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Weed Control in Soybean as Influenced by Residual Herbicide Use and Glyphosate-Application Timing Following Different Planting Dates

Ryan P. DeWerff, Shawn P. Conley, Jed B. Colquhoun, and Vince M. Davis*

Soybean planting has occurred earlier in the Midwestern United States in recent years; however, earlier planting subjects the crop to longer durations of weed interference. This may change the optimum timing of POST glyphosate applications, or increase the need for residual herbicides applied PRE to optimize yield. A field study was conducted in 2012 and 2013 near Arlington, WI to determine the effect of planting date, residual herbicide use, and POST glyphosate timing on weed control and soybean yield. Planting dates were late April, mid-May, and early June. A PRE application of sulfentrazone plus cloransulam was applied to half the plots following each planting date. Glyphosate was applied POST to all plots at the V1, V2, V4, or R1 soybean growth stage. Planting date and glyphosate timing did not affect soybean yield in this study. However, averaged across years, planting dates, and POST glyphosate timings, yield increased from 3,280 to 3,500 kg ha^{-1} when a PRE herbicide with residual soil activity was used. In POST-only treatments, delaying the planting date to June decreased weed density at POST application timing from 127 to 5 plants m^{-2} (96%) and from 205 to 42 plants m^{-2} (80%) in 2012 and 2013, respectively. Where a PRE was used, total weed density at POST application timing was always less within planting date, and also declined from early to late planting date 26 to 3 plants m^{-2} (89%) and 23 to 6 plants m^{-2} (74%) in 2012 and 2013, respectively. In conclusion, both PRE herbicide use and delayed soybean planting were effective strategies to reduce the number of in-crop weeds exposed to POST glyphosate and should be considered as strategies to reduce the number of weeds exposed to POST herbicides for resistance management.

Nomenclature: Glyphosate; cloransulam; sulfentrazone; soybean, *Glycine max* (L.) Merr.

Key words: Herbicide-resistant crops, integrated weed management, preemergence herbicide, weed interference.

La siembra de la soja se ha dado más temprano, en años recientes en el Medio oeste de los Estados Unidos. Sin embargo, la siembra temprana expone al cultivo a períodos más largos de interferencia de malezas. Esto podría cambiar el momento óptimo para las aplicaciones POST de glyphosate, o podría incrementar la necesidad de aplicación PRE de herbicidas residuales para optimizar el rendimiento. En 2012 y 2013, cerca de Arlington, Wisconsin, se realizó un estudio de campo para determinar el efecto de la fecha de siembra, el uso de herbicidas residuales, y el momento de aplicación POST de glyphosate sobre el control de malezas y el rendimiento de la soja. Las fechas de siembra fueron: al final de Abril, la mitad de Mayo, y el inicio de Junio. Se aplicó sulfentrazone más cloransulam PRE a la mitad de las parcelas después de cada fecha de siembra. Glyphosate fue aplicado POST a todas las parcelas en los estadios de desarrollo V1, V2, V4, o R1 de la soja. La fecha de siembra y el momento de aplicación de glyphosate no afectaron el rendimiento de la soja en este estudio. Sin embargo, al promediar los años, las fechas de siembra, y los momentos de aplicación POST de glyphosate, el rendimiento incrementó de 3,280 a 3,500 kg ha^{-1} cuando se usó un herbicida PRE con actividad residual. En tratamientos con solo aplicaciones POST, el retrasar la fecha de siembra a Junio redujo la densidad de malezas al momento de la aplicación POST de 127 a 5 plantas m^{-2} (96%) y de 205 a 42 plantas m^{-2} (80%) en 2012 y 2013, respectivamente. Donde se usó una aplicación PRE, la densidad total de malezas al momento de la aplicación POST fue siempre menor, dentro de cada fecha de siembra, y también disminuyó de la fecha de siembra temprana a la tardía de 26 a 3 plantas m^{-2} (89%) y de 23 a 6 plantas m^{-2} (74%) en 2012 y 2013, respectivamente. En conclusión, el uso de herbicidas PRE y la siembra retrasada de la soja fueron estrategias efectivas para reducir el número de malezas dentro del cultivo expuestas a glyphosate POST y deberían ser consideradas como estrategias para reducir el número de malezas expuestas a herbicidas POST para el manejo de resistencia.

