15.6 (5.7) C	10.8 (5.7) B	14.7 (5.7) A
		112	82.6 (5.7) B	27.2 (5.7) B	17.1 (5.7) B	21.0 (5.7) A
		224	184.0 (5.7 A)	76.8 (5.7) A	73.7 (5.7) A	9.6 (5.7) A
	Soil Moisture	Dryland	103 (4.7) a	34.7 (4.7) a	31.7 (4.7) a	12.6 (4.7) a
	Environment	Irrigated	107.1 (4.7) a	45.1 (4.7) a	36.0 (4.7) a	17.6 (4.7) a
2006	N rate	0	111.9 (20.7) B	58.1 (20.7) B	37.9 (20.7) B	22.4 (20.7) B
		112	126.4 (20.7) B	137.2 (20.7) A	49.1 (20.7) B	67.7 (20.7) A
		224	404.2 (20.7) A	166.4 (20.7) A	89.8 (20.7) A	70.9 (20.7) A
	Soil Moisture	Dryland	194.8 (16.9) b	158.6 (16.9) a	64.9 (16.9) a	47.9 (16.9) a
	Environment	Irrigated	233.5 (16.9) a	82.6 (16.9) b	52.9 (16.9) a	59.4 (16.9) a

[*] Means were compared within PA density between N rate or soil moisture environment. Means followed by the same upper case letter were not different P<0.05 level.

Table 2.5 Observed weed-free corn grain yields and parameter estimates (± SE) from Equation 1 for each year, environment, and N rate.

Year	Environment	N Rate	Obs. Yield	Y_{wf}	I	A
		kg N ha^{-1}	----------kg ha^{-1}-----------		-----------%---------	
2005	Dryland	0	6,055 (534.2)	6,031 (605)	74.8 (70.9)	57.9 (13.3)
		112	7,439 (320.2)	7,445 (413)	70.7 (37.7)	56.8 (7.4)
		224	7,005 (282.2)	7,007 (626)	88.6 (96.7)	48.5 (11.1)
		Pooled[b]	_____	_____	77.2 (32.6)	54.3 (5.6)
	Irrigated	0	9,974 (610.4)	9,974 (1,000)	675.3 (3101.1)	49.5 (10.6)
		112	11,167 (757.6)	11,165 (1,083)	124.4 (207.3)	42.1 (11.5)
		224	15,435 (288.1)	15,436 (565)	181.6 (131.6)	44.3 (4.2)
		Pooled	_____	_____	227.2 (227.9)	45.2 (4.5)
2006	Dryland	0	4,091 (1174.2)	4,093 (1,075)	173.9 (308.5)	88.1 (29.8)
		112	5,840 (1,367.4)	5,837 (1,225)	386.3 (756.5)	93.4 (21.0)
		224	7,663 (1,293.4)	7,664 (993)	691.8 (1,138.9)	100 (12.4)
		Pooled	_____	_____	326.2 (298.0)	94.6 (11.6)
	Irrigated	0	10,263 (855.4)	10,262 (841)	238.0 (197.1)	74.2 (8.7)
		112	13,887 (553.5)	13,899 (851)	62.6 (27.6)	74.5 (9.5)
		224	16,108 (180.5)	16,100 (385)	99.8 (21.7)	62.48 (3.0)

[a] Yield weed free

[b] Pooled data sets combined across N rates for a given year and soil moisture environment using percent yield loss (Y_L) to estimate parameters.

Table 2.6 Pairwise comparisons of estimated parameters from Equation 1 A) between soil moisture environments within years and N rate, B) between years within soil moisture environment and N rates, C) between N rates within year and soil moisture environment. *Comparisons were different at the P<0.05 level. NS comparisons were not significant.

Comparison	Year	Treatment	N rate	Y_{wf}	I	A
A	2005	Dryland vs.	0	*	NS	NS
		Irrigated	112	*	NS	NS
			224	*	NS	NS
	2006	Dryland vs.	0	*	NS	NS
		Irrigated	112	*	NS	NS
			224	*	NS	*
B	2005 vs	Dryland	0	NS	NS	NS
	2006		112	NS	NS	NS
			224	NS	NS	*
	2005 vs.	Irrigated	0	NS	NS	NS
	2006		112	*	NS	*
			224	NS	NS	*
C	2005	Dryland	0 vs 112	NS	NS	NS
			112 vs 224	NS	NS	NS
			0 vs 224	NS	NS	NS
		Irrigated	0 vs 112	NS	NS	NS
			112 vs 224	*	NS	NS
			0 vs 224	*	NS	NS
	2006	Dryland	0 vs 112	NS	NS	NS
			112 vs 224	*	NS	NS
			0 vs 224	NS	NS	NS
		Irrigated	0 vs 112	*	NS	NS
			112 vs 224	*	NS	NS
			0 vs 224	*	NS	NS

* Indicates values are significantly different from the mean.

NS Indicates values are not different from the mean.

