Weed Technology 2015 29:697–706

Effect of Drill-Seeded Soybean Density and Residual Herbicide on Palmer Amaranth (*Amaranthus palmeri*) Emergence

Holden D. Bell, Jason K. Norsworthy, and Robert C. Scott*

Palmer amaranth is the most troublesome weed of soybean in the southern United States. Field experiments were conducted at two Arkansas locations to determine the effect of drill-seeded soybean density on Palmer amaranth emergence. Experimental factors were multiple soybean seeding rates planted on a 19-cm-wide row spacing and the presence or absence of a PRE residual herbicide (flumioxazin plus pyroxasulfone). Soybean groundcover was measured throughout the growing season and daily soil temperature was recorded in selected soybean densities. In the absence of a PRE residual herbicide, at least a 1.7-fold reduction in Palmer amaranth emergence occurred when soybean were present. Differences in Palmer amaranth emergence occurred among soybean densities for both locations, suggesting the value of crop canopy in preventing Palmer amaranth emergence in the absence of an effective residual herbicide. In plots treated with the PRE herbicide, no difference in Palmer amaranth emergence occurred among soybean densities, except for the absence of soybean. Achievement of 95% groundcover by soybean reduced daily soil temperature fluctuations, which in turn reduced Palmer amaranth emergence. For both locations, soybean grain yields were greatest at the highest seeding rate (617,500 seed ha^{-1}). In the presence of flumioxazin plus pyroxasulfone applied PRE, greater grain yields occurred compared to the absence of a PRE herbicide at both Fayetteville and Marianna. Based on this research, an effective PRE-applied residual herbicide has more influence on Palmer amaranth emergence than soybean density, and Palmer amaranth germination and emergence are dependent upon daily soil temperature fluctuations, which is a function of soybean density.

Nomenclature: Flumioxazin; pyroxasulfone; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; soybean, *Glycine max* (L.) Merr.

Key words: Emergence, preemergence, residual, soil temperature, soybean density.

Amaranthus palmeri es la maleza más problemática en soja en el sur de los Estados Unidos. Se realizaron experimentos de campo en dos localidades en Arkansas para determinar el efecto de la densidad de la soja en siembra directa sobre la emergencia de *A. palmeri*. Los factores experimentales fueron múltiples densidades de soja sembrada en hileras espaciadas a 19 cm y la presencia o ausencia de herbicidas residuales aplicados PRE (flumioxazin más pyroxasulfone). La cobertura de la soja fue medida a lo largo de la temporada de crecimiento y la temperatura del suelo fue registrada diariamente en las densidades de soja seleccionadas. En ausencia de un herbicida residual PRE, se dio una reducción en la emergencia de *A. palmeri* de al menos 1.7 veces cuando la soja estaba presente. Hubo diferencias en la emergencia de *A. palmeri* entre las densidades de la soja en ambas localidades, lo que sugiere la importancia del dosel del cultivo para prevenir la emergencia de *A. palmeri* en ausencia de un herbicida residual efectivo. En las parcelas tratadas con herbicidas PRE, no hubo diferencias en la emergencia de *A. palmeri* entre las densidades de la soja, con excepción del tratamiento sin soja. El llegar a 95% de cobertura del suelo por parte del dosel de la soja redujo las fluctuaciones diarias de temperatura del suelo, lo que resultó en menor emergencia de *A. palmeri*. En ambas localidades, los rendimientos de la soja fueron mayores con la densidad de siembra más alta (617,500 semillas ha^{-1}). En presencia de flumioxazin más pyroxasulfone aplicados PRE, hubo rendimientos de grano mayores al compararse con tratamientos sin herbicidas PRE en Fayetteville y Marianna. Con base en esta investigación, un herbicida residual PRE efectivo tiene más influencia sobre la emergencia de *A. palmeri* que la densidad de la soja, y la germinación y emergencia de *A. palmeri* dependen de las fluctuaciones diarias en la temperatura del suelo, las cuales están en función de la densidad de la soja.

An understanding of the emergence pattern of problematic weeds within a particular cropping system is vital to making accurate and timely herbicide applications for control. A major factor in the success of Palmer amaranth is that its emergence pattern coincides with the production systems of

DOI: 10.1614/WT-D-14-00158.1

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common row crops in the southern United States such as corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean (DeVore et al. 2013; Jha et al. 2010; Scott and Smith 2011; Steckel 2007; Webster and Nichols 2012). Prior to glyphosate resistance, typically Palmer amaranth was controlled by multiple over-the-top (OT) broadcast applications of glyphosate. However, as a result of widespread glyphosate- and acetolactate synthase (ALS) –resistant Palmer amaranth, glyphosate, and ALS-inhibiting herbicides are no longer effective control options, leaving few OT herbicides available for Palmer amaranth control (Riar et al. 2013).

Therefore, controlling Palmer amaranth before or during emergence should be the management focus, rather than relying on POST herbicide applications. If Palmer amaranth can be prevented from emerging, the selection pressure placed on POST herbicides and the addition of seeds to the soil seedbank is reduced. No single method of weed control can completely control Palmer amaranth or stop it from emerging, but there are ways to reduce emergence, like PRE-applied residual herbicides and/or lessening diurnal soil temperature fluctuations through achieving a dense crop canopy (Jha et al. 2010; Jha and Norsworthy 2009; Steckel et al. 2004; Whitaker et al. 2010).