Soybean planting date is one of the most critical management decisions that can affect soybean seed yield (Cartter and Hartwig 1963). Historically, planting soybean any time in the month of May was sufficient to maximize yield (Egli and Cornelius 2009); however, improvements made in soybean

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* First, second, and fourth authors: Graduate Research Assistant, Professor, and Assistant Professor, respectively, Department of Agronomy, University of Wisconsin–Madison, 1575 Linden Drive, Madison, WI 53706; third author: Professor, Department of Horticulture, University of Wisconsin–Madison, 1575 Linden Drive, Madison, WI 53706 Corresponding author's E-mail: vmdavis@wisc.edu

genetics may alter the yield response to planting date. Recent research by Rowntree et al. (2013) evaluated planting date by genetic gain interaction, and the authors found the rate of yield gain for maturity group III cultivars was 3.10 kg ha^{-1} yr^{-1} greater for the early planting compared with late planting. These results suggest a more positive response to earlier planting dates for newer cultivars compared with older cultivars.

Regardless of whether the influence is from improved soybean genetics or other factors, soybean planting in the Midwestern United States has trended toward earlier calendar dates in recent decades. The percentage of soybean area planted in the United States by mid-May has increased from 32% in 1983 to 42% in 2013 (U.S. Department of Agriculture, National Agricultural Statistics Service [USDA-NASS] 2014). This trend is well supported, as several research reports have indicated soybean yield typically declines if planting is delayed beyond the middle of May (Bastidas el al. 2008; De Bruin and Pedersen 2008; Oplinger and Gaska 1996; Robinson et al. 2009). However, planting date recommendations are often based on the assumption that soybean will be grown in weed-free conditions for the entire season, conditions that rarely exist in production fields. Planting date can alter the competitive environment between the crop and weeds; therefore, agronomic decisions that maximized yield in a weed-free environment may change in the presence of weeds.

Results from experiments evaluating the impact of soybean planting date on weed interference have varied. Klingaman and Oliver (1994) reported soybean yield losses due to entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* Gray) and sicklepod [*Senna obtusifolia* (L.) H.S. Irwin and Barneby] interference were 10, 18, and 35% at the early-May, mid-May, and early-June planting dates, respectively, relative to a weed-free control. Oliver (1979) found a density of one velvetleaf (*Abutilon theophrasti* Medik.) 0.30 m^{-1} row resulted in soybean yield loss of 27 and 14% for the early and late planting dates, respectively, because of the short-day photoperiodic response of velvetleaf. In the Klingaman and Oliver (1994) and Oliver (1979) studies, the desired weed species were hand planted near the time of soybean planting. An alternate research method utilizes a natural population of weed species that allows early-emerging weeds in late-planted soybean to be controlled by preplant tillage or herbicide applications. Experiments using this approach have reported a reduction of in-crop weed density as the primary benefit of delayed soybean planting. In Minnesota, weed emergence between mid-May and early-June planting dates was 80, 25, and 100% of the total annual emergence for common lambsquarters (*Chenopodium album* L.), pigweed species (*Amaranthus* spp.), and velvetleaf, respectively (Buhler and Gunsolus 1996). Coulter et al. (2011) reported a 51% reduction in weed density at harvest when planting was delayed from May until mid-June; however, yield at the mid-June planting date was 21% lower than the May planting dates. This indicates planting soybean later to improve weed control may not be desirable or acceptable because of yield losses associated with later planting dates.

Weed management decisions may change as soybean growers continue to plant earlier in the growing season to achieve higher yields. Earlier planting dates subject the crop to weed interference for longer durations of time, which may impact the optimum timing of POST glyphosate application. Additionally, more intensive early-season weed control strategies, such as using a PRE herbicide with residual soil activity, may be necessary for adequate weed control and yield maximization. The objective of this research was to determine the influence of planting date, residual herbicide use, and POST glyphosate application timing on weed control and soybean yield.

Materials and Methods

Site Description. Field experiments were conducted in 2012 and 2013 at the University of Wisconsin Arlington Agricultural Research Station located near Arlington, WI (43°18′N, 89°20′W). Trials were established in 2012 following fallow ground and in 2013 following corn. The soil was a Plano silt loam (fine silty, mixed, superactive mesic Typic Agriudoll) with 3.6% organic matter, 6.0 pH in 2012 and 3.5% organic matter, 6.8 pH in 2013. Fields where trials were located were chisel plowed in the preceding fall and field cultivated in the spring in advance of the first planting date to prepare a seedbed. The planter used was equipped with row cleaners and wavy coulters for planting into no-till seedbed conditions, and the goal was for all planting

Table 1. Calendar dates of field operations and first rainfall event following the PRE application for the early, mid, and late planting dates in a soybean study near Arlington, WI conducted in 2012 and 2013.

