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Large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) intraspecific and interspecific interference in soybean

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Research Article

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Abstract

Field studies were conducted in 2016 and 2017 at Clinton, NC, to quantify the effects of season-long interference of large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and Palmer amaranth (*Amaranthus palmeri* S. Watson) on 'AG6536' soybean [*Glycine max* (L.) Merr.]. Weed density treatments consisted of 0, 1, 2, 4, and 8 plants m^{-2} for *A. palmeri* and 0, 1, 2, 4, and 16 plants m^{-2} for *D. sanguinalis* with (interspecific interference) and without (intraspecific interference) soybean to determine the impacts on weed biomass, soybean biomass, and seed yield. Biomass per square meter increased with increasing weed density for both weed species with and without soybean present. Biomass per square meter of *D. sanguinalis* was 617% and 37% greater when grown without soybean than with soybean, for 1 and 16 plants m^{-2} respectively. Biomass per square meter of *A. palmeri* was 272% and 115% greater when grown without soybean than with soybean for 1 and 8 plants m^{-2}, respectively. Biomass per plant for *D. sanguinalis* and *A. palmeri* grown without soybean was greatest at the 1 plant m^{-2} density. Biomass per plant of *D. sanguinalis* plants across measured densities was 33% to 83% greater when grown without soybean compared with biomass per plant when soybean was present for 1 and 16 plants m^{-2}, respectively. Similarly, biomass per plant for *A. palmeri* was 56% to 74% greater when grown without soybean for 1 and 8 plants m^{-2}, respectively. Biomass per plant of either weed species was not affected by weed density when grown with soybean due to interspecific competition with soybean. Yield loss for soybean grown with *A. palmeri* ranged from 14% to 37% for densities of 1 to 8 plants m^{-2}, respectively, with a maximum yield loss estimate of 49%. Similarly, predicted loss for soybean grown with *D. sanguinalis* was 0 % to 37% for densities of 1 to 16 m^{-2} with a maximum yield loss estimate of 50%. Soybean biomass was not affected by weed species or density. Results from these studies indicate that *A. palmeri* is more competitive than *D. sanguinalis* at lower densities, but that similar yield loss can occur when densities greater than 4 plants m^{-2} of either weed are present.

Introduction

Understanding weed–crop interactions and the potential for crop loss from weeds allows growers to optimize weed management strategies. Growers need to adopt and apply economic thresholds to minimize yield loss from weeds (Coble and Mortensen 1992; Cousins et al. 1987). Most published studies of weed and crop competition are for soybean [*Glycine max* (L.) Merr.], far exceeding studies of the same type for other crops (Barnes et al. 2018; Bensch et al. 2003; Song et al. 2017; Zimdahl 2004). Many of these studies focus on season-long weed interference in soybean.

Palmer amaranth (*Amaranthus palmeri* S. Watson) and large crabgrass [*Digitaria sanguinalis* (L.) Scop.] are consistently ranked as two of the most troublesome and common weeds, respectively, in many crops (Van Wychen 2016). *Amaranthus palmeri* has become increasingly troublesome across the U.S. Southeast, Midsouth, and Midwest, with the possibility of further expansion out of these regions (Bagavathiannan and Norsworthy 2016; Copeland et al. 2018;

Davis et al. 2015; Kohrt et al. 2017; Korres et al. 2019; Kumar et al. 2019; Rangani et al. 2019; Briscoe Runquist et al. 2019; Varanasi et al. 2018; Webster and Grey 2015). It has documented resistance to eight herbicide mechanisms of action, with some individual biotypes resistant up to five mechanisms of action (Heap 2019). Of the *Amaranthus* species (i.e., waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer], redroot pigweed [*Amaranthus retroflexus* L.], and tumble pigweed [*Amaranthus albus* L.]), *Amaranthus palmeri* is considered the most aggressive, because it has the highest growth rate, biomass accumulation, and total leaf area (Guo and Al-Khatib 2003; Horak and Loughin 2000) of these species. It can reduce yield in corn (*Zea mays* L.), peanut (*Arachis hypogaea* L.), cotton (*Gossypium hirsutum* L.), sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*], and sweetpotato [*Ipomoea batatas* (L.) Lam.] by up to 91 %, 68 %, 54 %, 63 %, and 79 %, respectively (Basinger et al. 2019; Burke et al. 2007; Massinga et al. 2001; Meyers et al. 2010; Moore et al. 2004; Morgan et al. 2001). *Amaranthus palmeri* has proven to be a problematic summer annual weed with the capacity to compete with crops for resources while still maintaining high reproductive capacity (Bensch et al. 2003). Several studies have evaluated the impact of *A. palmeri* interference in soybean (Bensch et al. 2003; Dieleman et al. 1995; Klingman and Oliver 1994; Monks and Oliver 1988). However, only limited information is available on the intraspecific interference of *A. palmeri* in a soybean cropping system.