Soil-applied residual herbicides are an effective weed management tool for controlling Palmer amaranth and many other weeds early in the cropping season, before crop canopy formation occurs. Whitaker et al. (2010) reported that in a conventional soybean production system, a PRE application of *S*-metolachlor or pendimethalin in addition to either flumioxazin, fomesafen, or metribuzin plus chlorimuron increased control of Palmer amaranth by 27, 29, and 22%, respectively, when the first POST herbicide application was applied to 10- to 15-cm–tall Palmer amaranth, compared to the nontreated control. Although the addition of the PRE herbicide applications controlled close to 25% of the initial Palmer amaranth emergence, producers might not see this input as beneficial, in terms of season-long control. Whitaker et al. (2010) also reported that Palmer amaranth control was $\geq$ 25% at 90 days after initiation, whenever a PRE application of either metribuzin plus chlorimuron, fomesafen, or flumioxazin was applied compared to no PRE herbicide application. Therefore, relying on a POST-only herbicide program may lead to minimal returns in regards to Palmer amaranth control and suppression.

Herbicides, relative to other means of weed control, are highly effective and often more consistent. However, other weed management practices must be integrated with herbicides to increase diversity and reduce selection for herbicide resistance (Norsworthy et al. 2012). Crop canopy formation has been reported to have a suppressive effect on weeds emerging late in the growing season (Amador-Ramirez et al. 2002; Dalley et al. 2004; Jha et al. 2010; Molin et al. 2004; Renner and Mickelson 1997). Norsworthy (2004) reported a reduction of 33 and 68% for common cocklebur (*Xanthium strumarium* L.) and sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby] emergence, respectively, as a result of soybean canopy formation compared with emergence of both weeds in the absence of soybean. Jha and Norsworthy (2009) concluded that daily soil thermal amplitudes of 10 to 16 C allowed for Palmer amaranth emergence whereas formation of a soybean canopy lessened soil thermal fluctuations, in turn reducing Palmer amaranth emergence. Soybean density is known to influence crop canopy formation and could potentially reduce selection pressure on POST-applied herbicides. Therefore, the objective of this experiment was to determine the effect of increasing soybean density with or without a PRE-applied residual herbicide on Palmer amaranth emergence and soybean grain yield.

Materials and Methods

A field experiment was conducted in 2013 at the University of Arkansas Research and Extension Center in Fayetteville, AR and at the Lon Mann Cotton Research Station in Marianna, AR. The soil series in Fayetteville was a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults) with 34% sand, 53% silt, 13% clay, 1.5% organic matter, and a pH of 6.9. The soil series in Marianna was a Convent silt loam (coarse–silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) with 9% sand, 80% silt, and 11% clay, 1.8% organic matter, and a pH of 6.8. This experiment was organized in a split-plot design and treatments were replicated four times. The main plot factor was soybean seeding rates [0 (no soybean); 123,500;

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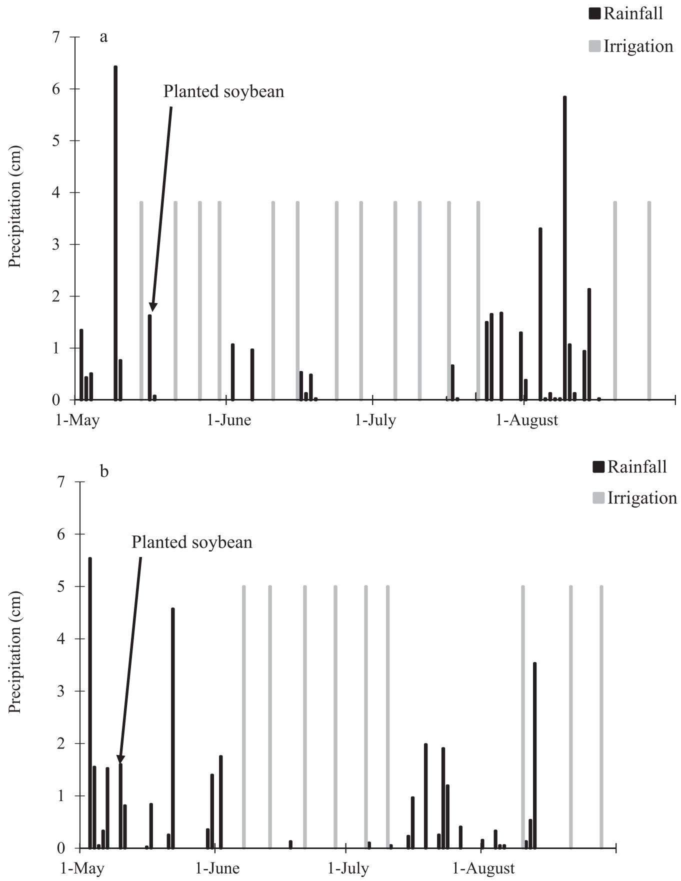

Figure 1. Rainfall and irrigation distribution at Fayetteville (a) and Marianna (b), AR in 2013.

