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Influence of Weed Management Practices and Crop Rotation on Glyphosate-Resistant Horseweed (*Conyza canadensis*) Population Dynamics and Crop Yield-Years III and IV

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

Horseweed is an increasingly common and problematic weed in no-till soybean production in the eastern cornbelt due to the frequent occurrence of biotypes resistant to glyphosate. The objective of this study was to determine the influence of crop rotation, winter wheat cover crops (WWCC), residual non-glyphosate herbicides, and preplant application timing on the population dynamics of glyphosate-resistant (GR) horseweed and crop yield. A field study was conducted from 2003 to 2007 in a no-till field located at a site that contained a moderate infestation of GR horseweed (approximately 1 plant m^{-2}). The experiment was a split-plot design with crop rotation (soybean–corn or soybean–soybean) as main plots and management systems as subplots. Management systems were evaluated by quantifying in-field horseweed plant density, seedbank density, and crop yield. Horseweed densities were collected at the time of postemergence applications, 1 mo after postemergence (MAP) applications, and at the time of crop harvest or 4 MAP. Viable seedbank densities were also evaluated from soil samples collected in the fall following seed rain. Soybean–corn crop rotation reduced in-field and seedbank horseweed densities vs. continuous soybean in the third and fourth yr of this experiment. 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 in-field horseweed densities and protecting crop yields since the growth habit of horseweed in this region is primarily as a summer annual. Management systems also influenced the GR and glyphosate-susceptible (GS) biotype population structure after 4 yr of management. The most dramatic shift was from the initial GR : GS ratio of 3 : 1 to a ratio of 1 : 6 after 4 yr of residual preplant herbicide use followed by non-glyphosate postemergence herbicides.
Nomenclature: Glyphosate; horseweed, *Conyza canadensis* (L.) Cronq. ERICA.
Key words: Integrated weed management, cropping systems, seedbank dynamics, cover crops, crop rotation, herbicide timing.

GR varieties are currently grown on 87 and 89% of soybean ha in the United States and Indiana, respectively (USDA NASS 2008). GR cropping systems enhanced the adoption of conservation tillage practices (Young 2006). In the United States, the amount of no-till increased from 6.8 million ha in 1990 to 25.3 million ha in 2004 (CTIC 2004). In 1995 there was approximately 353,000 kg ae glyphosate used on U.S. corn, cotton, and soybean crops, and by 2005, the total glyphosate use increased eightfold to nearly 3 million kg ae (USDA NASS 2008). Coincidentally, the increased reliance on glyphosate has increased the potential for the evolution of GR weeds. New herbicides containing novel mechanisms of action to control weed species that evolve glyphosate resistance 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 improve weed management systems.

Horseweed is commonly known as marestail or Canada fleabane and has long been a common plant along roadsides and field edges. Horseweed seed is wind-disseminated and plants can easily establish in no-till production fields (Bhowmik 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 complete its life cycle as a summer annual species (Buhler and Owen 1997; Davis and Johnson 2008; Fernald 1950; Regehr and Bazzaz 1979). At our research site in southeastern Indiana, greater than 90% of the horseweed present at the time of planting emerged in the spring (Davis and Johnson 2008). Davis and Johnson (2008) reported that horseweed emerged throughout May and early June and was one of the dominant summer annual weeds at this site. Thus, management tactics designed for managing horseweed as a winter annual weed in this region routinely fail to provide season-long control.

Horseweed is relatively easy to control with tillage (Brown and Whitwell 1988; Kapusta 1979); however, it has been difficult to control with postemergence soybean herbicides (Bruce and Kells 1990; Moseley and Hagood 1990; VanGessel et al. 2001). Furthermore, horseweed has demonstrated the propensity to evolve herbicide resistance (Zelaya et al. 2004). Currently, there are 40 documented cases of herbicide-resistant horseweed biotypes worldwide. Furthermore, there are three reported biotypes resistant to multiple modes of actions (Heap 2008). This includes populations in Ohio (Trainer et al. 2005) and Indiana (Kruger et al. 2007) that 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 16 states ranging from Delaware to California, and four additional countries including Brazil, China, Spain, and the Czech Republic (Heap 2008). In Indiana, GR horseweed is most prevalent in the southeastern region of the state where horseweed escapes were detected in 38% of 205 randomly surveyed late-season soybean fields from 2003 to 2005 (Davis et al. 2008).