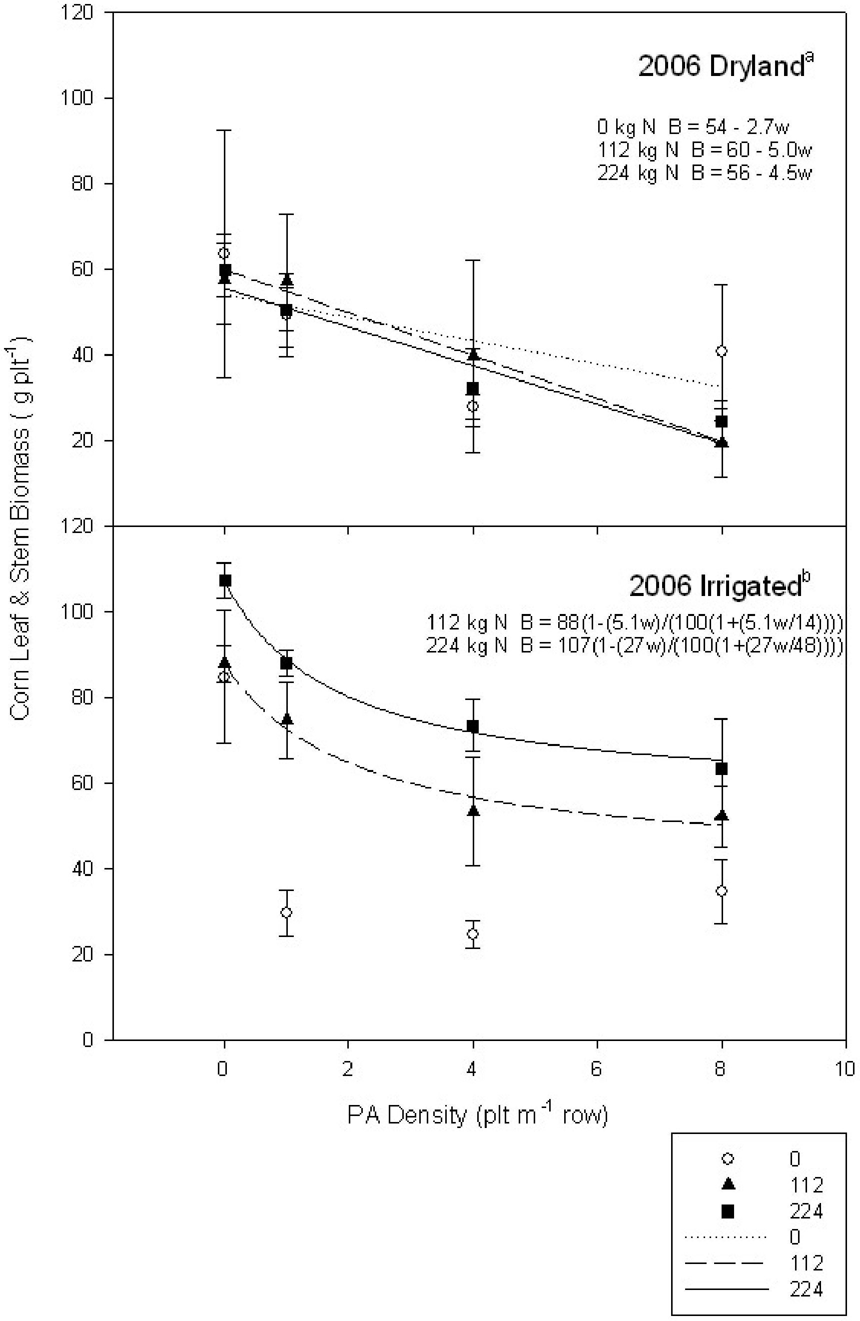

Figure 2.1 Dryland and irrigated corn biomass in 2006 as a function of Palmer amaranth density (plt m^{-1} row) and N rate (kg N ha^{-1}). Points represent mean leaf and stem biomass (±SE) and lines in figure a fit Equation 1 (B= mw + b) to data, lines in figure b fit Equation 2 [B= B_{wf} (1-(Iw/100(1+(Iw/A))))].