	Early		Mid		Late	
Field operations	2012	2013	2012	2013	2012	2013
Soybean planting	April 24	April 29	May 10	May 14	June 4	June 3
Date of first rainfall after PRE (mm)	April 25 (7.9)	April 30 (3.5)	May 24 (3.8)	May 15 (1.8)	June 11 (2.3)	June 4 (4.1)
POST application						
V1	May 30	June 3	June 4	June 14	June 26	June 26
V2	June 4	June 10	June 11	June 19	July 6	July 1
V4	June 15	June 20	June 22	June 27	July 12	July 11
R1	June 28	June 27	July 3	July 5	July 17	July 20
Soybean harvest	September 20	September 27	September 20	September 27	October 3	October 10

dates to be planted with the use of a stale-seedbed approach. This was accomplished by completing the final preplant tillage event 2 wk prior to the first planting date the first year. Unfortunately, wet soil conditions prevented final tillage the second year until just days before the first planting. However, all mid and late planting dates were planted into a stale seedbed, and weeds that emerged prior to each planting date were controlled with glyphosate (Roundup PowerMax®, Monsanto Co., St. Louis, MO) applied preplant at 0.87 kg ae ha^{-1} plus 2.86 kg ha^{-1} of granular ammonium sulfate (AMS). Weed species communities were similar in both years and predominantly consisted of common lambsquarters, common ragweed (*Ambrosia artemisiifolia* L.), and annual grasses (~70% giant foxtail [*Setaria faberi* Herrm.] and ~20% large crabgrass [*Digitaria sanguinalis* (L.) Scop.]).

Experimental Design. The experiment included a split-plot arrangement of treatments in a randomized complete block with four replications. Whole plots were three planting dates (early, mid, and late) and were established at approximately 2-wk intervals beginning in late April (Table 1). 'DSR-2105′ (Dairyland Seed Co., Inc., West Bend, WI), a glyphosate-resistant, maturity group II cultivar was planted at 296,400 seeds ha^{-1} in rows spaced 76-cm apart. Subplots were arranged in a two-by-four factorial treatment structure: (2) residual herbicide use (PRE) or no PRE by (4) POST glyphosate application timings at the V1, V2, V4, or R1 soybean growth stage (Fehr and Caviness 1977). A premix formulation of 0.26 kg ai ha^{-1} sulfentrazone plus 0.03 kg ai ha^{-1} cloransulam (Authority First®, FMC Corp., Philadelphia, PA) was applied as the PRE on the same day soybean seeds were planted, but after the planting operation. The first rainfall event that occurred following the PRE application is listed in Table 1. Glyphosate at 0.87 kg ae ha^{-1} plus 2.86 kg ha^{-1} of granular ammonium sulfate (AMS) was applied POST when soybean reached the appropriate growth stage. All herbicides were applied in water with a CO_2 backpack sprayer with the use of XR11002 flat-fan nozzle tips delivering 140 L ha^{-1} at 172 kPa. Subplots were 3 m wide by 15.2 m long and consisted of four soybean rows.

Data Collection. Prior to each POST glyphosate application, weed population densities and heights were determined within two 0.25-m^2 quadrats placed at two arbitrarily selected locations within each subplot. Weeds were counted by species, and five arbitrarily selected plants of each species, within each quadrat, were measured for height. Average weed heights prior to the POST glyphosate application of predominant species are reported in Table 2. End-of-season weed density and heights were assessed within 1 wk of soybean harvest with the use of the same method; therefore, end-of-season weed densities were not counted from the same quadrats used at the earlier timing. Soybean plants were counted from 5.3 m of row from each of the two center rows in each plot just prior to soybean harvest. Soybean grain was harvested from the center two rows with a plot combine and yield was adjusted to 13% grain moisture for analyses.

Statistical Analyses. Data were tested for homogeneity of variance and normality by examining the studentized residual versus predicted plots and quantile–quantile plots, respectively (Onofri et al. 2010). Weed densities of each species were subjected to a log base ten transformation, as suggested by the BoxCox method, in order to meet

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Table 2. Average heights of predominant weeds present at the time of POST glyphosate application in 2012 and 2013 in a soybean study conducted near Arlington, WI.

Planting date	PRE herbicide	POST timing	2012 AMBEL	2012 CHEAL	2012 Grass	2013 AMBEL	2013 CHEAL	2013 Grass
			cm					
Early	Sulfentrazone + cloransulam	V1	1	0	3	1	0	2
		V2	2	0	3	1	0	1
		V4	3	0	5	2	0	4
		R1	13	5	8	2	0	5
	No PRE	V1	7	2	8	3	2	6
		V2	9	4	9	5	3	7
		V4	22	6	18	12	6	14
		R1	35	12	18	24	13	15
Mid	Sulfentrazone + cloransulam	V1	5	5	5	2	0	1
		V2	5	1	5	0	0	1
		V4	11	9	9	1	0	3
		R1	23	8	18	2	0	7
	No PRE	V1	3	1	4	5	3	7
		V2	6	3	5	8	4	12
		V4	26	7	14	19	10	14
		R1	46	8	18	32	16	17
Late	Sulfentrazone + cloransulam	V1	0	1	2	2	0	4
		V2	0	2	1	0	0	4
		V4	1	0	6	2	0	5
		R1	0	2	5	7	0	11
	No PRE	V1	0	4	4	2	2	4
		V2	0	1	5	6	3	4
		V4	0	1	7	13	4	8
		R1	6	2	5	29	9	22

