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Corn and Palmer amaranth (*Amaranthus palmeri*) Interactions with Nitrogen in Dryland and Irrigated Environments

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Palmer amaranth influences selection of crop production practices such as irrigation, nitrogen (N) application, and weed control. The objectives of this research were to determine if Palmer amaranth was more responsive to applied N than corn and if this differed under dryland and irrigated conditions in Kansas. Field experiments were conducted near Manhattan, KS, in 2005 and 2006 to evaluate the influence of N rate and Palmer amaranth densities when grown with corn in two soil moisture environments. A very drought-stressed environment and a well-watered environment occurred in 2006, while both environments in 2005 were intermediate. Dryland weed-free corn yields were 46.5% of irrigated corn yields at the high N rate across years. Irrigated corn yields responded to increasing N rates. In the presence of Palmer amaranth, parameter estimates I and A for the yield loss relationship were not different across N rates for each environment and year except 2006 where 100% yield loss was estimated in dryland compared to 62.5% loss in irrigated environment at high N rates. In three of four environment-years, N rate did not affect the corn yield loss relationship with weed density. In 2006 irrigated environment, greater N rates had less corn yield loss caused by Palmer amaranth. By corn anthesis, weed-free corn biomass was 167.5% greater in irrigated than dryland environments in 2006. Palmer amaranth with no corn increased its biomass by 373 and 361% as N rate increased in 2005 and 2006, respectively. Nitrogen concentrations in plant tissues of corn or weed increased similarly as N rates increased from 0 to 224 kg N ha^{-1}, thus highlighting that both corn and Palmer amaranth responded similarly to increasing N. In general, soil moisture environment was most critical when determining potential corn yield, followed by Palmer amaranth density and N rate.

Nomenclature: Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; corn, *Zea mays* L. "DKC60-19RR".
Key words: Crop-weed competition, dryland corn, irrigated corn, nitrogen rate, yield loss.

Palmer amaranth is one of several members of the pigweed family that are troublesome weeds in the United States (Horak and Loughin 2000). Palmer amaranth was the most aggressive of four pigweed species (*Amaranthus* spp.) when its height, biomass, and leaf area were compared to common waterhemp (*A. rudis* Sauer), redroot pigweed (*A. retroflexus* L.), and tumble pigweed (*A. albus* L.) in Kansas (Horak and Loughin 2000). Previous corn-weed competition studies have documented that one Palmer amaranth plant per meter of crop row caused irrigated corn yield losses up to 41%; corn yield reductions were 11 to 91% as Palmer amaranth densities increased from 0.5 to 8 plants m^{-1} row at Garden City, KS (Massinga et al. 2001). In dryland corn production, one Palmer amaranth plant per meter of crop row caused 18% corn yield loss and up to 38% with 6 plants m^{-1} row at Manhattan, KS (Liphadzi and Dille 2006). Control of Palmer amaranth using herbicides have become limited as biotypes resistant to triazine, acetolactate synthase inhibitor, and glycine herbicides continue to be found throughout Kansas and the United States (Heap 2011; Horak and Peterson 1995).

Pigweed species have been characterized as being highly responsive to N (Blackshaw et al. 2003; Blackshaw and Brandt 2008; Teyker et al. 1991). Redroot pigweed biomass increased more than that of corn as N dose was increased from 0 to 220 mg N kg^{-1} soil (Teyker et al. 1991). Relative dry weight increases between 110 and 220 mg N kg^{-1} soil were 6.5% for redroot pigweed and only 1.9% for corn (Teyker et al. 1991). Redroot pigweed shoot biomass production in response to increasing amounts of N were similar to wild mustard and canola and were categorized as species being most responsive to N (Blackshaw et al. 2003). Blackshaw and Brandt (2008) observed that redroot pigweed was considerably less competitive than spring wheat at the lowest rate of 60 mg N kg^{-1} soil, but this relationship changed as N rate increased to 240 mg N kg^{-1} soil. The competitive ability of redroot pigweed was improved by higher soil N levels (Blackshaw and Brandt 2008). Will Palmer amaranth also be highly responsive and more competitive with increasing soil N levels? As N is applied to fields at recommended corn production rates, it is expected that pigweed species will also respond to the added N. However, the interaction between corn and Palmer amaranth under different N rates is unknown. Understanding the influence of nutrients, especially N, on crop-weed competition outcomes is important because it may be possible to use N management in an integrated weed management program (Barker et al. 2006).

It has been reported that C_4 plant species use N more efficiently than C_3 plant species (Nieto et al. 1961; Tollenaar et al. 1994), so several authors (Barker et al. 2006; Berger et al. 2010) expected that corn (C_4 species) would be a more efficient user of N compared to velvetleaf (*Abutilon theophrasti* Medik., a C_3 species), especially when N supply was limited. Their initial hypothesis was supported, in that velvetleaf height, leaf area index, and biomass accumulation did respond more to N addition than corn; however, corn yield loss due to velvetleaf competition did not consistently increase with increasing N addition (Barker et al. 2006). Since corn and Palmer amaranth are C_4 species, it is expected that they will react similarly to increasing N rates.

Both irrigated and dryland corn production systems occur across Kansas, and since N is a mobile nutrient, availability of soil water can influence the interaction of corn and Palmer amaranth in response to N. When more light was intercepted in mixtures of corn and weeds prior to full canopy cover, more soil water was extracted over the time course of the growing season in the weedy systems (Berger et al. 2010). Berger et al.