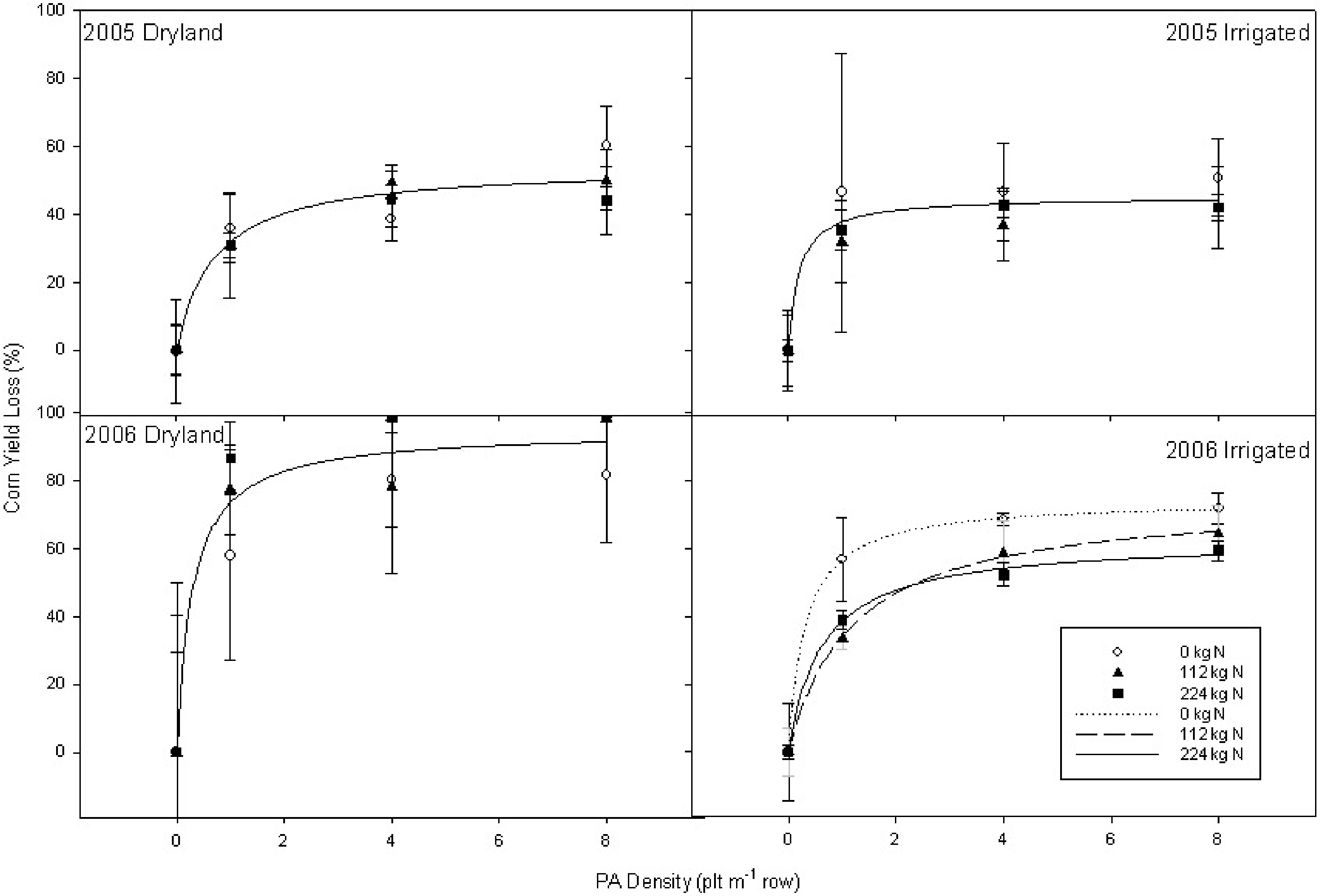

Figure 2.2 Percent corn yield loss for 2005 and 2006 dryland and irrigated environments as a function of Palmer amaranth density (plt m^{-1} row) and N rate (kg ha^{-1}). Points represent mean observed values (± SE) and the lines are the result of fitting Equation 5: Y_L=(I w)/((1+ IW)/A) to the data. Parameter estimates in Table 2.5.

CHAPTER 3 - Influence of Irrigation Method on Corn and Weed Growth

Abstract

A greenhouse study was conducted to determine the influence of surface and subsurface irrigation methods on above- and belowground growth of corn, Palmer amaranth (PA), and giant foxtail (GF). A total of 10 treatments were established in a 2 by 5 factorial arrangement of two irrigation methods and five crop-weed combinations of two plants (corn, PA, GF, corn/PA, and corn/GF). The study was conducted three times with two replications in each run. Two plants were grown in 25.4 cm diameter PVC pipe cut into 91.5 cm lengths. Water was delivered to the surface of the column for the surface irrigation method as compared to a subsurface application of water delivered through a 2 cm diameter PVC tube with perforations placed horizontally at 46 cm from the soil surface. Plants grew for 5 to 6 weeks and then above- and belowground plant material were harvested at the V10 corn growth stage. No differences were detected between irrigation methods for above- or belowground biomass production within each species. Aboveground biomass of corn was decreased by the presence of corn or PA but not GF. Belowground biomass information is presented as column totals because species' roots could not be separated. There was no impact of crop/weed combination on root to shoot ratio, total belowground biomass, rooting depth, or root area except for the monoculture GF for all these measures which was less than all other crop-weed combinations. Future research needs to

examine the rate of germination, and extent of successful emergence of these plants in response to the different irrigation methods as compared to establishing plants as in this study.

Introduction

Various irrigation methods have been devised for corn production in Kansas in order to both maximize water use efficiency and minimize total water use. Both these qualities are important to Kansas agriculture because approximately 1/3 of all corn hectares planted in Kansas is irrigated (NASS 2005). Irrigation methods include flood or furrow irrigation, overhead sprinkler, and more recently, subsurface drip irrigation (SDI). A great deal of research has been done to further increase irrigation efficiency, especially because of the significant decrease in the world's largest groundwater supply, the Ogallala Aquifer.

The Ogallala Aquifer is used in the United States to provide irrigation water to about 5.7 million hectares of cropland (Waskom et al. 2006). These hectares provide food to the world in the form of grain, for both human and livestock consumption. Approximately 23% of the cropland overlying the Ogallala is irrigated (McMahon 2000). There are an estimated 165,000 wells that currently pump from the aquifer and over the past 40 years, in combination with the aquifers slow to almost no ability to recharge this has caused the aquifer water level to decline to about 50% its original saturated thickness (Waskom et al. 2006).

Subsurface Drip Irrigation research began in Kansas in 1989 when Kansas State University developed the methodology for successful SDI application in corn production systems (Lamm and Trooien 1998). Subsurface Drip Irrigation is a somewhat complex system as it relies on pressure to release water, and because after installation belowground, we can no longer see what is going on. SDI involves burying a main pipe (approximately 1 m deep) that delivers water along one end of the field; the main pipe is connected to plastic drip tape which is buried below the soil surface that has regularly-spaced emitters or holes. The tape is buried deep enough to avoid most tillage operations (usually around 0.5 m) and is positioned parallel to the row orientation, most commonly at a spacing of every other row (approximately 1.5-1.8 m apart). When the drip tape is filled with water and pressure is built up, water is then released by the emitters below the soil surface to the crop roots. By providing water to the crop roots, less water is lost directly to the atmosphere via evaporation and more water is available for use by the plants, therefore, increasing water use efficiency. The major drawback to SDI is the installation cost and because it is a newer technology, it is uncertain how long the tape and the overall system will last. Therefore, SDI adoption has not been rapid in the Central Great Plains due to the low value crops grown in the region and the overall initial cost of installation. Due to the decline in the Ogallala Aquifer, however, many producers are being forced to reduce the amount of irrigation water applied and in order to continue to obtain higher yields producers are searching for more efficient systems. Irrigation water use for corn can be reduced 35 to 55% when using SDI compared with more traditional forms such as furrow- or center-pivot irrigation in the Central Great Plains region (Lamm and Trooien 2003).