the assumptions of ANOVA better (Box and Cox 1964). All data were subjected to ANOVA with the use of the PROC MIXED procedure in SAS (SAS Institute Inc., Cary, NC). When main effects of planting date (PD), PRE herbicide (PH), glyphosate timing (GT), or their interactions were statistically significant ($P \leq 0.05$), means were separated with the use of Fisher's protected $LSD_{0.05}$ test. Letter values were assigned with the use of the "PDMIX800" macro developed by Saxton (1998). For the analysis of grain yield, PD, PH, GT, and all two-way and three-way interactions were considered fixed effects. Year, replications within year, and the whole-plot error within year were considered random effects. All weed density data were analyzed by year. The highest-order interaction with year, PD, PH, and GT was not significant ($P > 0.05$) for any of the weed species analyzed prior to the POST applications or at soybean harvest; however, many two- and three-way interactions with year were significant ($P \leq 0.05$). Mean separation of treatments was based on analysis of the transformed data, but backtransformed data are presented for clarity.

Results and Discussion

Temperature and rainfall varied considerably between 2012 and 2013 (Figure 1). The 2012 growing season was very dry and warm during soybean vegetative growth, but late-July and August precipitation during reproductive growth aided pod formation and seed fill. In 2013, cumulative precipitation was considerably higher than in 2012. However, most precipitation occurred early in the season during vegetative growth, and conditions were much drier during soybean reproductive growth. Heavy rainfall and cool temperature immediately after the early planting date in 2012 led to harvest plant populations nearly 50% lower than the other planting dates because of crusting at the soil surface (Table 3).

Weed Density at POST Glyphosate Application. In-crop weeds did not have enough continued

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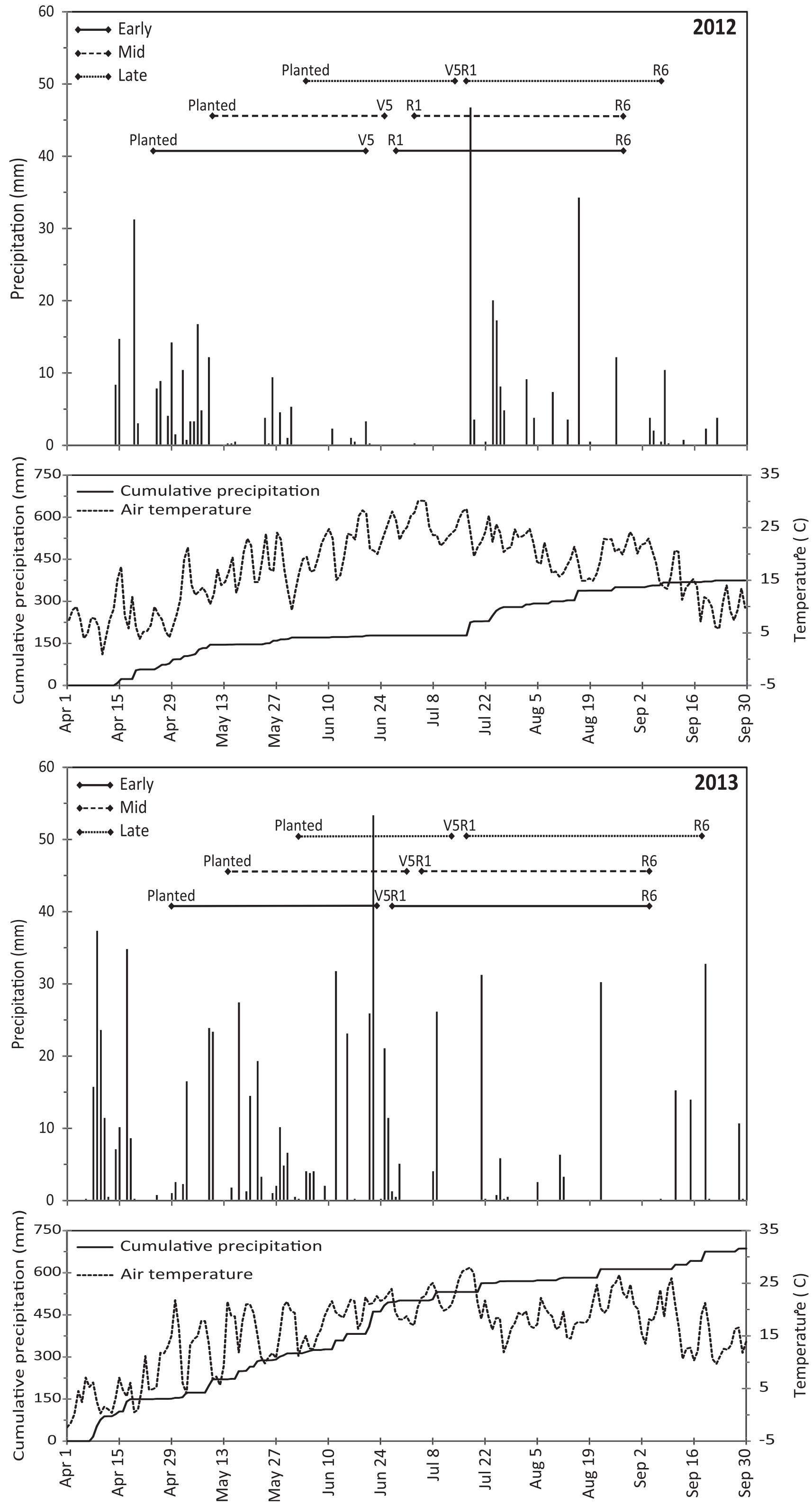