185,250; 247,000; 308,750; 432,250; 617,500 seed ha^{-1}] planted in lengths of 10 m and the subplot factor was no herbicide application or a prepackaged mix of flumioxazin plus pyroxasulfone (Fierce®, Valent U.S.A. Corporation, Walnut Creek, CA 94596) applied at 82 plus 104 g ai ha^{-1}, respectively. Each subplot measured 2 m by 4.5 m with a 1-m alley. Seed for both locations were counted with a Seedburo 801 Count-A-Pak® (Seedburo Equipment Co., Des Plaines, IL 60018) for each seeding rate to determine the correct number of seed to be planted in each subplot.

Immediately prior to planting, the seedbed was prepared using a field cultivator (Kongskilde Industries Inc., Hudson, IL 61748) to obtain a uniform weed-free seedbed. LibertyLink® (Bayer CropScience, Research Triangle Park, RTP, NC 27709) soybean, variety Halomax 494 (glufosinate-resistant soybean), were drill seeded with a 10-row Almaco (ALMACO, Nevada, IA 50201) cone-type planter on a 19-cm-wide row spacing on May 15 and May 9, 2013 in Fayetteville and Marianna, respectively. Plots were irrigated with the use of overhead sprinkler irrigation and border irrigation at Fayetteville (Figure 1a) and Marianna (Figure 1b), respectively. After planting, two 0.5-m^2 areas were marked with flags (Gempler's, P.O. Box 5175, Janesville, WI 53547) in the center of each plot to provide a uniform area to determine Palmer amaranth emergence from the natural seedbank throughout the growing season. Soybean density was measured in the same quadrats at four weeks after planting.

Palmer amaranth emergence was monitored weekly in the two quadrats in each subplot and Palmer amaranth seedlings were removed after each count at both locations until harvest. The entire test, at both locations, was oversprayed with glufosinate (Liberty®, Bayer CropScience) at 595 g ai ha^{-1} and/or clethodim (Select Max®, Valent U.S.A. Corporation, Walnut Creek, CA 94596) at 136 g ai ha^{-1}, as needed, for POST weed control at Fayetteville and Marianna (Table 1).

When soybean reached the cotyledon stage (VC), a digital camera was used to take weekly photographs of the center of each plot. The camera was mounted on a 5-cm-diameter pipe at a height of 1.5 m above the crop and facing downward at a 70° angle to ensure the pole and photographer's feet were not in the picture. Photographs were taken throughout the growing season from a marked position to decrease variation during the vegetative growth stages of the soybean. Photographs were transferred to a computer, sorted, and individually analyzed to determine the rate (days) of soybean canopy formation using the procedures described by Purcell (2000). Canopy formation was measured by processing the photographs of individual plots with SigmaScan® Pro 5.0 (Systat Software, Inc., San Jose, CA 95110). Values from SigmaScan® Pro were exported to Excel (Microsoft®, One Microsoft Way, Redmond, WA 98052), and a linear regression was fit to the data to determine the rate of canopy formation during soybean growth.

The use of digital imagery has been previously reported to be an accurate assessment tool when monitoring crop canopy formation (Purcell 2000; Richardson et al. 2001). Soybean vegetative growth is described as sigmoidal because of slow initial growth followed by a linear, more rapid growth and

Table 1. Herbicide, rate, and application date for herbicide applications throughout the growing season at Fayetteville and Marianna, AR in 2013.

Herbicide[a]	Rate	Application date	Location
	g ai ha^{-1}		
Flumioxazin + pyroxasulfone	82 + 104	May 15	Fayetteville
Glufosinate + clethodim	595 + 136	June 3	Fayetteville
Glufosinate	595	July 2	Fayetteville
Flumioxazin + pyroxasulfone	82 + 104	May 9	Marianna
Glufosinate	595	May 22	Marianna
Glufosinate + clethodim	595 + 136	May 30	Marianna
Glufosinate + clethodim	595 + 136	June 19	Marianna

[a] Flumioxazin plus pyroxasulfone applied at soybean planting, glufosinate used to control Palmer amaranth, and clethodim used to control broadleaf signalgrass at that particular application date.

then growth slows and tapers off as soybean reaches complete canopy formation or maturity (Norsworthy 2004).

Daily minimum/maximum soil temperature data were recorded with Onset HOBO U12 (Onset Computer Corporation, Inc., Bourne, MA 02532) data loggers with three soil temperature probes (TMC6-HD, Onset Computer Corporation, Inc., Bourne, MA 02532) placed at a 2.5-cm depth. Soil temperature was recorded every 15 min throughout the growing season for the no soybean density and selected soybean seeding rates of 247,000, 432,250, 617,500 seed ha^{-1} in plots treated with the residual herbicide. Soybean grain was harvested with a small-plot combine. Soybean grain yield was determined by weighing the seed from individual plots, standardized for 13% moisture, and reported in kilograms per hectare. Grain yield data were entered into Excel and then exported to SigmaPlot® 12.5 (Systat Software) and fit to a nonlinear regression and tested for normality by Shapiro-Wilk's test (Table 2). This approach has successfully been used in previous research (Cerrato and Blackmer 1990; Edwards and Purcell 2005; Edwards et al. 2005; Purcell et al. 2002; Ware et al. 1982).

