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Influence of Weed Management Practices and Crop Rotation on Glyphosate-Resistant Horseweed Population Dynamics and Crop Yield

Vince M. Davis, Kevin D. Gibson, Thomas T. Bauman, Stephen C. Weller, and William G. Johnson*

Horseweed is an increasingly problematic weed in soybean because of the frequent occurrence of glyphosate-resistant (GR) biotypes. The objective of this study was to determine the influence of crop rotation, winter wheat cover crops (WWCC), residual nonglyphosate herbicides, and preplant herbicide application timing on the population dynamics of GR horseweed and crop yield. A field study was conducted at a site with a moderate infestation of GR horseweed (approximately 1 plant m^{-2}) with crop rotation (soybean–corn or soybean–soybean) as main plots and management systems as subplots. Management systems were evaluated by quantifying horseweed plant density, seedbank density, and crop yield. Crop rotation did not influence in-field horseweed or seedbank densities at any data census timing. Preplant herbicides applied in the spring were more effective at reducing horseweed plant densities than when applied in the previous fall. Spring-applied, residual herbicide systems were the most effective at reducing season long horseweed densities and protecting crop yield because horseweed in this region behaves primarily as a summer annual weed. Horseweed seedbank densities declined rapidly in the soil by an average of 76% for all systems over the first 10 mo before new seed rain. Despite rapid decline in total seedbank density, seed for GR biotypes remained in the seedbank for at least 2 yr. Therefore, to reduce the presence of GR horseweed biotypes in a local no-till weed flora, integrated weed management (IWM) systems should be developed to reduce total horseweed populations based on the knowledge that seed for GR biotypes are as persistent in the seed bank as glyphosate-sensitive (GS) biotypes.

Nomenclature: Glyphosate; horseweed, *Conyza canadensis* L. ERICA; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; winter wheat, *Triticum aestivum* L.

Key words: Integrated weed management, cropping systems, seedbank dynamics, cover crops, crop rotation, herbicide timing.

Glyphosate-resistant (GR) varieties are currently grown on 87 and 89% of soybean hectares in the United States and Indiana, respectively (USDA NASS 2006). In the first 8 yr of GR soybean production, United States no-till production increased 227% (CTIC 2004). The increase in no-till production hectares was facilitated by the adoption of GR soybeans in the United States. However, the increased reliance on glyphosate has increased the potential for the development of GR weeds. New herbicides containing novel mechanisms of action to control GR weed biotypes will likely not be available in the marketplace in the near future. Therefore, understanding management options that influence the population dynamics of GR species such as horseweed could aid in developing better weed management systems.

Horseweed, also known as marestail or Canada fleabane, has long been a common species along roadsides and field edges. Horseweed seed is wind-disseminated and can easily establish in no-till production fields (Bowmik and Bekech 1993; Buhler and Owen 1997; Regehr and Bazzaz 1979; Weaver 2001). Horseweed has historically been considered a winter annual weed, but it can also behave as a summer annual species (Buhler and Owen 1997; Fernald 1950; Regehr and Bazzaz 1979). At our research site in southeastern Indiana, greater than 90% of the horseweed plants present at planting emerged in the spring (Davis 2006). Thus, management tactics designed for managing horseweed as a winter annual weed in this region routinely fail to provide season-long control for summer crops.

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Horseweed is relatively easy to control with tillage (Brown and Whitwell 1988; Kapusta 1979); however, it has been difficult to control with in-crop soybean herbicides (Bruce and Kells 1990; Moseley and Hagood 1990; VanGessel et al. 2001). Furthermore, horseweed has demonstrated the propensity to develop herbicide-resistant biotypes (Zelaya et al. 2004). Currently, there are 33 documented cases of herbicide-resistant horseweed biotypes worldwide. Furthermore, there are three reported biotypes resistant to multiple modes of actions (Heap 2006). This includes populations in Ohio (Trainer et al. 2005) and Indiana (Creech et al. 2004), which are resistant to glyphosate and acetolactate synthase (ALS)–inhibiting herbicides.

VanGessel (2001) first reported GR horseweed biotypes in Delaware in no-till soybean production following repeated glyphosate use only 3 yr after GR soybean commercialization. To date, GR horseweed biotypes have been reported in 13 states ranging from Delaware to California, including Indiana (Heap 2006). In Indiana, GR horseweed is most prevalent in the southeastern region of the state where 38% of 205 randomly surveyed soybean fields in 2003 had mature horseweed plants in the fall (Davis et al. 2005).

There are no published reports evaluating the influence of integrated weed management (IWM) systems in no-till production systems where horseweed is a dominant species because of glyphosate resistance. Furthermore, no previous research has been published on seed persistence or fitness characteristics in horseweed populations containing both GR and glyphosate-sensitive (GS) biotypes. Because horseweed behaves primarily as a summer annual weed in southeastern Indiana, effective season-long control measures are required to minimize horseweed seed production and soybean yield loss due to horseweed interference. The objective of this no-till study was to determine the influence of crop rotation, cover crops, residual herbicides, and preplant herbicide application timing on mixed GR and GS horseweed population dynamics

Management system	Strategy prior to planting fb[a] in-crop herbicide	Fall applied herbicide		Spring applied herbicide	In-crop herbicide		
1	fall glyphosate fb glyphosate	glyphosate	March soil sample timing	----	glyphosate	August soil sample timing	October sample timing
2	spring glyphosate fb glyphosate	----		glyphosate	glyphosate		
3	fall residual fb glyphosate	residual		----	glyphosate		
4	spring residual fb glyphosate	----		residual	glyphosate		
5	fall residual fb non-glyphosate	residual		----	non-glyphosate		
6	spring residual fb non-glyphosate	----		residual	non-glyphosate		
7	WWCC fb glyphosate	winter wheat planted		cover crop terminated	glyphosate		
8	WWCC fb non-glyphosate	winter wheat planted		cover crop terminated	non-glyphosate		

[a]Abbreviations: fb, followed by; WWCC, winter wheat cover crop; residual, residual herbicides are described in Table 1.

