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Management of Pigweed (*Amaranthus* spp.) in Glufosinate-Resistant Soybean in the Midwest and Mid-South

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Pigweeds are among the most abundant and troublesome weed species across Midwest and mid-South soybean production systems because of their prolific growth characteristics and ability to rapidly evolve resistance to several herbicide sites of action. This has renewed interest in diversifying weed management strategies by implementing integrated weed management (IWM) programs to efficiently manage weeds, increase soybean light interception, and increase grain yield. Field studies were conducted across 16 site-years to determine the effectiveness of soybean row width, seeding rate, and herbicide strategy as components of IWM in glufosinate-resistant soybean. Sites were grouped according to optimum adaptation zones for soybean maturity groups (MGs). Across all MG regions, pigweed density and height at the POST herbicide timing, and end-of-season pigweed density, height, and fecundity were reduced in IWM programs using a PRE followed by (fb) POST herbicide strategy. Furthermore, a PRE fb POST herbicide strategy treatment increased soybean cumulative intercepted photosynthetically active radiation (CIPAR) and subsequently, soybean grain yield across all MG regions. Soybean row width and seeding rate manipulation effects were highly variable. Narrow row width ($\leq$ 38 cm) and a high seeding rate (470,000 seeds ha^{-1}) reduced end-of-season height and fecundity variably across MG regions compared with wide row width ($\geq$ 76 cm) and moderate to low (322,000 to 173,000 seeds ha^{-1}) seeding rates. However, narrow row widths and high seeding rates did not reduce pigweed density at the POST herbicide application timing or at soybean harvest. Across all MG regions, soybean CIPAR increased as soybean row width decreased and seeding rate increased; however, row width and seeding rate had variable effects on soybean yield. Furthermore, soybean CIPAR was not associated with end-of-season pigweed growth and fecundity. A PRE fb POST herbicide strategy was a necessary component for an IWM program as it simultaneously managed pigweeds, increased soybean CIPAR, and increased grain yield.

Nomenclature: Glufosinate; pigweed, *Amaranthus* spp.; soybean, *Glycine max* (L.) Merr.

Key words: Cumulative intercepted photosynthetically active radiation, cultural weed control, digital imagery analysis, glufosinate-resistant soybean, integrated weed management, PRE herbicides.

Las especies del género *Amaranthus* están entre las especies de malezas más abundantes y problemáticas en los sistemas de producción de soja en el medio oeste y el sur medio debido a sus características de crecimiento prolífico y su habilidad para evolucionar rápidamente resistencia a varios sitios de acción de herbicidas. Esto ha renovado el interés en la diversificación de estrategias de manejo de malezas implementando programas de manejo integrado de malezas (IWM) para manejar eficientemente a las malezas, que incluyan una mayor intercepción de luz por parte de la soja a la vez que se

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aumente el rendimiento de grano. Se realizaron estudios de campo a lo largo de 16 sitios-años para determinar la efectividad de la distancia entre hileras, densidad de siembra, y la estrategia de herbicidas, como componentes de un IWM en soja resistente a glufosinate. Los sitios fueron agrupados de acuerdo a las zonas óptimas de adaptación según los grupos de madurez (MGs) de la soja. Al promediar todas las regiones MG, la densidad y altura de *Amaranthus*, al momento de la aplicación POST del herbicida, y la densidad, la altura y la fecundidad de *Amaranthus* al final de la temporada, fueron reducidas en programas IWM que usaron una estrategia de herbicidas PRE seguidos por (fb) POST. Además, un tratamiento con una estrategia de herbicidas PRE fb POST aumentó la intercepción acumulativa de radiación fotosintéticamente activa (CIPAR) de la soja y subsecuentemente el rendimiento de grano de la soja al promediar todas las regiones MG. Los efectos de la distancia entre hileras y la densidad de siembra de la soja fueron altamente variables. Hileras angostas ($\leq$ 38 cm) y una alta densidad de siembra (470,000 semillas ha^{-1}) redujeron la altura y la fecundidad al final de la temporada en forma variable entre las regiones MG al compararse con hileras anchas ($\geq$ 76 cm) y densidades de siembra de moderadas a bajas (322,000 a 173,000 semillas ha^{-1}). Sin embargo, las hileras angostas y las altas densidades de siembra no redujeron la densidad de *Amaranthus* al momento de la aplicación de herbicida POST o al momento de la cosecha de la soja. Al promediar todas las regiones MG, la CIPAR de la soja aumentó al disminuir la distancia entre hileras e incrementar la densidad de siembra. Sin embargo, la distancia entre hileras y la densidad de siembra tuvieron efectos variables sobre el rendimiento de la soja. Adicionalmente, la CIPAR de la soja no estuvo asociada con el crecimiento ni la fecundidad de *Amaranthus* al final de la temporada. Una estrategia que use herbicidas PRE fb POST fue un componente necesario para que el programa IWM simultáneamente manejara malezas *Amaranthus* e incrementara la CIPAR de la soja y su rendimiento de grano.

