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Soybean density and Palmer amaranth (*Amaranthus palmeri*) establishment time: effects on weed biology, crop yield, and economic returns

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Abstract

Knowledge of crop–weed interference effects on weed biology along with yield penalties can be used for the development of integrated weed management (IWM) tactics. Nevertheless, little is known about the beneficial effects of soybean [*Glycine max* (L.) Merr.] density, an important aspect of IWM, on late Palmer amaranth (*Amaranthus palmeri* S. Watson) establishment time. Two field experiments were conducted in 2014 and 2015 to investigate how various soybean densities and *A. palmeri* establishment timings in weeks after crop emergence (WAE) affect height, biomass, and seed production of the weed but also crop yield in drill-seeded soybean. Soybean density had a significant impact on dry weight and seed production of *A. palmeri* that established within the first 2 wk of crop emergence, but not for establishment timings of the weed 4 wk and later in relation to crop emergence. Differential performance of *A. palmeri* gender was observed, regarding greater biomass production of female than male plants under crop presence, and merits further investigation. Grain yield reductions were recorded at earlier *A. palmeri* establishment timings (i.e., 0 and 1 WAE) compared with 8 WAE establishment timing in 2014 and 2015. High soybean densities resulted in greater soybean yields compared with low soybean density, but no grain yield benefits were observed between medium and high soybean densities. Crop budget analysis revealed the benefits of moderate seeding rate (i.e., 250,000 seeds ha^{-1}) increases in comparison to lower (i.e., 125,000 seeds ha^{-1}) or high (i.e., 400,000 seeds ha^{-1}) on crop revenue, net income returns, and breakeven price. Earlier *A. palmeri* establishment timings (i.e., 0, 1, and 2 WAE) resulted in lower crop revenue and net income returns compared with later establishment timings of the weed.

Introduction

Palmer amaranth (*Amaranthus palmeri* S. Watson) is one of the most common and difficult to control weeds in many crops, including soybean [*Glycine max* (L.) Merr.], due to a range of ecophysiological (Korres et al. 2017b; Massinga et al. 2003) and biological characteristics (Korres and Norsworthy 2017) that enhance the adaptive ability of the weed (Korres et al. 2017a) in a wide range of environments (Korres et al. 2015a, 2015b, 2018). Furthermore, the continuous establishment of *A. palmeri* populations throughout the growing season enhances the adaptive and competitive ability of the weed (Bensch et al. 2003; Korres et al. 2019a). It has been shown that early *A. palmeri* establishment can cause significant soybean yield decreases of between 19% and 80% (Bensch et al. 2003; Korres et al. 2019a).

Manipulation of soybean density can counteract the competitive ability of the weed through canopy closure (Korres et al. 2019b), which results in reduced light transmission to the soil surface (Bell et al. 2015; Korres and Norsworthy 2017). Low light conditions reduce *A. palmeri* biomass production, leaf number, specific leaf area, photosynthetic capacity (Korres et al. 2017b), and density (Jha and Norsworthy 2009). Harder et al. (2007) reported that soybean densities of 124,000 to 198,000 plants ha^{-1} had no effect on weed biomass, whereas a 20% biomass reduction was observed at densities of 300,000 to 445,000 plants ha^{-1} compared with low soybean densities.

Nevertheless, the benefits associated with increased crop competitiveness as a result of increased crop density, especially after a density threshold, which depends on the crop and cropping system, are debatable and must be evaluated based on yield increases, economic returns, and long-term weed management benefits (DeWerff et al. 2014; Harder et al. 2007; Harker et al. 2003). Soybean yield is related to crop density (Fickett et al. 2013; Nave and Wax 1971), although compensatory effects in combination with environmental conditions impose a wide range of crop yield responses to density manipulation (Benbella and Paulsen 1998). Norsworthy and Oliver (2001) stated that seed cost associated with high crop densities (i.e., >450,000 plants ha^{-1}) can exceed the benefit for better weed control. Bell et al. (2015) found that weed control and soybean yield were greater at soybean seeding rates equal to 617,500 seed ha^{-1} (average density achieved was 400,000 to 580,000 plants ha^{-1}) than at lower soybean densities ranging between 78,000 to 250,000 plants ha^{-1}.

Profitability of agricultural production systems is a function of commodity prices, yield, and cost of production. Increased seed rates, particularly in genetically modified (GM) soybean systems, could increase the production cost significantly due to high seed cost (Place et al. 2009; Thompson et al. 2015). High prices for the seed exert a direct impact on farmers' decisions related to the range of allowable seeding rates (Epler and Staggenborg 2008; Shi et al. 2010; Thompson et al. 2015). Therefore, it is vital to address the effects of increased soybean density in association with soybean grain yield outcome (i.e., the cost of the production system) along with the weed suppression. If weed suppression due to increased crop density does not coincide with yield increases and, consequently, profit margin improvements, then further consideration of this option as a feasible IWM option to control *A. palmeri* is warranted. The evaluation of cropping systems, for example, as crop density increases, can be facilitated by crop budgeting, a management tool used to estimate costs and evaluate cropping alternatives (Anonymous 2019b).