It is unknown how the change in placement of irrigation water will impact the competitive interactions between crops and weeds. Palmer amaranth (*Amaranthus palmeri)* (PA) was the most aggressive *Amaranthus* species in terms of growth in Kansas when compared to common waterhemp (*Amaranthus rudis*), redroot pigweed (*Amaranthus retroflexus*), and tumble pigweed (*Amaranthus albus)* when grown under dryland conditions without a crop (Horak and Loughin 2000). Palmer amaranth has been known to cause corn yield losses up to 41% with only 1 plant m^{-1} row and ranges from 11 to 91% corn yield reduction with PA density increasing from 0.5 to 8 plants m^{-1} row, respectively, when grown under irrigated conditions (Massinga et al. 2001). Near Manhattan, KS in 2001, PA was estimated to cause 18% yield loss with only 1 plant m^{-1} row along with a 38% yield loss at 6 plants m^{-1} row under dryland conditions (Liphadzi and Dille 2006).

Giant foxtail (*Setaria faberi)* (GF) is a widespread annual grass species that is one of the most prevalent grass weeds in the Midwestern United States (Knake and Slife 1961). In more recent years, annual grass species have again became more prevalent in Kansas as producers are altering their tillage practices from conventional tillage to a minimum or no-tillage system. Giant foxtail can cause corn yield loss of 13 to 14% under dryland conditions (Fausey et al. 1997). Studies conducted in Illinois concluded that GF at high densities (200 plants m^{-1}) caused corn yield loss of 25% (Knake and Slife 1961).

Since SDI was introduced to Kansas, several studies have been conducted to evaluate SDI based on water use (timing, frequency, and amounts), drainage, and percolation, nitrogen fertilization, dripline spacing, system uniformity, system life, and finally economics (Lamm and Trooien 2000). Net irrigation needs have been reduced by nearly 25% when using SDI while still maintaining high corn grain yields of 12.5 Mg ha^{-1} (Lamm and Trooien 2000). Lamm et al. (1998) also determined that the optimum spacing, both economically and physically, for driplines in a silt loam soil was 1.5 m apart when planting corn in 0.76 m rows. In the past 17 years significant research has been conducted to evaluate the system of SDI itself and its impacts on corn specifically, however research has yet to be conducted to evaluate the impact SDI may have upon crop and weed growth. The objective of this study was to deliver water via surface or subsurface means to evaluate root growth and development, along with aboveground growth of corn, PA, and GF grown alone or in 2-way mixtures of crop and weed in the greenhouse.

Materials and Methods

A greenhouse study was designed to determine the above- and belowground growth and development of corn, PA, and GF grown with either surface or subsurface irrigation. The greenhouse was maintained between 27 and 37ºC with a 14/10 hr day/night period. A total of 10 treatments were established in a 2 by 5 factorial arrangement of two irrigation methods and five crop-weed combinations (corn, PA, GF, corn/PA, and corn/GF). Soil columns were constructed of 25.4 cm diameter PVC pipe cut into 91.5 cm lengths and covered at the bottom with two layers of mesh screen. Each soil column contained a locally excavated loam soil that was cleaned and steamed before being packed into each column in three layers using water to saturate and settle the soil. Approximately four grams of urea fertilizer (46-0-0) was mixed in the top 15 cm of soil before planting to insure nutrient sufficiency for all plants. Subsurface irrigation was accomplished by placing a 2-cm diameter PVC tube with perforations horizontally at 46 cm from the soil surface. Surface irrigation was delivered at the soil surface. Tensiometers[1] were installed horizontally within each column at 7, 23, and 38 cm depths from the soil surface to document soil water potential throughout the column.

After the columns had settled to a constant soil level, several seeds of each species were sown into the columns. Two days after emergence plants were thinned to two per column. Tensiometer readings were recorded using a tensimeter[3] and a standard reading of <-300 mbars at the 23 cm depth was used to determine if the columns needed to be irrigated. Irrigation events of 1300 mL for run 1 and 1000 mL for runs 2 and 3 were made to maintain water content at "field capacity." Run 1 of the experiment was initiated on June 1, 2006 followed by run 2 being initiated on April 2, 2007 and run 3 on June 1, 2007. At the corn V10 growth stage, approximately 5 to 6 weeks after planting, both crop and weed plants were harvested documenting height, growth stage (V number for corn, branch number for PA, and tiller number for GF) (Ritchie 1997). Dry weights of aboveground material for each plant were determined after plant material had dried at 66ºC to a constant weight (approximately 48 hours). Intact soil was removed from each column and gently washed to determine rooting depths, root length, and root biomass for each column. Five centimeter sections of the root from the following depths: 5-10 cm, 20-25 cm, 35-40 cm, and 60-65 cm were taken and stained with methyl violet stain, laid on transparencies, and scanned so they could be analyzed with the WinRhizo[4] program to determine root area in each 5-cm section. Dry weight of belowground material for each column was determined by collecting all root material, bagging and drying at 66 ºC to a constant weight (approximately 48 hours).

Statistical analyses of the data were conducted using PROC GLM in SAS[2] with irrigation method and crop-weed combination as main effects and replication as a random effect. Based on the results, further analyses were conducted based on individual crop-weed combinations and response variables of aboveground biomass, belowground biomass, total biomass, root to shoot ratio, root area, and rooting depth.

Results and Discussion

Growth conditions were comparable for all three runs of the experiment. Run 1 was initiated on June 1, 2006 and was completed in 6 weeks. Run 2 began earlier in the year on April 2, 2007 and it appeared that the weed species were growing more slowly than they did in the other runs that were later in the season. Run 3 began June 1, 2007 and was comparable to the growth of the weed species and corn in the first two runs.