Figure 1. Daily average temperature, precipitation, and cumulative precipitation at Arlington, WI during the 2012 and 2013 growing seasons. Soybean growth stages are also provided for each planting date.

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Table 3. Harvested plant populations of soybean by three planting dates for field studies conducted near Arlington, WI in 2012 and 2013.

Planting date	Harvest population[a] 2012		2013	
	plants ha^{-1}			
Early	121,850	(2,070)	251,850	(700)
Mid	239,110	(660)	260,420	(1,180)
Late	223,780	(1,040)	266,790	(1,130)

[a] Values in parentheses are standard errors of the mean.

emergence throughout the POST glyphosate application timing window following initial flushes to significantly affect ($P \leq 0.05$) densities at POST glyphosate application timings in either year; therefore data were pooled over timings (Table 4). There was a significant soybean planting date by PRE herbicide use interaction for all weed species analyzed in both years, with the exception of grass species in 2013. The nature of this interaction varied between weed species and years, but generally the number of weeds emerging with the crop decreased as soybean planting date was delayed and following PRE herbicide application (Table 4).

Without a PRE herbicide, broadleaf weed densities at the late planting date were 97 and 86% lower compared to the early planting date in 2012 and 2013, respectively. In plots receiving a PRE herbicide, the highest broadleaf weed density occurred at the mid and early planting dates in 2012 and 2013, respectively (Table 4). Grass weed density had a similar response in both years, although the interaction was not significant in 2013 ($P = 0.1309$). The higher broadleaf density following a PRE herbicide at the mid planting date relative to the early date in 2012 is likely because of the lack of precipitation following application. Stewart et al. (2010) reported a reduction in weed control with PRE herbicides when precipitation was low at least 7 d before and after application, and the first rainfall event did not occur until 14 d after the PRE application at this timing (Table 1). The relatively low weed densities that occurred in all herbicide treatments following the late planting date in 2012 was also likely due to a dry soil profile. Stoller and Wax (1973) reported that weed emergence after May 1 was generally stimulated by adequate soil moisture from rainfall. In POST-only treatments, delaying the planting date to June decreased weed density at POST application timing from 127 to 5 plants m^{-2} (96%) and from 205 to 42 plants m^{-2} (80%) in 2012 and 2013, respectively (Table 4). Where a PRE was used, total weed density at POST application timing was less at each planting date, and also declined from early to late planting date 26 to 3 plants m^{-2} (89%) and 23 to 6 plants m^{-2} (74%) in 2012 and 2013, respectively. Similarly, Coulter and Nafziger (2007) reported a 27 to 66% reduction in total weed density by the first POST application when planting was delayed until late May in Illinois.

Table 4. Weed density at the time of POST glyphosate application in soybean studies conducted in 2012 and 2013 as influenced by planting date (early, mid, and late) and PRE herbicide.

PRE herbicide	Species[a]	2012 Early[b]		2012 Mid		2012 Late		2013 Early		2013 Mid		2013 Late	
		plants m^{-2}											
Sulfentrazone + cloransulam	AMBEL	1	c	6	b	0	c	8	c	1	d	1	d
No PRE	AMBEL	14	a	5	b	0	c	52	a	24	b	6	c
Sulfentrazone + cloransulam	CHEAL	0	c	3	b	1	c	0	c	0	c	0	c
No PRE	CHEAL	22	a	19	a	1	c	51	a	39	a	8	b
Sulfentrazone + cloransulam	Grass	23	b	19	b	2	c	11	a	4	a	5	a
No PRE	Grass	79	a	26	b	4	c	59	a	57	a	22	a
Sulfentrazone + cloransulam	Broadleaf	1	c	10	b	1	c	8	c	1	d	1	d
No PRE	Broadleaf	37	a	25	a	1	c	126	a	80	a	18	b
Sulfentrazone + cloransulam	Total	26	c	29	c	3	e	23	c	6	d	6	d
No PRE	Total	127	a	55	b	5	d	205	a	153	a	42	b

[a] Abbreviations: AMBEL, common ragweed; CHEAL, common lambsquarters

[b] Means with the same letter within weed species and year are not significantly different at $P \leq 0.05$.