Therefore, this research aims to determine the extent to which increasing soybean plant density suppresses *A. palmeri* plants established at various periods of the growing season and to investigate the response of soybean yield to a range of *A. palmeri* establishment timings. We tested the following hypotheses: (1) whether increasing soybean density reduces the growth and seed production of early-establishing *A. palmeri* populations; 2) whether increasing soybean density is accompanied with greater yield up to a plateau, at which further yield increases cease to occur; (3) whether increasing soybean density is unable to delimit crop dry weight, pods per plant, and yield reductions caused by early-establishing *A. palmeri* populations; and (4) whether increasing soybean density compensates for greater production cost compared with lower crop densities. In addition, the differentiation of *A. palmeri* gender at a range of crop densities was investigated based on height and biomass production.

Materials and Methods

Experimental Setup and Study Site

Two field trials conducted during 2014 and 2015 at the University of Arkansas, Fayetteville, AR (36.095°N, 94.172°W) on Captina silt-loam soil (fine-silt, mixed, active, thermic Typic Albaquults) with pH of 6.7, organic matter 1.5%, and sand, silt, and clay content of 34%, 53%, and 13%, respectively. A four by six factorial experiment was arranged in a randomized complete block design with four replications. The soybean density factor consisted of four treatments: 0 (weedy monoculture), 125,000 or "low" density, 250,000 or "medium" density, and 400,000 or "high" density seeds ha^{-1}. The *A. palmeri* establishment timing factor, measured in weeks after soybean emergence (WAE), consisted of six treatments: 0, 1, 2, 4, 6, and 8 WAE. The harvestable plot size was 12 m^2 (6-m long by 2-m wide), whereas a predetermined plot (9-m long by 2-m wide) outside the harvested area was used for crop destructive sampling throughout the growing season.

Disking followed by a field cultivator (Kongskilde Industries, Hudson, IL, USA) was used on the entire experimental area to prepare the seedbed before soybean planting. Phosphorous and potassium fertilizer (0-40-60) (Slaton et al. 2005) was applied shortly before planting, assuming that crop removal of phosphorous equals 42 kg P_2O_5 ha^{-1} and crop removal of potassium equals 69 kg K_2O ha^{-1} (Anonymous 2019a, 2019b; Flanders 2014; Place et al. 2009; Plastina 2019; Schnitkey 2018). A glufosinate-resistant (LibertyLink®) soybean cultivar ('Pioneer® 95L01', maturity group 4.6, DuPont, Leland, MS, USA) was then seeded in a 10-row plot (20-cm row spacing) using an Almaco cone-drill planter (Almaco, Nevada, IA, USA). Insecticide as zeta-cypermethrin active ingredient was applied at the recommended rate for control of green stink bug (*Chinavia hilaris* Say) at R2-R3 soybean growth stage (GS).

Experimental plots were hand weeded on a weekly basis for the first 2 mo and regularly afterward to remove unwanted weeds and were irrigated using an overhead sprinkler irrigation system (Valmont Industries, Valley, NE, USA) when rainfall did not occur for an approximately 10-d period, to avoid drought stress.

Plant Material and Experimental Treatments

Amaranthus palmeri seeds were collected in the 2013 to 2014 growing season from a local population at the University of Arkansas farm, Fayetteville, AR, and were stored in sealed vials at 5 C until their use. The germination of *A. palmeri* seedling grown at 14-h photoperiod and 35/23 C day/night temperature under greenhouse conditions was planned to coincide at 0, 1, 2, 4, 6, and 8 wk in relation to soybean emergence. Sixteen randomly selected plots (i.e., four crop densities by four replications) were used for each *A. palmeri* establishment timing until all experimental treatments were completed. *Amaranthus palmeri* seedlings at the 2- to 4-leaf stage were randomly transplanted in the plot area (excluding the edge rows of the plot) targeting a density of 1 *A. palmeri* plant m^{-2}. Watering the young *A. palmeri* plants every 2 to 3 d for a 2- to 3-wk period minimized possible stress during their acclimatization period. The entire process of *A. palmeri* germination and transplanting for each establishment time has been described in detail by Korres et al. (2019a).

Data Collection

Soybean crop establishment for each seeding rate was evaluated at harvest to calculate the final crop density using a 1-m^2 quadrat at three randomly selected sampling points within each experimental plot. In addition, five randomly selected soybean plants from predetermined areas for destructive sampling were collected at R2-R3 and R6 soybean GS, and biomass production (at R2-R3 and R6 soybean GS) and pods per plant (at R6 soybean GS) were recorded after drying the plants at 70 C for approximately a week until no further dry weight reduction was observed.

Soybean grain was harvested with a small-plot combine; yield was adjusted to 13% moisture and recorded (in kg ha^{-1}). Before soybean harvesting, all *A. palmeri* plants, both male and female, were collected from each plot by cutting the stems at the soil level, and the height of each *A. palmeri* plant was recorded. The plants were then placed in paper bags and dried at 70 C for approximately a week until no further dry weight reduction was observed. *Amaranthus palmeri* biomass production was recorded and seeds from each female plant were estimated as described by Korres et al. (2019a).