Data were subjected to ANOVA with the MIXED procedure in JMP (JMP, Version 10. SAS Institute Inc., Cary, NC) to test for significant main effects and interactions. Locations were analyzed separately due to differences in Palmer amaranth emergence. Soybean density and the presence or absence of the PRE herbicide were considered fixed effects, and replication was considered a random effect. Mean separation was performed using Fisher's protected LSD test at the 5% level of significance.

Results and Discussion

Soybean Canopy Development. Both Fayetteville and Marianna demonstrated similar trends in terms of soybean growth, cumulative Palmer amaranth emergence, and soil temperature fluctuations. The inclusion of a PRE-applied herbicide slightly delayed early-season soybean growth, resulting in all soybean densities achieving 95% canopy formation 3 to 6 d later than plots that did not receive a PRE-applied herbicide (data not shown).

At Fayetteville, the soybean densities achieved 95% soybean canopy formation from 44 to 65 d

Table 2. Nonlinear regression models for determining soybean grain yield as a function of soybean density at Fayetteville and Marianna, AR in 2013.[a]

	Nonlinear regression soybean grain yield model			
	Fayetteville		Marianna	
Herbicide	Model	R^2	Model	R^2
–	$y = \alpha(1 - e^{-\beta x})$	–	$y = \alpha(1 - e^{-\beta x})$	–
None	$y = 3,226.9(1 - e^{-0.00001x})$	0.9950	$y = 3,286.3(1 - e^{-0.00001x})$	0.9384
Flumioxazion + pyroxasulfone	$y = 4,339.5(1 - e^{-0.00001x})$	0.9684	$y = 4,552.3(1 - e^{-0.00001x})$	0.9598

[a] y is soybean grain yield (kg ha^{-1}), e is the constant 2.718, x is soybean density (plants ha^{-1}), α and β are parameter estimates.

https://doi.org/10.1614/WT-D-14-00158.1 Published online by Cambridge University Press

Table 3. Days required for individual soybean densities, averaged over the presence and absence of a PRE-applied residual herbicide, to obtain 95% groundcover at Fayetteville, AR in 2013.

Soybean density	Emergence	DAE[a] to 95% groundcover	GDD[a] to 95% groundcover	R^{2b}
plants ha^{-1}	%			
78,000	63	65	967	0.97
145,000	78	61	914	0.99
150,000	61	60	897	0.98
243,000	79	55	822	0.91
280,000	65	47	700	0.95
383,000	62	44	654	0.94

[a] Abbreviations: DAE, days after soybean emergence; GDD, growing degree days.

[b] R^2 determined from linear regression of percent groundcover (Purcell 2000).

after soybean emergence (Table 3). At Marianna, 48 to 52 d were needed for all soybean densities to achieve 95% canopy formation (Table 4). A possible explanation for Marianna having a narrower range compared with Fayetteville could be attributed to the difference in soybean densities at the two locations and furthermore, Marianna had more growing degree days earlier in the growing season than Fayetteville, which would be beneficial to plant growth. The lowest density at Fayetteville was 78,000 plants ha^{-1} compared to 120,000 plants ha^{-1} at Marianna.

Cumulative Palmer Amaranth Emergence in the Absence of a PRE Herbicide. The presence of soybean first impacted cumulative Palmer amaranth

Table 4. Days required for individual soybean densities, averaged over the presence and absence of a PRE-applied residual herbicide, to obtain 95% groundcover at Marianna, AR in 2013.

Soybean density	Emergence	DAE[a] to 95% groundcover	GDD[a] to 95% groundcover	R^{2b}
plants ha^{-1}	%			
120,000	97	52	834	0.96
180,000	97	50	802	0.96
240,000	97	50	802	0.96
290,000	94	50	802	0.97
425,000	98	49	787	0.97
588,000	95	48	772	0.95

[a] Abbreviations: DAE, days after soybean emergence; GDD, growing degree days.

[b] R^2 determined from linear regression of percent groundcover (Purcell 2000).

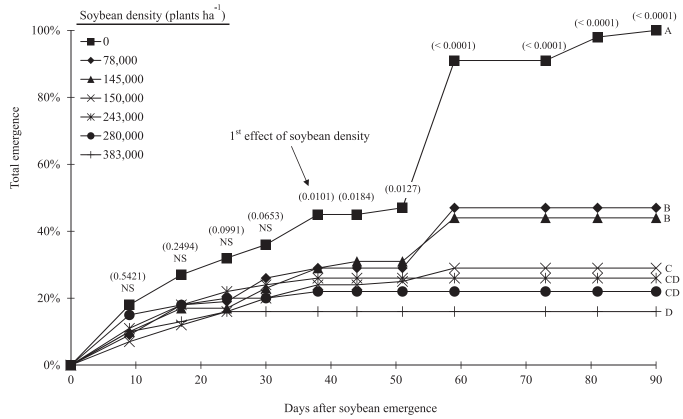

Figure 2. Percentage of total cumulative Palmer amaranth emergence (relative to no soybean, no herbicide treatment) after soybean emergence in the absence of a PRE herbicide at Fayetteville, AR in 2013. Nonsignificant (NS) indicates cumulative emergence at that specific observation timing was similar in the presence and absence of soybean according to Fisher's protected LSD test at $\alpha < 0.05$. *F* values for assessing treatment effects at that specific observation timing are represented in parentheses.