We previously reported on the influence of crop rotation, WWCC, residual non-glyphosate herbicides, and preplant application timing on the population dynamics of GR horseweed and crop yield for the first 2 yr of this study where horseweed was a dominant species due to glyphosate resistance (Davis et al. 2007). We reported no advantages to rotating corn with soybean vs. continuous soybean production to reduce

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Table 1. Eight management systems in a multi-year field study at Butlerville, IN.

Management system	Strategy prior to planting fb[a] postemergence herbicide	Fall-applied herbicide	Spring-applied herbicide	Postemergence herbicide
1	Fall glyphosate fb glyphosate	Glyphosate	—	Glyphosate
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; residual, residual herbicides are described in Table 2; WWCC, winter wheat cover crop.

horseweed densities. We were surprised by that result after 2 yr because previous in-field survey data suggested GR horseweed was associated with continuous soybean production fields in Indiana (Barnes et al. 2004). Furthermore, the first documented GR horseweed population was collected from a no-till field using a continuous soybean rotation (VanGessel 2001).

At the end of the growing season in 2005, there were 59 and 5 seed-producing horseweed plants per 10 m^2 in fall- and spring-applied preplant followed by postemergence glyphosate systems, respectively (Davis et al. 2007). Therefore, we reported spring-applied, residual herbicide systems were the most effective at reducing season long in-field horseweed densities and protecting crop yields since horseweed in this region primarily emerges in the spring as a summer annual weed (Davis and Johnson 2008). Management differences based on horseweed density were clear, but we reported that it was difficult to compare management systems based on ratios of GR and GS plants in the first 2 yr. This was due to lower than expected horseweed densities for some systems. At the beginning of the experiment in 2003, there were three GR plants for every GS plant derived from the soil seedbank (Davis et al. 2007). However, based on our results at the end of 2005, we expected system comparisons based on GR : GS ratios would become clearer in years three and four. There were 51 seed-producing horseweed plants per 10 m^2 in systems utilizing glyphosate for preplant and postemergence weed control and only 4 plants per 10 m^2 in systems that did not use glyphosate for either application (Davis et al. 2007). Therefore, the objective of this no-till study was to further evaluate the influence of crop rotation, cover crops, residual non-glyphosate herbicides, and preplant application timing on mixed GR and GS horseweed population dynamics by quantifying in-season horseweed plant densities, seedbank densities, and crop yield in the third and fourth year of this long-term experiment. Our hypotheses were that corn–soybean rotation would decrease horseweed demographics following more years of differing crop rotations, spring-applied preplant systems and systems using non-glyphosate herbicides would maintain lower horseweed densities, and ratios of GR : GS biotypes would change with different herbicide strategies over time.

Materials and Methods

Field Site History. A field experiment was conducted from 2003 to 2007 at the Southeast Purdue Agriculture Center (SEPAC) located near Butlerville, IN (N 39°20′20.3994″ and W 85°31′12.72″). Results for the first 2 yr (2003 to 2005) were reported by Davis et al. (2007). SEPAC is located in the region of Indiana where GR horseweed is most prevalent (Davis et al. 2008). The soil was a Clermont silt loam soil (fine silty, mixed, superactive, mesic Typic Glossaqualfs) with 1.5% organic matter, a pH of 6.3, a cation exchange capacity (CEC) of 7.6, a phosphorus level of 37 ppm, a potassium level of 54 ppm, a calcium level of 1,175 ppm, and a magnesium level of 191 ppm from 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 (non-glyphosate) herbicide programs used for postemergence weed control from 1996 to 1999. In 2000, GR soybeans were grown for the first time, and glyphosate was used for preplant and postemergence weed control. In 2001, glyphosate was used for the preplant treatment prior to no-till corn establishment, and conventional herbicides were used for postemergence weed control. No-till GR soybeans were then grown in both 2002 and 2003, with glyphosate used as the preplant and postemergence treatments in both years. Very few horseweed plants escaped glyphosate control in 2002, but the field was visually monitored during the summer of 2003, and moderate infestations (approximately 1 plant m^{-2}) of GR horseweed escapes protruding through the soybean canopy were present at soybean harvest. Horseweed seeds from those plants were collected prior to trial initiation. Glyphosate dose response experiments conducted in the greenhouse on seed samples indicated that the glyphosate I_{50} value for GR biotypes in this population was 1.8 kg ae ha^{-1} compared to 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 isolated from other plots by 4.5 m or six rows of border corn, which served as wind breaks to limit the dispersal of wind-blown horseweed seeds among plots. The management systems included WWCC and various herbicide programs. Herbicides and their respective rates used in the various herbicide programs are described in Tables 1 and 2. Horseweed sizes at each application timing are shown in Table 3. In 2007, an additional application of 0.14 kg ha^{-1} clethodim plus 0.025% v/v nonionic surfactant was applied postemergence at the R1 (flowering) soybean growth stage to provide additional control of fall panicum (*Panicum dichotomiflorum* Michx.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] in the non-glyphosate postemergence systems only.