Annual pigweeds such as Palmer amaranth (*Amaranthus palmeri* S. Wats.), common waterhemp (*Amaranthus rudis* Sauer), Powell amaranth (*Amaranthus powellii* S. Wats.), and redroot pigweed (*Amaranthus retroflexus* L.) are highly competitive broadleaf weed species that are becoming increasingly troublesome to manage in agricultural production systems. This is due to exceedingly high growth rates and development plasticity (Horak and Loughin 2000), prolific seed production (Sellers et al. 2003), and an ability to rapidly evolve resistance to multiple herbicide sites of action (Bell et al. 2013; Culpepper et al. 2006; Diebold et al. 2003; Heap 2014). Once pigweeds infest soybean fields, interference has shown to reduce soybean grain yield by up to 78% (Bensch et al. 2003). The need to manage pigweeds in soybean, especially herbicide-resistant pigweeds, has been a major contributor to the nearly 75% increase in total chemical expenditures over the last decade (USDA-NASS 2013). The use of more labor-intensive management methods, such as hand weeding, has also become more prevalent (Riar et al. 2013b).

Recent weed management strategies have lacked diversity, as cultural methods and the use of residual herbicides have had slow adoption in herbicide-resistant soybean production systems (Johnson et al. 2007; Riar et al. 2013a). This has led to increased selection pressure for the evolution of herbicide resistance. Therefore, many weed scientists have recently called for an increase in implementing integrated weed management (IWM) programs to effectively manage pigweeds and minimize the likelihood of herbicide resistance evolution (Norsworthy et al. 2012). The purpose of IWM is to diversify weed management practices and simultaneously increase crop light interception (LI), yield, and effectively manage weeds, while remaining economically viable (Swanton and Weise 1991).

Soybean row width and seeding rate manipulation is often a recommended component of a sound IWM program (Vencill et al. 2012; Walker and Buchanan 1982). Current Midwest recommendations of 247,000 soybean plants ha^{-1} (Conley and Gaska 2010; Davis 2010; Robinson and Conley 2007) and row widths less than 76 cm (Lambert and Lowenberg-DeBoer 2003; Pedersen 2007) are advised as part of an IWM program. Numerous studies have demonstrated the ability of soybean planted in narrow row widths (< 76 cm) to increase soybean yield (Cox and Cherney 2011; De Bruin and Pedersen 2008; Hanna et al. 2008), LI (Board and Harville 1993; Yelverton and Coble 1991), and more effectively manage weeds (Jha et al. 2008; Légère and Schreiber 1989; Wax and Pendleton 1968) compared with wider soybean row widths ($\geq$ 76 cm). Soybean seeding rate has also been extensively studied for those same outcomes, although seeding rate has resulted in less definitive conclusions. Edwards et al. (2005) found that high seeding rates increased LI and subsequently, cumulative intercepted photosynthetically active radiation (CIPAR), more quickly; however, low seeding rates still obtained the required CIPAR to achieve 90% of the asymptotic seed yield. More-over, seeding rate had little effect on reducing weed density in a conventional production system, but reduced weed biomass (Arce et al. 2009). These variable effects from seeding rate manipulation have been attributed to soybean physiological adaptations. Carpenter and Board (1997) observed increased branch partitioning of soybean grown in low plant populations. Branch dry matter per plant, branch nodes, branch reproductive nodes, and branch pods per plant all increased in low plant populations compared with high plant populations (Carpenter and Board 1997). The increased branch partitioning has been an inadvertent plant breeding trait to soybean over the past century. New cultivars demonstrate a threefold increase in yield per plant when grown in low plant populations, indicating a drastic reduction to the yield penalty normally associated with less-than-optimum plant populations (Suhre et al. 2014). This has stimulated the continued lowering of soybean seeding rates to provide growers more economic stability.

Herbicide-resistant pigweeds have renewed interest in diversifying herbicide sites of action and using PRE residual herbicides, both important aspects of an IWM program (Norsworthy et al. 2012). However, little research has been conducted to better understand how the use of PRE residual herbicides, coupled with reduced seeding rates and row width manipulations, influence IWM programs in a glufosinate-resistant soybean system. Our study aimed to evaluate these IWM components across the Midwest and mid-South. The objectives of our study were to determine the effect soybean row width, seeding rate, and herbicide strategy had on pigweed development, soybean CIPAR, and soybean grain yield. An additional objective was to determine the relationship between soybean CIPAR and pigweed growth and fecundity.

Materials and Methods

Field Sites. A field experiment was conducted across 16 site-years in 2013 and 2014 (Table 1). Sites were located in Arkansas, Illinois, Missouri, Nebraska, Ohio, Tennessee, and Wisconsin. The experiment was established following corn (*Zea mays* L.) at each site, using no-till, reduced, or conventional tillage practices. No-till sites had all vegetation controlled at planting with use of a nonselective herbicide. A competitive glufosinate-resistant (LibertyLink®) soybean cultivar with an appropriate relative maturity was planted at each site. Naturally occurring pigweed populations were observed at all sites except Wisconsin. To ensure consistent pigweed pressure in Wisconsin, Powell amaranth collected from the Arlington Agricultural Research Station was broadcast seeded into the research area at a rate of 600,000 seeds ha^{-1} using barn lime as a carrier (Légère and Schreiber 1989).