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The emergence patterns of the predominant weeds in this study may explain the effectiveness of delayed soybean planting at reducing in-crop weed density, as any weeds emerging before soybean planting could be controlled with preplant tillage or herbicides. Common ragweed emergence begins in March and April and has been reported to be 95% emerged by mid to late May in the northeastern United States (Myers et al. 2004) and 100% complete by early June in Illinois (Stoller and Wax 1973). Buhler and Gunsolus (1996) observed that nearly 80% of common lambsquarters emerged between mid-May and early June in Minnesota. In eastern Nebraska, common lambsquarters emergence has been reported as 90% complete by mid-May (Hilgenfeld et al. 2004). However, delaying soybean planting may not be as effective if the predominant species in a particular field emerge later, such as pigweed species. Hartzler et al. (1999) observed that peak emergence of common waterhemp (*Amaranthus rudis* Sauer) occurred as late as July 5 in Iowa. The predominant annual grasses in this study, giant foxtail and large crabgrass, do not complete emergence until later in the growing season. In the northeastern United States, 95% emergence did not occur until mid-June and early to mid-July for giant foxtail and large crabgrass, respectively (Myers et al. 2004). Despite evidence that giant foxtail and crabgrass emerge later in the season, their primary emergence flush was high enough at the beginning of soybean planting not to negate the benefit of later planting dates or influence POST glyphosate timings.

The primary goal of herbicide resistance management (HRM) is to reduce selection pressure on a single herbicide site of action (Norsworthy et al. 2012). Results of this experiment suggest that PRE residual herbicide and delayed soybean planting were both effective at reducing the number of weeds exposed to the in-crop POST herbicide, thus reducing resistance selection pressure. It should be reiterated that in this study weeds were controlled with glyphosate applied preplant. Therefore, in the plots that did not receive a residual herbicide, all weeds in the system (both preplant and in-crop) were controlled with only one herbicide site of action. In order to address HRM with multiple tactics as Norsworthy et al. (2012) suggested either alternative herbicides, or alternative weed control mechanisms, must be used at the preplant timing in glyphosate-resistant soybean systems where glyphosate is applied POST for weed management. This could be accomplished by (1) using other effective burndown herbicides that do not have residual activity in the soil, (2) using tank-mix combinations of herbicides that provide both contact activity and soil-residual activity with the glyphosate, or (3) additional preplant tillage operations. This study, however, did not examine additional preplant tillage operations, which may have resulted in much different results because repeated tillage may stimulate additional weed seed germination by bringing weed seeds into the upper soil profile.

End-of-Season Weed Density. The PD × PH × GT interaction was not significant for broadleaf, grass, or total weed densities in 2012 or 2013. In 2012, the only two-way interactions not significant were PD × PH and PD × GT for grass weeds. In contrast, the only two-way interaction that was significant in 2013 was PD × PH for broadleaf weeds, but all main effects were significant except GT.

Planting Date (PD). The PD × PH interaction was significant for broadleaf weed density in both years. Broadleaf density was highest at the early planting date in POST-only treatments and decreased by 95 and 81% (10.8 and 13.7 plants m^{-2}), as planting was delayed from late April to early June in 2012 and 2013, respectively (Table 5). In PRE followed by POST treatments, only marginal decreases in broadleaf density occurred as planting was delayed, but this is largely because the PRE reduced broadleaf density at the first planting date by 99 and 91% (Table 5). In general, broadleaf weeds were more abundant than grass weeds in 2012, so the total end-of-season weed densities were also influenced by PD × PH interaction. PD reduced total end-of-season weeds in the no-PRE treatments from 18.9 to 1.7 plants m^{-2} between early and late; however, the PRE herbicide reduced total end-of-season weeds by the same magnitude within the early PD (Table 5). We suggest from this response that as soybean is planted earlier in the year, PRE herbicides are more necessary to reduce end-of-season weed density.

In 2012, the PD × GT interaction was also significant for end-of-season broadleaf and total weed densities where the lowest densities occurred at the V2, V1, and V2, and V1 to R1 growth stages

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Table 5. End-of-season broadleaf and total weed densities in 2012 and broadleaf weed densities in 2013 for the significant interaction between planting date (PD) and PRE herbicide (PH) in a soybean study conducted near Arlington, WI.