Figure 1. Eight management systems and soil sample collection timeline in a 2-yr field study at Butlerville, IN.

by quantifying in-season horseweed plant densities, seedbank densities, and crop yield.

Materials and Methods

Field Site History. A field experiment was conducted from 2003 to 2005 at the Southeast Purdue Agriculture Center (SEPAC) located near Butlerville, IN (39°2′2.04″N, 85°31′12.72″). SEPAC is located in the region of Indiana where GR horseweed is most prevalent (Davis et al. 2005). The soil was a Clermont silt loam soil (fine silty, mixed, superactive, mesic Typic Glossaqualfs) with 1.5% organic matter, pH of 6.3, and sufficient soil fertility based on soil samples analyzed in December 2002.

Plots were established in the fall of 2003 in a no-till field following a GR soybean crop. The field was in a no-till corn–soybean rotation with conventional (nonglyphosate) herbicide programs used for in-crop weed control from 1996 to 1999. In 2000, GR soybeans were grown for the first time, and glyphosate was used before planting and for in-crop weed control. In 2001, glyphosate was used before planting no-till corn and conventional herbicides were used for in-crop weed control. No-till GR soybeans were then grown in both 2002 and 2003 with glyphosate used before planting and in-crop in both years. Very few horseweed plants escaped glyphosate control in 2002, but the field was monitored during the summer of 2003, and moderate infestations (approximately 1 plant m^{-2}) of GR horseweed plants were protruding through the soybean canopy at soybean harvest. Horseweed seeds from those plants were collected before trial initiation. Glyphosate dose–response experiments conducted in the greenhouse on seed samples (Davis et al. 2004) indicated that the glyphosate value at 50% inhibition (I_{50}) for GR biotypes in this population was 1.8 kg ae ha^{-1} compared with a mean I_{50} value of 0.3 kg ae ha^{-1} for an average of four susceptible populations (unpublished data).

Crop and Weed Management System Field Procedures. The experiment was a split-plot design with crop rotation (soybean–corn or continuous soybean) as the main plots and management systems as subplots. Plot size was 4.5 m wide by 4.5 m long, and each plot was separated from other plots by 4.5 m (or 6 rows of corn) to serve as wind breaks to limit the dispersal of wind-blown horseweed seeds among plots. The management systems included winter wheat cover crop (WWCC) and various herbicide programs described in Figure 1. Herbicides and their respective rates used in the various herbicide programs are described in Table 1. The horseweed growth stage at each application timing is shown in Table 2. Each weed management system was replicated 5 times within each crop rotation. A GR soybean variety[1] was planted for the soybean-rotation years in 20-cm-wide rows at 420,000 seeds ha^{-1} and at a depth of 3 cm. A GR corn hybrid[2] was planted in 76-cm-wide rows for the borders and plots in corn-rotation years at 80,000 seeds ha^{-1} and at a depth of 3 cm. The WWCC[3] was planted no-till in 20-cm-wide rows at 4 million seeds ha^{-1} and at a depth of 3 cm. Corn plots received 28 kg ha^{-1} nitrogen and 25 kg ha^{-1} phosphorous in the form of 19–17–0 (N–P–K) starter fertilizer at planting and was later side-dressed with 140 kg ha^{-1} of nitrogen in the form of 28% urea ammonium nitrate (UAN). WWCC systems received no nitrogen fertilizer.

Crop rotations and management systems were assessed by quantifying in-season horseweed densities, seedbank densities, and crop yield by machine harvest. Horseweed densities were evaluated throughout the season by counting horseweed plants in three randomly placed 0.25-m^2 quadrats at 1 mo after spring preplant burndown (MAB), 1 mo after planting (MAP), and two 1-m^2 randomly placed quadrats at the time of crop harvest (4 MAP) in each plot. Horseweed densities were determined in the fall, and then the seedheads in each plot were severed and placed on the ground just before machine harvest of the border rows to limit horseweed seed movement to other plots.

Table 1. Herbicides and rates used for herbicide management systems in 2004 and 2005 in a multiyear field study at Butlerville, IN.