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Table 1. Soil type, nutrient, and texture analysis of soils observed in field studies in 2005 and 2006 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

(2010) found that cumulative soil water depletion was higher when velvetleaf emerged just prior to or with corn as compared to monoculture corn, and most differences were observed before anthesis. Amount of soil water depletion was similar between weedy corn and monoculture corn when they each intercepted similar amounts of light (identical leaf area index). Conversely, in a high yield loss scenario such as early velvetleaf emergence in corn, soil water depletion was 17% higher than in monoculture corn, corn yield losses were 43%, and crop water productivity (crop grain yield divided by the season-long water use) was reduced by almost 50% (Berger et al. 2010). An additional scenario under which weeds may exacerbate crop water stress would be in drought-type situations where full canopy cover is never achieved and presence of weeds leads to persistent increases in light interception and transpiration by the weed community. Corn yield reductions due to weeds were related to the vertical distribution of leaf area density of corn and weeds within the canopy (Berger et al. 2010; Massinga et al. 2003). In both studies, there were little to no differences in the soil water balance between weed-free and weedy systems, but crop water productivity was lower in weedy systems due to crop yield reductions rather than due to increases in total soil water use (Berger et al. 2010). Under nonlimiting soil water conditions, water use by plant stands is usually tightly coupled to solar radiation interception. This was observed by Massinga et al. (2003) in irrigated conditions in Garden City, KS, such that Palmer amaranth densities ranging from 0 to 8 plants m^{-1} of row at corn densities of 75,000 plants ha^{-1} had no significant impact on canopy light interception and water use for each site in each of 2 yr. Berger et al. (2010) found that radiation interception by the plant canopy was often similar when weeds were either present or absent in the canopy. Even though the presence of weeds may not cause crop water stress, results from Berger et al. (2010) demonstrated that weeds can have a large impact on crop yield and crop water productivity.

We anticipate that Palmer amaranth is highly responsive to increasing soil N levels, similar to redroot pigweed. We know that corn is also highly responsive to N, thus the null hypothesis would be that there is no difference in corn-Palmer amaranth interactions with increasing levels of N fertilizer. If Palmer amaranth was more responsive to N than corn, we expect greater negative impacts on corn yield as N fertilizer rates increase, and if Palmer amaranth was less responsive to N than corn, we expect less negative impacts on corn yield as N fertilizer rates increase. Since N is a mobile soil resource and requires sufficient soil water for uptake, we anticipate that in dryland conditions, there will be no difference in corn-Palmer amaranth interactions with varying levels of N fertilizer as compared to irrigated conditions, whereas we anticipate that the corn yields will be impacted more by Palmer amaranth as N fertilizer rates increase.

This field study was initiated to examine the interactions of corn and Palmer amaranth under diverse cropping situations of water-stress and N-stress in Kansas. By reducing N-stress, we hypothesized that weed-free corn yields would increase, but in the presence of Palmer amaranth, the negative effect on corn yield would worsen. In addition, we hypothesized that the relative effect of N on corn yield would be even greater when water was limiting. The objective of the study was to document the impact of N-, water-, and Palmer amaranth-stresses on end-of-season corn yield, as well as measurable impacts on crop and weed biomass and tissue N concentrations occurring at corn anthesis.

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. 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 (Table 1). The previous crop was soybean providing a soil residual N level of 25 ppm. The field was fertilized with 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, and then incorporated by field cultivation. The field was then set up for furrow irrigation 1 mo 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 (Table 1). The previous crop was soybean followed immediately with winter wheat, which was terminated in early April providing a soil residual N level of 2.3 ppm. The field was fertilized with 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 1 mo prior to planting, which also incorporated the fertilizer.

Plots were arranged 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 subplots were three N rates of 0, 112, and 224 kg N ha^{-1}. Sub-subplots were five crop-weed communities including corn monoculture, Palmer amaranth monoculture at 1 plant m^{-1} row, and corn with 1, 4, and 8 Palmer amaranth plants m^{-1} row. Each treatment was replicated four times within each soil moisture environment.

In 2005, the N source was 28% urea-ammonium nitrate (UAN), while in 2006, it was 32% UAN, and it was applied broadcast to the appropriate subplots 2 wk prior to planting. 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 10-m long ridged rows. Plots consisted of three crop rows in 2005 and four crop rows in 2006. Immediately after

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the corn was planted, Palmer amaranth seed was overseeded 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 Palmer amaranth monoculture plots, and Palmer amaranth was hand thinned to the desired densities by 20 d after emergence. Plots were hand weeded thereafter to maintain densities and remove any additional weeds. Irrigation management was determined using Time Domain Reflectrometry (TDR; Time-Domain Reflectometer [TDR100], Campbell Scientific, Inc., 815 West 1800 North, Logan, UT 84321) with approximately 50 mm of water being applied with each irrigation event when field capacity was below 50% (Rule 2007). 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.

At corn anthesis, aboveground destructive plant harvests of corn and Palmer amaranth were taken. Two plants from each plot were clipped at the soil surface, leaf area determined using LiCor 3100 leaf area meter (LI-COR Biosciences, 4647 Superior St., Lincoln, NE 68504), leaves and stems placed in paper bags, dried at 66 C for 5 d, and dry weight determined. In 2005, corn leaves, corn stems, Palmer amaranth leaves, and Palmer amaranth stems were ground and analyzed for tissue N concentration, while in 2006, corn ear leaf and Palmer amaranth branch (both leaves and stems) were harvested, dried, ground, and analyzed for tissue N concentration. Crop and weed plant biomass at anthesis and tissue N concentrations were analyzed using PROC MIXED in SAS (version 9.1; SAS Institute, Inc., SAS Campus Dr., Cary, NC 27513) with soil moisture environment, N rate, and weed density as main effects with all interactions tested for each year. Replication was a random effect in the mixed model.