In addition, ground cover, leaf area index (LAI), and light interception measurements were recorded throughout the growing period. More particularly, crop canopy photographs for each *A. palmeri* establishment time along with light interception by the crop canopy and LAI measurements were obtained immediately before each transplanting treatment, and only from the plots designated to that particular *A. palmeri* transplanting treatment, as described by Korres et al. (2019a). Digital imagery, a technique reported to be an accurate approach to monitor crop canopy formation (Purcell 2000) was used to estimate ground cover. The Monsi-Saeki extinction coefficient (hereafter called "extinction coefficient"), based on light interception and LAI, was estimated based on Equation 1 (Monsi and Saeki 1953):

$$I = I_0 e^{-kL} \qquad [1]$$

where k is the extinction coefficient, I_0 is the light intensity above the crop canopy, I is the light intensity below the crop canopy, and L is the LAI of soybean leaves causing the light attenuation. The extinction coefficient relates crop leaf area and canopy architecture with light interception by crop canopy, hence shading conditions beneath crop canopy where the weed is growing.

Data Analysis

A two-parameter exponential decay model was employed to analyze *A. palmeri* dry weight and seed production, whereas a single linear regression analysis was best fit on *A. palmeri* height. In addition, a correlation analysis was used to identify the relationships between ground cover and extinction coefficient for each crop density used. Finally, an ANOVA was used to compare *A. palmeri* dry weight between male and female *A. palmeri* plants, soybean dry weight, pods per plant, and yield. An LSD test was used for means separation. The employment of ANOVA for the analysis of soybean yield facilitated the crop budget analysis described in the following section. All data analyses were performed using JMP Pro v. 14.0.0 software (SAS Institute, Cary, NC, USA). Values from SigmaScan Pro were exported to SigmaPlot v. 13.0 (Systat Software, CA, USA) to examine the correlation between groundcover and extinction coefficient.

Crop Budget Analysis

In addition to the analysis of the experimental data, a crop budget analysis was performed to evaluate the profitability of the cropping systems under investigation. Soybean production inputs typical to current production systems, that is, fixed and variable costs for preharvest machinery (i.e., moldboard plow, disk/field cultivator, and direct drill), crop husbandry (i.e., seed, fertilizing, irrigation, and crop protection), labor (mechanical weed control, insecticide application, irrigation, and fertilizing), and harvesting and grain storage (i.e., combine and storage) were balanced against crop revenue, net return, and breakeven price for each soybean seeding rate used for both 2014 and 2015. Fixed and variable costs for preharvest machinery were estimated at US\$51.38 ha^{-1} and US\$48.66 ha^{-1}, respectively, totaling US\$100.04 ha^{-1} for both 2014 and 2015. Fixed and variable costs for crop husbandry were estimated at US\$192.66 ha^{-1} and US\$162.66 ha^{-1} for low crop density (125,000 seeds ha^{-1}); US\$192.66 ha^{-1} and US\$207.69 ha^{-1} for medium (250,000 seeds ha^{-1}) crop density; and US\$192.66 ha^{-1} and 261.69 ha^{-1} for high (400,000 seeds ha^{-1}) crop density. The average soybean seed price for LibertyLink® soybean is US\$54 per 150,000 seed-containing packages, which also includes a technology fee (Anonymous 2019a; Thompson et al. 2015). Seeding rates were the same for both experimentation years, with the fixed cost (i.e., US\$45, US\$90, and US\$144 ha^{-1} for 125,000, 250,000, and 400,000 seeds ha^{-1}, respectively). Variable costs for phosphorus and potassium fertilizer and irrigation fuel were estimated at US\$20.3, US\$22.35, and US\$78 per unit of fertilizer (Anonymous 2019a, 2019b; Flanders 2014; Place et al. 2009; Plastina 2019; Schnitkey 2018). Labor was estimated at US\$14.5 h^{-1} (Place et al. 2009; Plastina 2019). Finally, fixed and variable costs for harvesting and grain storage operations were equal to US\$23.24 and US\$12.45 ha^{-1} for low crop density; US\$23.81 and 12.97 ha^{-1} for medium crop density; and US\$23.95 and US\$13.11 ha^{-1} for high crop density (Anonymous 2019a; Flanders 2014; Place et al. 2009; Plastina 2019; Schnitkey 2018). Final grain yield and the total production costs (fixed and variable) were used for the determination of total expenses, breakeven point, and total market revenue for each soybean seeding rate used (Table 1). Inputs in this analysis were held constant, except those associated with seeding rates. Crop revenue under various seeding rates was determined using annual average soybean prices between 2010 to 2018 (USDA-NASS 2019b, 2019c; World Bank 2019); the mean soybean price was estimated at US\$0.39 kg^{-1} (approximately US\$10.6 bu^{-1} of soybean grain). In addition, a budget analysis was developed based on *A. palmeri* establishment timings and the corresponding soybean yields (Table 2). Because no interaction was recorded between *A. palmeri* establishment timing and soybean density, the average value of production costs (i.e., fixed and variable) across soybean seeding rates (i.e., 125,000, 250,000, and 400,000 seeds ha^{-1}) from Table 1 was considered for the estimation of total expenses, breakeven prices, crop revenue, and net return depicted in Table 2. Inputs in this analysis were held constant, except those associated with soybean yields at 0, 1, 2, 4, 6, and 8 WAE *A. palmeri* establishment timings.