Experimental Design. Two row widths ($\leq$ 38 and $\geq$ 76 cm), three seeding rates (173,000 [low], 322,000 [moderate], and 470,000 [high] seeds ha^{-1}), and two herbicide strategies (PRE followed by [fb] POST vs. a single POST application [POST only]) were arranged in a randomized complete block split-plot design with row width as the main plot factor and a 3 by 2 factorial of seeding rate and herbicide strategy as the subplot factors. Treatments were replicated a minimum of four times across sites.

The PRE fb POST treatment was a PRE tank-mix formulation of *S*-metolachlor at 1.21 kg ai ha^{-1} plus fomesafen at 0.27 kg ai ha^{-1} (Prefix®-Syngenta Crop Protection, Inc., Greensboro, NC) plus metribuzin at 0.42 kg ai ha^{-1} (Sencor®-Bayer CropScience, Research Triangle Park, NC) fb glufosinate at 0.59 kg ai ha^{-1} (Liberty®-Bayer CropScience, Research Triangle Park, NC) POST. The POST-only treatment was a tank-mix formulation of glufosinate at 0.59 kg ha^{-1} plus *S*-metolachlor at 1.21 kg ha^{-1} plus fomesafen at 0.27 kg ha^{-1} POST. PRE herbicide treatments were applied within 2 d of soybean planting, and POST herbicide treatments were applied when pigweed height was 7 to 13 cm tall, in accordance with glufosinate label recommendations.

Data Collection. Indigenous pigweed populations were variable across site-years. Palmer amaranth, common waterhemp, Powell amaranth, and redroot pigweed were observed at seven, five, two, and two site-years, respectively. Adverse weather conditions and variable pigweed pressures caused some data components to be excluded from analysis. For example, CIPAR data were excluded from three site-years because of interference with the digital imagery analysis because POST herbicide performance was low or additional pigweeds emerged

Table 1. Maturity group (MG) region, tillage program, soybean cultivar, pigweed species, and data collected for individual site-years.[a]

						Pigweed data							
						Density		Height				Soybean data	
MG region	Site; year	GPS coordinates	Tillage	Soybean cultivar	Pigweed species	POST timing	End of season	POST timing	End of season	Biomass	Seed	CIPAR	Grain yield
MG II	Nebraska; 2013	41.47°N, 96.46°W	No-till	S30LC28 (Stine)	AMATA	N	N	N	N	N	Y	Y	Y
MG II	Nebraska; 2014	41.47°N, 96.46°W	No-till	S30LC28 (Stine)	AMATA	N	N	N	N	N	N	Y	Y
MG II	Nebraska; 2013	40.86°N, 96.60°W	No-till	S30LC28 (Stine)	AMAPA	N	N	N	N	N	Y	Y	Y
MG II	Nebraska; 2014	40.86°N, 96.60°W	No-till	S30LC28 (Stine)	AMAPA	Y	Y	Y	N	N	N	Y	Y
MG II	Wisconsin; 2013	43.30°N, 89.33°W	Conventional	T3314LL (Tracy Seeds, LLC)	AMAPO	Y	Y	Y	Y	Y	Y	Y	Y
MG II	Wisconsin; 2014	43.30°N, 89.33°W	Conventional	T3314LL (Tracy Seeds, LLC)	AMAPO	Y	Y	Y	Y	Y	Y	Y	Y
MG III	Ohio; 2013	39.86°N, 83.67°W	Conventional	SC3833LL (Seed Consultants, Inc.)	AMARE	N	N	N	N	N	N	Y	Y
MG III	Ohio; 2014	39.86°N, 83.67°W	Conventional	P34T35L (Pioneer)	AMARE	Y	Y	N	Y	Y	Y	Y	Y
MG III	Missouri; 2014	38.90°N, 92.21°W	Conventional	MSLL3759 (MFA Incorporated)	AMATA	Y	Y	N	N	N	N	N	Y
MG IV	Arkansas; 2013	36.10°N, 94.18°W	Conventional	HBK4950LL (Bayer CropScience)	AMAPA	Y	Y	Y	N	N	N	Y	Y
MG IV	Arkansas; 2014	36.10°N, 94.18°W	Conventional	HBK4950LL (Bayer CropScience)	AMAPA	Y	Y	Y	Y	N	N	N	Y
MG IV	Illinois; 2013	38.69°N, 90.02°W	Reduced	HS42L02 (FS-Growmark, Inc.)	AMAPA	Y	N	N	N	N	N	Y	Y
MG IV	Illinois; 2013	37.80°N, 89.26°W	No-till	HS42L02 (FS-Growmark, Inc.)	AMATA	Y	Y	N	Y	Y	Y	Y	Y
MG IV	Illinois; 2014	37.80°N, 89.30°W	No-till	HS42L22 (FS-Growmark, Inc.)	AMATA	Y	Y	N	Y	Y	N	Y	Y
MG IV	Tennessee; 2013	35.62°N, 88.85°W	No-till	P45T77L (Pioneer)	AMAPA	Y	Y	N	Y	Y	N	Y	Y
MG IV	Tennessee; 2014	35.62°N, 88.85°W	No-till	HBK4650LL (Bayer CropScience)	AMAPA	Y	Y	N	Y	Y	Y	N	N