Final crop yield was determined by hand-harvesting ears from 4 m of row at corn physiological maturity. Ears were shelled, grain dried, and weighed to determine final yield at 15.5% moisture. Corn yield data were analyzed using MIXED in SAS (SAS Institute, Inc.) with soil moisture environment, N rate, and weed density as main effects with all interactions tested for each year. Replication was random effect in the mixed model.

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

$$Y = Y_{wf}[1 - \{Iw/100(1 + (Iw/A))\}] \quad [1]$$

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 Palmer amaranth density (plants m^{-1} row). Parameter Y_{wf} is estimated weed-free yield, I is the percent yield loss as weed density approaches zero, and A is maximum percent yield loss as weed density approaches infinity. Parameter estimates were determined for Equation 1 using nonlinear regression techniques (SigmaPlot version 10, Systat Software, Inc., 501 Canal Blvd., Suite E, Richmond, CA 94804).

A test for lack of fit of Equation 1 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, Equation 1 was 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 Equation 1 were compared among soil moisture environments, N rates, and year using the method proposed by Chism et al. (1992) and used by Deines et al. (2004). 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:

$$Y_L = (Y_{wf} - Y/Y_{wf})100 \quad [2]$$

where Y_L is the calculated observed corn yield loss (%), Y_{wf} is the parameter estimate from Equation 1, 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 was then evaluated using the extra sum of squares principle for nonlinear regression analysis as described by Lindquist et al. (1996). If I and A do not differ for a given soil moisture environment, across N rates, and for years, data were pooled and Equation 3 fit to a pooled data set:

$$\hat{Y}_L = (Iw/1 + [Iw/A]) \quad [3]$$

where $\hat{Y}_L$ is predicted corn yield loss (%) and other parameters are as described for Equation 1.

Results and Discussion

Corn Grain Yield – In Absence of Palmer amaranth Competition. Dryland weed-free corn yields were 46.5% of the irrigated weed-free corn yields across both years when produced with high N rates (224 kg N ha^{-1}) (Table 2). Weed-free corn yields had a significant two-way interaction with soil moisture environment and N rate ($P < 0.10$) such that yields increased by 155 and 157% with increasing N rate from 0 to 112 and to 224 kg N ha^{-1}, respectively, in the irrigated soil moisture environment but there were no significant differences in weed-free yield across N rates in the dryland soil moisture environment (Table 2). Water was the more limiting resource for greater corn yields in dryland environments than access to N fertilizer. Irrigated weed-free yields were comparable to those obtained by Massinga et al. (2001) in their corn-Palmer amaranth competition study, ranging from 11,154 kg ha^{-1} to 15,273 kg ha^{-1} across four site-years with fall-applied 158 kg N ha^{-1} as anhydrous ammonia. Dryland weed-free corn yields can vary dramatically depending on site-year, such as those observed by Liphadzi and Dille (2006) in their corn-Palmer amaranth study, with yields ranging from 1,220 to 5,790 kg ha^{-1} across 2 yr with only 22 kg N ha^{-1} applied compared to 13,090 kg ha^{-1} at an irrigated site with 180 kg N ha^{-1} applied.

Parameter estimates for weed-free yield (Y_{wf}) based on Equation 1 were similar to observed weed-free yields (Table 2). Estimates were compared between dryland and irrigated environments and were different from each other within a year by N rate combination (Table 3). Most comparisons of corn Y_{wf} estimates between N rates were different if in an irrigated environment, but not if in a dryland environment. This indicated that again, water was the more limiting resource as compared to available N in dryland environments.

Total precipitation from April to September in 2005 and 2006 was 677 and 556 mm of rainfall, respectively (Table 4).

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Table 2. Observed weed-free corn grain yields, parameter estimates (± SE), and adjusted regression coefficient (R^2) from Equation 1 and pooled estimates from Equation 3 for each year, soil moisture environment, and nitrogen (N) rate when corn was competing with Palmer amaranth at Manhattan, KS.

Year	Environment	N rate	Observed weed-free yield	Parameter estimates[a] Y_{wf}	I	A	R^2
			——— kg ha^{-1} ———		——— % ———		
2005	Dryland	0	6,060 (534)	6,030 (605)	74.8 (70.9)	57.9 (13.3)	0.50
		112	7,440 (320)	7,450 (413)	70.7 (37.7)	56.8 (7.4)	0.77
		224	7,010 (282)	7,010 (626)	88.5 (96.7)	48.5 (11.1)	0.49
		Pooled[b]	____	____	77.2 (32.6)	54.3 (5.6)	0.62
	Irrigated	0	9,970 (610)	9,970 (1,000)	675.3 (3101)	49.5 (10.6)	0.50
		112	11,170 (758)	11,160 (1,083)	124.4 (207.3)	42.1 (11.5)	0.38
		224	15,430 (288)	15,440 (565)	181.6 (131.6)	44.3 (4.2)	0.86
		Pooled	____	____	227.2 (227.9)	45.2 (4.5)	0.57
2006	Dryland	0	4,090 (1174)	4,090 (1,075)	173.9 (308.5)	88.1 (29.8)	0.22
		112	5,840 (1,367)	5,840 (1,225)	386.3 (756.5)	93.4 (21.0)	0.41
		224	7,660 (1,293)	7,660 (993)	691.8 (1,139)	100 (12.4)	0.72
		Pooled	____	____	326.2 (298.0)	94.6 (11.6)	0.47
	Irrigated	0	10,260 (855)	10,260 (841)	238.0 (197.1)	74.2 (8.7)	0.76
		112	13,890 (554)	13,900 (851)	62.6 (27.6)	74.5 (9.5)	0.81
		224	16,110 (181)	16,100 (385)	99.8 (21.7)	62.5 (3.0)	0.96

[a] Y_{wf} is estimated weed-free corn yield, I is percent yield loss as Palmer amaranth density approaches 0, and A is maximum percent yield loss as Palmer amaranth density approaches infinity.