Results and Discussion

Site Specifications

The 2014 growing season was characterized by more erratically distributed precipitation compared with the 2015 growing season. In 2015 the monthly precipitation was 125% higher than in 2014 and 55% higher than the 30-yr average. The average monthly precipitation between June and July was recorded at 10.2 and 6.1 mm compared with 17 and 20 mm for the years 2014 and 2015 respectively.

Soybean achieved densities in 2014 were 121,300 (±478.7 standard error of mean [SE]), 242,600 (±629.1 SE) and 389,300 (±1,417.6 SE) plants ha^{-1}, representing 97% of the 125,000, 250,000, and 400,000 seeds ha^{-1} targeted seeding rates respectively. Soybean densities in 2015 were underachieved owing to severe weather conditions. More specifically, for a targeted crop density of 125,000 plants ha^{-1}, the achieved density was 98,500 (±1,121.7 SE), for 250,000 the achieved density was 198,200 (±2,178.1 SE), and for targeted crop density 400,000 plants ha^{-1} the achieved density was recorded at 323,200 (±4,333.7 SE) plants ha^{-1}.

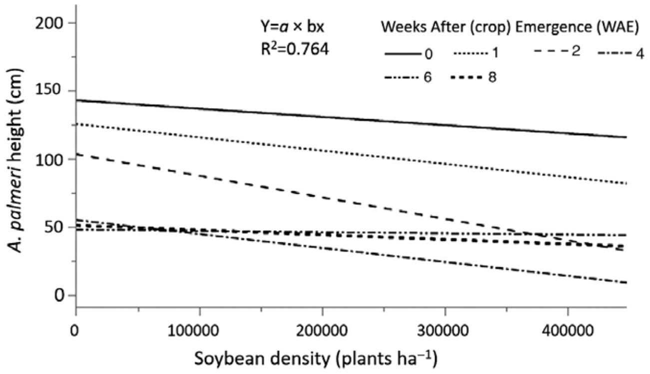

Figure 1. Effects of soybean density by *Amaranthus palmeri* establishment time on *A. palmeri* height (recorded at harvest) in weeks after emergence of the weed relative to soybean emergence.

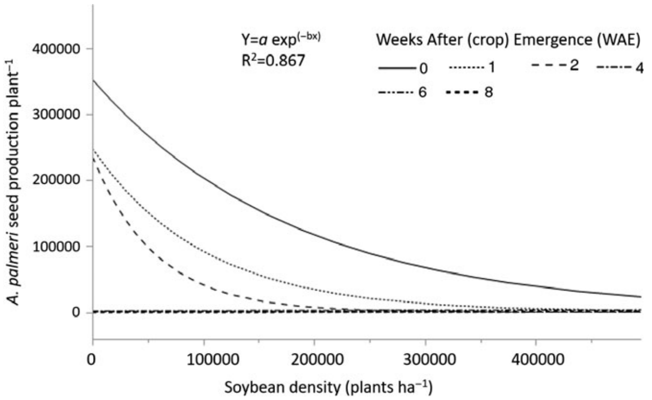

Figure 3. Effects of soybean density by *Amaranthus palmeri* establishment time on *A. palmeri* seed production (recorded at harvest) in weeks after emergence of the weed relative to soybean emergence.

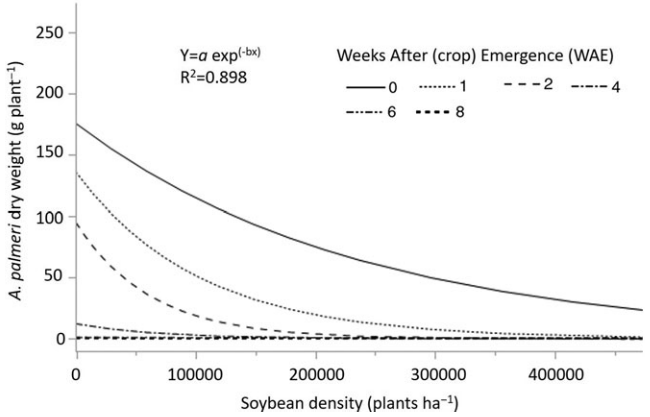

Figure 2. Effects of soybean density by *Amaranthus palmeri* establishment time on *A. palmeri* dry weight (recorded at harvest) in weeks after emergence of the weed relative to soybean emergence.

Does Soybean Density Similarly Affect Growth and Seed Production of Early- and Late-Established Amaranthus palmeri Populations?

The effects of soybean density on *A. palmeri* biological characteristics became apparent for the weed plants established at 2 WAE establishment timing onward. Great crop density, for example, caused *A. palmeri* height reductions in comparison to the *A. palmeri* height in weedy monoculture, particularly at 1 and 2 WAE establishment timings. When *A. palmeri* establishment time coincided with crop emergence (i.e., 0 or 1 WAE establishment timing), the competitive effects of the crop at low densities almost ceased, as the height of the weed was no different compared with the height of *A. palmeri* growing under crop-free conditions (Figure 1; Supplemental Table 1).

The effects of soybean density on weed dry weight production were assessed at crop harvest. Significant reductions were recorded when the biomass produced in weedy monoculture was compared with that produced under crop competition, especially on biomass of early *A. palmeri* establishment (Figure 2; Supplemental Table 2).

