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Competitive ability of drought-tolerant corn hybrids in the presence of redroot pigweed (*Amaranthus retroflexus*) under optimal and reduced irrigation levels

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Abstract

Redroot pigweed (*Amaranthus retroflexus* L.) is among the most troublesome weeds in the Intermountain West affecting corn (*Zea mays* L.) production and contributing to significant yield losses, in addition to losses caused by water stress. Improvements in agricultural technology such as use of drought-tolerant (DT) corn hybrids has helped minimize the impact of water stress on corn yields. However, it is not known how the use of hybrids affects the interactions between weeds and corn. This work evaluated the competitive effects of *A. retroflexus* on DT and drought-susceptible (DS) corn hybrids exposed to optimal and reduced irrigation levels in a semi-controlled study. The semi-controlled environment was established in a rainout shelter with corn maintained at a density of 66,482 plants ha^{-1} and *A. retroflexus* varied at densities of 0, 33,241, and 66,482 plants ha^{-1} that were then provided either optimal or reduced irrigation (100% and 50%). We observed a 45% reduction in the shoot biomass of DS corn under reduced irrigation, while the shoot biomass of DT corn remained the same under both irrigation levels in Season 1. In Season 2, both hybrids experienced a decrease in shoot biomass under reduced irrigation. *Amaranthus retroflexus* exhibited an 80% increase in shoot biomass when growing with DS corn exposed to reduced irrigation, compared with its growth with DS corn exposed to optimal irrigation. Conversely, DT corn negatively impacted *A. retroflexus* shoot biomass under reduced irrigation, resulting in only a 9% difference between the reduced and optimally irrigated plots. These findings suggest that DT corn may mitigate water stress while also providing the additional benefit of improved competition against weeds, effectively suppressing their growth in water-stressed environments.

Introduction

Frequent droughts due to climate change pose a significant threat to corn (*Zea mays* L.) production not just in the United States, but globally (Aliniaeifard et al. 2023). For example, the historic drought of 2012 in the United States led to loss of nearly 27% of the projected corn production, despite the planting of drought-resistant varieties and a larger total cropped area (Pitt 2013; USDA 2013). Moreover, Chipanshi et al. (2003) estimated corn yield losses of up to 36% in Botswana under simulated climate change conditions like lower rainfall and potentially dry or drought conditions. Studies have also reported the impacts of moisture stress on corn production. For example, Cakir (2004) noted that moisture stress during rapid vegetative growth period led to 28% to 35% loss in final dry matter weight, with even greater yield losses of 66% to 93% resulting from prolonged water stress during the tasseling and ear formation stages. To overcome the negative impacts of drought on corn hybrids, drought-tolerant (DT) corn hybrids that are more resilient to water stress are being developed, enhancing crop viability in water-stressed environments (Adee et al. 2016). Farmers have been adopting these hybrids (McFadden et al. 2019); however, there is limited information on the interaction of DT corn hybrids with different weed species during the growing season.

Weeds compete with crops for limited resources like water, nutrients, and light. This competition between individuals or populations negatively impacts both organisms in situations where resources are limited (Rajcan and Swanton 2001). Competition can lead to reduced crop growth, survival, and yield (Gallandt and Weiner 2015). Crop production losses of greater than 10% due to weeds have been reported worldwide (Oerke 2006) despite the availability and implementation of various weed-management practices and technologies. For example, the impact of weeds on corn yields in North America was assessed in a study conducted by Soltani et al. (2016). Grain yields from fields with greater than 95% weed control were compared with those without any weed control in studies conducted from 2007 to 2013. It was observed that an average yield loss of 50% occurred due to weed interference, which is an equivalent loss of 148 billion kg of corn valued at more than US$26.7 billion annually. Weeds can absorb mineral nutrients faster than many crops and store them within their tissues in relatively large amounts (Lehoczky et al. 2003). This can make weeds more aggressive and competitive, therefore affecting corn growth and yield, especially under drought conditions (Radosevich et al. 2007). Corn yield loss due to redroot pigweed (*Amaranthus retroflexus* L.) competition was reported to be 5% to 34% (Knezevic et al. 1994) and <50% (Bosnic and Swanton 1997), depending on the *A. retroflexus* density. In addition, Sheibany et al. (2009) observed reduction in total dry matter, leaf area index, and crop growth rate due to *A. retroflexus* competition with corn. Combined effects of drought and weed competition on crop production can be severe, making weed management a priority for farmers.

To minimize losses from weeds, farmers often rely heavily on the use of herbicides (Soltani et al. 2016). However, with the risks associated with herbicide application like human exposure and development of herbicide resistance by weeds (Powles and Yu 2010), there is growing interest in additional alternative methods of weed management (Bastiaans et al. 2008). For example, two hybrids of DT *Desmodium* species (creeping beggarweed [*Desmodium incanum* DC] and branched tick-trefoil [*Desmodium ramosissimum* G. Don]) have been shown to effectively suppress parasitic witchweed (*Striga* spp.) weed infestation under both controlled and field conditions, resulting in significant grain yield increase in western Kenya (Midega et al. 2017). In addition, corn and wheat (*Triticum aestivum* L.) systems using hybrids with DT traits were able to deter outbreaks of spider mites (*Tetranychus* spp.) (Ruckert et al. 2021; Zhang et al. 2012). This demonstrates that DT crops can improve resilience to water stress as well as provide the added benefit of suppressing a variety of pests. However, more information is needed on how drought tolerance impacts the interaction between weeds and corn, particularly when exposed to water-stress conditions. Understanding these types of crop–weed interactions is important in determining whether DT crops are more competitive in dry conditions, thus expanding the understanding of available alternatives for managing weeds.