[a] Abbreviations: CIPAR, cumulative intercepted photosynthetically active radiation; GPS, global positioning system; AMAPA, Palmer amaranth; AMAPO, Powell amaranth; AMATA, common waterhemp; AMARE, redroot pigweed.

after the POST herbicide application. Two site-years were excluded from analysis for effects on pigweeds because of a lack of pigweed pressure, but soybean CIPAR and yield data were usable for comparisons. Details regarding specific site-year pigweed species, data collected, tillage programs, soybean cultivars, and maturity group (MG) region groupings can be found in Table 1.

Pigweed plant density and height data were collected twice during the growing season to characterize emergence and growth. The first pigweed density and height measurements occurred before the POST herbicide application to assess early-season emergence and exposure to the impending POST-applied herbicides. Plant density was counted in a 1-m^2 quadrat randomly placed near the center of each plot, and the average height was determined from 10 randomly selected pigweeds. The second pigweed density and height measurements occurred before soybean harvest as described above. Additionally, mature pigweeds observed at soybean harvest in the aforementioned quadrats were clipped at the soil surface and immediately placed into paper bags for shoot mass and seed production measurements. Pigweed shoot mass and seed inflorescences were collectively dried at 55 C for 5 to 7 d and weighed to determine shoot dry mass. Subsequently, seed inflorescences were hand threshed and cleaned. The mass of 100 pigweed seeds was recorded and divided by the total mass of cleaned seed to determine seed production per square meter. Soybean grain was harvested from the center 1.5 m of each plot and adjusted to 13% moisture before data analysis.

Soybean LI was measured through the growing season using digital imagery analysis (Purcell 2000) to determine its relationship with canopy closure and soybean yield. Weekly digital images were recorded in the center of each plot from the V1 soybean growth stage to August 1. A standard digital camera was mounted 1.8 m above the soil surface and inclined 65° from the ground. Images were analyzed using Sigma Scan Pro Version 5® (Systat Software, Inc., San Jose, CA) computer software coupled with the Turf Analysis 1.2 macro for automation developed by Karcher and Richardson (2005). The output provided soybean LI estimations for each plot, which was previously demonstrated to be a 1 : 1 relationship with LI obtained from a light quantum sensor (De Bruin and Pedersen 2009; Purcell 2000). In the POST-only treatments, early-season pigweed emergence interfered with the LI estimates; therefore, LI was linearly modeled from soybean emergence to the POST application timing after pigweeds were effectively removed to interpolate accurate weekly LI estimates as previous research demonstrated a linear growth of soybean during that time frame (McWilliams et al. 1999). Quadratic models were developed for each plot to interpolate LI estimates on days when images were not taken. The resulting daily LI estimations obtained were used to calculate soybean CIPAR.

Calculation of CIPAR. Soybean LI and total solar radiation were required to calculate CIPAR of the crop as illustrated by the following equation:

$$CIPAR_t = \sum_t [\mathit{Daily\ total\ solar\ radiation}\ (\mathit{megajoule}(MJ)\,m^{-2}) \times 0.5 \times \mathit{Daily\ LI}] \qquad [1]$$

Daily total solar radiation was estimated at each site using the Hargreaves–Samani model (Ball et al. 2004), and was multiplied by a constant of 0.5 to attain daily incidence PAR (Edwards et al. 2005; Monteith 1977). The product of incidence PAR and LI estimates was daily intercepted PAR (Edwards et al. 2005; Purcell 2000). Daily intercepted PAR estimates were summed from V1 through 50 d after V1 to standardize the intercepted PAR accumulation time frame and analyzed within individual MG regions for comparisons with soybean yield and end-of-season pigweed data.

Statistical Analyses. Data were subjected to ANOVA using a mixed-effect model in SAS (SAS v9.3, SAS Institute Inc., Cary, NC). Year was analyzed as a fixed effect, and was not significant at $P \leq 0.05$. Therefore, sites and years were pooled for analysis as site-years. Soybean row width, seeding rate, and herbicide strategy were designated as fixed effects, and site-year, replications (nested within site-year), and row width by replication (nested within site-year) were considered random effects. Site-years were significant when pooled across all regions for grain yield ($P = 0.0046$), CIPAR ($P = 0.0078$), and POST timing pigweed counts ($P = 0.0119$). Therefore, site-years were grouped on the basis of the optimum adaptation zones for soybean MGs (Zhang et al. 2007).