The amount of water applied varied by crop-weed combination and irrigation method with PA-PA surface requiring the most water to be applied overall, followed closely by PA-PA subsurface, then Corn- PA surface, Corn-Corn subsurface, and Corn-PA subsurface (Table 3.1). GF-GF required the least amount of water to be applied for both irrigation methods (Table 3.1). This was expected as many weed species, especially *Amaranthus* species are believed to extract all available water from the soil and use it for biomass production. The limited amount of water required by the GF was also somewhat expected due to its much smaller size and shallower root system in comparison with corn and PA.

Corn aboveground biomass was not influenced by the interaction of irrigation method by corn-weed combination; however the main effect of crop-weed combination was significant. These results indicate that irrigation method did not influence aboveground biomass production of corn and that corn achieved optimal growth conditions using either surface or subsurface irrigation techniques. The significant effect of crop-weed combination on corn aboveground biomass was indicative of the interspecific competition between corn and PA and the ability of PA to compete with corn to reduce biomass (Table 3.1). The significant effect of crop-weed combination also indicates that GF was not able to capture resources and compete with the corn nearly as effectively as the PA and allowed corn to produce 18 g plt^{-1} and 24 g plt^{-1} more biomass than when grown with either another corn plant or PA, respectively(Table 3.1).

Aboveground biomass for PA and GF had no significant interactions or main effects with irrigation method or crop-weed combination. This indicated that the competition of either corn or the other weed species had no impact on the aboveground biomass of either weed species (Table 3.1).

When including the belowground root biomass information, calculated root to shoot ratio had no significant interactions or main effects. Total rooting depth and total root biomass had no significant interactions; however both responses did have a significant crop-weed combination effect. The rooting depth and root biomass for GF was much smaller than that of PA and/or corn (Table 3.2).

Total root area of the four 5-cm sub-samples taken from the total roots had significant differences present in the main effects of crop-weed combination and of irrigation method (Table 3.2). GF had much less root material than either corn or PA. The differences between water application method was because GF did not require as much water to be applied since it had not fully explored the entire depth of the column, nor had the plants encountered water stress as the columns were saturated at the beginning of the study.

This study determined that effective irrigation for corn can be accomplished using subsurface drip irrigation methods in the greenhouse. Early season growth characteristics measured in corn when grown in competition with PA were similar to that of corn grown with another corn plant. Growth characteristics for PA and GF were similar whether the partner species was another weed of the same species or corn.

Future research would evaluate surface and subsurface irrigation methods by allowing the study to run through to yield, both in the greenhouse and in the field. This study evaluated weed species that were successfully established as seedlings. Another question is the impact of surface and subsurface irrigation methods on successful germination and emergence of weed species in the field in order to further evaluate the true benefits and drawbacks of SDI. Research involving corn and weed competition under both surface and subsurface water application methods needs to be conducted in a field-setting to determine if similar results will be obtained as in the greenhouse.

Sources of Materials

[1] Tensiometer-Made by Dr. Loyd Stone, Professor, Department of Agronomy, Kansas State University, Manhattan, KS 66506.

[2] SAS Version 9.1 SAS Institute Inc. Cary NC.

[3] Tensimeter-Soil Measurement Systems, 7090 North Oracle Road, Tucson AZ 85704.

[4] CR 23X Datalogger- Campbell Scientific Inc., 815 West 1800 North, Logan, Utah 84321.

[5] WinRHIZO 2002a,b,c, Regent Instruments Inc. sales@regentinstruments.com.

Acknowledgement

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Tables and Figures

Table 3.1 Amount of irrigation water applied, aboveground biomass, and maximum height of main species in a column averaged across replications.

Crop-weed combination (Main-Partner)	Irrigation method		Aboveground Biomass (Main species)[*+]	Height[++]
	Surface	Subsurface		
	----------mm---------		g plt^{-1}	cm
Corn-Corn	6128	6628	41.4 (3.3) b A	123 (6.9)A
Corn –PA	6461	5747	35.4 (4.7) b	116 (6.9)AB
Corn –GF	5701	4726	59.5 (4.7) a	105 (6.9)B
PA –PA	8192	7248	42.3 (4.6) a A	115 (6.8)AB
PA –Corn	______	_______	42.6 (6.3) a	________
GF –GF	1068	1709	10.9(1.2) a B	55 (6.8)C
GF –Corn	________	________	8.5 (1.7) a	________

[*] Means compared across main species followed by the same lower-case letter were not different at the P=0.05 level.

[+] Means for aboveground biomass of monoculture treatments followed by the same upper-case letter were not different at the P=0.05 level.

[++] Means for maximum height followed by the same upper-case letter were not different at the P=0.05 level.

Table 3.2 Column means for belowground biomass, root depth, and root area as a function of irrigation method and crop-weed combination.