The greater the crop density, the greater the reduction of *A. palmeri* biomass, particularly at early establishment timings of the weed (i.e., 0 and 1 WAE establishment timings). Biomass produced at late establishment times (i.e., 4 to 8 WAE establishment timings) was affected less by crop interference, irrespective of crop density, due to shorter season. It is known that the establishment time affects the size of the plant, because the transition time from vegetative to reproductive growth is shorter, especially for plants like *A. palmeri* that flower in response to photoperiod (Goyne and Schneiter 1988). Therefore, preventing early-establishing *A. palmeri* cohorts and enhancing crop competitiveness that results in reducing biomass production would have a direct effect on fecundity of the weed. Korres and Norsworthy (2017) and Korres et al. (2019a) have reported the association of biomass and seed production in *A. palmeri*.

Amaranthus palmeri seed production exhibited a pattern similar to biomass, particularly at the early establishment timings of the weed. Significant seed production reductions were recorded at 0 and 1 WAE establishment timings compared with seed produced in the absence of the crop (Figure 3; Supplemental Table 3). No differences in *A. palmeri* seed production were recorded at 4, 6, and 8 WAE establishment timings, possibly due to late establishment timing of the weed. Nevertheless, *A. palmeri* plants at late establishment timings were capable, even when growing with soybean, to produce 60 to approximately 3,500 seeds plant^{-1} (Figure 3; Supplemental Table 3).

Increased crop densities accelerate canopy closure and reduce the amount of light penetrating the canopy and reaching the soil surface, hence lessening weed growth and biomass accumulation beneath the crop canopy (Kudsk et al. 2019). Indeed, the percentage ground cover and the extinction coefficient were greater under great crop density than at low crop density (Figure 4).

It can therefore be concluded that greater soybean density suppresses growth and seed production of early-establishing *A. palmeri*. In contrast, greater soybean density offers no suppression advantages for late-establishing *A. palmeri*. The growth plasticity of late-establishing *A. palmeri* (i.e., 6 and 8 WAE establishment timings) at greater soybean densities is noticeable. These late-establishing plants were taller compared with *A. palmeri* plants established at 2 or 4 WAE establishment timing (Figure 1) when ground cover was between 40% and 60% (Figure 4).

Differential Performance between Amaranthus palmeri Gender

There was greater biomass production ($P_{2014,\ 2015} < 0.001$) by the female *A. palmeri* plants at early establishment timings (i.e., 0 and 1 WAE establishment timings) compared with biomass produced

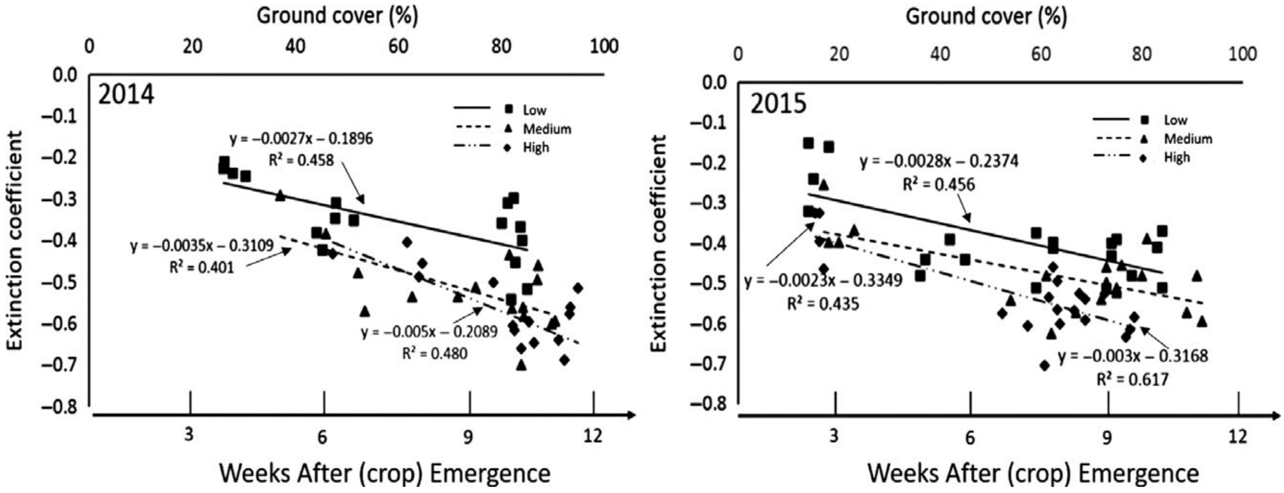

Figure 4. Effects of ground cover and extinction coefficient of light interception at low, medium, and high crop densities. Ground cover, leaf area, and light interception were measured immediately before each *Amaranthus palmeri* establishment time. Note: Average low density achieved for 2014 was 121,302 plants ha^{-1} (120,311, 122,292) and for 2015 was 98,437 plants ha^{-1} (96,117, 100,758); average medium density achieved for 2014 was 242,604 plants ha^{-1} (241,302, 243,906) and for 2015 was 198229 plants ha^{-1} (193,724, 202,735); and average high density achieved for 2014 was 389,333 plants ha^{-1} (386,401, 392,266) and for 2015 was 323,167 plants ha^{-1} (314,202, 332,132). Numbers in parentheses indicate the lower and upper 95% means, respectively. The additional *x* axis at the bottom of the graph approximates ground cover using *A. palmeri* establishment time in weeks after crop emergence (WAE). Arrows indicate the corresponding line for each regression equation provided in the graph.