This research evaluated the competitive effects of three *A. retroflexus* densities (66,482, 33,241, and 0 plants ha^{-1}) on two corn hybrids: DT and drought susceptible (DS), exposed to two irrigation levels: optimal and reduced (100% and 50% replacement of evapotranspiration, respectively) in a semi-controlled environment (rainout shelter). *Amaranthus retroflexus* is a common weed in corn fields in Utah, and its competition has been shown to significantly reduce corn yields. The rainout shelter was utilized to effectively implement the drought treatments. The tested hypothesis is that DT corn hybrids have a competitive advantage over *A. retroflexus* even when exposed to water-stress conditions.

Materials and Methods

To evaluate the competitive ability of DT corn hybrids with *A. retroflexus*, field trials were conducted in a rainout shelter at the Evans Research Farm, at Utah State University, Logan, UT, USA (41.69579°N, 111.83277°W). This rainout shelter had been left fallow for more than 3 yr, and no herbicides had been applied before the study. The soil type in this field was silty clay loam (fine-silty, mixed, superactive, mesic Typic Calciaquolls), with a 2% to 4% slope, a soil organic matter of 0.93%, and a pH of 8.1. A granular fertilizer (15N-9P-12K Osmocote® Smart Release® (Marysville, OH, USA) Plus outdoor and indoor all-purpose fertilizer, Scotts Miracle-Gro®) was applied at planting at the rate of 0.1 kg m^{-2} according to the nutrient requirements of the plots.

The trial was set up in a randomized block design with individual plots measuring 1.9 by 1.9 m. The trial was conducted in two seasons (2021 and 2022) in the same field. Treatments were arranged in a 2 by 2 by 3 factorial design experiment using two corn hybrids (DT DKC 47-27 DroughtGard® Double Pro® and DS 'DKC 46-36', Bayer Crop Science, Whippany, NJ, USA), two irrigation levels (optimal and reduced irrigation level), and three *A. retroflexus* weed densities (66,482, 33,241 and 0 plants ha^{-1}). Each plot received a single treatment of corn hybrid, irrigation level, and *A. retroflexus* density of either no weeds, 66,482, or 33,241 *A. retroflexus* plants ha^{-1}, with each treatment combination replicated four times. For corn establishment, 66,482 plants ha^{-1} representing each corn hybrid were planted by hand in each plot with corn spaced at 0.38 m. Planting was done on May 23, 2021, and May 24, 2022.

The plant densities were determined by following the procedure in Vazin (2012). Corn and *A. retroflexus* densities were arranged in an additive design maintaining a constant corn density while varying *A. retroflexus* densities. Weeds that were not of interest in the plots were manually uprooted each week until no further weeds emerged. For different irrigation levels, plots had 3-m borders to ensure that the two distinct irrigation levels were achieved.

All plots were uniformly irrigated during plant germination and for 5 wk after planting (Figure 1). After this period, plots were randomly assigned either optimal or reduced irrigation levels. The rainout shelter was closed during rainfall. Plots receiving optimal irrigation (100% replacement of evapotranspiration) were irrigated every other day for 40 min, while plots receiving reduced irrigation (50% replacement of evapotranspiration) were irrigated twice per week for approximately 40 min each time, using a 360° water flow drip-irrigation system with 4/7-mm tube polyethylene pipe. Soil moisture sensors (Teros 10, Meter Group, Pullman, WA, USA) were used to monitor the volumetric water content (VWC) of the soil to maintain distinct soil moisture levels. The sensors were installed 30 cm deep in every plot, and VWC was monitored every other day. To determine the VWC for the two irrigation levels, an average VWC across all plots within an irrigation level ($n = 24$) was calculated. The plots were then watered to achieve two distinct average moisture levels (Figure 1).

Plants (both corn and *A. retroflexus*) were grown for a period of 80 d in 2021 and 100 d in 2022. The mean air temperatures experienced during the growing seasons were about 32 C in 2021 and 29 C in 2022. Additionally, the average rainfall was 345.44 mm in 2021 and 466.85 mm in 2022. To determine plant growth, plant height (both corn and *A. retroflexus*) from three randomly selected plants per plot per species (subsamples) were measured from the base at ground level to the tip of the plant once every month for the entire growing season. Stem diameter of two randomly selected plants (subsamples) were also measured 10 cm from the soil surface using a digital caliper. All plants of both species were harvested at the end of the growing season, and each species was stored separately in paper bags. Corn harvesting in the 2022 season was done at physiological maturity. Extreme drought in 2021 resulted in loss of irrigation at the research farm, requiring plants