Irrigation Method	Crop-Weed Combination	Belowground biomass	Root Depth	Root Area
		g column^{-1}	cm	cm^2
Surface	Corn-Corn	18.5 (±5.2)	88 (±6.4)	2,906 (±324.7)
	Corn-PA	22.1 (±5.7)	89 (±7.0)	2,075 (±351.3)
	Corn-GF	28.2 (±5.1)	94 (±6.2)	2,053 (±312.6)
	PA-PA	18.7 (±5.2)	85 (±6.4)	1,512 (±323.9)
	GF-GF	6.0 (±6.2)	29 (±7.6)	849 (±554.5)
Subsurface	Corn-Corn	23.8 (±5.7)	91.9(±7.0)	2,573 (±351.3)
	Corn-PA	18.0 (±5.1)	87 (±6.2)	1,345 (±312.5)
	Corn-GF	13.1 (±5.6)	85 (±7.0)	1,448 (±348.8)
	PA-PA	17.9 (±5.4)	81 (±6.6)	1,375 (±334.7)
	GF-GF	3.2 (±6.4)	57 (±7.9)	554 (±474.0)

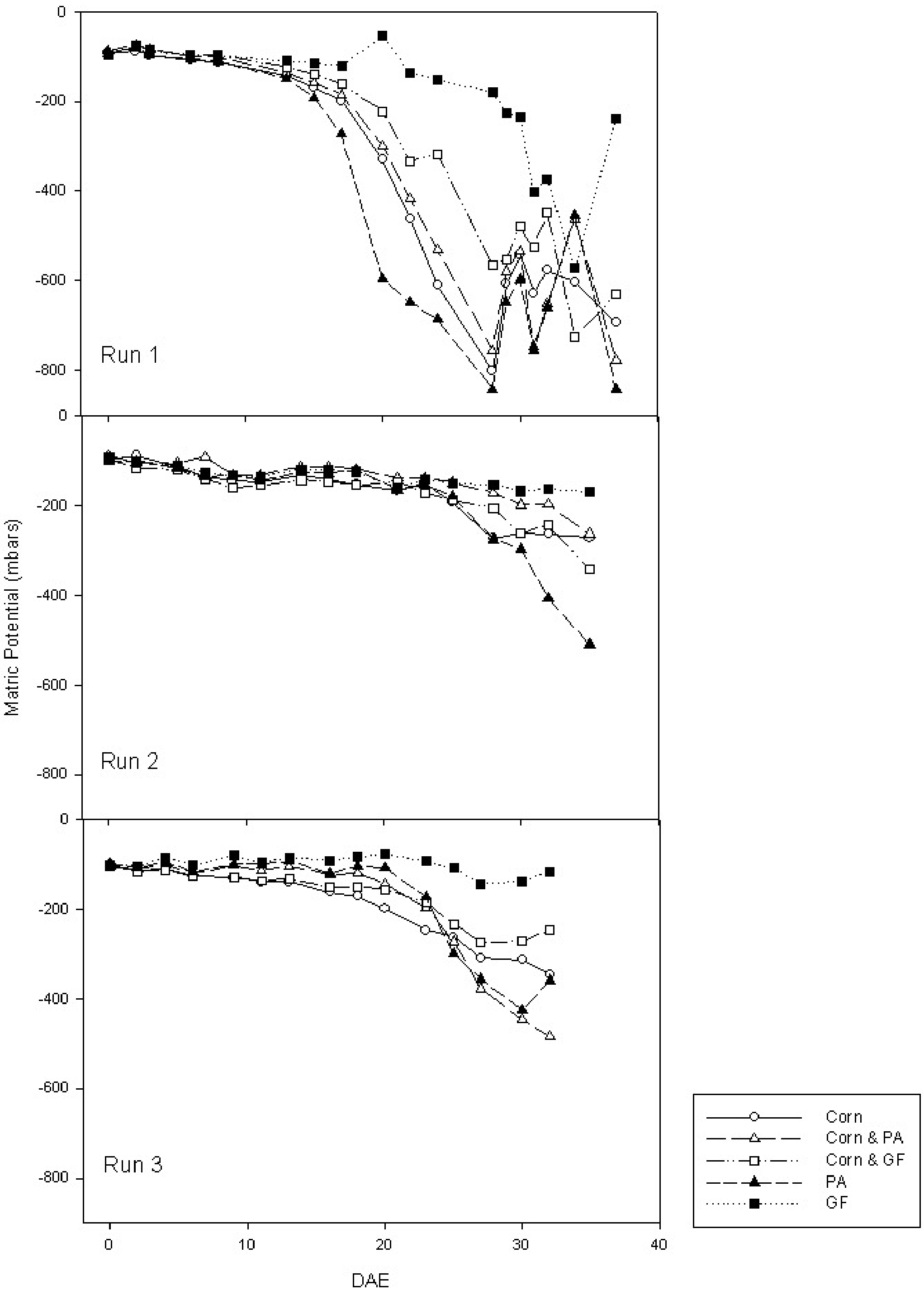

Figure 3.1 Change in matric potential at the 23 cm depth as a function of days after emergence (DAE) across irrigation methods for each run of the greenhouse experiment.

Appendix A - Corn and Palmer amaranth growth in response to water and nitrogen levels.

Introduction

In the Great Plains region, yield loss is often attributed to water stress and limited soil nitrogen. The goal of this experiment was to determine the effects of crop-weed competition between corn and Palmer amaranth established in two soil water environments and three nitrogen application levels. The specific objective of this experiment was to obtain mid and final season plant tissue data for nitrate and phosphorus contents. This information could then be used to improve predictions and modeling of crop yield loss due to nitrogen and water stress with weed competition. The improved yield loss predictions could aid farm managers in making management decisions for N fertilizer, irrigation, and weed control based on crop yield potential and crop yield loss.