Digitaria sanguinalis is recognized as a common weed in many crops (Van Wychen 2016) and was originally brought to the United States as a forage grass (Dickinson and Royer 2014). Although *Digitaria* species have declined in importance (Webster and Coble 1997) due to effective herbicide control options, reports exist of resistance to acetyl CoA carboxylase inhibitors in the United States and resistance to acetolactate synthase (ALS) and photosystem II inhibitors abroad (Heap 2019; Hidayat and Preston 1997; Laforest et al. 2017; Volenberg and Stoltenberg 2002). Additionally, resistant biotypes of *D. sanguinalis* do not show reduced fitness when compared with susceptible biotypes (Wiederholt and Stoltenberg 1996). Although *D. sanguinalis* is not ranked highly as a problematic weed, significant yield losses of 6 %, 50 %, 74 %, 76 %, 89 %, and 100 % in cotton, watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai], grain sorghum, sweetpotato, snap bean (*Phaseolus vulgaris* L.), and bell pepper (*Capsicum annum* L.), respectively, have been documented (Aguyoh and Masiunas 2003; Basinger et al. 2019; Byrd and Coble 1991; Fu and Ashley 2006; Monks and Schultheis 1998; Smith et al. 1990). Although *D. sanguinalis* has been studied in several cropping systems, there has been limited focus on interspecific interference in a soybean cropping system (Oreja and Gonzalez-Andujar 2007) and intraspecific interference of *D. sanguinalis*.

Despite a large amount of research conducted on season-long weed interference in soybean, much of the focus is on yield loss associated with measured weed densities. The present research was conducted to measure yield loss from season-long competition of *D. sanguinalis* and *A. palmeri* when seeded at various densities in soybean. A second objective determined intraspecific competition of each weed species under North Carolina climatic conditions. Studying intraspecific competition allows for an understanding of how weeds perform when a crop is not present. Intraspecific interference is not often studied in agricultural systems. However, understanding the effects of intraspecific weed competition can allow for a better understanding of weed population dynamics, weed biomass accumulation, and intraspecies competition. Lack of a crop may be due to poor crop emergence or crop predation and can mimic areas such as turnrows and crop field edges, where weeds can persist without a crop. Limited information is available on intraspecific competition of *A. palmeri* or *D. sanguinalis* and interference of *D. sanguinalis* in soybean in the United States (Schwartz et al. 2016). Yet *D. sanguinalis* and *A. palmeri* are pervasive in soybean, and understanding the weed–crop and weed–weed interactions in this system would provide valuable information that growers can use when making weed management decisions.

Materials and Methods

Field studies were conducted in 2016 and 2017 in conventionally grown soybean (Stowe et al. 2018) at the Horticultural Crops Research Station (35.1°N, 81.16°W), Clinton, NC. The studies were conducted on a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with humic matter 0.31 % and pH 5.9 in 2016, and an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with humic matter 0.47 % and pH 5.9 in 2017. A preplant fertilizer of 0 (N)–0 (P_2O_5)–168 (K_2O) kg ha^{-1} was applied on June 7, 2016, and June 6, 2017, and disked to approximately 10-cm deep. Seven days after fertilizer application, soybean ‘AG6536’ (Monsanto Company, St Louis, MO, USA) seeds were planted with a four-row vacuum planter 0.1 m apart within row and 0.3 m between rows, resulting in a seeding rate of 321,000 seeds ha^{-1}. Plots were 1.2-m wide by 5-m long and consisted of four soybean rows. Treatments were combinations of soybean presence or absence, weed species (*A. palmeri* or *D. sanguinalis*), and weed density arranged in a randomized complete block design with three replications. At 1 d after soybean planting, *A. palmeri* or *D. sanguinalis* seeds were broadcast by hand into treatment plots designated to receive either *A. palmeri* or *D. sanguinalis* and then raked to approximately 0.6-cm deep. The same day, 1.3 cm of overhead irrigation water was applied to facilitate soybean and weed seed germination. Supplemental irrigation was not applied in either study year after the initial irrigation event. *Amaranthus palmeri* seeds used in this experiment were hand harvested from adjacent fields at the Clinton site in 2015, and *D. sanguinalis* seeds were purchased from Azlin Seed Service (Azlin Seed Service, Leland, MS, USA). *Amaranthus palmeri* (collected seed) and *D. sanguinalis* were not screened for resistance. However, *A. palmeri* populations in the region of the state where seeds were collected have exhibited resistance to glyphosate and ALS herbicides (Heap 2019). No resistant biotypes have been reported for *D. sanguinalis* in the state from which the seed for this species was purchased (Heap 2019). Weeds emerged with the crop and were thinned by hand to densities of 1, 2, 4, and 8 for *A. palmeri* (by 8-cm stage), and 1, 2, 4, and 16 plants m^{-2} for *D. sanguinalis* (by 2–expanded leaves stage), using a 1-m^2 quadrat to ensure uniform spatial densities, and establishing 5 subsample populations per plot. Within each block, a weed-free treatment was maintained by hand removal for comparison. Weed densities were based on previous research to ensure levels of interference that would allow for estimations of maximum yield loss (Cowan et al. 1998; Fu and Ashley 2006; Klingman and Oliver 1994; Meyers et al. 2010; Norsworthy et al. 2008). Soybean was removed immediately after emergence in the plots where intraspecific competition was studied; weed densities were the same as in the interspecific competition plots. All plots were hand weeded weekly to maintain treatment densities and remove other emerged weed species.