Application[a]	Crop	2003 to 2004		2004 to 2005	
		Herbicide[b]	Rate	Herbicide	Rate
			kg ai ha^{-1}		kg ai ha^{-1}
Fall glyphosate	corn	—	—	glyphosate	0.87
Fall glyphosate	soybean	glyphosate	0.87	glyphosate	0.87
Spring glyphosate	corn	—	—	glyphosate	0.87
Spring glyphosate	soybean	glyphosate	0.87	glyphosate	0.87
Fall residual	corn	—	—	metribuzin	0.28
				+ flumetsulam	+ 0.07
				+ 2,4-D	+ 0.56
Fall residual	soybean	chlorimuron	0.02	metribuzin	0.42
		+ sulfentrazone	+ 0.12	+f lumetsulam	+ 0.07
		+ tribenuron	+ 0.01	+ 2,4-D	+ 0.56
		+2,4-D	+ 0.56		
Spring residual	corn	—	—	metribuzin	0.28
				+ flumetsulam	+ 0.07
				+ 2,4-D	+ 0.56
Spring residual	soybean	chlorimuron	0.02	metribuzin	0.42
		+ sulfentrazone	+ 0.12	+flumetsulam	+ 0.07
		+ 2,4-D	+ 0.56	+2,4-D	+ 0.56
In-crop glyphosate	corn	—	—	glyphosate	0.87
In-crop glyphosate	soybean	glyphosate	0.87	glyphosate	0.87
In-crop nonglyphosate	corn	—	—	nicosulfuron	0.03
				+ rimsulfuron	+ 0.01
				+ mesotrione	+ 0.12
				+ atrazine	+ 0.56
In-crop nonglyphosate	soybean	cloransulam	0.02	cloransulam	0.02
		+ fomesafen	+ 0.42	+ fomesafen	+ 0.42
		+ fluazifop	+ 0.25	+ fluazifop	+ 0.25
		+ fenoxaprop	+ 0.07	+ fenoxaprop	+ 0.07
WWCC termination	wheat	glufosinate	0.47	glufosinate	0.47

[a] Abbreviations: WWCC, winter wheat cover crop.
[b] Herbicide adjuvants were included according to manufacturers recommendations.

Soil Collection and Greenhouse Grow-Out Procedure. Fluctuations of viable horseweed seed in the seedbank under various management systems were assessed by collecting soil samples and germinating viable seeds in the greenhouse. Soil samples were collected from each plot in March before spring germination, in August before seed rain, and in October following seed rain and crop harvest. Ten soil cores measuring 5 cm wide by 5 to 7 cm in depth were randomly collected in each plot. Each sample was homogenized through a 6.4-mm by 6.4-mm mesh wire screen, and 1 kg of soil was mixed with 350 g of autoclaved sand. Because the soil at this site contains substantial amounts of clay, soil samples were processed when moist shortly after collection. A subsample of each soil sample was dried at for 5 to 7 d in a drier at 40 C to determine the water content of each sample. Seedbank densities were converted to seedlings per kilogram of dry soil. The soil : sand mixtures were spread approximately 2 cm deep on fiber weed cloth[4] in 26-cm by 26-cm by 5.5-cm plastic greenhouse flats. The weed cloth and soil : sand mixture was placed over a 1.5-cm layer of vermiculite[5] in the bottom of the flats to aid in sub-irrigation (Cardina and Sparrow 1996; Forcella 1992).

Soil samples were maintained under greenhouse conditions for 4 wk with day/night temperatures ranging from 18 to 22 C and no supplemental lighting. Horseweed seedlings that germinated and emerged from each soil sample were counted after 4 wk of growth. After data collection, the soil samples were allowed to dry in the greenhouse for 3 d and stirred. Each sample was then placed in the greenhouse for another 4 wk of growth. From the October soil samples, horseweed seedlings were transplanted to other flats to determine the number of GR and GS individuals from each plot.

After recording horseweed emergence from the second 4-wk growth period, October soil samples were placed in a freezer for 7 to 8 mo at −5 C to simulate an overwintering period and break any possible seed dormancy even though horseweed does not have maternally inherited seed dormancy (Weaver 2001). Once October samples were removed from the freezer, they were again subjected to two more 4-wk growth cycles in the greenhouse. Because March and August

Table 2. Herbicide application dates and horseweed sizes for herbicide application timings in a multiyear management study at Butlerville, IN.

Application	2003/2004		2004/2005	
	Date	Horseweed size	Date	Horseweed size
Fall burndown	November 21, 2003	—[a]	November 15, 2004	Cotyledon to 14-cm-wide rosettes
Spring preplant burndown	May 7, 2004	Cotyledon to 4-cm-wide rosettes	May 3, 2005	Cotyledon to 10-cm-wide rosettes[b]
In-crop	June 30, 2004	Cotyledon to 30 cm tall	June 16, 2005	Cotyledon to 30 cm tall

[a] No fall emergence of horseweed was observed in the fall of 2003.
[b] Horseweed rosettes were smaller because of a high mortality (over 95%) of fall emerging horseweed and thus primarily spring emerging horseweed were measured at this timing.

soil samples were exposed to a cold temperature vernalization in the field, samples were discarded at the conclusion of recording horseweed emergence after two 4-wk growth cycles.

Glyphosate Screen to Determine Frequency of GR : GS Biotypes in the Seedbank. Horseweed transplants from October soil samples were grown to a 5 to 10 cm rosette size and sprayed with a 2× field-use rate (1.7 kg ae ha^{-1}) of glyphosate[6] to determine the number of GR and GS plants from the seedbank in each management system (Davis et al. 2004). Glyphosate was applied in 187 L ha^{-1} carrier volume with the addition of 2.8 kg ha^{-1} dry commercial spray grade ammonium sulfate. At 21 d after the glyphosate application (21 DAT), the plants were visually assessed as dead (no green plant vegetation) or alive (some green plant vegetation). After that assessment, all living plants were sprayed with a 4× rate (3.4 kg ae ha^{-1}) of glyphosate and assessed again at 21 d after the respray as an additional step to confirm glyphosate resistance in these plants.