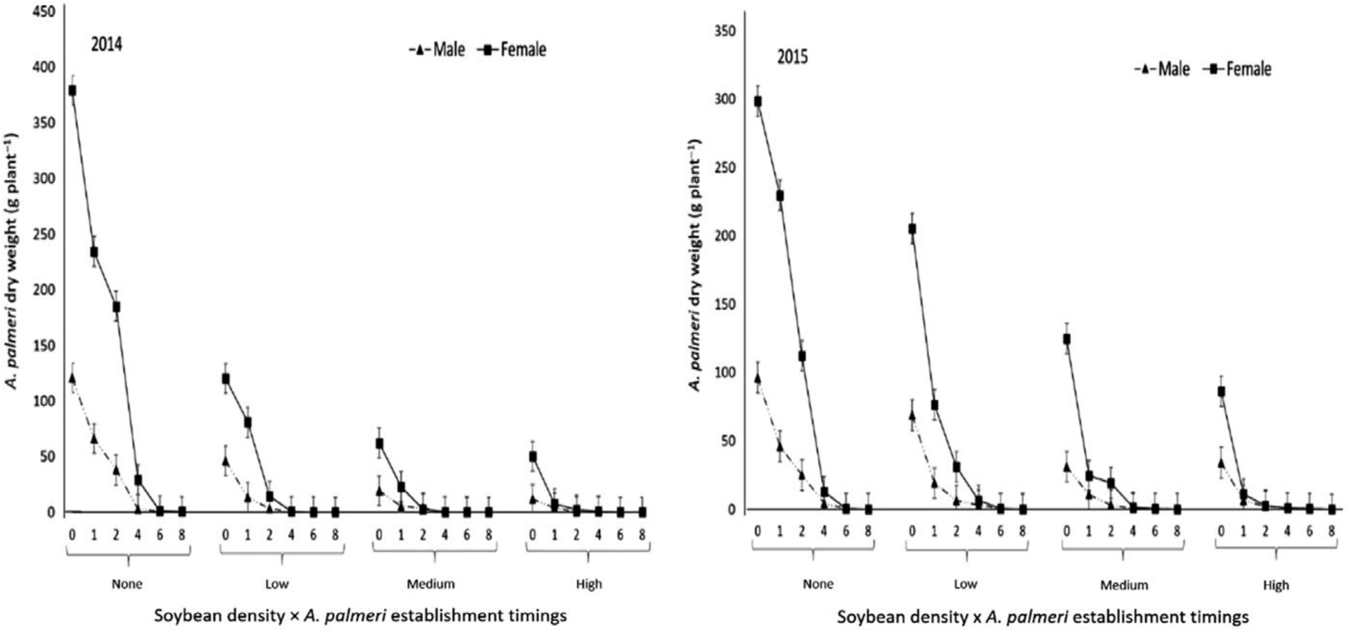

Figure 5. Differential performance of female and male *Amaranthus palmeri* plants at different establishment times (0, 1, 2, 4, 6, and 8 weeks after crop emergence [WAE]) and crop densities. Vertical bars represent LSD values for mean separation at $P < 0.001$. Note: Average low density achieved for 2014 was 121,302 plants ha^{-1} (120,311, 122,292) and for 2015 was 98,437 plants ha^{-1} (96,117, 100,758); average medium density achieved for 2014 was 242,604 plants ha^{-1} (241,302, 243,906) and for 2015 was 198,229 plants ha^{-1} (193,724, 202,735); and average high density achieved for 2014 was 389,333 plants ha^{-1} (386,401, 392,266) and for 2015 was 323,167 plants ha^{-1} (314,202, 332,132). Numbers in parentheses indicated the lower and upper 95% means, respectively.

by the male *A. palmeri* plants at the same establishment timings (Figure 5). These differences dissipated as crop density increased in relation to increases of the establishment timing interval from soybean emergence, except for *A. palmeri* plants that were grown under crop-free conditions. This trend occurred in both 2014 and 2015 (Figure 5). Differences in height between *A. palmeri* male and female plants were not found in this work (data not shown).

Nevertheless, differences in height and biomass production between *A. palmeri* genders have been previously reported (Keeley et al. 1987; Korres et al. 2017b; Webster and Grey 2015). The differential response in size between female and male *A. palmeri* plants might contribute to variation in fitness (Solbrig 1981), which may convey an adaptive plasticity that is imposed by the effort of the female plants for reproduction (Korres et al. 2017b; Obeso 2002).