At physiological maturity, 5 plants each of soybean (R6 growth stage) (Stowe et al. 2018), *A. palmeri* (seed beginning to ripen, but all foliage still present), and *D. sanguinalis* (seed set and beginning of seed shatter), were randomly selected from the center two rows of each plot (when crop and/or weed species were present in treatment plot) and cut at the soil surface. Harvested plants were cut into small pieces and placed in separate two-ply paper bags (40 by 30 by 89 cm) by species. The bags containing fresh plant biomass were weighed to determine fresh biomass and subsequently dried in a propane-fueled forced-air heated drier for 96 h at 80 C and weighed to determine plant dry biomass. Fresh and dry weights of each plant sample per plot (individual bag) were divided by the number of plants harvested (5) to determine fresh and dry biomass weight per plant. Biomass per plant was then multiplied by the number of soybean plants per square meter or weed density per square meter to determine crop and weed biomass per square meter.

To determine soybean yield, soybean was cut at the soil surface at full maturity (R8 growth stage) using a hand-held hedge trimmer (HL 100 K, Stihl USA, Virginia Beach, VA, USA), then placed in large two-ply paper bags, as previously described. Soybean plants from each plot were threshed using a small-plot soybean thresher (B-1, Swanson Agricultural Research Equipment, Seymour, IL, USA) and placed in a seed cleaner (ASC-3, Agriculex, Guelph, ON, Canada) to remove any remaining plant material. Clean soybean seeds were then weighed to determine soybean yield for each plot. Yield loss was calculated as a percent of the weed-free control for each replication. Soybean yield reductions were modeled as a percent reduction in yield as compared with weed-free yield using a rectangular hyperbola function (Cousins 1985):

$$\mathrm{Y_R} = (ID)/[1 + (ID/A)]$$

Descriptions of each variable are as follows: Y_R is the reduction in yield as a function of weed density, I is the yield loss associated per weed as weed density approaches zero, A is the asymptote of yield loss as weed density approaches infinity, and D is the weed density. Yields from weed-free plots were used as 100 % yield or zero percent yield loss, and were used to calculate yield loss estimates. PROC NLIN in SAS v. 9.4 (SAS Institute, Cary, NC, USA) was used to obtain yield loss estimates as a percent yield loss, using the rectangular hyperbola model.

For dry biomass weight of crop and weed per square meter, weed biomass per plant, and soybean yield, homogeneity of variance was tested before statistical analysis by plotting residuals. Data were subjected to ANOVA using PROC MIXED in SAS v. 9.4. Year, treatment, and the interaction of treatment and year were treated as fixed effects, and replication within each year was treated as a random effect. Contrast statements to test for linear trends were used if the interaction of treatment and year was not significant with $\alpha \geq 0.05$, and means were averaged over years. When the year and treatment interaction was significant, response variables were analyzed by year. Weed biomass per square meter, weed biomass per plant, and yield were log transformed for analysis. Log-transformed data for weed biomass per square meter, weed biomass per plant, and crop biomass were subjected to ANOVA using PROC MIXED in SAS v. 9.4.

Interactions for weed density and year were not significant for weed biomass per plant response to weed density; therefore, data were averaged over years. Predictions using linear quadratic or other higher-order regression models did not fit the response of weed biomass per plant for *D. sanguinalis* or *A. palmeri*. Weed biomass per plant was compared using differences of least-squares means at each density for weeds grown with and without soybean. Comparisons of weed density were according to Tukey's honestly significant difference (HSD) for each weed species at $\alpha = 0.05$. All means reported are nontransformed.