Statistical Analysis. Emerged horseweed seedlings from the soil sample grow-outs (seedbank densities) were converted to seedlings per kilogram of dry soil before analysis. Seedbank and in-field horseweed densities were log transformed as determined by the Box-Cox procedure (Box et al. 1978), and all data presented are back-transformed for clarity. Crop rotation was tested for significance with a repeated measures analysis using PROC MIXED[7] with soil sample timings and in-field census timings as repeated collections in 2005. Crop rotation interactions with management systems and the crop rotation main effects were not significant for seedbank or in-field densities. Because there was no crop rotation interaction with management systems, subsequent management system analyses were analyzed by pooling data over crop rotations in both years ($n = 10$). Also, because there were no crop rotation effects, a repeated measures mixed-model was used to reanalyze year effects with year as main plots, management system as subplots, and census timings as repeated measures within year.

For seedbank densities, year by management system by census timing and management system by sample timing interactions were not significant. However, the year by sample timing interaction was significant, and management systems were significant. Management systems and sample timings within year were compared using Tukey's multiple pairwise comparison at $P = 0.05$.

For in-field densities, year by management system by census timing interactions were highly significant. Because separation between management systems was of primary interest, final in-field density analysis was completed as a randomized complete-block design in PROC GLM within a specific year and specific census timings pooled across crop rotation. Management system effects were separated using P values of preplanned contrasts.

Crop yields were collected by machine harvest and adjusted to 13 and 15% moisture before statistical analysis for soybeans and corn, respectively. Crop yields were analyzed separately by year because crop rotations were different. Only soybeans were grown in 2004 so yields were analyzed in a randomized complete-block design with 10 replications. In 2005, corn and soybean yields were analyzed in randomized complete-block designs within their respective rotation ($n = 5$). Management system effects on crop yields were separated using P values of preplanned contrasts.

Results and Discussion

Influence of Management Systems on Horseweed Densities. After two complete growing seasons, crop rotation and all crop-rotation interactions for horseweed densities were not significant. Because crop rotation did not have a significant effect on densities, data were pooled across crop rotations for subsequent analyses. The soybean–soybean rotation did not result in an increase in horseweed density as previously reported in fields surveyed by Barnes et al. (2004).

Herbicides applied before planting and in-crop influenced horseweed densities. The nonglyphosate herbicides used in this study were chosen because they provide residual control as well as in-crop control of horseweed. Non-glyphosate herbicides applied either in the fall, spring or in-crop reduced horseweed densities in both years compared with systems that relied only on glyphosate applied before planting or in-crop (Tables 3 and 4). Similar results for nonglyphosate residual vs. glyphosate alone applied preplant were observed in systems using in-crop glyphosate. Residual herbicides applied before planting reduced in-season densities compared with glyphosate treatments because additional horseweed plants emerged after the nonresidual glyphosate treatment. When comparing in-crop herbicides, nonglyphosate in-crop herbicides had lower horseweed densities 1 MAP than glyphosate alone treatments but similar densities of mature seed producing plants at the end of the season in both years.

Herbicide application timing also influenced horseweed densities in the herbicide management systems. Spring preplant applications reduced early and midseason horseweed densities more than fall applications. However, late-season horseweed densities were similar in both years when preplant timings were compared in systems that only used residual herbicides. This suggests that horseweed plants surviving the fall residual applications were not highly competitive with the crop, and significant late-season mortality occurred before horseweed plants matured to produce seed. All fall-applied herbicide treatments provided at least 95% horseweed control (data not shown). Spring-applied treatments that included glyphosate alone provided 60 to 75% control of horseweed. Spring-applied treatments that included other herbicides with residual and foliar activity on horseweed provided at least 90% control of horseweed at 2 wk after treatment (data not shown).

WWCC showed variable effects on horseweed densities. In 2004, WWCC were effective in reducing horseweed densities at 1 MAB and 1 MAP, but not 4 MAP, compared with fall-applied residual herbicides. Horseweed densities with spring-applied residual herbicides were similar to WWCC at all three sample timings. In 2005, WWCC were less effective than either fall- or spring-applied residual herbicides in reducing horseweed densities at 1 MAB. Differences between WWCC and either fall or spring-applied residual herbicides were minor at 1 MAP and 4 MAP.

The lack of significant differences in horseweed densities from crop rotation is somewhat surprising considering a survey of Indiana soybean fields in 2003 showed that GR horseweed populations were found predominately in fields using no-till practices and continuous soybean production systems (Barnes

Table 3. Contrast means and P values ($P < 0.05$, in boldface) for 2004 in-field horseweed counts in a multiyear management study at Butlerville, IN. Contrasts are between weed management systems in no-tillage soybean–soybean and soybean–corn cropping systems. Data were pooled across crop rotation.