Effects of Crop Density on Soybean Yield

The lower number of pods per plant at higher crop densities due to different impacts of intraspecific competition on the crop (Yamada

Table 1. Effects of soybean seeding rate on total expenses, breakeven price, crop revenue, and net revenue for 2014 and 2015.[a]

Seeding rate	Yield[b]	Total expenses	Breakeven price[c]	Crop revenue[d]	Net return[e]
—seeds ha^{-1}—	—kg ha^{-1}—	—US$ ha^{-1}—	—US$ kg^{-1}—	————US$ ha^{-1}————	
2014					
125,000	2,723 a	772	0.28	1,062	290
250,000	3,343 b	818	0.24	1,304	486
400,000	3,504 b	873	0.25	1,366	443
2015					
125,000	2,204 a	772	0.35	860	88
250,000	2,923 b	818	0.28	1,140	322
400,000	2,818 b	873	0.31	1,099	226

[a] U.S. soybean grain price (average marketing price 2010–2018) = US$0.39 kg^{-1} (USDA-NASS 2019b, 2019c; World Bank 2019). All calculations are based on Pendell et al. (2003) and Thompson et al. (2015).

[b] Values with the same letter in yield column are not different at $P < 0.05$.

[c] Breakeven price = Total crop expenses (US$ ha^{-1})/soybean grain yield (kg ha^{-1}).

[d] Crop revenue = Yield (kg ha^{-1}) × soybean grain price (US$ kg^{-1}).

[e] Net return = Crop revenue − total expenses (US$ ha^{-1}).

Table 2. Effects of *Amaranthus palmeri* establishment time on total expenses, breakeven price, crop revenue, and net revenue for 2014 and 2015.[a]

Establishment time[b]	Yield[c]	Total expenses	Breakeven price[d]	Crop revenue[e]	Net return[f]
	—kg ha^{-1}—	—US$ ha^{-1}—	—US$ kg^{-1}—	————US$ ha^{-1}————	
2014					
0 WAE	2,925 a	821	0.28	1,141	320
1 WAE	2,972 a	821	0.28	1,159	338
2 WAE	3,040 a	821	0.27	1,185	364
4 WAE	3,295 ab	821	0.25	1,285	464
6 WAE	3,336 ab	821	0.25	1,301	480
8 WAE	3,463 b	821	0.24	1,350	529
2015					
0 WAE	2,406 a	821	0.34	938	117
1 WAE	2,411 a	821	0.34	940	119
2 WAE	2,517 a	821	0.33	981	160
4 WAE	2,773 b	821	0.30	1,081	260
6 WAE	2,815 b	821	0.29	1,098	277
8 WAE	3,048 b	821	0.27	1,189	368

[a] U.S. soybean grain price (average marketing price 2010–2018) = US$0.39 kg^{-1} (USDA-NASS 2019b, 2019c; World Bank 2019). All calculations are based on Pendell et al. (2003) and Thompson et al. (2015).

[b] Establishment time expressed in weeks after emergence (WAE).

[c] Values with the same letter in yield column are not different at $P < 0.05$.

[d] Breakeven price = Total crop expenses (US$ ha^{-1})/soybean grain yield (kg ha^{-1}).

[e] Crop revenue = Yield (kg ha^{-1}) × soybean grain price (US$ kg^{-1}).

[f] Net return = Crop revenue − total expenses (US$ ha^{-1}).

et al. 2011) did not affect yield per unit area (Table 1), with yield increases ($P_{2014,\ 2015} < 0.05$) at medium and high crop densities observed compared with low crop density, in agreement with French (2004).

The greater the crop density, the greater the grain yield ($P_{2014,\ 2015} < 0.05$) averaged across *A. palmeri* establishment timings. However, grain yield was no different between medium and high crop densities in both years (Table 1). As stated by Board (2000), Kane and Grabau (1992), and Weaver et al. (1991), a positive correlation between grain yield and crop density is not always evident in soybean. Murdoch (2019) reported that one problem with increasing seed rate is that intraspecific competition among crop plants may increase due to the increase in rectangularity of the crop.

Increasing Soybean Density Cannot Diminish Crop Yield Reductions Caused by Early Amaranthus palmeri Populations

Early *A. palmeri* establishment timings reduced soybean biomass production, an effect that was observed at R2-R3 and R6 crop GS. Crop biomass reductions ($P_{2014,\ 2015} < 0.05$) due to competition by the early-established *A. palmeri* plants were recorded at R2-R3 and R6 crop GS or 8 and 12 WAE irrespective of crop density (Supplemental Figure 1), indicating the importance of weed control at the early soybean growth stages (Hartzler and Battles 2004; Korres et al. 2019a; VanAcker et al. 1993).

Nevertheless, soybean response to *A. palmeri* competition in terms of biomass production was determined by the establishment time of the weed. Greater soybean biomass production at late *A. palmeri* establishment timings, that is, 6 and 8 WAE, resulted in more ($P_{2014,\ 2015} < 0.05$) pods per plant (Supplemental Figure 2), especially at lower crop density. In medium or high crop densities, the number of pods per plant was no different.