emergence at Fayetteville 38 d after soybean emergence (DAE) (Figure 2). At this observation, soybean groundcover for the three highest soybean densities of 243,000, 280,000, and 383,000 plants ha^{-1} was 77, 87, and 90%, and Palmer amaranth emergence was 26, 22, and 16% relative to the total emergence in the bare-ground treatment. No further Palmer amaranth emergence occurred after 38 DAE at these densities. This research strongly corresponds with that of Jha and Norsworthy (2009) where soybean canopy negatively impacted Palmer amaranth emergence 32 DAE when soybean light interception was 75%. At 59 DAE, the soybean densities of 78,000, 145,000, and 150,000 had 47, 44, and 29% total Palmer amaranth emergence relative to the total emergence in the bare-ground treatment, and soybean groundcover was 96, 97, and 98%, respectively. No further emergence occurred at later dates for these densities.

In Marianna at 32 DAE, Palmer amaranth emergence for the three highest soybean densities of 290,000, 425,000, and 588,000 plants ha^{-1} ranged from 31 to 34% of the total bare-ground emergence, and soybean groundcover was from 65 to 78% (Figure 3). No further Palmer amaranth emergence occurred past 32 DAE for these densities. The presence of soybean first significantly impacted Palmer amaranth emergence relative to

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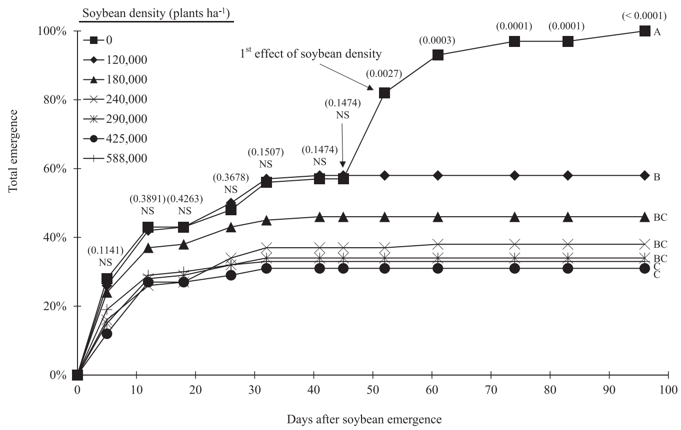

Figure 3. Percentage of total cumulative Palmer amaranth emergence (relative to no-soybean, no-herbicide treatment) after soybean emergence in the absence of a PRE herbicide at Marianna, AR in 2013. Nonsignificant (NS) indicates cumulative emergence at that specific observation timing was similar in the presence and absence of soybean according to Fisher's protected LSD test at $\alpha < 0.05$. *F* values for assessing treatment effects at that specific observation timing are represented in parentheses.

the bare-ground treatment at 52 DAE. The soybean densities of 120,000 and 180,000 plants ha^{-1} had no further Palmer amaranth emergence relative to the total season emergence of the bare-ground treatment by 52 DAE when soybean groundcover was 95 and 98%, respectively. All soybean densities had ≥ 95% canopy formation by 52 DAE at Marianna.

At both locations a similar trend was observed. As soybean groundcover increased, late-season Palmer amaranth emergence decreased and ultimately ceased. Thus, this research reiterates the importance of rapid canopy formation to aid in suppressing late-season Palmer amaranth emergence.

Cumulative Palmer Amaranth Emergence in the Presence of a PRE Herbicide. At Fayetteville, from the day 95% soybean canopy formation was achieved until the conclusion of the study, average daily soil temperature fluctuations for the soybean densities of 150,000 to 383,000 plants ha^{-1} ranged from 4.9 to 5.6 C compared to 12.9 C in the absence of soybean (Figure 4). At Marianna, average daily soil temperature fluctuations followed a similar trend to that of Fayetteville. Once 95% soybean canopy formation was achieved, average daily soil temperature fluctuations for the soybean densities of 240,000 to 588,000 plants ha^{-1} ranged from 4.4 to 7.5 C compared to 10.2 C in the