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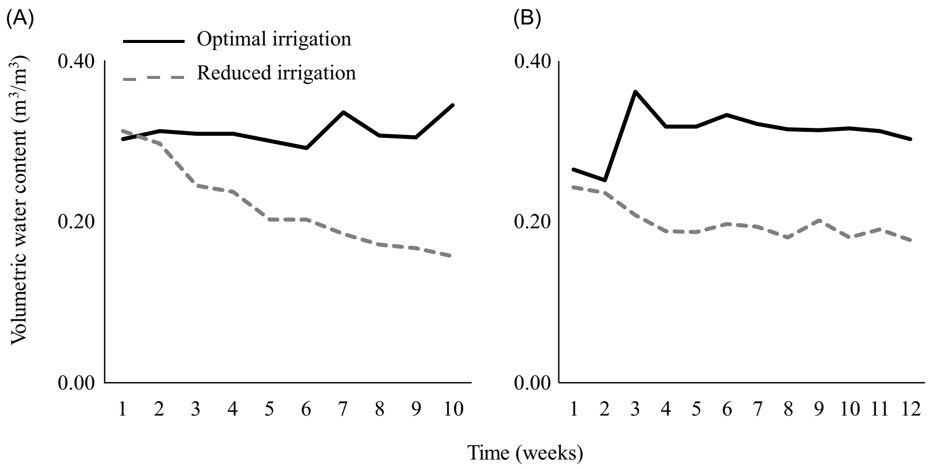

Figure 1. Average volumetric soil water content (average across all plots within an irrigation level, $n = 24$) for optimal and reduced irrigation treatments in the field study in (A) 2021 (Season 1) and (B) 2022 (Season 2) throughout the growing season.

to be harvested before corn reached maturity. To estimate corn shoot biomass, the aboveground biomass was weighed, excluding corn cobs. Harvested samples were then dried at 70 C in a drying oven for 3 d and weighed to determine the aboveground biomass. Corn cobs were also weighed after drying. Four roots were then randomly harvested at the end of the growing season for each plant species per plot (subsamples). The roots were harvested to a depth of 20 cm and a diameter around the base of the plant of 20 cm. Extracted roots were then washed, dried at 70 C in a drying oven for 3 d, and weighed to determine the belowground biomass.

Statistical Analysis

Statistical analyses were performed using SAS v. 9.4 (SAS Institute, Cary, NC, USA) and GenStat 15th edition. Stem diameter, shoot biomass, root biomass, and cob weight were analyzed using the PROC MIXED for ANOVA, with replicates considered a random factor. Plant height data were analyzed using repeated-measures analysis. Data from the two seasons were analyzed separately, as the effect due to season was significant for corn shoot ($P < 0.0001$), corn root ($P = 0.0004$), weed shoot ($P < 0.0001$), and weed root ($P < 0.0001$).

Normality was also assessed using normal probability plots of the residuals and histograms, and the data were normally distributed. When the two-way interaction effect was significant, the slice procedure was used to separate significant effects. When no significant interactions were observed, differences within significant main effects were determined using Tukey's honestly significant difference post hoc test.

Results and Discussion

Effect of Irrigation Level on Corn and Amaranthus retroflexus Root Biomass

Results from the first season (2021) indicate that the DT corn hybrid exhibited higher root biomass (30 g plant^{-1}) compared with the DS corn hybrid (20 g plant^{-1}) in the optimal irrigation level. However, reducing the irrigation level significantly reduced the root biomass of both hybrids, with the two hybrids having similar root biomass under reduced irrigation (Table 1; Figure 2A). This aligns with the findings of Benjamin et al. (2014) and Cai et al. (2017), who also reported reduced root biomass under water-stress conditions. This finding implies that the DT corn hybrid in this study did not optimize root development under water-stress conditions. It contrasts with the observations of Gregory (2006), who found that dry soils prompted plants to develop more extensive root systems, leading to deeper rooting, greater total weight, and increased root length compared with well-watered plants, an adaptation that helps plants in enhancing water absorption under water-stress conditions. In the subsequent season (2022), no factors affected corn root biomass (Table 1; Figure 2B). This could have been attributed to the differences in time of harvesting. In 2021, harvesting was done early, before physiological maturity, whereas in 2022, it was done at physiological maturity. This allowed the plants more time to grow and neutralize the differences observed in the first season.

Irrigation level did not significantly ($P = 0.805$) affect *A. retroflexus* root biomass in Season 1 (Table 1; Figure 3A). However, in Season 2, a reduction in irrigation level led to a significant ($P = 0.0003$) decrease in *A. retroflexus* root biomass from 2 g plant^{-1} to 1.1 g plant^{-1} (Table 1; Figure 3B). This finding contrasts with the results of Lima et al. (2016), who reported an increase in root biomass accumulation in several weed species, including rattle weed (*Crotalaria retusa* L.), sleepy morning (*Waltheria indica* L.), and tropical spiderwort (*Commelina benghalensis* L.) under water-stress conditions. These contradicting results could be attributed to the perennial nature of these weeds, which allows them to accumulate root biomass over a long period compared with the annual *A. retroflexus*, which were grown for a short period and might not exhibit the same resilience under water-stress conditions. In addition, perennial weeds may have deeper or more extensive root systems that enable them to access moisture more effectively under water-stress conditions, whereas *A. retroflexus* may not possess similar adaptive strategies.