Establishment time of *Amaranthus* spp. regulates the extent of competition with crops (Korres et al. 2019a). Soybean yield was significantly ($P_{2014,\ 2015} < 0.05$) affected by the *A. palmeri* establishment timing. The sooner the establishment time of the weed in relation to soybean emergence, the greater the yield reduction (Table 2). On the contrary, no differences in soybean yield occurred at *A. palmeri* establishment times of 2 WAE onward

(Table 2). *Amaranthus palmeri* plants established with the crop (0 WAE) caused soybean reductions of 15% and 22% for 2014 and 2015, respectively, compared with yield recorded at 8 WAE *A. palmeri* establishment timing (Table 2). Yield reductions declined progressively with late weed establishment, that is, 12%, 5%, and 4% for 2, 4, and 6 WAE in 2014 and 17%, 9%, and 8% for 2, 4, and 6 WAE in 2015 when compared with the yields recorded at 8 WAE (Table 2). According to Ciuberkis et al. (2007), there is a positive relationship between the timing of weed emergence and the degree of the pressure exerted on the crop, which usually causes crop yield losses. In addition, Keramati et al. (2008), Suryanto et al. (2017), and Korres et al (2019a) reported that late weed infestations (including *A. palmeri*) long enough after crop emergence rarely cause significant yield reductions in soybean.

It can be concluded that early establishment time of *A. palmeri* in relation to the crop (i.e., 0 and 1 WAE establishment timings) reduces soybean dry weight and pods produced per plant, a result that is particularly notable at low soybean density. In addition, earlier *A. palmeri* establishment (0, 1, and 2 WAE establishment timings) causes greater soybean yield reductions irrespective of crop density, as no interactions between *A. palmeri* establishment time and soybean density were recorded in both 2014 and 2015.

Effects of Soybean Plant Density and Weed Establishment Timing on Production Cost and Economic Returns

The soybean seed cost is one of the greatest production inputs, especially after the introduction of GM soybean cultivars in 1996, and subsequent attempts by technology and seed companies to protect their intellectual property (Epler and Staggenborg 2008; Shi et al. 2010; Thompson et al. 2015). As farmers attempt to use seed inputs more effectively, decisions on seeding rate should be reevaluated occasionally (Thompson et al. 2015). Inputs in this analysis were held constant, except those associated with seeding rates; hence the differences in final production costs for each cropping system (i.e., US\$772 for 125,000 seeds ha^{-1}, US \$818 for 250,000 seeds ha^{-1}, and US\$873 for 400,000 seeds ha^{-1}) are due to costs linked with increased seeding rate. Although, seed prices can vary widely due to seed traits such as conventional versus GM cultivars (Popp et al. 2006), herbicide-tolerant (HT) soybeans dominate U.S. (94% by 2018) and worldwide (57% of the entire area under GM cultivation or 64% of the cultivated area worldwide in 2006) soybean cropping systems (Bonny 2008; USDA-NASS 2019a). HT soybean cultivation in the United States is approximately 35 million ha (USDA-FSA 2019) with LiberyLink® soybean occupying 7 million ha with a 25% potential increase in 2018 onward (Bayer 2017). Therefore, the estimations presented in this work are widely applicable, even though the budget analysis presented here aims to highlight the importance of a judicious seed rate as a sustainable tool for *A. palmeri* control. Increases in seeding rate resulted in increases of grain yield followed by increased crop revenue, and thus increased net returns: US\$290, US\$486, and US\$493 ha^{-1} for 125,000, 250,000, and 400,000 seeds ha^{-1}, respectively, in 2014 (Table 1). In 2015, net return was US\$88, US\$322, and US\$226 ha^{-1} for 125,000, 250,000, and 400,000 seeds ha^{-1}, respectively (Table 1). It is worth mentioning that the greatest net return of 250,000 seeds ha^{-1} compared with 400,000 seeds ha^{-1}, due to high yields in both years, indicating the importance of selecting a judicious seed rate as an added-value agronomic and weed management tool. The lower the grain yield, the greater the breakeven price, as in the case of the low seeding rate of 125,000 seeds ha^{-1} compared with the 250,000 and 400,000 seeds ha^{-1} seeding rates (Table 1). According to Hofstrand (2018) and Dillon (1993), breakeven prices denote the lower price level at which a farmer can market the product and still be able to cover the production costs. In this study, lower breakeven prices, such as those obtained for the two high seeding rates (i.e., 250,000 and 400,000 seeds ha^{-1}), permit the establishment of a solid marketing foundation and facilitate marketing decisions that favor the optimization of the production system (Dillon 1993) through the selection of competing production alternatives. The inclusion of miscellaneous overhead, crop insurance, interest, fixed machinery cost, fixed building cost, land real estate taxes, land interest, and other costs in the crop budget analysis would have most probably increased the breakeven prices, as the numerator for its calculation would have increased if they were included in the analysis.

Earlier *A. palmeri* establishment timings (i.e., 0, 1, and 2 WAE establishment timings) resulted in greater yield reductions compared with later *A. palmeri* establishment timings (i.e., 4, 6, and 8 WAE) for both 2014 and 2015, with subsequent decreases in crop revenue and net returns (Table 2). As stated by Bensch et al. (2003), Keramati et al. (2008), Korres et al. (2019a), and Suryanto et al. (2017), late weed infestations (i.e., an 8 WAE weed establishment time) rarely cause significant soybean yield losses. Therefore, lower yields resulted in greater breakeven prices, as in the case of *A. palmeri* establishment times of 0, 1, and 2 WAE (Table 2). The disadvantages of lower breakeven prices, as discussed earlier, also apply in this scenario.

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