Planting date	PRE herbicide program	Broadleaf density 2012[a]		Total density 2012		Broadleaf density 2013	
		plants m^{-2}					
Early	Sulfentrazone + cloransulam	0.1	a	1.7	b	1.5	bc
	No PRE	11.4	d	18.9	d	16.9	e
Mid	Sulfentrazone + cloransulam	1.1	b	1.7	b	0.7	ab
	No PRE	2.3	c	4.5	c	7.6	d
Late	Sulfentrazone + cloransulam	0.0	a	0.0	a	0.2	a
	No PRE	0.6	ab	1.7	b	3.2	c

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

in the early, mid, and late planting dates, respectively (Table 6). Therefore as planting was delayed, the timing of effect POST glyphosate applications was more forgiving, likely because the overall interference was lower. This is likely also supported by the significant main effect of PD for end-of-season grass weeds in both years and total weeds in 2013. In 2012 end-of-season grass weed densities were $3.6 > 1.4 = 0.6$ plants m^{-2} and in 2013 were $10.4 > 3.8 > 1.9$ plants m^{-2} for the early, mid, and late planting dates, respectively (Table 7). Total end-of-season weed densities also declined with later planting dates, as there were $18.7 > 7.2 > 3.2$ plants m^{-2} for the early, mid, and late planting dates, respectively. These results support previous findings from Coulter et al. (2011), who reported a 51% reduction in total weed density at harvest when planting was delayed from May until mid-June in Minnesota.

PRE Herbicide Use (PH). In addition to the PH × PD effects discussed above, PH × GT effects were significant for all end-of-season weed densities in 2012, but only the main effect of PH was significant for all weeds in 2013. In treatments with a PRE herbicide, total weed density at soybean harvest was lowest when glyphosate was applied from the V2 to R1 growth stage (Table 7). Without a PRE herbicide to slow early-season weed emergence and growth, a delay in glyphosate application until the V4 or R1 growth stages led to higher end-of-season weed density in these treatments because a large number of weeds were not effectively controlled.

Glyphosate Timing (GT). The response of end-of-season weed density to GT differed between years and among weed type (Table 8). In 2012, broadleaf and total weed density was highest when glyphosate was applied at the V4 and R1 soybean growth stages, and grass density was highest after glyphosate application at the V1, V4, and R1 growth stages. In 2013, the response to glyphosate timing was nearly the opposite, as the highest grass and total weed densities occurred at the V1 growth stage and lowest densities were in the V4 and R1 POST timing

Table 6. End-of-season weed densities for broadleaf and total weeds in a soybean study conducted in 2012 as influenced by the significant interaction between planting date (PD) and the timing of POST glyphosate (GT).

Planting date	V1[a]		V2		V4		R1	
	plants m^{-2}							
	Broadleaf weed density by GT							
Early	3.2	Bb	1.2	Ba	5.2	Cb	4.5	Bb
Mid	0.4	Aa	0.0	Aa	2.7	Bb	5.9	Bc
Late	0.0	Aa	0.2	Aa	0.4	Aa	0.6	Aa
	Total weed density by GT							
Early	12.7	Bb	2.1	Aa	6.9	Bb	8.9	Bb
Mid	1.2	Aa	0.5	Aa	4.8	Bb	8.6	Bb
Late	0.0	Aa	0.5	Aab	0.9	Aab	1.8	Ab

[a] Within a column of a given weed type, means with the same uppercase letter are not significantly different ($P \leq 0.05$). Within a row, means with the same lowercase letter are not significantly different ($P \leq 0.05$).

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Table 7. End-of-season grass weed densities in 2012 and 2013 and total weed densities in 2013 as influenced by planting date (PD), PRE herbicide (PH), and the timing POST glyphosate was applied (GT) in a soybean study conducted near Arlington, WI.

Factor	2012		2013			
	Grass[a]		Grass		Total	
	plants m^{-2}					
PD						
Early	3.6	b	10.4	c	18.7	c
Mid	1.4	a	3.8	b	7.2	b
Late	0.6	a	1.9	a	3.2	a
PH						
Sulfentrazone + cloransulam	—	—	3.3	a	3.9	a
No PRE	—	—	6.1	b	14.7	b
GT						
V1	—	—	11.6	c	17.5	c
V2	—	—	5.4	b	8.8	b
V4	—	—	2.6	ab	5.1	ab
R1	—	—	2.0	a	4.6	a

[a] Means with the same letter within a factor (PD, PH, or GT) are not significantly different ($P \leq 0.05$). Dashes indicate that data for the significant interaction of these factors are presented in Table 8.

treatments. The broadleaf weed population was not influenced by glyphosate timing in 2013 ($P = 0.1565$). The difference in response between the years was likely due to different rainfall and temperature patterns (Figure 1). A tall, dense canopy combined with moisture stress at the V4 and R1 POST application timings in 2012 likely reduced herbicide coverage and translocation, leading to a large number of escapes that survived until soybean harvest. More favorable weather conditions in 2013 enhanced glyphosate efficacy, and very few weeds survived POST glyphosate at the V4 and R1 timings (Figure 1).