Table 2. Influence of soybean herbicide strategy on pigweed density and height at the POST application timing for maturity group (MG) II + III and MG IV regions.[a,b]

Factor	MG II + III		MG IV	
	Density	Height	Density	Height[c]
	plants m^{-2}	cm	plants m^{-2}	cm
Herbicide strategy				
PRE fb POST	1 a	2.1 a	3 a	—
POST only	47 b	8.2 b	116 b	—
ANOVA				
RW	NS	NS	NS	NS
SR	NS	NS	NS	NS
RW × SR	NS	NS	NS	NS
HS	< 0.0001	< 0.0001	< 0.0001	NS
RW × HS	NS	NS	NS	NS
SR × HS	NS	NS	NS	NS
RW × SR × HS	NS	NS	NS	0.0266

[a] Abbreviations: RW, row width; SR, seeding rate; HS, herbicide strategy; fb, followed by.

[b] Means within a column with the same letter are not significantly different ($P \leq 0.05$).

[c] Pigweed height in the MG IV region was influenced by a three-way interaction, and no biologically significant conclusions could be drawn. Therefore, the data are not shown.

Subsequently, soybean yield and CIPAR data were pooled into regions by MGs; MG II region comprised Nebraska and Wisconsin, MG III region comprised Ohio and Missouri, and MG IV region comprised Arkansas, southern Illinois, and Tennessee. MG II and MG III were pooled into one region and MG IV was a region for analysis of pigweed density, height, biomass, and seed production data because of individual region significance at $P \leq 0.05$. No significant interactions between main effects and MG region were observed for grain yield, CIPAR, or pigweed density, height, and fecundity data at $P \leq 0.05$. When main effects or their interactions were significant ($P \leq 0.05$), means were separated using Fisher's Protected LSD test. To better meet the assumptions of ANOVA, pigweed density and heights at the POST application timing, end-of-season pigweed heights, and pigweed seed production data were subjected to a natural log transformation; end-of-season pigweed density and pigweed dry biomass per plant data were subjected to an inverse transformation; and pigweed dry biomass per square meter was subjected to an inverse square-root transformation as suggested by the Box–Cox method (Box and Cox 1964). Back-transformed data are presented.

Results and Discussion

Pigweed Density, Biomass, and Fecundity. A measurement of success for IWM components is efficacy of weed suppression. Soybean row width and seeding rate did not affect pigweed density and height before the POST application timing in the MG II + III region (Table 2). In contrast, pigweed density decreased by 46 plants m^{-2} and height by 74% in the PRE fb POST herbicide strategy treatment compared with the POST-only strategy. Similarly, in the MG IV region, a PRE herbicide reduced pigweed density at the POST application timing by 113 plants m^{-2}, which was a 97% reduction compared with the POST-only treatments. However, pigweed height in the MG IV region was influenced by a three-way interaction between soybean row width, seeding rate, and herbicide strategy, and no discernable pattern was found that elicited a biologically significant conclusion. Furthermore, soybean row width and seeding rate did not affect pigweed density and height before the POST herbicide application in either MG region when POST-only treatments were evaluated alone (data not shown). Since soybean row width and seeding rate were not associated with reduced pigweed density or height before the POST herbicide application, they contributed little to early-season pigweed management and subsequently, herbicide resistance management. This result coincides with previous research conducted by DeWerff et al. (2014).

Soybean row width and seeding rate did not affect pigweed growth at the POST herbicide timing; however, row width and seeding rate did influence end-of-season pigweed growth and fecundity. Across all regions, the main effects of row width and seeding rate did not influence end-of-season pigweed density; in the MG IV region, a three-way interaction did not result in a biologically significant effect (Table 3). In the MG II + III region, narrow row width (≤ 38 cm) reduced pigweed height, biomass per square meter, and biomass per plant by 69, 62, and 67%, respectively, compared with wide row width (≥ 76 cm) (Table 3). In the MG IV region, narrow row width (≤ 38 cm) reduced

Table 3. Influence of soybean row width, seeding rate, and herbicide strategy on end-of-season pigweed density, height, biomass, and seed production for maturity group (MG) II + III and MG IV regions.[a,b]

	MG II + III					MG IV				
Factor	Density	Height	Biomass	Biomass	Seed	Density[c]	Height	Biomass	Biomass	Seed
	plants m^{-2}	cm	g m^{-2}	g $plant^{-1}$	seeds m^{-2}	plants m^{-2}	cm	g m^{-2}	g $plant^{-1}$	seeds m^{-2}
Row width										
$\leq$ 38 cm	1 a	1.7 a	0.5 a	0.2 a	10 a	—	6.8 a	1.1 a	0.5 a	22 a
$\geq$ 76 cm	1 a	5.4 b	1.3 b	0.6 b	17 a	—	11.8 a	2.1 a	0.8 b	62 b
Seeding rate[d]										
173,000	1 a	4.6 a	1.3 a	0.5 a	17 a	—	10.5 a	2.3 b	0.9 b	57 b
322,000	1 a	2.3 a	0.8 a	0.3 a	16 a	—	11.4 a	1.9 b	0.7 b	51 b
470,000	1 a	2.9 a	0.7 a	0.4 a	7 a	—	5.9 a	0.7 a	0.3 a	17 a
Herbicide strategy										
PRE fb POST	0 a	0.3 a	0.1 a	0.1 a	1 a	—	5.3 a	0.8 a	0.4 a	17 a
POST-only	1 b	12.2 b	3.0 b	1.1 b	123 b	—	14.9 b	2.6 b	1.0 b	78 b
ANOVA										
RW	NS	0.0059	0.0105	0.0028	NS	NS	NS	NS	0.0464	0.0409
SR	NS	NS	NS	NS	NS	NS	NS	0.0001	0.0001	0.0426
RW × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
HS	$<$ 0.0001	$<$ 0.0001	$<$ 0.0001	$<$ 0.0001	$<$ 0.0001	$<$ 0.0001	0.0001	$<$ 0.0001	$<$ 0.0001	0.0005
RW × HS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SR × HS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
RW × SR × HS	NS	NS	NS	NS	NS	0.0203	NS	NS	NS	NS