Effect of Irrigation Level on Corn and Amaranthus retroflexus Shoot Biomass

In Season 1, shoot biomass of DS corn was reduced by 45% with reduced irrigation compared with the optimal irrigation level. Yet the shoot biomass of DT corn was unaffected by reduced irrigation (Table 1; Figure 4A). The ability of DT corn hybrids to maintain high shoot biomass despite reduced irrigation level indicates their resilience to water-stress conditions. These results are in line with

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Table 1. ANOVA of the effect of corn hybrids (drought tolerant and drought susceptible), irrigation level (optimal and reduced irrigation), and *Amaranthus retroflexus* densities (66,482, 33,241, and 0 plants ha^{-1}) on plant root biomass, plant shoot biomass, plant height, corn cob, and stem diameter in 2021 (Season 1) and 2022 (Season 2) in the rainout shelter.

	Factor significance[a]								
	Corn					*A. retroflexus*			
Source of variation	Root biomass	Shoot biomass	Total biomass	Stem diameter	Cob	Shoot biomass	Root biomass	Total biomass	Stem diameter
Season 1	PR > F								
Density (D)	0.041	0.715	0.641	0.708	N/A	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation (I)	0.067	0.0001	0.0002	0.092	N/A	0.067	0.805	0.073	0.834
D × I	0.469	0.063	0.087	0.111	N/A	0.002	0.234	0.002	0.293
Hybrid (H)	0.039	0.623	0.498	0.001	N/A	0.776	0.303	0.694	0.064
H × D	0.924	0.902	0.898	0.594	N/A	0.273	0.187	0.216	0.795
H × I	0.009	0.085	0.178	0.358	N/A	0.020	0.080	0.016	0.303
H × I × D	0.139	0.715	0.688	0.824	N/A	0.187	0.436	0.171	0.495
Season 2									
D	0.446	0.260	0.425	N/A	0.818	<0.0001	<0.0001	<0.0001	N/A
I	0.759	0.0005	0.0006	N/A	<0.0001	0.012	0.003	0.012	N/A
D × I	0.232	0.276	0.398	N/A	0.333	0.593	0.368	0.596	N/A
H	0.690	0.023	0.036	N/A	0.603	0.439	0.203	0.436	N/A
H × D	0.757	0.011	0.128	N/A	0.643	0.235	0.354	0.241	N/A
H × I	0.167	0.031	0.017	N/A	0.212	0.067	0.181	0.067	N/A
H × I × D	0.314	0.231	0.36	N/A	0.594	0.852	0.633	0.850	N/A

[a]N/A, data not available

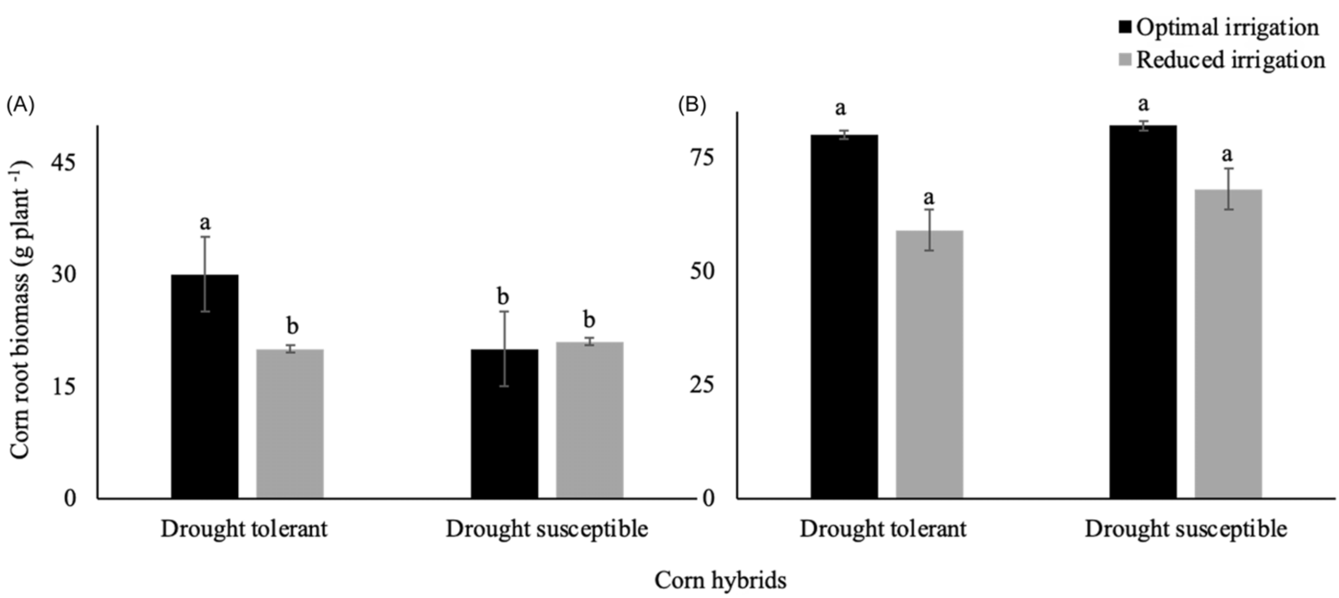

Figure 2. Mean (±SE) corn root biomass for drought-tolerant and drought-susceptible hybrids under varied irrigation levels (optimal and reduced irrigation) in (A) 2021 (Season 1) and (B) 2022 (Season 2). Bars labeled with the same letter are not significantly different ($P \geq 0.05$) based on Tukey's honestly significant difference post hoc test.

previous studies that have reported higher yields with drought-tolerant corn hybrids in water-stressed environments with no penalty in nonstressed environments (Adee et al. 2016). In Season 2, results showed a significant ($P = 0.031$) two-way interaction between hybrid and irrigation level on shoot biomass (Table 1; Figure 4B). The interaction was apparently driven by a high shoot biomass for DT corn exposed to increased irrigation levels that decreased with reduced irrigation, while DS corn had lower biomass with optimal irrigation that remained similar when irrigation was reduced (Table 1; Figure 4B). This interaction suggests that water management strategies should be tailored to the specific characteristics of each hybrid. It also demonstrates the importance of selecting appropriate corn hybrids for specific water conditions.