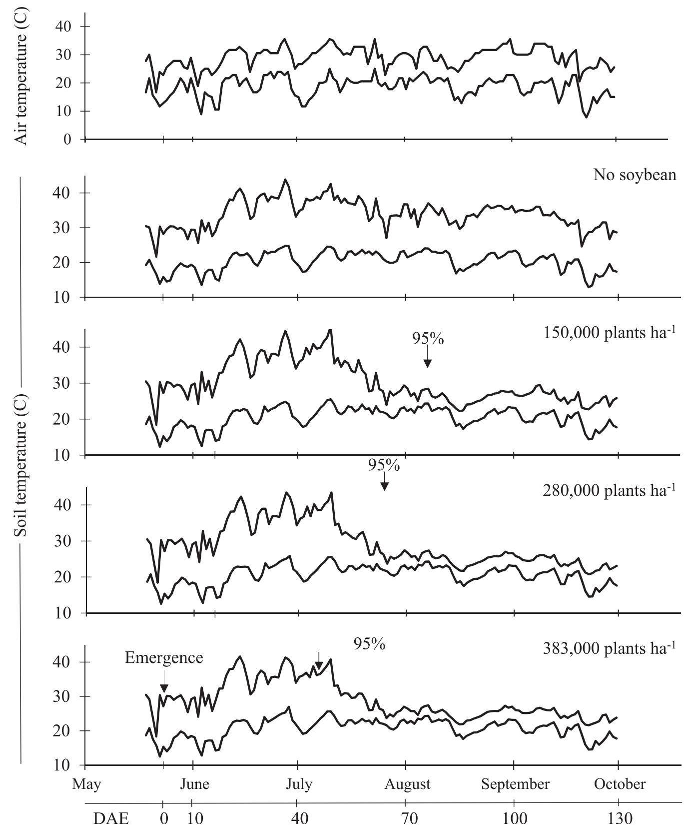

Figure 4. Daily maximum and minimum air and soil temperatures at a 2.5-cm soil depth and onset of 95% soybean canopy formation in 2013 at Fayetteville, AR in plots treated with flumioxazin plus pyroxasulfone at soybean planting.

absence of soybean (Figure 5). Jha and Norsworthy (2009) reported a 76% reduction in Palmer amaranth emergence in soybean at a density of 432,000 seed ha^{-1} compared to bare ground when daily soil temperature fluctuations were 5.1 C at a 2.5-cm soil depth in the presence of soybean compared to 10.1 C in the absence of soybean.

At both Fayetteville and Marianna, a similar relationship occurred between diurnal soil temperature fluctuations and soybean canopy formation. As soybean canopy formation increased, diurnal soil temperature fluctuations decreased. Previous research has reported temperatures ≥ 25 C and daily soil thermal amplitudes of ≥ 7.5 C are conducive for germination of Palmer amaranth and other *Amaranthus* species (Jha and Norsworthy 2009; Leon et al. 2004; Steckel et al. 2004; Thomas et al. 2006). Therefore, the reduction of daily soil temperatures because of soybean canopy formation could possibly be the main factor contributing to the change in emergence of Palmer amaranth,

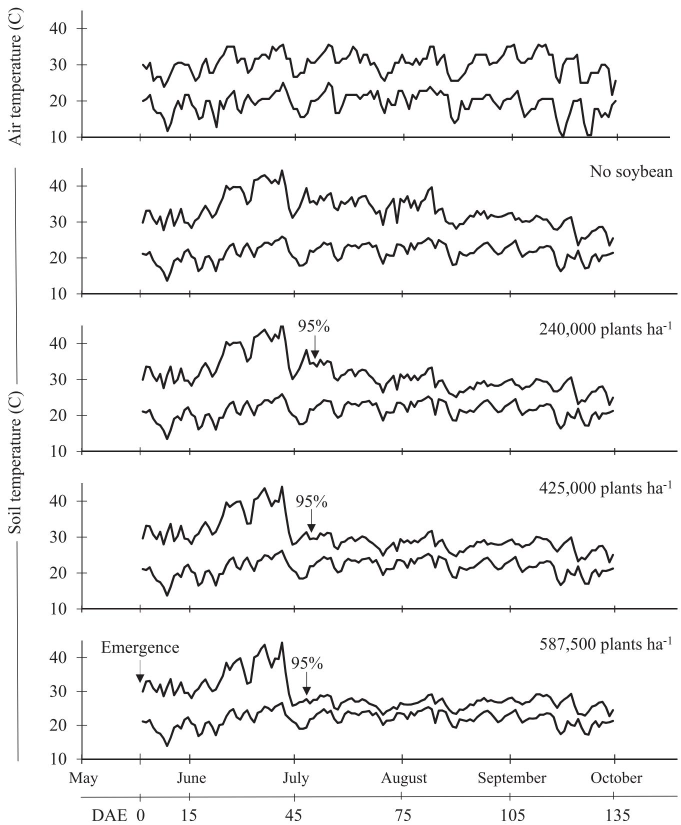

Figure 5. Daily maximum and minimum air and soil temperatures at a 2.5-cm soil depth and onset of 95% soybean canopy formation in 2013 at Marianna, AR in plots treated with flumioxazin plus pyroxasulfone at soybean planting.

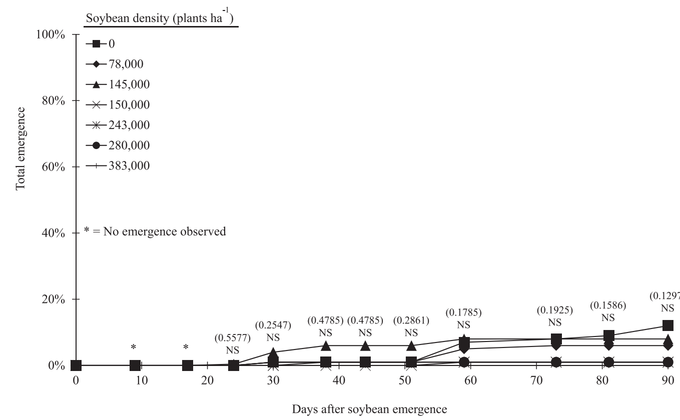

Figure 6. Percentage of total cumulative Palmer amaranth emergence (relative to no soybean, no herbicide treatment) after soybean emergence in the presence of a PRE herbicide at Fayetteville, AR, in 2013. Nonsignificant (NS) indicates cumulative emergence at that specific observation timing was similar in the presence and absence of soybean according to Fisher's protected LSD test at $\alpha < 0.05$. *F* values for assessing treatment effects at that specific observation timing are represented in parentheses.