[b] Pooled data sets combined across N rates for a given year and soil moisture environment using percent yield loss (Y_L) calculated with Equation 2 to estimate parameters.

Differences in timing of precipitation events influenced the extent of drought conditions observed in the dryland environment. For example in May, 302 mm of rainfall occurred in 2005, whereas only 29 mm occurred in 2006. Also, 47% of the growing season rainfall occurred in August in 2006, once the corn had started grain fill. Temperatures were not different from year to year or from the 30-yr average (Table 4).

Differences in soil characteristics between the 2 yr played a role in the amount of water-deficit stress observed in 2006 compared to 2005. In 2005, the Eudora field soil had a much higher available water content (0.26 cm^3-cm^{-3}) than that of the Bellevue soil in 2006 (0.18 cm^3-cm^{-3}) in the 30-cm profile depth (Rule 2007). Soil texture characteristics for the Eudora soil were 30% sand, 59% silt, and 11% clay, while in 2006 the soil texture characteristics for the Bellevue soil were 44% sand, 47% silt, and 8% clay at the 0 to 30 cm depth (Table 1). Thus, very droughty conditions were experienced in the 2006 dryland environment with low actual available water content and little rainfall between May and August 2006.

Corn Grain Yield – With Palmer amaranth Competition. Corn grain yields decreased with increasing Palmer amaranth density and were modeled separately using Equation 1 across years, soil moisture environments, and N rates (Figure 1). A comparison of parameter estimates of Y_{wf}, I, and A revealed that estimates of I were not different across any of the comparisons, and estimates of A only differed when comparing dryland and irrigated corn yields at high N rate in 2006 (Table 3). With high Palmer amaranth densities in 2006, the parameter estimate for A (maximum corn yield loss) in the dryland environment was predicted to be 100% as compared to estimated maximum yield loss of 62.5% in the

Table 3. Pairwise treatment comparisons of parameter estimates from Equation 1 between soil moisture environments within years and nitrogen (N) rate, and between N rates within year and soil moisture environment.

Year	Treatment comparison: Environment	N rate	Parameter estimates: Y_{wf}	I	A
2005	Dryland vs. irrigated	0	*	NS	NS
		112	*	NS	NS
		224	*	NS	NS
2006	Dryland vs. irrigated	0	*	NS	NS
		112	*	NS	NS
		224	*	NS	*
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

[a] Asterisks denote treatment comparisons were different at the $P < 0.05$ level; NS, treatment comparisons were not different at the $P < 0.05$ level.

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Table 4. Monthly precipitation and maximum and minimum temperatures during the 2005 and 2006 growing seasons and the 30-yr average for Manhattan, KS.

	Precipitation			Temperature					
				2005		2006		30-yr Average	
Month	2005	2006	30-yr average	Max	Min	Max	Min	Max	Min
	mm			C					
April	40	70	78	20	6	23	7	20	6
May	302	29	129	25	10	31	17	25	11
June	51	29	133	31	19	34	21	31	17
July	51	94	104	32	29	34	21	34	20
August	142	283	83	31	19	33	20	33	18
September	91	51	93	29	15	24	11	28	13
Total	667	556	620						

irrigated environment (Table 2). Therefore, the starting point or weed-free corn grain yield (Y_{wf}) differed in response to different N rates and soil moisture environments and, as shown in Figure 1, the impact of Palmer amaranth on corn yield was consistent across N rates in three of four environment-years, that is, responses were nearly parallel. Radosevich et al. (2007) proposed that with incremental increases in available resources for plant growth, the relationship of crop plant density and crop plant yield per unit area would increase and at higher plant densities, the responses for each resource level would be parallel. By substituting weed density for crop density, the relationship between weed density and crop yield at different resource levels responds similarly. These yield results support the null hypothesis that Palmer amaranth and corn respond similarly to increasing N rates in three of four environment-years.

Since Y_{wf} varied among most of the comparisons, observed yield losses (Y_L) were calculated for each year, soil moisture environment, and N rate using Equation 2. Based on tests for parameter estimate stability (Lindquist et al. 1996), results