Contrast	Management systems	1 MAB[a]		1 MAP		4 MAP	
		plants m^{-2}	Pr > *F*	plants m^{-2}	Pr > *F*	plants m^{-2}	Pr > *F*
Fall preplant timing vs.	1,3,5	51.4	**< 0.0001**	10.2	**< 0.0001**	2.6	**< 0.0001**
Spring preplant timing	2,4,6	0.7		1.0		0.2	
Fall preplant timing fb gly POST vs.	1,3	65.4	**< 0.0001**	14.8	**< 0.0001**	3.8	**< 0.0001**
Spring preplant timing fb gly POST	2,4	1.0		1.6		0.0	
Fall residual[b] timing vs.	3,5	13.0	**< 0.0001**	1.9	**< 0.0001**	0.2	0.2782
Spring residual timing	4,6	0.0		0.1		0.0	
Gly preplant fb gly POST vs.	1,2	65.2	**< 0.0001**	15.0	**< 0.0001**	3.7	**< 0.0001**
Residual preplant fb gly POST	3,4	1.2		1.4		0.2	
Residual or WWCC fb gly POST vs.	3,4,7	—	—	1.0	**0.0424**	0.2	0.1677
Residual or WWCC fb nongly POST	5,6,8	—		0.4		0.0	
Residual fb gly POST vs.	3,4	—	—	1.4	0.0931	0.2	0.5049
Residual fb nongly POST	5,6	—		0.6		0.0	
Gly preplant fb gly POST vs.	1,2	65.2	**< 0.0001**	15.0	**< 0.0001**	3.7	**< 0.0001**
No gly preplant or POST	5,6,8	8.2		0.4		0.0	
Spring residual vs.	4,6	0.0	0.2495	0.1	0.6296	0.0	0.3031
WWCC	7,8	0.5		0.2		0.2	
Fall residual vs.	3,5	13.0	**< 0.0001**	1.9	**< 0.0001**	0.2	0.9558
WWCC	7,8	0.5		0.2		0.2	

[a] Abbreviations: MAB, months after burndown application; MAP, months after in-crop application; fb, followed by; gly, glyphosate; WWCC, winter wheat cover crop.
[b] Residual, residual herbicides are described in Table 1.

et al. 2004). It is likely that crop rotation did not have a significant impact on densities because all systems evaluated in our study, except for the fall glyphosate followed by in-crop glyphosate system, were effective at reducing densities because of timely herbicide applications (data not shown). Furthermore, a lack of significance may also be the result of only one cycle of a 2-yr crop rotation.

Preplant herbicides applied in the spring provided more consistent reductions in horseweed populations than fall applications because germination of horseweed in the region occurs primarily in the spring (Davis 2006). Selecting an effective herbicide can be a critical component of any integrated weed management system. Herbicides that provided residual control of horseweed provided the most consistent horseweed control. Bruce and Kells (1990) also emphasized the importance of controlling horseweed populations before soybean establishment in no-till production before the commercialization of GR soybeans. An alternative approach to using residual herbicides to control GR horseweed is to tank-mix nonglyphosate herbicides during the in-crop application. Models have shown that approach may reduce or delay the occurrence of herbicide-resistant biotypes (Gressel and Segel 1990). Currently, the only effective options for this approach would include the use of cloransulam or chlorimuron herbicides, which are ALS inhibitors. However, horseweed has repeatedly demonstrated the propensity to develop herbicide resistance (Zelaya et al. 2004), and ALS-resistant biotypes have been documented (Heap 2006). Thus, the use of in-crop ALS herbicides tank-mixed with glyphosate should be considered a secondary

Table 4. Contrast means and P values ($P < 0.05$, in boldface) for 2005 in-field horseweed counts in a multi-ear management study at Butlerville, IN. Contrasts are between weed management systems in no-tillage soybean–soybean and soybean–corn cropping systems. Data were pooled across crop rotation.

Contrast	Management systems	1 MAB[a]		1 MAP		4 MAP	
		plants m^{-2}	Pr > *F*	plants m^{-2}	Pr > *F*	plants m^{-2}	Pr > *F*
Fall preplant timing vs.	1,3,5	46.0	**< 0.0001**	4.8	**0.0002**	4.1	**< 0.0001**
Spring preplant timing	2,4,6	0.7		1.3		0.5	
Fall preplant timing fb gly POST vs.	1,3	67.9	**< 0.0001**	7.2	**< 0.0001**	5.9	**< 0.0001**
Spring preplant timing fb gly POST	2,4	1.1		2.0		0.5	
Fall residual[b] timing vs.	3,5	1.6	**0.0180**	1.3	**0.0232**	1.2	0.0961
Spring residual timing	4,6	0.0		0.3		0.4	
Gly preplant fb gly POST vs.	1,2	68.6	**< 0.0001**	7.7	**< 0.0001**	5.1	**0.0054**
Residual preplant fb gly POST	3,4	0.4		1.5		2.3	
Residual or WWCC fb gly POST vs.	3,4,7	—	—	1.8	**< 0.0001**	0.9	0.3259
Residual or WWCC fb nongly POST	5,6,8	—		0.0		0.4	
Residual fb gly POST vs.	3,4	—	—	1.5	**0.0006**	1.2	0.2442
Residual fb nongly POST	5,6	—		0.1		0.5	
Gly preplant fb gly POST vs.	1,2	68.6	**< 0.0001**	7.7	**< 0.0001**	5.1	**< 0.0001**
No gly preplant or POST	5,6,8	2.0		0.0		0.4	
Spring residual vs.	4,6	0.0	**< 0.0001**	0.3	**0.0394**	0.4	0.7924
WWCC	7,8	5.9		1.3		0.3	
Fall residual vs.	3,5	1.6	**0.0075**	1.3	0.8253	1.2	0.0551
WWCC	7,8	5.9		1.3		0.3	

[a] Abbreviations: MAB, months after spring preplant application; MAP, months after in-crop application; fb, followed by; gly, glyphosate; nongly, nonglyphosate; WWCC, winter wheat cover crop.
[b] Residual, residual herbicides are described in Table 1.