Weed species response in the presence and absence of the soybean crop for weed biomass per square meter was fit to a linear regression model with Equation 2:

$$Y = y_0 + bx$$

where Y is the estimated biomass per square meter, y_0 is the y intercept for the regression line, and b is the slope for the predicted values of weed biomass per square meter, regressed against weed density.

For comparison to current recommendations for crop loss due to weed interference, weed densities measured in this study were entered into the North Carolina Web Herbicide Application Decision Support System (WebHADSS; Lassiter and York 2009). Loss estimates using WebHADSS are calculated based on the 10-yr average soybean yield (2,320 kg ha^{-1}) (USDA-NASS 2018) and average farm size (68 ha^{-1}) (USDA-NASS 2012) for North Carolina.

Results and Discussion

Interspecific Interference

Interactions of weed density by year were not significant for biomass per plant or biomass per square meter of either weed. Thus, the data for these parameters were averaged across years for *D. sanguinalis* or *A. palmeri*. Biomass per square meter of *D. sanguinalis* or *A. palmeri* with soybean increased with increasing weed density (Figures 1 and 2). Biomass per square meter increases were due to increasing weed number not to increased weed biomass per plant (Table 1). Klingman and Oliver (1994) also reported increases of *A. palmeri* biomass per square meter with increasing density in soybean. Biomass of both weed species per square meter was greater in the absence of soybean.

Biomass per plant of either weed growing with soybean did not vary across density (Table 1). Data for weed biomass per plant did not fit linear or nonlinear models, and thus were compared for each weed using Tukey's HSD. The lack of weed biomass per plant changing with increasing weed density is in contrast to the findings of Burke et al. (2007), who reported decreasing weed biomass per plant for *A. palmeri* with increasing weed density when grown with peanut. In the present study, soybean biomass per square meter was unaffected by *A. palmeri* and *D. sanguinalis* density (data not shown). Loss of soybean biomass has been seen with other weeds [common ragweed (*Ambrosia artemisiifolia* L.), barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], annual sowthistle (*Sonchus oleraceus* L.), American sloughgrass [*Beckmannia syzigachene* (Steud.) Fernald], and common lambsquarters (*Chenopodium album* L.)] at densities greater than those evaluated in this study (up to 140 plants m^{-2}) and at a wider row spacing (70 cm) (Song et al. 2017). Soybean biomass may vary and weed species may respond differently with wider rows or at higher planting densities, which are factors that influence soybean and weed plant heights or leaf area index and contribute to crop and weed biomass (Howe and Oliver 1987; McWhorter and Sciumbato 1988; Song et al. 2017).

Intraspecific Interference

Biomass per square meter response for intraspecific interference increased with increasing density, similar to the biomass per square

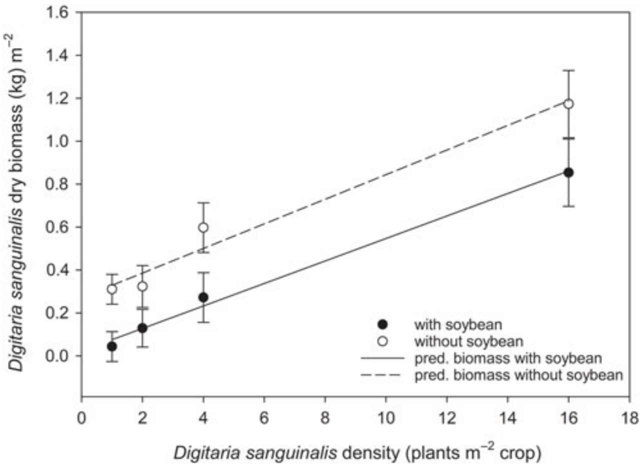

Figure 1. *Digitaria sanguinalis* dry biomass (kg) per square meter as a function of increasing *D. sanguinalis* density per square meter. *Digitaria sanguinalis* was grown with 'AG6536' soybean or without soybean at the Horticultural Crops Research Station, Clinton, NC, in 2016 and 2017. Dry biomass per square meter (averaged over years) of *D. sanguinalis* growing with and without soybean were fit to a linear model (equation: $y = y_0 + bx$). When grown with soybean, $y_0 = 0.023$ (0.025), $b = 0.0524$ (0.003), $R^2 = 0.99$. When grown without soybean, $y_0 = 0.27$ (0.057), $b = 0.0573$ (0.007), $R^2 = 0.97$, with SEs in parentheses.