Evaluation of *A. retroflexus* shoot biomass in Season 1 and Season 2, when *A. retroflexus* was grown with DT corn, showed that weed biomass remained the same regardless of irrigation level. This suggests that increasing water stress did not impact the interaction between DT corn and *A. retroflexus*. DT corn was able to suppress *A. retroflexus* shoot growth under both optimal and reduced irrigation levels. This finding highlights the ability of DT corn to maintain competitive advantage over *A. retroflexus*, regardless of water-stress conditions. However, when *A. retroflexus* was growing with DS corn, reducing the irrigation level led to a

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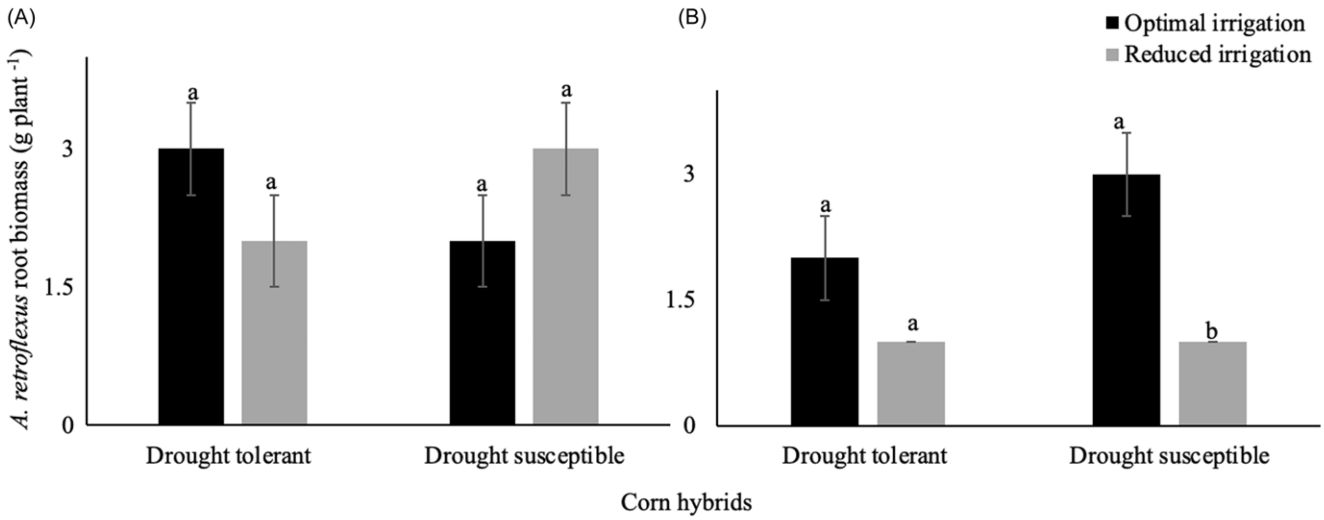

Figure 3. Mean (±SE) *Amaranthus retroflexus* root biomass when growing with drought-tolerant and drought-susceptible hybrids under varied irrigation levels (optimal and reduced irrigation) in (A) 2021 (Season 1) and (B) 2022 (Season 2). Bars labeled with the same letter are not significantly different ($P \geq 0.05$) based on Tukey's honestly significant difference post hoc test.