[a] Abbreviations: RW, row width; SR, seeding rate; HS, herbicide strategy; fb, followed by.

[b] Means within a column and factor with the same letter are not significantly different ($P \leq 0.05$).

[c] Pigweed density in the MG IV region was influenced by a three-way interaction, and no biologically significant conclusions could be drawn. Therefore, the data are not shown.

[d] Seeding rates are in seeds ha^{-1}.

biomass per plant and seeds per square meter by 38 and 65%, respectively, compared with wide row width ($\geq$ 76 cm). Additionally, in the MG IV region, the high seeding rate reduced pigweed biomass per square meter, biomass per plant, and seeds per square meter by 63, 57, and 67%, respectively, compared with the moderate and low seeding rates. Therefore, our results are consistent with previous findings that soybean row width and seeding rate reduced weed biomass and seed production, but not pigweed density (Arce et al. 2009; Légère and Schreiber 1989). The PRE fb POST herbicide strategy was the most consistent factor to influence end-of-season pigweed density, height, biomass, and fecundity. It reduced pigweed density at soybean harvest compared with the POST-only treatment, and pigweed height, biomass per square meter, biomass per plant, and seeds per square meter by more than 90% in the MG II + III region (Table 3). In the MG IV region, pigweed height, biomass per square meter, biomass per plant, and seeds per square meter were reduced by at least 60% by the PRE fb POST herbicide strategy compared with the POST-only strategy. Therefore, soybean row width and seeding rate contributed to less end-of-season pigweed growth and fecundity. However, the PRE fb POST herbicide strategy was deemed the most important component of the IWM program for early-season and end-of-season pigweed management as density, growth, and fecundity were lower compared with a POST-only treatment.

Soybean CIPAR. Another measurement of the effectiveness of an IWM program is soybean LI development and subsequently, soybean CIPAR. Previous research has shown that as soybean CIPAR increases, late-season weed emergence decreases

Table 4. Influence of soybean row width, seeding rate, and herbicide strategy on cumulative intercepted photosynthetically active radiation (CIPAR) for maturity group (MG) II, MG III, and MG IV regions.[a,b]

Factor	CIPAR		
	MG II	MG III[c]	MG IV
	MJ m^{-2}		
Row width			
$\leq$ 38 cm	310 a	—	385 a
$\leq$ 76 cm	270 b	—	361 b
Seeding rate[d]			
173,000	252 c	—	343 c
322,000	294 b	—	378 b
470,000	324 a	—	397 a
Herbicide strategy			
PRE fb POST	308 a	338 a	385 a
POST-only	272 b	311 b	360 b
ANOVA			
RW	< 0.0001	0.0013	< 0.0001
SR	< 0.0001	< 0.0001	< 0.0001
RW × SR	NS	0.0334	NS
HS	< 0.0001	< 0.0001	< 0.0001
RW × HS	NS	NS	NS
SR × HS	NS	NS	NS
RW × SR × HS	NS	NS	NS

[a] Abbreviations: MJ, megajoule; RW, row width; SR, seeding rate; HS, herbicide strategy; fb, followed by.

[b] Means within a column and factor with the same letter are not significantly different ($P \leq 0.05$).

[c] Because of significant RW by SR interaction, values are presented in Table 5.

[d] Seeding rates are in seeds ha^{-1}.

Table 5. Influence of the soybean row width and seeding rate interaction on cumulative intercepted photosynthetically active radiation (CIPAR) for the maturity group (MG) III region.[a,b]

Factor	CIPAR
	MJ m^{-2}
Row width × seeding rate[c]	
$\leq$ 38 cm × 173,000	300 de
$\leq$ 38 cm × 322,000	346 b
$\leq$ 38 cm × 470,000	370 a
$\geq$ 76 cm × 173,000	289 e
$\geq$ 76 cm × 322,000	317 cd
$\geq$ 76 cm × 470,000	328 c

[a] Means within a column with the same letter are not significantly different ($P \leq 0.05$).

[b] Abbreviation: MJ, megajoule.

[c] Seeding rates are in seeds ha^{-1}.

(Yelverton and Coble 1991), and soybean yield increases (Edwards et al. 2005).