especially considering that light transmittance through soil is limited to a depth of 4 mm (Benvenuti 1995). It is likely that some Palmer amaranth seeds were present on or near the soil surface and that light may have had some impact on reducing germination as shown previously; however, light quality was not examined in this study

At both Fayetteville and Marianna, a similar trend was observed between increasing soybean canopy formation and decreasing Palmer amaranth emergence. This inverse relationship of a reduction in weed seedling emergence due to a developing crop has been previously reported in other weed species such as curly dock (*Rumex crispus* L.) and *Amaranthus* species emergence in alfalfa (*Medicago sativa* L.) (Huarte and Benech Arnold 2003), common lambsquarters (*Chenopodium album* L.), common purslane (*Portulaca oleracea* L.), large crabgrass (*Digitaria sanguinalis* L.), and redroot pigweed (*Amaranthus retroflexus* L.) in sweet corn (*Zea mays* var. *rugosa*) (Mohler and Calloway 1992), and common cocklebur (*Xanthium strumarium* L.) and sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby] in soybean (Norsworthy 2004; Norsworthy et al. 2007).

Soybean density had no influence on Palmer amaranth emergence in Fayetteville when plots were treated with a PRE application of flumioxazin plus pyroxasulfone (Figure 6). In PRE-treated plots, no Palmer amaranth emergence occurred for the first 30 d nor did Palmer amaranth emerge in the highest soybean density of 383,000 plants ha^{-1} throughout the growing season. The fact that no emergence occurred at the highest density likely indicates that soybean canopy formation does reduce Palmer amaranth emergence similar to that observed in the absence of a PRE herbicide.

Conversely, soybean densities did impact Palmer amaranth emergence at Marianna, first at 41 DAE. The use of flumioxazin plus pyroxasulfone applied PRE in combination with soybean densities reduced Palmer amaranth emergence 50-fold compared to the season-long emergence in the bare-ground treatment (Figure 7). No further Palmer amaranth emergence occurred in the presence of soybean after 41 DAE. These results correspond with previous research from Mahoney et al. (2014), where the combination of flumioxazin plus pyroxasulfone controlled *Amaranthus* spp. 99 to 100%. Further-

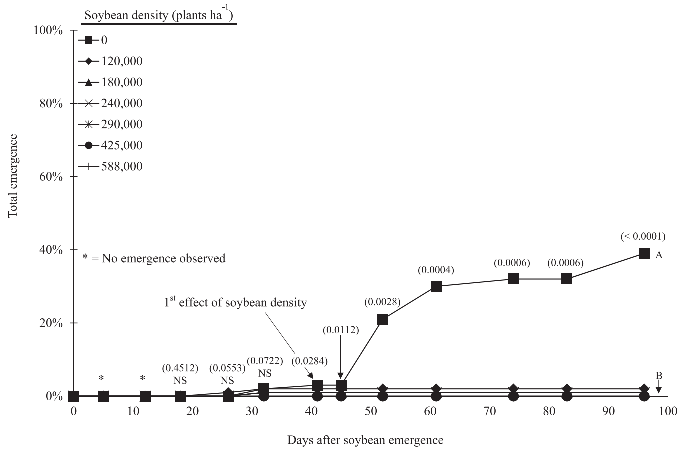

Figure 7. Percentage of total cumulative Palmer amaranth emergence (relative to no-soybean, no-herbicide treatment) after soybean emergence in the presence of a PRE herbicide at Marianna, AR in 2013. Nonsignificant (NS) indicates cumulative emergence at that specific observation timing was similar in the presence and absence of soybean according to Fisher's protected LSD test at $\alpha < 0.05$. F values for assessing treatment effects at that specific observation timing are represented in parentheses.