Table 5. Contrast means and P values ($P < 0.05$, in boldface) for crop yield for 2004 and 2005. Contrasts are between weed management systems in no-tillage soybean-soybean and soybean-corn cropping systems. All plots were soybeans in 2004 (treatment $n = 10$), whereas soybean and corn were planted in 2005 (treatment $n = 5$).

Contrast[a]	Management systems	2004 Soybean		2005 Soybean		2005 Corn	
		kg ha^{-1}	Pr > F	kg ha^{-1}	Pr > F	kg ha^{-1}	Pr > F
Fall preplant timing vs.	1,3,5	2,690	0.3603	2,520	**0.0003**	7,800	0.5949
Spring preplant timing	2,4,6	2,750		3,230		7,540	
Fall preplant timing fb gly POST vs.	1,3	2,640	0.0699	2,300	< **0.0001**	7,780	0.7842
Spring preplant timing fb gly POST	2,4	2,770		3,300		7,940	
Fall residual[b] preplant timing vs.	3,5	2,710	0.4177	2,730	0.1168	7,990	0.7863
Spring residual preplant timing	4,6	2,760		3,060		7,830	
Gly preplant fb gly POST vs.	1,2	2,690	0.8302	2,840	0.6985	7,190	**0.0260**
Residual preplant fb gly POST	3,4	2,710		2,760		8,530	
Residual or WWCC fb gly POST vs.	3,4,7	2,710	0.0660	2,950	0.3722	8,130	0.1561
Residual or WWCC fb nongly POST	5,6,8	2,820		3,100		7,450	
Residual fb gly POST vs.	3,4	2,710	0.4884	2,760	0.2091	8,530	**0.0372**
Residual fb nongly POST	5,6	2,760		3,030		7,280	
Gly preplant fb gly POST vs.	1,2	2,690	0.0570	2,840	0.1847	7,190	0.6248
No gly at preplant or POST	5,6,8	2,820		3,100		7,450	
Spring residual vs.	4,6	2,760	0.3628	3,060	0.3028	7,830	0.6236
WWCC	7,8	2,830		3,280		7,550	
Fall residual vs.	3,5	2,710	0.0879	2,730	**0.0125**	7,990	0.4478
WWCC	7,8	2,830		3,280		7,550	

[a] Abbreviations: fb, followed by; gly, glyphosate; WWCC, winter wheat cover crop.
[b] Residual, residual herbicides are described in Table 1.

management practice to controlling horseweed before crop establishment.

Influence of Management Systems on Crop Yield. Preplant application timing did not influence soybean or corn yields in either year when a residual herbicide was used (Table 5). Corn yields were higher when a residual herbicide was included in the preplant application than when only glyphosate was used. Furthermore, preplant application timing affected crop yields when contrasts were pooled over residual and nonresidual herbicides. The spring preplant application pooled over all herbicide systems produced higher soybean yield than fall applications in 2005. When application timing was pooled over preplant herbicides but limited to in-crop glyphosate, the fall timing resulted in slightly lower soybean yield in 2004 ($P = 0.0699$) and lower soybean yield in 2005 ($P = 0.0001$) than spring applications. WWCC systems also increased soybean yield in 2005 compared with fall residual systems pooled over in-crop applications. In-crop herbicide selection influenced corn yield but not soybean yield in either year. Corn yields in 2005 were higher when glyphosate was used in-crop than nonglyphosate herbicides. The difference in corn yield from in-crop herbicide selection was likely because of better control of fall panicum (*Panicum dichotomiflorum* Michx.) in the corn plots with in-crop glyphosate rather than with nicosulfuron (data not shown), which was used for grass control in the nonglyphosate systems. When GR weed species were controlled with residual herbicides, glyphosate was an effective in-crop herbicide for control of the remaining weed flora and protecting crop yield.

The importance of controlling GR horseweed before crop establishment proved that the selection of preplant or PRE herbicides is critical for an effective weed management system in this region. Results from the WWCC system imply it is as effective for increasing crop yields as a spring-applied residual herbicide system. However, practitioners must consider the importance of timeliness in cover crop termination for yield gains to be realized (W. G. Johnson, personal observation).

Influence of Management Systems on Annual and Seasonal Horseweed Seedbank Densities. Initial seedbank densities ranged from 2.8 to 4.0 seedlings kg^{-1} dry soil in October 2003 (Table 6), and there were no differences among management systems for seasonal sample timings or for total annual seedbank densities in 2004. In 2005, seedbank densities were less than 1 kg^{-1} dry soil in all management systems except the fall glyphosate followed by in-crop glyphosate system (Table 7). From October 2003 to October 2005, fall glyphosate followed by in-crop glyphosate reduced seedbank densities 45% compared with a 91 to 99% density reductions for the other seven management systems (Tables 6 and 7). There were seasonal declines in seedbank density between October and August sample timings in both years, but there were no annual decreases in seedbank density between October 2004 and October 2005. The management system that relied on fall glyphosate followed by in-crop glyphosate had a seedbank density that was higher than all other management systems at the end of 2 yr (Table 7).