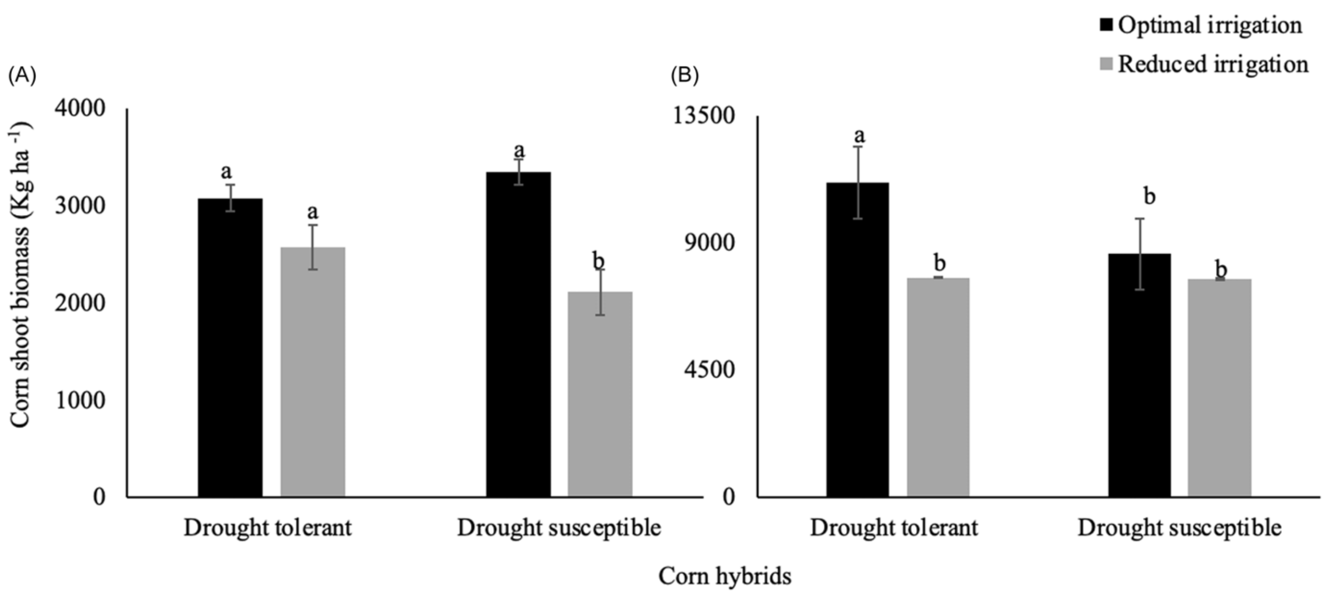

Figure 4. Mean (±SE) corn shoot biomass for drought-tolerant and drought-susceptible hybrids under varied irrigation levels (optimal and reduced irrigation) in (A) 2021 (Season 1) and (B) 2022 (Season 2). Bars labeled with the same letter are not significantly different ($P \geq 0.05$) based on Tukey's honestly significant difference post hoc test.

significant increase in *A. retroflexus* shoot biomass (Table 1; Figure 5). A low *A. retroflexus* shoot biomass accumulation when it was growing with DS corn under optimal irrigation could be attributed to the fact that DS corn has been bred to perform better under favorable environments (Sah et al. 2020). Therefore, DS corn was more competitive with *A. retroflexus* through its rapid shoot biomass accumulation under optimal irrigation, contributing to reduced shoot biomass accumulation for *A. retroflexus*. However, under water stress, *A. retroflexus* was able to accumulate higher shoot biomass when growing with DS corn, suggesting that it was able to outcompete DS corn that had low shoot biomass accumulation under water stress. This is attributed to the fact that *A. retroflexus* had a faster growth rate and more aggressive establishment than DS corn under water-stress conditions. Weeds are also more adapted in suboptimal conditions; this adaptability allows them to take advantage of the vulnerabilities of DS corn, leading to higher weed biomass accumulation when irrigation is reduced. In Season 2, the main effect of irrigation on *A. retroflexus* shoot biomass was significant ($P = 0.012$). Here, reducing the irrigation level led to an increase in *A. retroflexus* shoot biomass from 1,545 kg ha^{-1} to 2,785 kg ha^{-1}. This further emphasizes the impact of water stress on *A. retroflexus* growth, particularly in the presence of DS corn, which struggles to maintain competitive biomass under these conditions.

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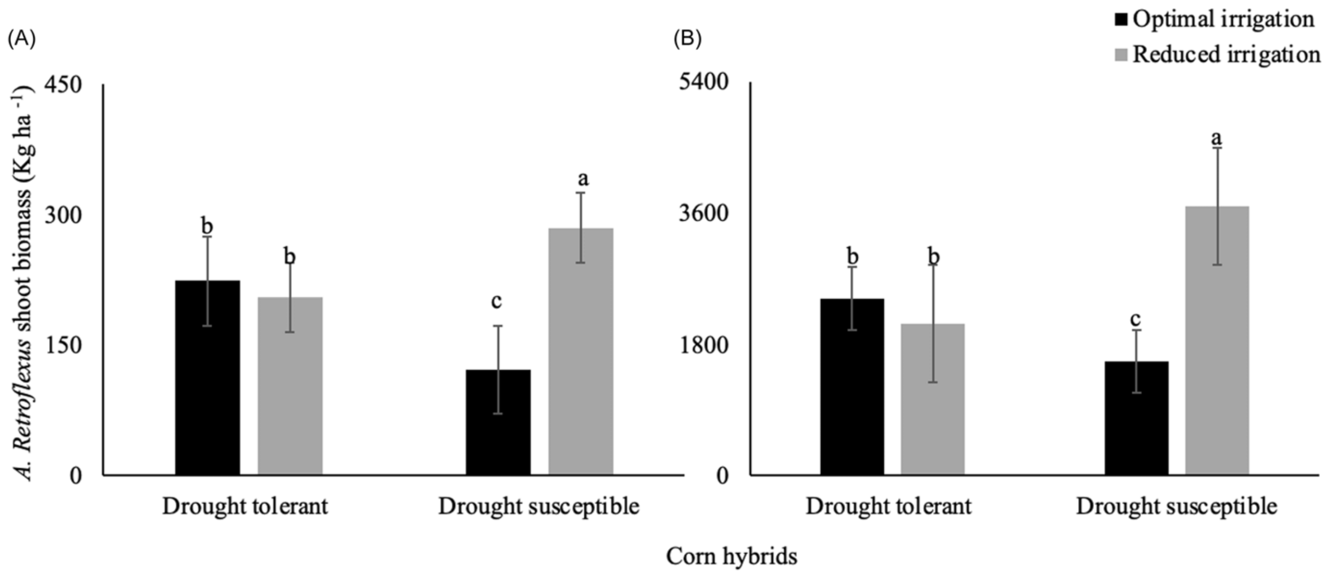

Figure 5. Mean (±SE) *A. retroflexus* shoot biomass when growing with drought-tolerant and drought-susceptible hybrids under varied irrigation levels (optimal and reduced irrigation) in (A) 2021 (Season 1) and (B) 2022 (Season 2). Bars labeled with the same letter are not significantly different (P≥0.05) based on Tukey's honestly significant difference post hoc test.