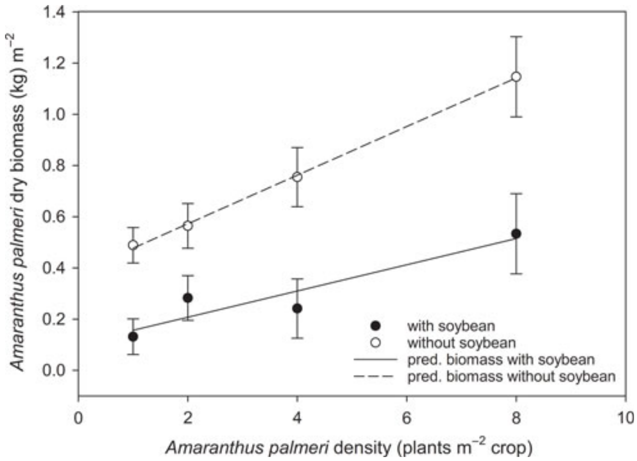

Figure 2. *Amaranthus palmeri* dry biomass (kg) per square meter as a function of increasing *A. palmeri* density per square meter. *Amaranthus palmeri* was grown with 'AG6536' soybean or without soybean at the Horticultural Crops Research Station, Clinton, NC, in 2016 and 2017. Dry biomass per square meter (averaged over years) of *A. palmeri* growing with and without soybean was fit to a linear model (equation: $y = y_0 + bx$). When grown with soybean, $y_0 = 0.105$ (0.065), $b = 0.051$ (0.014), $R^2 = 0.87$. When grown without soybean, $y_0 = 0.382$ (0.010), $b = 0.095$ (0.002), $R^2 = 0.99$, with SEs in parentheses.

meter response when *D. sanguinalis* and *A. palmeri* were grown with soybean (Figures 1 and 2). Biomass per square meter of *D. sanguinalis* was 617 % and 37 % greater for 1 plant m^{-2} and 16 plants m^{-2}, respectively, when grown without soybean than when grown with soybean. Biomass per square meter of *A. palmeri* was 272 % and 115 % greater for 1 and 8 plants m^{-2}, respectively, when grown without soybean than when grown with soybean. Weed densities higher than those measured in this study would likely result in additional biomass losses for both weed species. Density of each weed species was maintained throughout each season, and no weed mortality was noted after thinning, indicating the carrying capacity of this system is likely to be greater than the combination of the density of the planted soybeans and the weed densities measured. If the carrying capacity were to be met, biomass per square meter would stabilize, and no further recruitment from seeds would be needed. Additional recruitment would only be possible if weed densities dropped below the carrying capacity.

For *D. sanguinalis*, biomass per plant was greater when grown without soybean than with soybean for all weed densities, except for the two highest measured densities, 4 and 16 plants m^{-2} (Table 1). This finding indicates that intraspecific competition for resources may be occurring with *D. sanguinalis* at a density as low as 4 plants m^{-2}, affecting biomass per plant. Biomass per plant for either weed when grown without soybean was greatest at the lowest density (1 plant m^{-2}). Furthermore, similar slopes seen in Figure 1 indicate that intraspecific competition did not reduce weed biomass per square meter for *D. sanguinalis*, even in the presence of soybean.

For *A. palmeri*, biomass per plant was higher across all densities when grown without soybean, and biomass per plant was the lowest at 4 and 8 plants m^{-2} compared with 1 plant m^{-2}. Weed biomass per plant was similar across all densities of *A. palmeri* when grown with soybean, indicating that soybean was competitive with *A. palmeri*, reducing biomass per plant despite increases in weed density. *Amaranthus palmeri* results for biomass per square meter were similar to results for *D. sanguinalis*, showing increasing biomass per square meter with increasing weed density (Figure 2). Additionally, different slopes between soybean presence and absence for *A. palmeri* indicate that there is both intraspecific and interspecific competition occurring at 4 and 8 plants m^{-2} when soybean is present.

Lower biomass of *D. sanguinalis* or *A. palmeri* with soybean relative to without soybean suggests that interspecific interference is occurring between soybean and both weed species across all densities. Within density, *D. sanguinalis* or *A. palmeri* biomass per plant was higher when grown without soybean, except for *D. sanguinalis* at 4 and 16 plants m^{-2} (Table 1). These results suggest that *D. sanguinalis* may be able to tolerate higher intraspecies densities than *A. palmeri*. Results from the present study suggest that increased weed biomass per square meter is due to increasing weed density, not increased weed biomass per plant (Table 1). In previous studies, similar responses were seen in *E. crus-galli* in the absence of tomato (*Solanum lycopersicum* L.), spiny amaranth (*Amaranthus spinosus* L.) in lettuce (*Lactuca sativa* L.), and with *A. palmeri* and *D. sanguinalis* in absence of sweetpotato, with increasing biomass per meter of row and decreasing biomass per plant with increasing density (Basinger et al. 2019; Norris et al. 2001; Shrefler et al. 1994). Previous work done by the authors showed greater biomass accumulation per plant at the same densities of *D. sanguinalis* and *A. palmeri* in sweetpotato compared with the present study (Basinger et al. 2019). Although a direct comparison cannot be made, these results suggest that the cropping system may have an effect on weed intraspecific interference. The authors believe that greater weed biomass accumulation per plant in sweetpotato may be due to weed spatial distribution due to tillage events that coincide with potassium fertilizer application. Previous work done by Norris et al. (2001) indicated that weeds that were clumped reduced plant biomass and seed production compared with random or evenly spaced plants at the same density.