Materials and Methods

Field experiments were conducted in 2005 and 2006 at the Kansas State University Department of Agronomy Ashland Bottoms Research Farm approximately 8 km south of Manhattan, KS. The soil type in 2005 was a Eudora silt loam (1.1% OM, pH 5.6) and in 2006 a Bellvue silt loam (1.1% OM, pH 5.6) (Table 2.1). Plots were established as a split-split plot design with two soil moisture environments (dryland and irrigated) established side-by-side as main plots. Within each soil moisture environment sub-plots were three nitrogen rates of 0, 112, and 224 kg N ha^{-1}. Sub-sub plots were five populations including corn monoculture, PA monoculture at 1 plt m^{-1} row, and corn with 1, 4, and 8 PA plt m^{-1} row. The treatments had four replications within each soil moisture environment. Urea ammonium nitrate solution (32%) was broadcast applied to the appropriate treatments two weeks prior to planting. DeKalb (DKC) 60-19 RR corn was planted on May 6, 2005 and May 11, 2006 at a seeding rate of 76,600 seeds ha^{-1} in 0.76 m rows that were 10 m long. Plots consisted of three rows in 2005 and four rows in 2006. Immediately after the corn was planted, PA seed was over-seeded and hand raked into the appropriate plots. Following planting the entire study was furrow irrigated to ensure even emergence for both species. Corn was removed from the PA monoculture plots and PA was hand thinned to the desired densities by 20 days after emergence. Plots were hand weeded thereafter to maintain densities and remove any additional weeds. Irrigation management was determined using Time Domain Reflectrometry[1] (TDR) probes with approximately 50 mm of water being applied for each irrigation event when field capacity was below 50%.

At corn tasseling (VT) two plants of each species in each treatment were harvested. Plant height was measured from the soil surface to the top of the corn tassel and to the top of the PA inflorescence. Corn growth stage was recorded as described by Ritchie et al. (1997). Palmer amaranth growth staging was determined using leaf number. Leaves, stems, and reproductive material were separated and green leaf tissue was measured for leaf area using a leaf area meter[2]. Dry biomass was determined using the partitioned leaf, stem, and reproductive parts being placed into separate bags and dried at 66°C until constant weight. In 2005, two whole corn plants and two whole PA plants per plot were separated into leaf and stem parts before being ground separately in a Wiley Mill to pass through a 1-mm screen. In 2006, five to ten corn ear leaves were harvested and one or two branches of the PA plant were harvested per plot and ground in a Wiley Mill to pass through a 1-mm screen. Sub-samples of approximately 10 g were sent to the KSU Soil Testing lab for a salicylic-sulfuric acid digest to determine percent total N and P content within the plant. Corn tasseling did occurred at different times across the different N rates with the high 224 kg N ha^{-1} rate occurring first followed by the 112 kg N ha^{-1} rate and finally the low 0 kg N ha^{-1} rate occurring approximately 7 to 10 days after the high rate.

At corn physiological maturity, two corn and two PA plants were harvested, dried for 48 hours, and all dried material were ground in a Wiley Mill to pass through a 1-mm screen. Sub-samples of approximately 3 g were sent to the KSU Soil Testing lab for the salicylic-sulfuric acid digest to determine percent total N and P content remaining in the plant.

Statistical analysis were conducted by determining means for each

Sources of Materials

[1] Time Domain Reflectrometer (TDR100). Campbell Scintific 815 West 1800 North, Logan, Utah 84321-1784

[2] LI-Cor, LI 3100. LI-Cor Biosciences, 4647 Superior Street Lincoln, NE 68504-0425.

[3] Seed Blower Model #757. Seedburo Equipment Company, 1022 W. Jackson Blvd, Chicago, IL 60607.

[4] SAS Version 9.1 SAS Institute Inc. Cary NC 27513

Tables and Figures

Table A.1 Percent total N and P for corn at VT in 2005 as a function of environment, N rate and PA density.

Year	Environment	N rate	PA Density	Total N		Total P	
				Leaf	Stem	Leaf	Stem
		kg N ha^{-1}	Plants m^{-1}row	-------------------%-------------------			
2005	Dryland	0	0	1.86	0.44	0.19	0.17
			1	1.58	0.36	0.19	0.22
			4	1.39	0.35	0.20	0.28
			8	1.39	0.36	0.19	0.23
		100	0	2.49	0.57	0.20	0.12
			1	1.93	0.38	0.19	0.13
			4	1.74	0.36	0.18	0.16
			8	1.85	0.35	0.20	0.17
		200	0	2.54	1.11	0.25	0.15
			1	2.33	1.20	0.25	0.15
			4	3.39	0.87	0.22	0.13
			8	2.14	0.66	0.21	0.17
	Irrigated	0	0	2.18	0.43	0.21	0.18
			1	1.55	0.41	0.23	0.23
			4	1.42	0.38	0.22	0.35
			8	1.50	0.40	0.25	0.37
		100	0	2.49	0.55	0.24	0.17
			1	1.91	0.42	0.22	0.20
			4	1.92	0.43	0.24	0.22
			8	2.04	0.52	0.24	0.25
		200	0	2.80	1.36	0.29	0.22
			1	2.71	1.07	0.28	0.19
			4	2.63	1.14	0.28	0.20
			8	2.46	0.87	0.26	0.20

Table A.2 Percent total N and P for corn at VT in 2006 as a function of environment, N rate and PA Density.

Year	Environment	N rate	PA Density	Total N	Total P
		kg N ha^{-1}	Plants m^{-1} row	------------%-----------	
2006	Dryland	0	0	2.185	0.274
			1	1.812	0.209
			4	1.778	0.258
			8	1.695	0.245
		100	0	2.723	0.264
			1	2.488	0.248
			4	2.388	0.268
			8	2.308	0.258
		200	0	2.878	0.256
			1	2.813	0.254
			4	2.705	0.253
			8	2.598	0.273
	Irrigated	0	0	1.923	0.230
			1	1.575	0.289
			4	1.733	0.347
			8	1.570	0.318
		100	0	2.828	0.269
			1	2.365	0.269
			4	1.913	0.275
			8	2.005	0.262
		200	0	2.783	0.267
			1	2.895	0.270
			4	2.515	0.254
			8	2.455	0.247

Table A.3 Percent total N and P for PA at VT in 2005 as a function of environment, N rate and PA density.