Effect of Irrigation Level on Corn and *Amaranthus retroflexus* Total Biomass

In Season 1, for both corn hybrids, reduced irrigation resulted in a decrease in total corn biomass (DT total biomass for optimal and reduced irrigation was 3,404 kg ha^{-1} and 2,784 kg ha^{-1}, respectively; and DS total biomass for optimal and reduced irrigation was 3,558 kg ha^{-1} and 2,341 kg ha^{-1}, respectively). This finding demonstrates the negative impact of water stress on biomass production for both corn hybrids; however, the DS hybrid appears to be more adversely affected by reduced irrigation than the DT hybrid. In Season 2, results showed a significant ($P = 0.017$) two-way interaction between corn hybrid and irrigation level on total biomass, while DS corn had lower biomass with optimal irrigation that remained similar when irrigation was reduced.

Evaluating total *A. retroflexus* biomass (roots plus shoot biomass) in both seasons, we found a significant ($P = 0.016$) two-way interaction between hybrid and irrigation level in Season 1. When *A. retroflexus* was growing with DT corn, its biomass remained the same regardless of irrigation level. However, when it was grown with DS corn, reducing the irrigation level led to a significant increase in its total biomass. These findings emphasize the competitiveness of DT corn in maintaining its growth and limiting *A. retroflexus* growth, consistent with the results explained earlier showing that DT corn can effectively suppress *A. retroflexus* shoot growth under both optimal and reduced irrigation levels. This also supports the previously discussed results that under reduced irrigation level, *A. retroflexus* thrives at the expense of DS corn. The adaptability of weeds to water stress allows them to capitalize on the reduced competitive ability of DS corn.

Effect of Irrigation Level on Corn and *Amaranthus retroflexus* Height

In Season 1, corn height was affected by the main effect of irrigation during the third and fourth months of the experiment (Table 2). For both hybrids, reducing the irrigation level led to a decrease in corn height. For example, corn height was reduced from an average of 226 cm to 199 cm in the fourth month (Table 3). Similarly, in the 2022 season, reducing the irrigation level led to reduction in corn height; however, height reduction started as early as in the second month (Tables 2 and 3). Previous studies have also reported reduction in plant heights due to water stress; for example, a study by Cakir (2004) determining the effect of water stress at different development stages on vegetative and reproductive growth of corn reported a reduction in corn height due to water stress. A study by Guo et al. (2023) also reported a reduction in plant height due to water stress resulting in the decrease in dry matter accumulation. However, in the present study, *A. retroflexus* heights were only affected by the main factor of irrigation level in Season 2 at the fourth month (Table 2). Weeds can adjust more quickly to environmental stress than many crops (Singh et al. 2022), this could have attributed to their height remaining the same under both optimal and reduced irrigation in 2021 season and in most parts of 2022 season. The consistent decline in corn height under reduced irrigation levels confirms the critical role of water availability for corn growth. While *A. retroflexus* heights were affected by irrigation level in Season 2, this effect was only observed in the fourth month. The ability of weeds to maintain their height under both optimal and reduced irrigation levels suggests their inherent resilience to environmental stress.

Effect of Irrigation Level on Corn Cob

Reducing the irrigation level led to a reduction in corn cob biomass for both DT and DS corn hybrids in Season 2 (Table 1). This is in line with previous findings by Vennam et al. (2022), who also noted a decrease in cob size with an increase in water stress. However, DT corn revealed a higher corn cob biomass than DS corn under reduced irrigation (11,895 kg ha^{-1} and 10,172 kg ha^{-1}, respectively). This suggests that DT corn is better equipped to allocate resources effectively even when water is limited. This could

Table 2. ANOVA of the effect of corn hybrids (drought tolerant and drought susceptible), irrigation level (optimal and reduced irrigation), and *Amaranthus retroflexus* densities (66,482, 33,241, and 0 plants ha^{-1}) on plant height in 2021 (Season 1) and 2022 (Season 2) in the rainout shelter.

Source of variation	Corn height				*A. retroflexus* height			
Season 1	———	———	———	——— PR > F	———	———	———	———
Density (D)	0.293	0.677	0.150	0.410	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation level (I)	0.687	0.298	0.008	<0.0001	0.693	0.103	0.668	0.796
D × I	0.798	0.705	0.466	0.250	0.016	0.660	0.898	0.439
Hybrid (H)	0.782	0.773	0.410	0.153	0.113	0.271	0.890	0.790
H × D	0.129	0.512	0.443	0.587	0.448	0.460	0.775	0.078
H × I	0.949	0.293	0.995	0.679	0.016	0.090	0.259	0.390
H × I × D	0.561	0.377	0.459	0.689	0.075	0.480	0.548	0.589
Season 2								
Density (D)	0.160	0.01	0.970	0.828	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation level (I)	0.344	<0.0001	<0.0001	<0.0001	0.981	0.025	0.903	0.034
D × I	0.349	0.672	0.494	0.671	0.989	0.238	0.658	0.480
Hybrid (H)	0.125	0.187	0.0008	0.093	0.507	0.942	0.633	0.886
H × D	0.980	0.883	0.324	0.224	0.635	0.838	0.701	0.984
H × I	0.513	0.690	0.120	0.379	0.724	0.645	0.401	0.761
H × I × D	0.982	0.860	0.870	0.944	0.618	0.550	0.479	0.256