Yield

Soybean yield responses to densities of *A. palmeri* and *D. sanguinalis* lacked year by treatment interactions and therefore were combined

Table 1. Mean weed biomass per plant (kg) followed by SE in parentheses, for *Digitaria sanguinalis* and *Amaranthus palmeri* at four densities, grown in the presence and absence of 'AG6536' soybean at the Horticultural Crops Research Station, Clinton, NC, averaged over 2016 and 2017.

Density	Crop present		Crop absent		P-value[a]
m^{-2}	———kg[b]———				
Digitaria sanguinalis					
1	0.06 (0.03)	A	0.36 (0.24)	A	<0.0001
2	0.08 (0.04)	A	0.17 (0.09)	B	0.0479
4	0.08 (0.03)	A	0.18 (0.08)	B	0.0648
16	0.06 (0.03)	A	0.09 (0.02)	B	0.2376
Amaranthus palmeri					
1	0.15 (0.08)	a	0.57 (0.37)	a	0.0045
2	0.16 (0.06)	a	0.37 (0.17)	ab	0.0096
4	0.07 (0.06)	a	0.23 (0.13)	b	0.0008
8	0.08 (0.05)	a	0.20 (0.08)	b	0.0176

[a] P-values are the result of differences in least-squares means comparing crop and no-crop plots for each weed at the given density.

[b] Different letters within the same column and species indicate significance ($P \leq 0.05$) according to Tukey's HSD.

Table 2. Monthly rainfall (mm) and growing degree days (GDD; base 10 C) at the Horticultural Crops Research Station, Clinton, NC, from May to September 2016 and 2017.[a]

Month	Rainfall		GDD	
	2016	2017	2016	2017
	———mm———			
May	136	142	330	357
June	93	150	473	437
July	155	86	569	527
August	107	125	538	493
September	287	132	437	393
Total	778	635	2,347	2,207

[a] Data were collected from an on-site weather station.

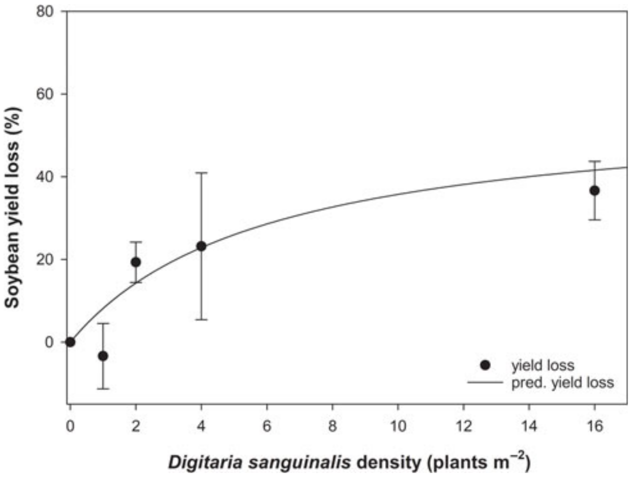

Figure 3. 'AG 6536' Soybean yield loss (%), based on weed-free soybean maximum yield, from *Digitaria sanguinalis*. Mean soybean yield loss for 2016 and 2017 is plotted as a function of increasing large crabgrass density per square meter at the Horticultural Crops Research Station, Clinton, NC. Data were fit to a rectangular hyperbola model (equation: $Y_R = (ID)/[1+(ID/A)]$), with $I = 9.17$ (4.75), $A = 50.47$ (17.34), $R^2 = 0.84$; SE is given in parentheses.