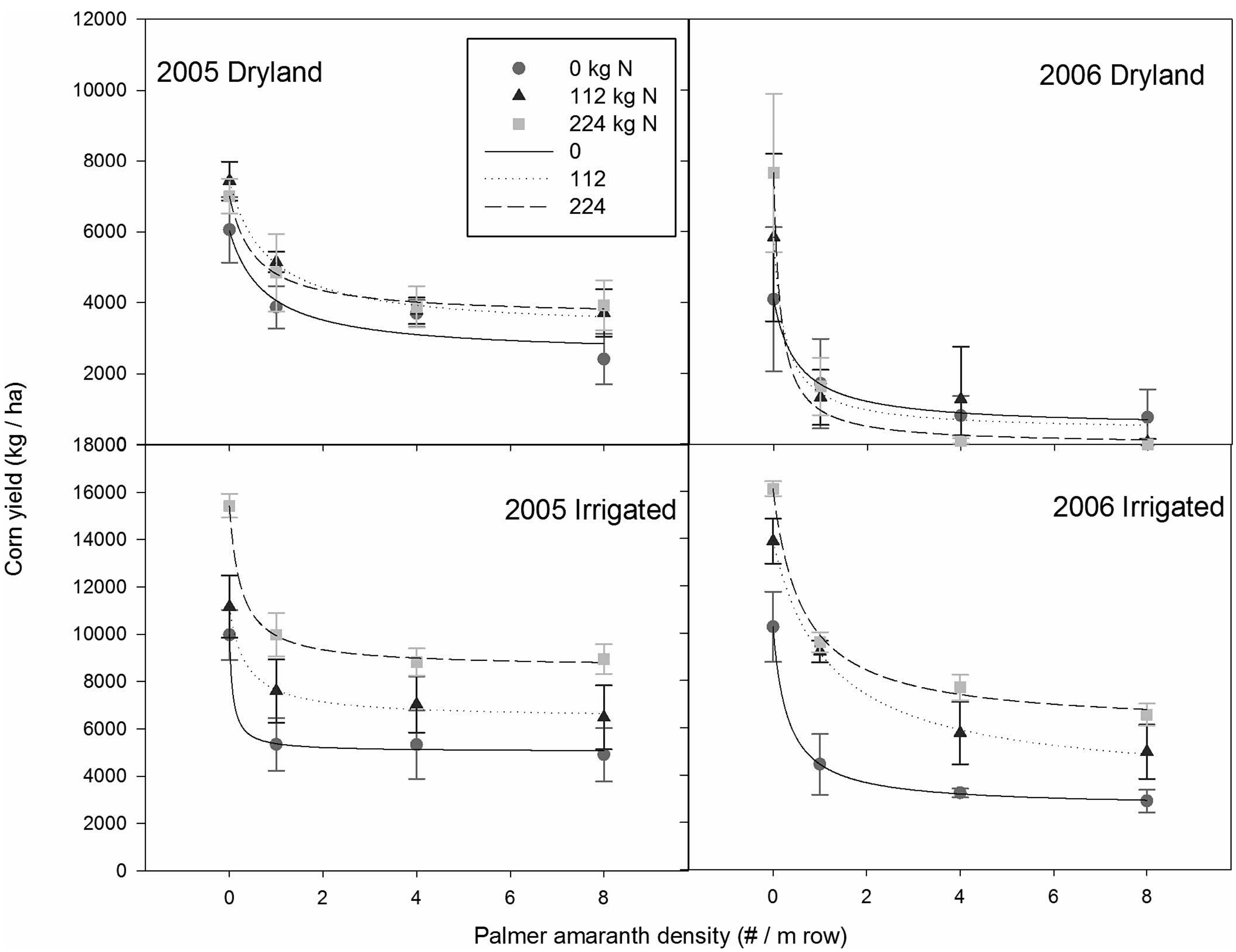

Figure 1. Corn grain yield (kg ha^{-1}) in 2005 and 2006 dryland and irrigated environments as a function of Palmer amaranth density (plants per m row) and nitrogen rate (kg ha^{-1}). Points represent mean observed values (± SE), and the lines are the result of fitting Equation 1 to data for each N rate. Parameter estimates in Table 2.

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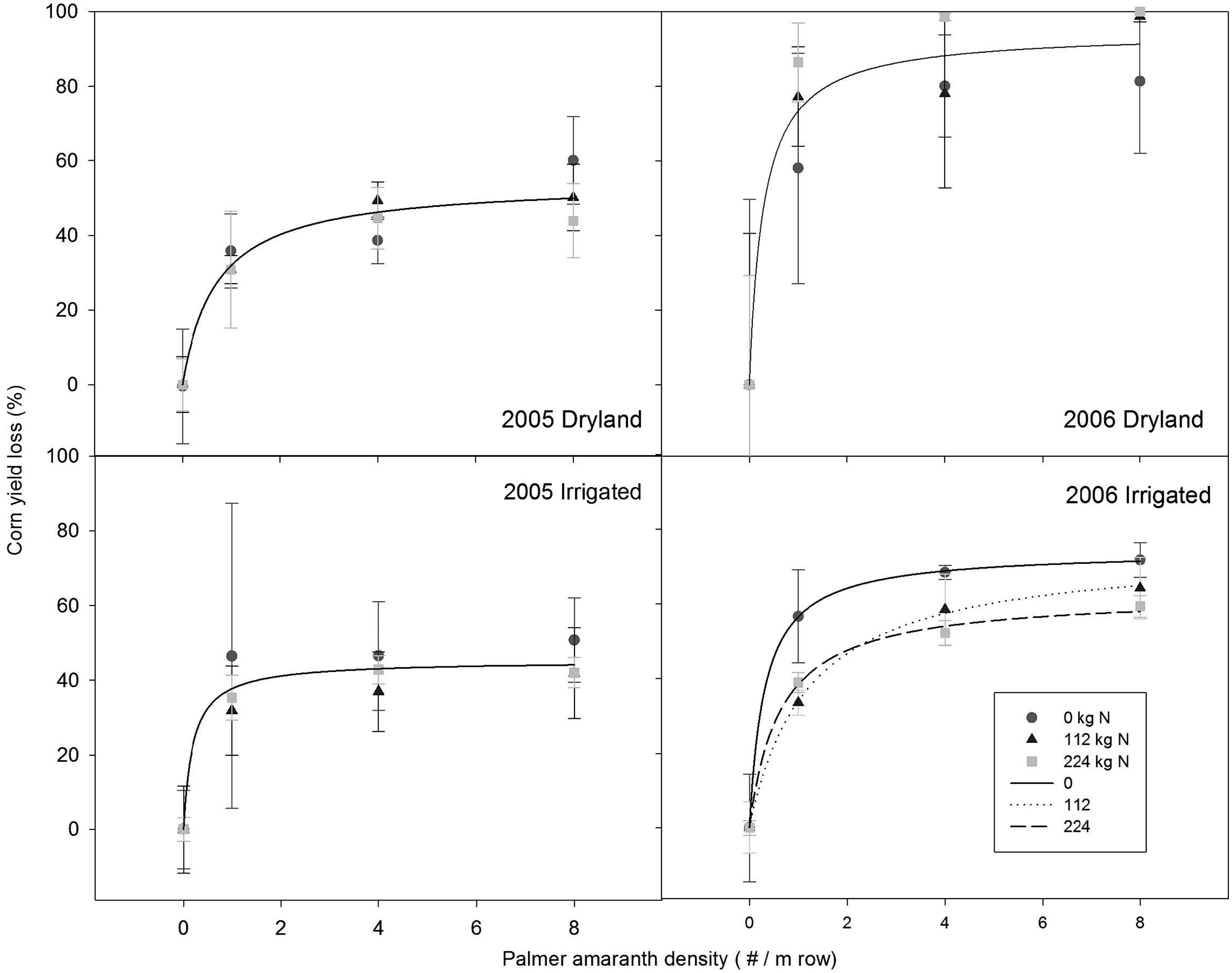