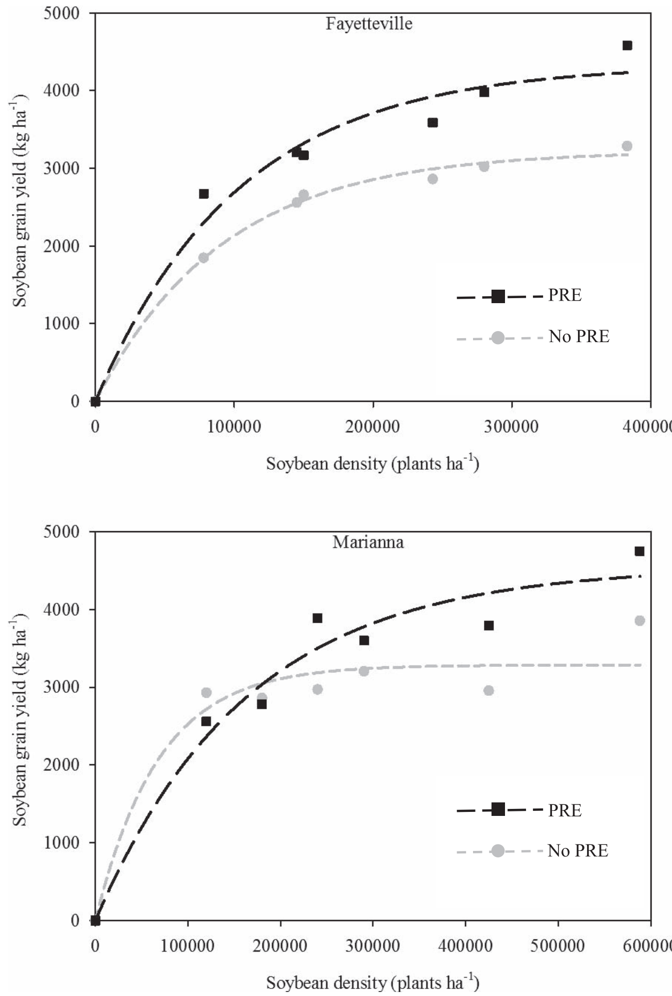

Figure 8. Soybean grain yield as influenced by soybean density in the presence (PRE) or absence (no PRE) of flumioxazin plus pyroxasulfone applied PRE at Fayetteville and Marianna, AR in 2013. (See Table 2 for model specifics.)

more, in the absence of soybean, Palmer amaranth emergence occurred until 96 DAE, when emergence was 39% of the nontreated bare-ground treatment. Hence, this research shows that a properly selected and activated PRE herbicide effectively controls early-season Palmer amaranth, whereas a dense soybean canopy is a strong suppressant of late-season emergence once the PRE-applied herbicide has dissipated.

Soybean Grain Yield. For both locations, only the main effects of PRE herbicide use and soybean seeding rate impacted soybean grain yield. Soybean grain yield was greater in the presence of flumioxazin plus pyroxasulfone applied PRE compared with its absence at Fayetteville and Marianna; hence, a loss of grain yield likely occurred because of early-season weed interference (Figure 8). Increasing the seeding rate positively impacted soybean grain yield at Fayetteville and Marianna; hence, soybean grain yield was maximized at the highest seeding rate.

These results are comparable with previous research from Norsworthy and Oliver (2001) who reported increasing soybean seeding rates of a late maturity group V, determinate soybean resulted in increased soybean grain yields, up to 988,000 seeds ha^{-1} (average density of 821,000 plants ha^{-1}), then soybean grain yield begins to diminish. Edwards and Purcell (2005) likewise reported increased soybean yields in response to increased soybean densities for maturity group 0 and IV cultivars.

Practical Implications. Because Palmer amaranth is considered the most problematic weed throughout the midsouth (Arkansas, Louisiana, Mississippi, and Tennessee) in soybean (Riar et al. 2013), producers need information about how to control this weed successfully and minimize its effects on crops. In narrow-row, drill-seeded soybean (19-cm-wide row spacing), increased soybean densities can reduce Palmer amaranth emergence in the absence of a PRE residual herbicide or when a PRE residual herbicide is selected that is not as effective as flumioxazin plus pyroxasulfone or fails to be activated due to lack of rainfall or irrigation. Even with soybean canopy formation reducing Palmer amaranth emergence, some plants still emerged regardless of the soybean density or use of flumioxizan plus pyroxasulfone applied PRE. Hence, multifaceted strategies that include POST-applied herbicides are still needed in soybean; albeit, drill-seeded soybean and PRE-applied herbicides will reduce selection on POST-applied herbicides (reduces the number of Palmer amaranth plants that must be controlled POST). Based on this research, the application of an effective PRE residual herbicide, like flumioxazin plus pyroxasulfone, in combination with a soybean seeding rate of $\geq$ 123,500 seed ha^{-1} (lowest seeding rate evaluated with actual stands of 78,000 to 120,000 plants ha^{-1}) can reduce the selection on POST herbicides compared to POST-only herbicide programs.

Because Palmer amaranth germination and emergence have previously been reported to be dependent on soil temperature fluctuations $\geq$ 7.5 C (Guo and Al-Khatib 2003; Jha and Norsworthy 2009; Steckel et al. 2004), achieving rapid canopy formation is critical to reducing soil thermal amplitudes and suppression of late-season Palmer amaranth emergence. In the presence of a PRE herbicide, increased soybean densities had no impact on Palmer amaranth emergence. Therefore, increasing the soybean seeding rate can be costly, with minimal returns in regards to suppression of Palmer amaranth emergence, especially if a highly effective PRE herbicide is applied.

In conclusion, Palmer amaranth emergence can be minimized throughout the growing season by providing irrigation to the soybean crop for rapid canopy formation and activation of the residual herbicide and seeding soybean at the recommended seeding rate of 370,500 seed ha^{-1} for a narrow-row spacing (P. Chen, personal communication). However, producers could use lower seeding rates if they are (1) using an effective PRE herbicide at planting; (2) consistently achieving a high percentage of soybean emergence in narrow rows, which would reduce soil thermal amplitudes and late-season Palmer amaranth emergence; and (3) relying on a properly timed effective POST herbicide to control Palmer amaranth plants that escape early-season control measures.

Acknowledgments

Funding provided for this research by the Arkansas Soybean Promotion Board is gratefully appreciated. The authors wish to thank Edward Gbur and Andy Mauromoustakos for their assistance with the statistical analyses.

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Received December 18, 2014, and approved June 24, 2015.

Associate Editor for this paper: Lawrence E. Steckel, University of Tennessee.