over years. Rainfall and growing degree days were higher in 2016 than in 2017 but did not affect yield between years (Table 2). Weed-free yields averaged 3,093 kg ha^{-1}, above the 10-yr NC soybean average of 2,320 kg ha^{-1} (USDA-NASS 2018). Soybean yield reductions were fit to a rectangular hyperbola model (Cousins 1985) for *D. sanguinalis* (Figure 3) and *A. palmeri* (Figure 4), with yield reduction increasing as weed density increased. Yield loss ranged from 0 % at 1 *D. sanguinalis* plant m^{-2} to 37 % at 16 *D. sanguinalis* plants m^{-2}, and from 19 % at 1 *A. palmeri* plant m^{-2} to 37 % at 8 *A. palmeri* plants m^{-2}. The I parameter, yield loss as weed density approaches zero, for *D. sanguinalis* and *A. palmeri* was calculated as 9 % and 20 % respectively. Yield loss as weed density approaches zero estimates for *D. sanguinalis* averaged 33 % for snap bean and 40 % for bell pepper (Aguyoh and Masiunas 2003; Fu and Ashley 2006). Lower yield loss as weed density approaches zero values indicated that *D. sanguinalis* is less competitive with soybean compared with *A. palmeri*. *Amaranthus palmeri* interference estimates for yield loss were 118 % for corn (Massinga et al. 2001), 87 % for soybean (Bensch et al. 2003), and constrained to 100 % in peanut (Burke et al. 2007). Yield loss as weed density approaches zero for *A. palmeri* was reported as 11.8 % to 104.6 % in soybean (Bensch et al. 2003), 39 % in peanut (Burke et al. 2007), and 90 % in corn (Massinga et al. 2001).

Parameter A, the asymptote for the regression model that estimates the maximum estimated yield loss according to the rectangular hyperbola model, was 50 % and 49 % for *D. sanguinalis* and *A. palmeri*, respectively. Predicted values for maximum yield loss were considered reliable estimates for *D. sanguinalis* and *A. palmeri*, as the standard errors of the parameter estimates were less than half of the estimated values (Koutsoyiannis 1973). *Digitaria sanguinalis* interference estimates for maximum yield loss have been reported as 62 % in snap bean (Aguyoh and Masiunas 2003) and 91 % to 100 % in bell pepper (Fu and Ashley 2006). Although maximum yield loss parameters indicate that *A. palmeri* is more competitive than *D. sanguinalis* at lower densities, similar yield reductions did occur in our study at 8 and 16 plants m^{-2} for *A. palmeri* and *D. sanguinalis*, respectively. Yield reductions, estimated as 50 % and 49 % for *D. sanguinalis* and *A. palmeri*, respectively, indicate that management of these weeds is needed to prevent significant yield loss. The greater interference of *A. palmeri* compared with *D. sanguinalis* in soybean may be due to morphological differences between these two weed species. *Digitaria sanguinalis* has small leaf blades and is lower in height than *A. palmeri*, which may allow *D. sanguinalis* to compete well with the crop, but does not allow for it to shade out the crop, as *A. palmeri* can. Biomass accumulation (plant^{-1} and m^{-2}) of *A. palmeri* is almost double that of *D. sanguinalis* at densities less than 4 plants m^{-2}. Greater biomass accumulation at densities less than 4 plants m^{-2} may be a contributing factor to higher yield reductions at lower densities for *A. palmeri*. Although the impact of *A. palmeri* on light and water was not measured in this study, competition for these resources may have contributed to yield reductions, as is seen in previous work in corn and soybean (Green-Tracewicz et al. 2012; Massinga et al. 2003). Biomass accumulation for *D. sanguinalis* was less than for *A. palmeri*, which may have limited the interference of *D. sanguinalis* at lower measured densities ($\leq$4 plants m^{-2}). However, at the higher densities measured in this study ($\geq$4 plants m^{-2}), *D. sanguinalis* had similar (4 plants m^{-2}) or greater biomass (16 plants m^{-2}) than *A. palmeri*. The similarity in biomass at higher densities ($\geq$4 plants^{-2}) in this study may have been a contributing factor to similar soybean yield reductions.

Results from this study suggest that control of *A. palmeri* is necessary at 1 plant m^{-2} and control must be implemented for *D. sanguinalis* at greater than 2 plants m^{-2} to prevent yield loss.

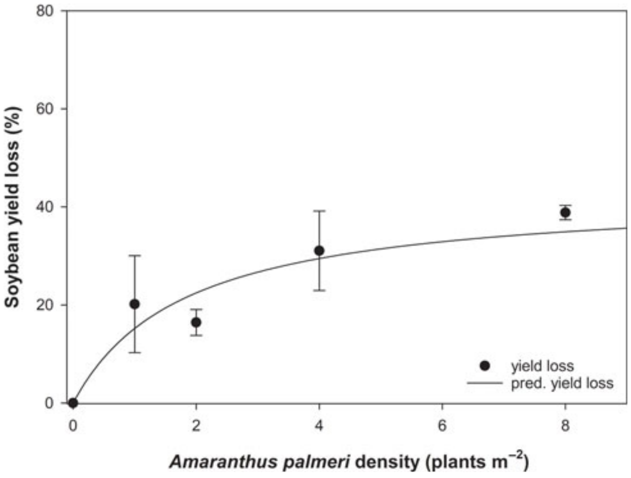

Figure 4. 'AG 6536' soybean yield loss (%), based on weed-free soybean maximum yield, from *Amaranthus palmeri*. Mean yield loss of soybean for 2016 and 2017 is plotted as a function of increasing *A. palmeri* density per square meter at the Horticultural Crops Research Station, Clinton, NC. Data were fit to a rectangular hyperbola model (equation: $Y_R = (ID)/[1 + (ID/A)]$), where $I = 20.28$ (7.19), $A = 49.42$ (10.40), $R^2 = 0.84$; SE is given in parentheses.