Figure 2. Percent corn yield loss for 2005 and 2006 dryland and irrigated environments as a function of Palmer amaranth density (plants per m row) and N rate (kg ha^{-1}). Points represent mean observed values (± SE), and the lines are the result of fitting Equation 1 to data for each N rate in 2006 irrigated environment or fit of Equation 3 to data pooled across N rates in 2005 dryland and irrigated and 2006 dryland environments. Parameter estimates in Table 2.

indicated that neither *I* nor *A* varied in 2005 dryland, 2005 irrigated, or in 2006 dryland environments. Thus, the yield loss model (Equation 3) was fit to the observed yield loss data pooled across N rates of these three data sets and estimates included in Table 2. In the 2006 irrigated environment, both parameter estimates *I* and *A* varied, and separate models were fit for each N rate (Table 2; Figure 2). The interaction of increasing Palmer amaranth and no additional N caused the greatest amount of corn yield loss in the irrigated environment, while added N (either 112 or 224 kg N ha^{-1}) caused similar but less yield loss across weed densities.

Pooled estimates across N rates for parameter *I* were 77.2 and 326.2% in dryland environments in 2005 and 2006, respectively, while in 2005 irrigated, the pooled estimate was 227.2% and in 2006 irrigated, *I* ranged from 62.6 to 238% (Table 2). In this study, parameter estimates for *I* for Palmer amaranth in corn were greater than those reported by Massinga et al. (2001), which were 33 to 86%, and were greater than those reported by Liphadzi and Dille (2006), which ranged from 24 to 27%. By substituting one Palmer amaranth plant m^{-1} of corn row into the yield loss model (Equation 1 or 3), yields were predicted to be reduced by 32 to 73% (Figure 2).

Pooled estimates across N rates for parameter *A* were 45.2% in 2005 irrigated, 54.3% in 2005 dryland, and 94.6% in 2006 dryland, while it ranged from 62.5 to 74.5% yield loss with high Palmer amaranth densities in the 2006 irrigated environments (Table 2). These estimates were less than those reported by Massinga et al. (2001), which ranged from 79 to 118% when Palmer amaranth emerged with irrigated corn, and estimates were similar to Liphadzi and Dille (2006), which were 52 to 95% across dryland and irrigated corn environments.

Nitrogen stress impacted corn yield but to a lesser extent than water- and weed-stresses, ranging from 19 to 47%. In this study, corn yield increased as N rates increased in the absence of Palmer amaranth, but as weeds were added, corn grain yields decreased as N applied increased. Corn grain yield in the absence of green foxtail [*Setaria viridis* (L.) Beauv.] increased with the addition of N (Cathcart and Swanton 2003), but in the presence of variable densities of green foxtail that emerged with the crop, corn grain yield decreased by an

Table 5. Weed-free corn biomass and nitrogen (N) concentration in tissues at corn anthesis in 2005 and 2006 across main effects of N rate and soil moisture environment.

Main effect[a]	Biomass		N concentration		
			2005		2006
	2005	2006	Leaf	Stem	Ear-leaf
	g per plant		% N		
Nitrogen rate (kg ha^{-1})					
0	112.0 a	79.1 a	2.02 B	0.43 C	2.05 B
112	144.0 b	83.7 a	2.49 A	0.56 B	2.78 A
224	104.8 a	94.0 a	2.67 A	1.23 A	2.83 A
Soil moisture environment					
Dryland	113.1 A	64.0 B	2.50 a	0.71 a	2.60 a
Irrigated	127.4 A	107.2 A	2.29 b	0.78 a	2.51 a

[a] Means followed by the same letter within a column and main treatment effect were not different at P = 0.05.

average of 18 to 23% despite increasing rates of N. In the presence of green foxtail, corn yield reductions were 35 to 40% with 0 kg N ha^{-1}, were only 20 and 8% at 100 kg N ha^{-1}, and were 12 to 17% at 200 kg N ha^{-1}, for 1999 and 2000–2001, respectively (Cathcart and Swanton 2003). These losses indicated that green foxtail was not as responsive to available N as corn and amount of yield loss decreased as N rate increased. Barker et al. (2006) also observed corn grain yield increased with addition of N in the absence of velvetleaf, but the effect of velvetleaf competition was variable depending on site-year. For example at one site-year, 10 velvetleaf plants m^{-1} of corn row resulted in corn yield reductions of 6.0, 28.1, 21.9, and 14.1% with 0, 45, 90, and 180 kg N ha^{-1}, respectively (Barker et al. 2006). In this example, it was hypothesized that corn yield loss in response to velvetleaf competition would increase with increasing N supply, but this was not observed. Our study suggests that in one of four environment-years, less corn yield loss was observed in the presence of Palmer amaranth competition at higher N rates as compared to no added N in irrigated environment in 2006, while in the other three environment-years, no differences in percent corn yield loss were observed across N rates.