A GR soybean variety[1] was planted for the soybean rotation years in 20-cm-wide rows at 420,000 seeds ha^{-1}, and 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

Table 2. Herbicides and rates used for herbicide management systems in 2006 and 2007 in a multi-year field study at Butlerville, IN.

Application	Crop	2006 Herbicide[b]	2006 Rate	2007 Herbicide	2007 Rate
			kg ae or ai ha^{-1}		kg ae or 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	+ flumetsulam	+ 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
Postemergence glyphosate	Corn	—	—	Glyphosate	0.87
Postemergence glyphosate	Soybean	Glyphosate	0.87	Glyphosate	0.87
Postemergence non-glyphosate	Corn	—	—	Nicosulfuron	0.03
				+ rimsulfuron	+ 0.01
				+ mesotrione	+ 0.12
				+ atrazine	+ 0.56
Postemergence non-glyphosate	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[a] early termination	Wheat	Glufosinate	0.47	Glufosinate	0.47
WWCC late termination	Wheat	Fluazifop	0.35	—	—
		+ fenoxaprop	+ 0.1		

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

ha^{-1} and a depth of 3 cm. The WWCC[3] was planted in 20-cm-wide rows at 4 million seeds ha^{-1} and a depth of 3 cm. Corn received 28 kg ha^{-1} nitrogen and 25 kg ha^{-1} phosphorous in the form of 19–17–0 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. In-field horseweed densities were evaluated by counting horseweed plants in three randomly placed 0.25-m^2 quadrats at 1 mo after burndown (MAB) and 1 MAP, and in two 1-m^2 randomly placed quadrats at the time of crop harvest (4 MAP) in each plot. After horseweed densities were determined in the fall, the seedheads in each plot were severed and placed on the ground just prior to machine harvest of the border rows, to limit horseweed seed movement to other plots.

Soil Collection and Greenhouse Grow-Out Procedure. Fluctuations of viable horseweed seed 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 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 × 6.4-mm mesh wire screen, and one kg of soil was mixed with 350 g of autoclaved sand. The soil : sand mixtures were spread approximately 2 cm deep on fiber weed cloth[4] in 26-cm × 26-cm × 5.5-cm plastic greenhouse flats. Vermiculite[5] was placed at a depth of 1.5 cm below the soil surface as a barrier between the weed cloth and the bottom of the flats to aid in subirrigation (Cardina and Sparrow 1996; Forcella 1992).

Soil samples were maintained under greenhouse conditions for 4 wk with daytime/nighttime temperatures ranging from 18 to 22 C and no supplemental lighting. Horseweed seedlings that germinated and emerged from each soil sample were counted after 6 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 6 wk of growth. Horseweed seedlings were transplanted to other flats to determine the number of GR and GS individuals from each plot.

Table 3. Application dates and horseweed sizes for herbicide application timings in a multi-year management study at Butlerville, IN.

Application	2005–2006 Date	2005–2006 Horseweed size	2006–2007 Date	2006–2007 Horseweed size
Fall burndown	11/3/2005	—	11/22/2006	—
Spring burndown	5/3/2006	Cotyledon to 10 cm tall	5/8/2007	Cotyledon to 8 cm tall
In-crop	6/22/2006	Cotyledon to 35 cm tall	6/6/2007	Cotyledon to 30 cm tall

Table 4. Means and P values for crop rotation effects for 2006 and 2007 in-field horseweed counts and horseweed seedling densities kg^{-1} dry soil from October soil sample collections in a multi-year management study at Butlerville, IN. Rotations are either soybean–soybean or soybean–corn in no-till cropping systems.

Contrast	In-field horseweed densities						October seedbank	
	At POST		1 MAP[a]		4 MAP			
	plant m^{-2}	P[b]	plant m^{-2}	P	plant m^{-2}	P	plant kg^{-1} dry soil	P
2006								
Soybean–soybean vs.	3.3	*	2.0	0.06	0.2	*	2.3	0.54
Soybean–corn	1.6		0.5		0.1		1.6	
2007								
Soybean–soybean vs.	4.7	NS	6.6	*	2.9	***	28	*
Soybean–corn	3.1		2.7		1.4		10	

[a] Abbreviations: MAP, months after postemergence.
[b] Symbols *, **, and *** designate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. All other P-values are rounded to the nearest hundredth.