This study also brings to light the competitive nature of *D. sanguinalis*, which can be controlled with POST herbicides but could be overlooked with the integration of new soybean seed technologies resistant to dicamba and 2,4-D, which are ineffective in controlling grasses such as *D. sanguinalis*. Therefore, an efficacious herbicide with grass activity should be included as part of a weed management program for soybean. This study focused on high planting densities of soybean, which could have limited the competitive nature of these weeds due to a high crop population density. In this study, soybean planting density was at a high seeding rate (321,000 seeds ha^{-1}) and narrow row spacing (0.3 m between rows). Row spacing can have an effect on total weed biomass accumulation and soybean yield loss (Hock et al. 2006). Wider row spacing than in the present study may alter the interference of *A. palmeri* and *D. sanguinalis* on soybean.

Decision support systems such as WebHADSS, Pocket HERB, and PAM (Palmer Amaranth Management) have been developed to determine thresholds for weeds and assist growers in making management decisions (Bennett et al. 2003). As a means of comparison, weed densities in the present study were entered into the WebHADSS system to estimate soybean yield loss. For *A. palmeri*, yield loss estimates from WebHADSS were 33 % and 70 % for 1 and 8 plants m^{-2}, respectively. These estimates were higher than yield loss from 1 and 8 plants m^{-2} observed in the study (14 % and 38 %, respectively). Results from our study suggest that *D. sanguinalis* may be more competitive than indicated by the data used in WebHADSS. WebHADSS yield loss estimates were 1 % and 16 % for 1 and 16 *D. sanguinalis* plants m^{-2}, which were lower than predicted losses from this study (9 % and 38 %, respectively). One of the issues with the WebHADSS system is that it does not allow for input of soybean stand density and row spacing. Furthermore, these systems need additional updates to reflect current crop varieties and more recent research. The planting density of soybean in this study could have contributed to greater soybean competition for light and other resources with *A. palmeri* than is assumed by the WebHADSS system. Additionally, the underestimation of yield loss due to *D. sanguinalis* interference may be due to lack of specificity of *Digitaria* species in the WebHADSS system, as this system does not allow for selection of specific *Digitaria* species.

Results from this study provide estimations for the effect of season-long interference of *D. sanguinalis* and *A. palmeri* on soybean and the impact of intraspecific and interspecific interference of these weeds in soybean. *Digitaria sanguinalis* and *A. palmeri* reduced soybean yield when present at 2 and 1 plants m^{-2}, respectively. The presence of soybean resulted in reduced weed biomass across all weed densities, reducing weed growth. Furthermore, resistant *A. palmeri* or *D. sanguinalis* biotypes that are not controlled by herbicide applications show only moderate reductions (Chandi et al. 2012) or no reductions in fitness (Giacomini et al. 2014; Wiederholt and Stoltenberg 1996), resulting in crop yield reductions from weeds. Therefore, it may be advantageous to use management practices such as increased seeding density and narrow row spacing to further reduce the competitiveness of weeds with soybean (Hock et al. 2006; Howe and Oliver 1987).

Both interspecific and intraspecific interference of *D. sanguinalis* and *A. palmeri* were observed in our studies. Evidence of interspecific interference in our studies was the observed reduction in weed biomass with soybean and the decrease in soybean yield as weed density increased. Decreasing weed biomass per plant with increasing density without soybean indicated the impact of intraspecific competition of *D. sanguinalis* and *A. palmeri*. Future studies should consider using additional densities of *D. sanguinalis* and *A. palmeri* to allow for more precise estimation of intraspecific and interspecific interference between soybean and *A. palmeri* or *D. sanguinalis* under different environments. Additional studies should investigate the competitive nature of *D. sanguinalis* in other row-crop and horticultural cropping systems, as there is limited research concerning its interference. Finally, quantifying impacts of resistant biotypes, weed emergence timings, and varying management conditions (irrigation, tillage systems, row spacing, and fertilization regimes) on weed interference would provide insight into additional management strategies to limit weed interference.

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