Weed-Free Corn Biomass and Tissue N Concentration by Corn Anthesis. The impacts of soil moisture environment, N rate, and weed presence on corn biomass were observed by anthesis. In weed-free conditions, no two-way interactions of soil moisture environment and N rate on corn biomass or on tissue N concentration were detected in 2005 or 2006. In 2005, the main effect of N rate revealed that corn plants were heavier with 112 kg N ha^{-1} than for either 0 or 224 kg N ha^{-1} (Table 5), likely due to occurrence of sufficient and timely rainfall during the growing season (Table 4), higher residual soil N (Table 1), and some fertilizer mobility in the field. In 2006, there was no main effect of N rate on corn biomass in weed-free conditions. Main effect of soil moisture environment on weed-free corn biomass was not significant in 2005, while in 2006 weed-free corn biomass in dryland and irrigated environments were 64.0 and 107.2 g per plant, respectively, averaged across N rates (Table 5).

Increasing fertilizer N rates from 0 to 224 kg N ha^{-1} increased corn leaf and stem tissue N concentration by 132 and 286%, respectively in 2005, while in 2006, corn ear leaf tissue N concentration increased by 138% from 2.05 to 2.83% (Table 5). These values were comparable to those observed by Cathcart and Swanton (2004) when N content of corn ear leaf tissue at silking and under weed-free conditions increased from 1.8 to 3.2% when fertilizer N rates increased from 0 to 200 kg N ha^{-1} in 2001. This was also comparable to the 2.85% measured at tasseling by Reddy et al. (1991) where corn was grown under a 50 : 50 NH_4 : NO_3 solution.

Table 6. ANOVA table of results for plant biomass and nitrogen concentration.

Plant species	Source	df	Biomass		Nitrogen concentration		
					2005		2006
			2005	2006	Leaf	Stem	Ear leaf
Corn	E	1	NS	****	**	**	**
	N	2	****	**	****	****	****
	E × N	2	NS	**	NS	NS	NS
	W	3	****	****	****	***	***
	E × W	3	NS	NS	NS	NS	NS
	N × W	6	NS	NS	*	**	*
	E × N × W	6	NS	NS	NS	NS	NS
Palmer amaranth	E	1	*	NS	NS	NS	**
	N	2	****	****	***	****	****
	E × N	2	NS	NS	NS	NS	NS
	W	3	****	****	NS	***	**
	E × W	3	NS	**	NS	NS	NS
	N × W	6	****	****	NS	****	NS
	E × N × W	6	NS	NS	NS	NS	NS

[a] Abbreviations: E, environment; N, nitrogen rate; NS, not significant; W, weed density.
* P < 0.10; ** P < 0.05; *** P < 0.001; **** P < 0.0001.

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Table 7. Monoculture Palmer amaranth biomass and tissue nitrogen (N) concentration at corn anthesis in 2005 and 2006 across main effect of N rate.

	Biomass		N concentration		
			2005		2006
N rate[a]	2005	2006	Leaf	Stem	Branch
kg ha^{-1}	g per plant		% N		
0	49.7 c	116.8 b	3.19 b	0.99 b	2.71 b
112	84.4 b	140.8 b	3.60 a	1.13 b	3.13 b
224	185.2 a	421.1 a	3.99 a	2.87 a	3.84 a

[a] Means followed by the same letter within a column were not different at P = 0.05.

Main effect of soil moisture environment on corn leaf tissue N concentration was significant such that N was more concentrated in 2005 dryland environment compared to the irrigated environment where N was diluted across greater corn biomass (Tables 5 and 6).

Monoculture Palmer amaranth Biomass and Tissue N Concentration by Corn Anthesis. Palmer amaranth in the absence of corn competition increased its biomass by 373 and 361% as N rate increased from 0 to 224 kg N ha^{-1} in 2005 and 2006, respectively (Table 8). Palmer amaranth was highly responsive to available N, as expected. There was no two-way interaction of N rate and soil moisture environment on monoculture weed biomass or on tissue N concentration.

The corresponding N concentration in monoculture Palmer amaranth leaf and stem tissue increased by 125 and 290%, respectively in 2005, while branch tissue N concentration increased by 142% as N rate increased from 0 to 224 kg N ha^{-1} (Table 7). Palmer amaranth stems appear to store a large amount of N. Other studies have suggested that some weeds are luxury consumers of nutrients (Di Tomaso 1995; Qasem 1992; Teyker et al. 1991), and this might contribute to their ability to take up greater amounts of N at higher fertilizer rates. In the study by Blackshaw and Brandt (2008), redroot pigweed and wheat often had similar shoot N concentrations as N fertilizer rates were increased. It was a combination of greater total shoot biomass and N tissue concentration that allowed for the competitive ability of redroot pigweed to improve with greater soil N levels. In this study, percent increases in tissue N concentrations were similar for corn and Palmer amaranth, but monoculture Palmer amaranth had greater leaf and stem and branch N concentrations compared to weed-free corn (Tables 5 and 7). The hypothesis was that when they were in competition, their responses would be similar.

Table 8. Corn biomass at anthesis for each Palmer amaranth density averaged across soil moisture environments and nitrogen rates in 2005 and 2006.

Weed density	2005	2006
plants per m row[a]	g per plant	
0	120.27 a	85.75 a
1	79.89 b	64.65 b
4	80.52 b	44.07 c
8	77.67 b	42.90 c

[a] Means followed by the same letter within a year were not different at P < 0.05.