Glyphosate Screen to Determine Frequency of GR : GS Biotypes in the Seedbank. Horseweed transplants from fall soil samples were grown to a 5- to 10-cm rosette size and sprayed with 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. 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 (DAT), the plants were visually assessed as dead (no green plant vegetation) or living (some green plant vegetation). Living plants treated with this rate of glyphosate were considered GR.

Statistical Analysis. Emerged horseweed seedlings from the soil sample grow-outs (seedbank densities) were converted to seedlings kg^{-1} dry soil before analysis. Seedbank densities were square root transformed, and in-field horseweed densities were inverse log transformed for analysis as suggested by the Box-Cox procedure (Box et al. 1978). Because only single mean preplanned contrasts are presented, non-transformed data are used for clarity. Data were analyzed in a split-plot mixed model analysis using PROC MIXED in SAS.[7] Year by crop rotation by management system interactions were not significant for seedling densities and were not significant for a majority of in-field density census timings. Therefore, crop rotation and management systems were analyzed and presented within year. There were significant crop rotation by management system effects at $P < 0.01$ for the 2007 postemergence and 4 MAP timings. Therefore, data are presented for each crop rotation within count timing. Management system effects were separated using P values of preplanned contrasts. GR and GS horseweed transplants that were recovered from the soil sample grow-outs were analyzed by chi-square analyses within year.

Crop yields were collected by machine harvest and adjusted to 13 and 15% moisture for soybeans and corn, respectively, before statistical analysis. Crop yields were analyzed separately by year since crop rotations were different. Soybean yields from 2006 were analyzed as a split-plot design since they followed 2 previous yr of different rotations. In 2007, corn and soybean yields were analyzed as 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 Crop Rotation on Horseweed Densities. Crop rotation influenced horseweed densities in the third (2006) and fourth (2007) year of this experiment. The continuous soybean rotation contained higher in-field horseweed densities throughout the 2006 growing season at the $P < 0.1$ level. During the fourth year of the study (2007), the continuous soybean rotation had higher in-field horseweed densities than the soybean–corn rotation throughout the growing season. There was a twofold difference in densities at the end of season (4 MAP) timing (Table 4). A similar difference was present in the soil seedbank at the conclusion of the fourth year as the continuous soybean rotation had 28 plants kg^{-1} dry soil vs. 10 plants kg^{-1} dry soil from the soybean–corn rotation.

A soybean–corn rotation consistently lowered horseweed densities compared to the continuous soybean rotation. It would be difficult to discern whether the differences observed were due to differences in corn and soybean competition with horseweed, use of postemergence herbicides other than glyphosate in corn, or both. However, in 2007 the largest differences between the soybean–corn and continuous soybean rotation occurred between the non-glyphosate postemergence vs. the glyphosate postemergence comparisons, suggesting that herbicide rotation perhaps was more important than crop competition. Crop rotation effects were not observed during the first 2 yr of the experiment. We previously reported in-field and soil seedbank horseweed densities were not influenced by crop rotation after 2 yr (Davis et al. 2007). We were surprised by that result after 2 yr because in-field survey data previously suggested GR horseweed was associated with continuous soybean production fields in Indiana (Barnes et al. 2004). Furthermore, the first documented GR horseweed population was collected from a no-till field using a continuous soybean rotation (VanGessel 2001).

From these results after 4 yr and two complete crop rotation cycles in the corn–soybean rotation, we conclude that horseweed demographics are likely to elevate in continuous soybean cropping systems. This supported findings reported by Barnes et al. (2004) prior to continuing the experiment and findings by Davis et al. (2009). Davis et al. (2009) found continuous soybean cropping systems was the second most important descriptive factor behind greater than 30% residue cover to model late-season in-field horseweed presence in Indiana. However, more than 2 yr of a soybean–soybean rotation was needed for differences to be observed. These data would then suggest no-till crop producers with GR horseweed may consider growing soybean following soybean as a viable management decision as long as the practice is not continued for 3 or more yr.

Influence of Management Systems on In-Field Horseweed Densities. Herbicide application timing influenced in-field

Table 5. Contrast means and P values for 2006 in-field horseweed counts in a multi-year management study at Butlerville, IN. Contrasts are between weed management systems in no-tillage soybean–soybean (SSS) and soybean–corn (SCS) cropping systems.