Seedbank densities were significantly lower in October following seed rain than in March or August for all systems (Table 6 and 7). In the first year of the study, seasonal densities were similar between October 2003 and March 2004, but reductions were evident between March and August (Table 6). In the second year of the study, total annual seedbank density was 86% less than the first year for the average of all management systems. Decreases in seasonal densities between October and August were again evident in 2005 when no viable seeds were found in six of the eight management systems in the August samples. There were no late-season in-field mature horseweed plants in three of those six systems in October 2004 (Davis 2006). Those three systems included the two spring-applied residual preplant systems and the WWCC followed by a nonglyphosate in-crop system. Viable seeds in those systems were detected in the seedbank following the last seed rain at 12 mo (October 2004) and 17 mo (March 2005) but not at 22 mo (August 2005).

Table 6. Horseweed seedbank densities from soil sample collections for eight weed management systems in no-tillage soybean–soybean and soybean–corn cropping systems in a multiyear management study at Butlerville, IN. Data were pooled across crop rotation ($n = 10$). October collections were before any fall herbicide applications, March collections were before spring preplant herbicide applications, and August collections were before horseweed seed rain.

	2003	2004			
Preplant strategy fb[a] in-crop treatment	Oct	Mar	Aug	Oct	Row mean[b]
	seedlings kg^{-1} dry soil				
Fall glyphosate fb glyphosate	3.8	8.6	0.8	1.9	3.8 a
Spring glyphosate fb glyphosate	3.8	3.6	0.8	0.4	2.2 a
Fall residual fb glyphosate	3.4	0.6	0.6	0.6	1.3 a
Spring residual fb glyphosate	4.0	6.6	0.8	0.2	2.9 a
Fall residual fb nonglyphosate	3.4	0.3	0.7	0.3	1.2 a
Spring residual fb nonglyphosate	4.0	5.0	0.6	0.1	2.4 a
Winter wheat cover crop fb glyphosate	2.8	6.8	2.0	0.5	3.0 a
Winter wheat cover crop fb nonglyphosate	3.9	7.4	0.7	1.1	3.3 a
Column mean[c]	3.6 A	4.9 A	0.9 B	0.6 B	—

[a] Abbreviations: fb, followed by; residual, residual herbicides are described in Table 1.

[b] Management system means averaged across sample timing followed by the same letter are not significantly different using Tukey's multiple pairwise comparison at P = 0.05.

[c] Sample timing means averaged across management systems followed by the same letter are not significantly different using Tukey's multiple pairwise comparison at P = 0.05.

There has not been previous research published regarding horseweed seedbank persistence. Regehr and Bazzaz (1979) suggested that substantial fall emergence comes from seeds deposited the previous year. Our data suggest that, at least for some years in this region of the United States, seedling emergence is good for both horseweed seed deposited in the fall just after seed rain or in the following spring. Low seed mortality during overwintering conditions may help facilitate the spring germinating populations observed in this region of the United States (Davis 2006). Reductions in seedbank density may be because of a combination of factors such as germination, decay, predation, and physical movement (Buhler et al. 1997).

Significant seasonal seedbank density reductions were observed between October and August in both years of the study. Despite the causes of seedbank decline, drastic reductions in seedbank densities between 18 and 23 mo after study initiation suggest horseweed is very reliant on either annual seed rain or seed immigration for prolonged occupancy of a habitat. This observation would coincide with its ability to disperse seed long distances and germinate on the soil surface in a wide range of habitats (Bhowmik and Bekech 1993; Buhler and Owen 1997; Weaver 2001). Furthermore, it supports the Bhowmik and Bekech (1993) hypothesis that horseweed survival is due to germination of as many seeds as soon as possible to occupy as much ground space as possible and prevent successful establishment of other species. Our results indicate that, except for weed management systems that use fall application of glyphosate alone and a single in-crop glyphosate treatment, there are several weed management systems that will effectively reduce horseweed seedbank density. However, annual seedbank decline was not significant in systems that allowed annual seed rain to occur. Therefore, IWM systems that eliminate in-field horseweed seed producing plants and/or seed immigration should be of most interest to cause significant and relatively rapid reductions in horseweed populations.

Frequency and Persistence of GR and GS Horseweed Biotypes. There were 435 horseweed transplants screened for glyphosate resistance from the October 2003 soil sample timing. The ratio of GR : GS plants ranged from 52 to 92% for all management systems (data not shown). Because of the success of reducing horseweed seedbank density in all

Table 7. Horseweed seedbank densities from soil sample collections for eight weed management systems in no-tillage soybean–soybean and soybean–corn cropping systems in a multi-year management study at Butlerville, IN. Data were pooled across crop rotation ($n = 10$). October collections were before any fall herbicide applications, March collections were before spring preplant own herbicide applications, and August collections were before horseweed seed rain.

	2004	2005			
Preplant strategy fb[a] in-crop treatment	Oct	Mar	Aug	Oct	Row mean[b]
	seedlings kg^{-1} dry soil				
Fall glyphosate fb glyphosate	1.9	0.8	0.0	2.1	1.2 a
Spring glyphosate fb glyphosate	0.4	0.2	0.2	0.2	0.3 b
Fall residual fb glyphosate	0.6	0.1	0.0	0.3	0.3 b
Spring residual fb glyphosate	0.2	0.3	0.0	0.2	0.2 b
Fall residual fb nonglyphosate	0.3	0.3	0.1	0.2	0.2 b
Spring residual fb nonglyphosate	0.1	0.1	0.0	0.1	0.1 b
Winter wheat cover crop fb glyphosate	0.5	0.2	0.0	0.2	0.2 b
Winter wheat cover crop fb nonglyphosate	1.1	0.3	0.0	0.3	0.4 b
Column mean[c]	0.6 A	0.3 B	0.0 B	0.5 A	—

[a] Abbreviations: fb, followed by; residual, residual herbicides are described in Table 1.