In Mixture - Corn Biomass and Tissue N Concentration. When in mixture, there were no three- or two-way interactions among soil moisture environment, N rate, or weed density on corn biomass (Table 6). There was a significant main effect of weed density such that corn biomass produced in the presence of any Palmer amaranth was significantly less than weed-free corn biomass by anthesis in both 2005 and 2006. In 2005, corn biomass was similar across all weed densities, while in 2006, corn competing with one Palmer amaranth plant m^{-1} row was heavier than when competing with four or eight Palmer amaranth plants m^{-1} row (Table 8). In 2006, there was a significant two-way interaction of N rate and soil moisture environment (Table 6) such that more corn biomass was produced in irrigated conditions with 112 and 224 kg N ha^{-1} across Palmer amaranth densities compared to other treatment levels (Table 9). Availability of water in 2006 allowed the corn to respond to applied N fertilizer. This corresponds to the subsequent corn yields observed at the end of the season (Figure 2) such that less yield loss occurred under irrigated conditions with N applications.

In Mixture – Palmer amaranth Biomass and Tissue N Concentration. There was a two-way interaction of N rate and weed density on Palmer amaranth biomass by corn anthesis when in mixture across both years (Table 6). In general with low N rates and high weed densities, less Palmer amaranth biomass was produced by corn anthesis (Table 10). Palmer amaranth was heavier in 2006 compared to 2005 across all treatments, and this included monoculture Palmer amaranth (no corn) and densities of one, four, and eight Palmer amaranth plants per m^{-1} row (with corn) (Table 10).

Based on these results, the extent to which each stress contributed to corn grain yield loss can be summarized. Water-deficit stress reduced corn yield potential the most by 52% when comparing weed-free irrigated corn yield in 2006 (16,110 kg ha^{-1}) to dryland corn yield in 2006 (7,660 kg ha^{-1}). Next, the addition of one Palmer amaranth

Table 9. Corn biomass at anthesis for each soil moisture environment and nitrogen rate averaged across Palmer amaranth densities in 2006.

Nitrogen rate	Dryland[a]	Irrigated
kg ha^{-1}	g per plant	
0	48.9 b	46.0 b
112	47.4 b	77.6 a
224	43.7 b	92.5 a

[a] Means followed by the same letter were not different at P < 0.05.

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Table 10. Palmer amaranth biomass in 2005 and 2006 and nitrogen concentration in stem tissue in 2005 observed at corn anthesis based on significant two-way interaction with nitrogen (N) rate and Palmer amaranth density.

N rate	Weed density[a]	2005	2006	2005 Stem
kg ha^{-1}	plants per m row	——g per plant——		% N
0	Mono (1)	49.7 c	116.8 bcde	0.99 de
	1	16.1 d	61.6 cdef	0.78 def
	4	11.0 d	39.9 def	0.61 ef
	8	15.3 d	23.6 ef	0.81 def
112	Mono (1)	84.4 b	140.8 bcde	1.13 de
	1	28.0 d	141.0 bcd	0.85 def
	4	17.5 d	50.6 def	1.08 de
	8	21.9 d	70.2 cdef	1.05 de
224	Mono (1)	185.2 a	421.1 a	2.87 a
	1	77.5 b	172.4 bc	2.74 a
	4	74.1 b	93.1 bcdef	2.55 b
	8	9.7 d	72.9 cdef	1.74 c

[a] Means followed by the same letter within a column were not different at $P < 0.05$.

plant further reduced corn yield between 32 and 73% (Figure 2). Nitrogen stress impacted corn yield but to a lesser extent, ranging from 19 to 47%; for example, in irrigated corn in 2006, high N rate produced 16,110 kg ha^{-1} corn grain yield, and it was reduced to 10,260 kg ha^{-1} with the 0 N rate, which is equivalent to 36% reduction (Table 2). In 2006 dryland environment, corn yield was reduced by 47% when comparing yields under 0 and high N rates. Corn and Palmer amaranth appear to produce biomass similarly to increases in N rate. Across N rates, the impact of Palmer amaranth varied; however, results indicate that most of the yield loss suffered by corn across N rates was due to the first Palmer amaranth plant m^{-1} row, and that as Palmer amaranth density increases from 1 to 8 plants m^{-1} of row, there was little increased effect on corn yield due to great intraspecific competition among Palmer amaranth plants. A number of competition studies have demonstrated the dramatic impact of Palmer amaranth on corn grain yield in differing environments (Liphadzi and Dille 2006; Massinga et al. 2001, 2003).

Corn production in Kansas is most influenced by available moisture, followed by Palmer amaranth competition and N rate factors. Water management in dryland environments is possible with proper selection of tillage systems, residue management, choice of crops in rotation, and weed management (Nielsen et al. 2005). Soil fertility and weeds can be more easily managed in dryland environments. This research study concludes that corn and Palmer amaranth respond similarly to N, except in one site-year where corn was able to perform better with N addition compared to Palmer amaranth. The goal of managing N as part of an IWM program might not be possible, unless future studies determine that N placement and timing, or improved nitrogen use efficiency of corn, might significantly influence corn and Palmer amaranth interactions. However, as more and more Palmer amaranth populations are found to be resistant to different herbicide modes of action, as well as increased occurrence or Palmer amaranth in more and new corn production areas, this research increases the awareness risk of significant corn yield loss with Palmer amaranth and the need to control weed populations through proper integrated management strategies. Additional strategies include selection of PRE herbicides and use of cover crops. It is very important to plan ahead for managing weed populations than trying to control the weed problem after it exists. This will allow producers to maximize corn yield potential in both dryland and irrigated environments in Kansas.

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