One of the important goals of HRM is to reduce the weed seed bank by preventing weed escapes capable of producing viable seed (Norsworthy et al. 2012). If low weed-seed numbers in the soil can be achieved, weeds exposed to herbicides applied in future years will be reduced (Neve et al. 2011). Therefore, any weed management strategy that reduces the number of weeds at soybean harvest, and their subsequent seed production, should be adopted. The results of this experiment suggest that POST-only herbicide treatments increase the risk of late-season weed escapes either by poor efficacy because the weeds are larger when the treatment is applied too late (2012), or because of additional

Table 8. End-of-season weed densities for broadleaf, grass, and total weeds in a soybean study conducted in 2012 as influenced by the significant interaction between PRE herbicide (PH) and the timing of POST glyphosate (GT).

PRE herbicide	V1[a]		V2		V4		R1	
	plants m^{-2}							
	Broadleaf weed density by GT							
Sulfentrazone + cloransulam	0.1	Aab	0.0	Aa	0.5	Aab	0.9	Ab
No PRE	2.0	Ba	0.9	Ba	5.6	Bb	7.0	Bb
	Grass weed density by GT							
Sulfentrazone + cloransulam	1.9	Ab	0.2	Aa	0.3	Aa	0.5	Aa
No PRE	1.6	Aab	1.1	Aa	3.8	Bb	7.5	Bc
	Total weed density by GT							
Sulfentrazone + cloransulam	2.1	Ab	0.2	Aa	0.8	Aab	1.3	Aab
No PRE	3.1	Aa	2.0	Ba	9.3	Bb	15.5	Bb

[a] Within a column of a given weed type, means with the same uppercase letter are not significantly different ($P \leq 0.05$). Within a row, means with the same lowercase letter are not significantly different ($P \leq 0.05$).

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weed emergence after application when the treatment is applied too early (2013). This risk may be mitigated by applying a herbicide with soil-residual activity either PRE or early POST in a tank-mix combination. The 2012 results suggest that a PRE herbicide can extend the time from the V2 to R1 soybean growth stages before glyphosate needs to be applied POST without an increase in end-of-season weed density (Table 7). Moreover, delayed soybean planting also reduced total end-of-season weed escapes, which did not change due to POST glyphosate applied any time between V2 and R1 (Table 6).

Soybean Yield. Grain yield data were pooled across years since there were no significant higher or lower order interactions of year with planting date, PRE herbicide, or glyphosate timing. Only the PRE herbicide main effect was significant ($P = 0.0150$). Therefore, averaged across years, planting date, and glyphosate timings, treatments including an application of sulfentrazone plus cloransulam PRE yielded 3,500 versus 3,280 kg ha^{-1} in the POST-only glyphosate treatments, or a 6.7% increase in seed yield.

In summary, the results of this experiment indicate that delayed soybean planting is an effective method to reduce in-crop and end-of-season weed density. For this reason, this strategy is often used by organic soybean producers to reduce weed interference; however, the yield potential of late-planted soybean is often less than earlier planting dates because of a shorter growing season (Coulter et al. 2011). Although planting date did not affect grain yield in this experiment, numerous studies have shown a positive response to planting earlier (Bastidas et al. 2008; De Bruin and Pedersen 2008; Robinson et al. 2009); therefore, the goal for soybean producers in the Midwest should be to plant soybean before the middle of May. However, as shown by the results of this experiment, weed interference is greater at earlier planting dates and this interference can reduce yield if weeds are not also controlled with a PRE. Moreover, the risk of developing herbicide-resistant weeds may be greater at earlier planting dates because more weeds are exposed to herbicide from the greater interference. The use of an effective PRE herbicide limited the early-season weed interference and reduced the number of weeds exposed to the POST herbicide application. The PRE herbicide used in this experiment also reduced end-of-season weeds present at soybean harvest, which is another critical element of HRM. In conclusion, there was a benefit to HRM from both delayed planting and PRE herbicide use; however, earlier planting placed greater reliance on a PRE herbicide to reduce weeds exposed to POST herbicides and reduced end-of-season weed density. To help growers adopt these multiple HRM strategies, it should be reiterated the PRE herbicide also significantly increased yield across all planting dates.

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