[b] Management system means averaged across sample timing followed by the same letter are not significantly different using Tukey's multiple pairwise comparison at P = 0.05.

[c] Sample timing means averaged across management systems followed by the same letter are not significantly different using Tukey's multiple pairwise comparison at P = 0.05.

management systems, the number of transplanted and screened horseweed plants from the fall of 2004 and 2005 were too low for confident statistical comparison of systems based on GR to GS ratios. Although the number of viable horseweed seeds in the seedbank decreased, the ratios of GR : GS plants did not appear to decrease for any systems in either season. Detection of GR biotypes occurred in all systems in October 2004 and October 2005. In 2005, we recovered 32 plants in the fall glyphosate followed by glyphosate system, and less than five plants in the other seven systems. Although recovered seedbank densities were low, GR : GS ratios were above 96% for all systems.

Boerboom (1999) suggested IWM systems can be developed to delay herbicide resistance by reducing herbicide-selection pressure or by reducing the density of resistant populations. Maxwell et al. (1990) suggested predictive models to show the influence management systems may have on the ratios of R and S biotypes in the soil seedbank. Unfortunately, the study of population dynamics in populations with both herbicide-resistant and -susceptible biotypes at present is limited. Furthermore, the model proposed by Maxwell et al. (1990) requires a great deal of understanding about the differences in phenotypic fitness characteristics of both R and S biotypes. Because we recovered too few plants from the greenhouse growth procedures for screening, and the horseweed populations at our research site had no observable phenotypic or fitness differences, we were not able to compare systems based on ratios of GR to GS biotypes. Once GR biotypes are in a local horseweed population, management systems that control both GR and GS biotypes will be required for successful protection of crop yield.

Management Implications for Horseweed Populations with GR Biotypes in No-Till Soybean Production. This research evaluated horseweed populations that primarily emerge in the spring and can be particularly troublesome to manage due to GR biotypes. No previous research has focused on IWM options, such as crop rotation, WWCC systems, fall vs. spring preplant timings, and residual vs. nonresidual herbicide selection, in systems where horseweed is the predominant summer annual weed because of glyphosate resistance. Tillage is an important tool for IWM systems for agriculture production, and it has been shown to be effective for controlling horseweed (Brown and Whitwell 1988; Kapusta 1979). Use of tillage is not a desired approach for no-till soybean producers in this region with infestations of GR horseweed because of high erosion potential on these soil types.

This research showed no advantages to rotating corn with soybean vs. continuous soybean production to reduce horseweed densities after 2 yr when timely and effective herbicide applications are used. The cumulative effects over several rotations need to be further evaluated, but crop rotation should still be considered for other agronomic and pest management reasons. Our research revealed that spring-applied residual herbicides were successful in reducing in-field densities and maximizing crop yields. Proper herbicide selection is important to any effective herbicide based weed control system. Although selecting only nonglyphosate herbicides for horseweed management in a population that includes GR biotypes seems logical, the cost of glyphosate is relatively inexpensive, and growers will likely continue to use glyphosate in their weed control systems until multiple GR weed species makes it undesirable. This study suggested that controlling horseweed in the spring before crop establishment and selecting a herbicide with residual activity on horseweed is critical to manage this weed in this U.S. region. Reliance on in-crop glyphosate in no-till crop systems is an acceptable weed management choice as long as GR weeds, such as horseweed, are effectively controlled before crop establishment with timely preplant and residual herbicide applications.

Our investigation of the seedbank revealed seasonal seedbank densities significantly decline even in management systems that rely solely on glyphosate for preplant and in-crop weed control. This suggests that widespread occurrence of GR biotypes in this region of the United States may be because of a lack of understanding about horseweed emergence patterns for populations that primarily germinate in the spring. Furthermore, annual seedbank densities can be drastically reduced and maintained at very low levels under several management systems that are aimed at eliminating seed-producing plants. Overall seedbank densities were significantly reduced during the course of the study, but viable seed for GR biotypes in the soil seedbank were found in all management systems at the conclusion of 2 yr. Therefore, IWM systems to control horseweed in no-till soybean production should be designed to effectively control both GR and GS biotypes. Using herbicides with residual horseweed activity in the spring before crop establishment should be considered as the most consistent weed management approach for reducing horseweed densities, and it can be implemented by soybean producers with minimal cost and effort.

Sources of Materials

[1] Pioneer soybean variety 93M80, Pioneer Hi-Bred International, Inc., Resource Connection, P.O. Box 1000, Johnston, IA 50131-0184.

[2] Dekalb corn hybrid DKC58-73, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[3] Pioneer wheat variety P25R78, Pioneer Hi-Bred International, Inc., Resource Connection, P.O. Box 1000, Johnston, IA 50131-0184.

[4] Weed Control Fabric, E.I. du Pont de Nemours and Company, Laurel Run Building, P.O. Box 80, 705 Wilmington, DE 19880-0705.

[5] Medium vermiculite, SUN GRO Horticulture, P.O. Box 140, Seneca, IL 61360.

[6] Roundup Weathermax, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[7] SAS software, Version 9.1, 2002–2003, SAS Institute Inc. Cary, NC 27513.

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