Soybean CIPAR in the MG II and MG IV regions was affected by all three main effects (Table 4). In the MG II region, narrow soybean row width ($\leq$ 38 cm), a seeding rate increase from low to moderate, and a PRE fb POST herbicide strategy increased CIPAR by 15, 17, and 13%, respectively. Similarly, in the MG IV region, narrow soybean row width ($\leq$ 38 cm), a seeding rate increase from low to moderate, and a PRE fb POST herbicide strategy increased CIPAR by 7, 10, and 7%, respectively. For MG III, the PRE fb POST herbicide strategy increased CIPAR by 9% (Table 4). However, a significant row width by seeding rate interaction affected CIPAR in the MG III region (Table 5). Soybean CIPAR was the greatest in the narrow row width environment paired with the high and moderate seeding rates; however, the wide row width environment coupled with the high and moderate seeding rates achieved greater CIPAR than the narrow row width environment when planted at a low seeding rate.

The importance of increasing soybean CIPAR was further demonstrated by its positive association with soybean yield in two of three MG regions. An asymptotic model as used by Edwards et al. (2005) was fit to the data for the MG II and MG IV regions (Figure 1). As soybean CIPAR increased, soybean grain yield increased asymptotically. In the MG III region, a positive relationship between CIPAR and grain yield was observed; however, because of a very weak association, no model was fit to the data. Linear regressions and asymptotic models were investigated to associate CIPAR with end-of-season pigweed data; however, no significant associations were found (data not shown).

These results demonstrate that CIPAR increased similarly across all factors whether row width was reduced, seeding rate was increased by 149,000 seeds ha^{-1}, or a PRE fb POST herbicide strategy was used. Therefore, all three factors could be used as components in an IWM program to increase soybean CIPAR, depending on the economic feasibility of each.

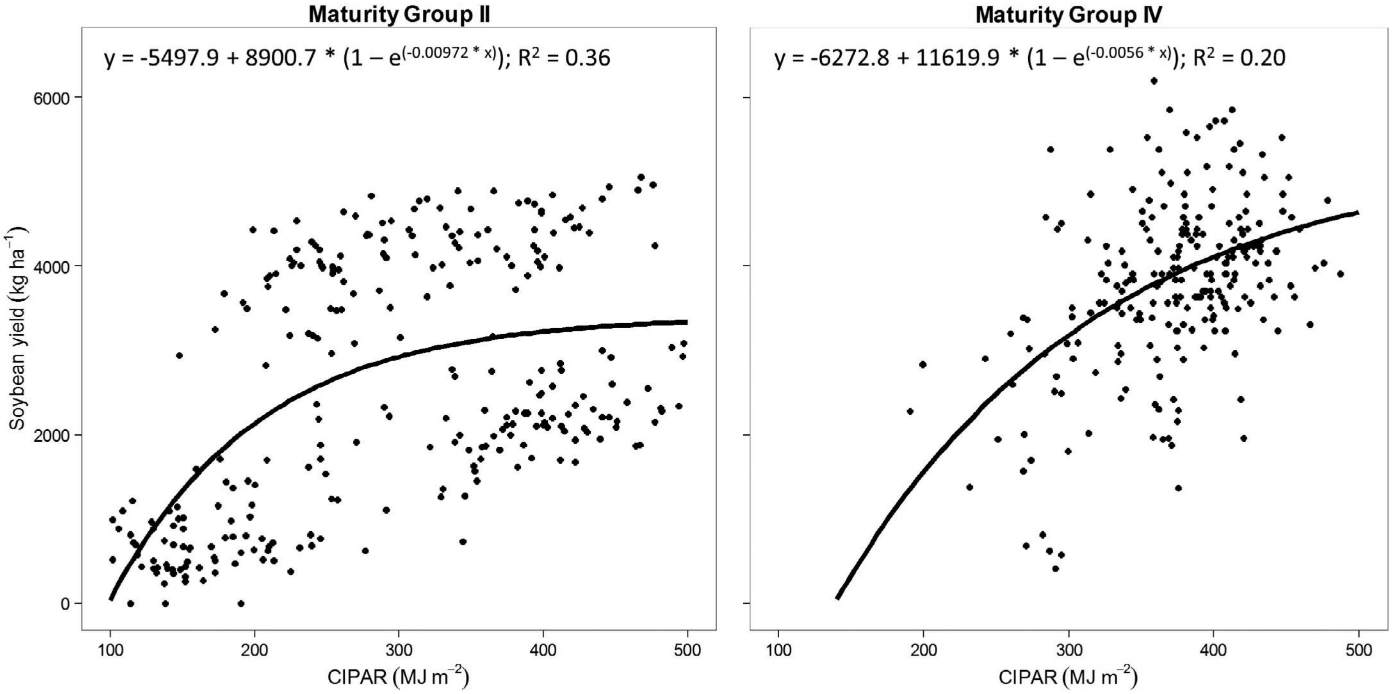

Figure 1. Asymptotic relationship between soybean cumulative intercepted photosynthetically active radiation (CIPAR) and grain yield. Data were pooled within maturity group (MG) and across site-years. Soybean CIPAR and grain yield data from Arkansas and Tennessee in 2014 were excluded because of weed interference affecting the digital imagery analysis. No model could be fit to MG III data.