Table 3. Mean (±SE) plant height of corn and *Amaranthus retroflexus* across 4 months (May, June, July and August) in 2021 (Season 1) and 2022 (Season 2) as influenced by irrigation levels (optimal and reduced irrigation) and corn hybrid (drought tolerant and drought susceptible).

	Plant height[a]							
	Corn				*A. retroflexus*			
Factor	May	June	July	August	May	June	July	August
Season 1	———	———	———	——— cm	———	———	———	———
Irrigation level								
Optimal irrigation	60.34 a	78.48 a	167.73 a	226.00 a	13.60 a	16.53 a	50.54 a	64.04 a
Reduced irrigation	61.71 a	84.10 a	152.53 b	199.23 b	14.06 a	20.51 a	48.39 a	65.47 a
Hybrid								
Drought tolerant	61.50 a	80.52 a	162.40 a	209.41 a	14.76 a	19.86 a	49.12 a	64.02 a
Drought susceptible	60.55 a	82.06 a	157.86 a	215.82 a	12.89 a	17.19 a	49.81 a	85.50 a
Season 2								
Irrigation level								
Optimal irrigation	61.72 a	222.03 a	225.74 a	232.79 a	13.40 a	68.06 a	63.93 a	73.65 a
Reduced irrigation	63.82 a	193.65 b	194.75 b	198.29 b	13.44 a	58.51 b	85.30 a	64.24 b
Hybrid								
Drought tolerant	61.06 a	205.11 a	206.15 b	213.27 a	13.87 a	63.43 a	87.30 a	69.26 a
Drought susceptible	64.49 a	210.57 a	214.33 a	217.81 a	12.97 a	63.13 a	61.93 a	68.64 a

[a]Means labeled by the same letter within each factor are not significantly different (P ≥ 0.05) based on Tukey's honestly significant difference post hoc test.

be attributed to its physiological adaptations such as more efficient water use. These results also demonstrate the potential of DT corn to enhance yield stability in water-stressed environments.

Effect of Hybrid on Corn Height and Stem Diameter

The heights of the two corn hybrids were similar in 2021 and 2022, except in the third month of 2022, when DS corn was taller than DT corn (Tables 2 and 3). However, the DT corn hybrid demonstrated greater early-season growth than the DS hybrid, as shown by its greater height in a parallel study that was conducted in the greenhouse (64.5 cm and 55.0 cm, respectively; data not shown). This gave the DT hybrid an early competitive advantage over *A. retroflexus*, leading to its higher shoot biomass compared with DS corn and reduced *A. retroflexus* shoot biomass.

Stem diameter shrinkage has been used as an indicator of soil moisture status, providing information on when to irrigate and leading to development of a more precise irrigation program (Meng et al. 2017). In this case, stems of the two corn hybrids were not significantly different (P = 0.06; DT = 24.3 mm and DS = 23.4 mm), suggesting that they were similarly affected by irrigation levels.

Effect of *Amaranthus retroflexus* Density on Corn Root Biomass

Amaranthus retroflexus density significantly (P < 0.0001) impacted corn root biomass in Season 1 (Table 1). Increasing *A. retroflexus* density caused a reduction in corn root biomass from 26 kg plant^{-1} to 21 kg plant^{-1} at *A. retroflexus* densities of 33,241 and 66,482 plants ha^{-1}, respectively. This could be attributed to the fact that the crops reallocated resources to favor shoot rather than root growth when the density of *A. retroflexus* was increased (Rajcan et al. 2004), indicating an adaptive response to competition. Corn plants prioritized shoot growth to ensure adequate light capture for photosynthesis.

Weed density affected *A. retroflexus* root biomass in both Seasons 1 and 2. As expected, increasing *A. retroflexus* density led to an increase in its total root biomass (Table 1). As *A. retroflexus*

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density increases, it not only competes for aboveground resources like light, but also for belowground resources like water and nutrients, leading to increase in root biomass.

Results from this study show that the DT corn hybrid can reduce weed shoot and total biomass of *A. retroflexus* under reduced irrigation levels. This was demonstrated by low weed shoot and total biomass accumulation when weeds were growing with DT corn under reduced irrigation level in the semi-controlled environment. These results were confirmed by the greenhouse experiment, in which weeds growing with DS corn revealed a higher shoot biomass than those growing with DT corn, suggesting that the DT hybrid suppressed their growth. DT corn hybrids have been bred to perform better under water stress, and they might have an added advantage of competing with nearby weeds. Consequently, incorporating DT hybrids in an integrated weed management program could be beneficial, especially in water-stressed environments. Future research should evaluate more weed species, more weed densities, various row spacings, and more irrigation levels to ascertain the role of this technology in managing weeds under varied water-stress levels.

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