Year	Environment	N rate	PA Density	Total N		Total P	
				Leaf	Stem	Leaf	Stem
		kg N ha^{-1}	Plants m^{-1} row	------------------	%	------------------	
2005	Dryland	0	0	3.05	.86	0.27	0.20
			1	3.19	.83	0.25	0.11
			4	2.65	.61	0.20	0.09
			8	3.21	.96	0.19	0.08
		100	0	3.55	1.12	0.31	0.18
			1	3.53	.95	0.26	0.10
			4	3.29	.96	0.27	0.18
			8	3.54	1.06	0.23	0.11
		200	0	3.92	2.93	0.37	0.22
			1	4.10	2.92	0.31	0.16
			4	4.01	2.76	0.32	0.15
			8	3.64	1.98	0.28	0.13
	Irrigated	0	0	3.33	1.13	0.32	0.32
			1	2.62	.73	0.27	0.18
			4	2.48	.61	0.23	0.22
			8	3.16	.67	0.28	0.2
		100	0	3.65	1.13	0.37	0.27
			1	3.21	.76	0.29	0.26
			4	3.60	1.19	0.28	0.21
			8	3.47	1.04	0.34	0.21
		200	0	4.05	2.82	0.43	0.29
			1	3.97	2.56	0.41	0.26
			4	3.94	2.35	0.35	0.24
			8	3.81	1.50	0.31	0.22

Table A.4 Percent total N and P for PA at VT in 2006 as a function of environment, N rate and PA density.

Year	Environment	N Rate	PA Density	Total N	Total P
		kg N ha^{-1}	Plants m^{-1} row	------------%	-----------
2006	Dryland	0	0	2.825	0.36
			1	2.945	0.321
			4	2.975	0.334
			8	2.638	0.336
		100	0	3.188	0.351
			1	3.538	0.359
			4	3.213	0.346
			8	3.388	0.352
		200	0	3.745	0.374
			1	3.878	0.347
			4	3.695	0.344
			8	3.558	0.348
	Irrigated	0	0	2.600	0.328
			1	2.890	0.306
			4	2.595	0.267
			8	2.640	0.286
		100	0	3.068	0.350
			1	3.155	0.304
			4	2.883	0.289
			8	2.623	0.284
		200	0	3.940	0.394
			1	4.003	0.371
			4	3.568	0.349
			8	3.205	0.307

Table A.5 Percent total N and P for corn at harvest as a function of year, environment, N rate and PA density.

Year	Environment	N rate	PA Density	Total N	Total P
		kg N ha^{-1}	Plants m^{-1} row	---------------%---------------	
2005	Dryland	0	0	0.57	0.19
			1	0.49	0.22
			4	0.54	0.33
			8	0.62	0.39
		100	0	0.54	0.09
			1	0.43	0.09
			4	0.52	0.25
			8	0.42	0.11
		200	0	0.75	0.05
			1	0.79	0.08
			4	0.66	0.08
			8	0.51	0.11
	Irrigated	0	0	0.56	0.16
			1	0.51	0.35
			4	0.59	0.40
			8	0.48	0.32
		100	0	0.54	0.10
			1	0.50	0.18
			4	0.52	0.22
			8	0.54	0.30
		200	0	0.85	0.12
			1	0.63	0.08
			4	0.59	0.08
			8	0.54	0.18
2006	Dryland	0	0	0.950	0.183
			1	0.763	0.228
			4	0.713	0.194

		8	0.930	0.305
	100	0	1.080	0.151
		1	0.890	0.160
		4	1.167	0.251
		8	1.293	0.268
	200	0	1.273	0.153
		1	1.147	0.209
		4	1.443	0.240
		8	1.550	0.263
Irrigated	0	0	0.423	0.116
		1	0.567	0.158
		4	0.613	0.331
		8	0.647	0.330
	100	0	0.573	0.084
		1	0.500	0.103
		4	0.460	0.118
		8	0.603	0.211
	200	0	0.538	0.077
		1	0.533	0.064
		4	0.650	0.100
		8	0.530	0.075

Table A.6 Percent total N and P for Palmer amaranth at harvest as a function of year, environment, N rate and PA density.

Year	Environment	N rate	PA Density	Total N	Total P
		kg N ha^{-1}	# m row^{-1}	------------------%	------------------
2005	Dryland	0	0	0.90	0.22
			1	0.85	0.14
			4	0.73	0.13
			8	0.90	0.14
		100	0	1.02	0.16
			1	1.13	0.16
			4	1.22	0.16
			8	1.04	0.13
		200	0	1.41	0.17
			1	1.74	0.17
			4	1.26	0.12
			8	1.57	0.17
	Irrigated	0	0	0.60	0.14
			1	0.56	0.18
			4	0.87	0.12
			8	0.59	0.14
		100	0	0.76	0.13
			1	0.73	0.09
			4	0.85	0.09
			8	1.02	0.12
		200	0	1.32	0.18
			1	0.93	0.14
			4	1.33	0.166
			8	1.07	0.10
2006	Dryland	0	0	0.903	0.217
			1	0.853	0.141

		4	0.730	0.134
		8	0.900	0.142
	100	0	1.023	0.159
		1	1.127	0.156
		4	1.220	0.159
		8	1.043	0.129
	200	0	1.410	0.170
		1	1.743	0.171
		4	1.257	0.122
		8	1.573	0.169
Irrigated	0	0	0.603	0.138
		1	0.563	0.180
		4	0.870	0.123
		8	0.593	0.137
	100	0	0.757	0.134
		1	0.733	0.086
		4	0.850	0.094
		8	1.023	0.117
	200	0	1.323	0.180
		1	0.933	0.139
		4	1.327	0.166
		8	1.073	0.103