Soybean Yield. Another goal of a successful IWM program is to increase soybean grain yield to achieve economic viability. In the MG II region, soybean yield was 12% greater in the wide row width ($\geq$ 76 cm) (Table 6), which conflicts with results of previous research (Cox and Cherney 2011; De Bruin and Pedersen 2008; Hanna et al. 2008); however, row width was not significant in the MG III or MG IV regions. Soybean grain yield increased by 6% for every increase in seeding rate of 149,000 seeds ha^{-1} in the MG II region. In the MG III region, the moderate and high seeding rates had 17% greater soybean yield compared with the low seeding rate. Soybean yield increased by 20 and 27% in the PRE fb POST herbicide strategy treatment in the MG II and MG III regions, respectively. A significant seeding rate by herbicide strategy interaction affected soybean yield in the MG IV region (Table 7). The two highest-yielding treatments were the high and moderate seeding rates paired with the PRE fb POST herbicide strategy. These results demonstrate the ability of soybean to maintain yield with reduced seeding rates (322,000 seeds ha^{-1}) in two of the three MG regions, which is similar to previous research conducted (Carpenter and Board 1997; Cox and Cherney 2011; Suhre et al. 2014). From our results, a PRE fb POST herbicide strategy was the most significant component that could be used as part of an IWM program to increase soybean grain yield across all MG regions.

In summary, a PRE fb POST herbicide strategy was the primary component of an IWM program as it simultaneously achieved multiple goals of a successful program across all MG regions in this study. The PRE fb POST herbicide strategy decreased pigweed density at the POST herbicide timing and at soybean harvest, as well as reduced end-of-season pigweed growth and fecundity. Subsequently, the PRE fb POST herbicide strategy increased soybean CIPAR, which was shown to have a positive relationship with soybean grain yield. Although relationships could not be established between CIPAR and pigweed data, previous research has demonstrated that increased LI can reduce pigweed emergence and growth (Yelverton and Coble 1991). Furthermore, the PRE fb POST

Table 6. Influence of soybean row width, seeding rate, and herbicide strategy on soybean grain yield for maturity group (MG) II, MG III, and MG IV regions.[a,b]

	Grain yield		
Factor	MG II	MG III	MG IV[c]
	kg ha^{-1}		
Row width			
$\leq$ 38 cm	2,390 b	3,570 a	3,660 a
$\geq$ 76 cm	2,670 a	3,550 a	3,500 a
Seeding rate[d]			
173,000	2,370 c	3,170 b	—
322,000	2,520 b	3,710 a	—
470,000	2,680 a	3,800 a	—
Herbicide strategy			
PRE fb POST	2,750 a	3,980 a	—
POST only	2,300 b	3,140 b	—
ANOVA			
RW	0.0287	NS	NS
SR	$<$ 0.0001	$<$ 0.0001	$<$ 0.0001
RW × SR	NS	NS	NS
HS	$<$ 0.0001	$<$ 0.0001	0.0021
RW × HS	NS	NS	NS
SR × HS	NS	NS	0.0445
RW × SR × HS	NS	NS	NS

[a] Abbreviations: RW, row width; SR, seeding rate; HS, herbicide strategy; fb, followed by.

[b] Means within a column and factor with the same letter are not significantly different ($P \leq 0.05$).

[c] Because of significant SR by HS interaction, values are presented in Table 7.

[d] Seeding rates are in seeds ha^{-1}.

Table 7. Influence of the soybean seeding rate and herbicide strategy interaction on grain yield for the maturity group (MG) IV region.[a,b]

Factor	Grain yield
	kg ha^{-1}
Seeding rate × herbicide strategy[c]	
173,000 × PRE fb POST	3,250 d
322,000 × PRE fb POST	3,850 ab
470,000 × PRE fb POST	4,050 a
173,000 × POST only	3,290 d
322,000 × POST only	3,410 cd
470,000 × POST only	3,620 bc

[a] Abbreviation: fb, followed by.

[b] Means within a column with the same letter are not significantly different ($P \leq 0.05$).

[c] Seeding rates are in seeds ha^{-1}.

herbicide strategy increased soybean grain yield by a larger margin compared with any other factor in this study. Although soybean row width did not affect soybean yield in two of three MG regions, narrow row width ($\leq$ 38 cm) is still a viable IWM component as it reduced end-of-season pigweed growth and fecundity and increased soybean CIPAR across MG regions. Soybean seeding rate was the most variable factor in this study and because of reduced economic returns when seeding rates are raised, the Midwest recommendation of seeding rates to establish 247,000 plants ha^{-1} is the most appropriate for a sound IWM program. In conclusion, to simultaneously increase crop LI, yield, and effectively manage pigweeds, a PRE fb POST herbicide strategy in a glufosinate-resistant soybean system is the main component of a successful IWM program for pigweed management.

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