Contrast	SYS	At POST				1 MAP				4 MAP			
		SSS		SCS		SSS		SCS		SSS		SCS	
		plant m^{-2}	P[b]	plant m^{-2}	P	plant m^{-2}	P	plant m^{-2}	P	plant m^{-2}	P	plant m^{-2}	P
Fall preplant timing vs.	1,3,5	6.1	*	4.1	*	3.7	*	1.1	*	0.3	0.06	0.1	0.08
Spring preplant timing	2,4,6	0.1		0.0		0.1		0.0		0.04		0.0	
Fall preplant timing fb[a] gly POST vs.	1,3	8.9	**	6.1	**	5.4	*	1.7	*	0.5	*	0.2	*
Spring preplant timing fb gly POST	2,4	0.1		0.0		0.1		0.0		0.1		0.0	
Fall residual timing vs.	3,5	0.2	0.76	0.1	0.82	0.2	0.71	0.0	1.0	0.2	0.27	0.03	0.69
Spring residual timing	4,6	0.1		0.0		0.04		0.0		0.03		0.0	
Gly preplant fb gly POST vs.	1,2	9.0	**	6.0	**	5.5	*	1.7	*	0.4	0.48	0.2	0.16
Residual preplant fb gly POST	3,4	0.1		0.04		0.04		0.0		0.1		0.03	
Residual or WWCC fb gly POST vs.	3,4,7	1.2	0.35	0.1	0.94	1.5	0.43	0.1	0.66	0.3	*	0.04	0.48
Residual or WWCC fb nongly POST	5,6,8	1.7		0.1		0.2		0.0		0.04		0.0	
Residual fb gly POST vs.	3,4	0.1	0.67	0.04	1.0	0.04	0.71	0.0	1.0	0.1	0.39	0.03	0.69
Residual fb nongly POST	5,6	0.3		0.04		0.2		0.0		0.04		0.0	
Gly preplant fb gly POST vs.	1,2	9.0	0.13	6.0	**	5.5	*	1.7	**	0.4	0.09	0.2	0.06
No gly at preplant or POST	5,6,8	1.7		0.1		0.2		0.0		0.04		0.0	
Spring residual vs.	4,6	0.1	**	0.0	0.48	0.04	0.12	0.0	0.59	0.03	0.10	0.0	0.53
WWCC	7,8	4.1		0.2		2.3		0.1		0.3		0.04	
Fall residual vs.	3,5	0.2	*	0.1	0.63	0.2	0.24	0.0	0.59	0.2	0.58	0.03	0.82
WWCC	7,8	4.1		0.2		2.3		0.1		0.3		0.04	

[a] Abbreviations: fb, followed by; gly, glyphosate; residual, residual herbicides are described in Table 2; WWCC, winter wheat cover crop; nongly, herbicides other than glyphosate; SYS, management system; MAP, months after postemergence.
[b] Symbols *, **, and *** designate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. All other P values are rounded to the nearest hundredth.

horseweed densities. Preplant herbicides applied in the spring contained lower in-field horseweed densities than when applied in the fall at nearly all count timings in both years at the $P < 0.1$ level when both glyphosate and residual herbicide systems were used for preplant applications (Tables 5 and 6). However, in systems using only residual herbicides, no differences were observed between fall and spring preplant timings in 2006. In 2007, the continuous soybean systems had higher in-field densities than soybean–corn systems at the postemergence and 4 MAP count timings in systems using residual herbicides.

Herbicide selection at both the preplant and postemergence timing influenced in-field horseweed densities. Residual preplant followed by postemergence glyphosate herbicide systems had lower early-season (at POST and 1 MAP) horseweed densities in 2006 than glyphosate preplant followed by postemergence glyphosate systems (Table 5). There were similar differences in 2007 at all sample timings (Table 6). These data further support previous efficacy studies that indicate horseweed can be difficult to control with non-glyphosate postemergence herbicides in soybean (Bruce and Kells 1990; Moseley and Hagood 1990; VanGessel et al. 2001).

Postemergence herbicides used following residual preplant or WWCC systems were also compared. In 2006, there were higher in-field horseweed densities following postemergence glyphosate than non-glyphosate at the 4 MAP count timing (Table 5). In contrast, there were higher in-field densities in residual followed by non-glyphosate postemergence herbicide

Table 6. Contrast means and P values for 2007 in-field horseweed counts in a multi-year management study at Butlerville, IN. Contrasts are between weed management systems in no-tillage soybean–soybean (SSS) and soybean–corn (SCS) cropping systems.

Contrast	SYS	At POST				1 MAP				4 MAP			
		SSS		SCS		SSS		SCS		SSS		SCS	
		plant m^{-2}	P[b]	plant m^{-2}	P	plant m^{-2}	P	plant m^{-2}	P	plant m^{-2}	P	plant m^{-2}	P
Fall preplant timing vs.	1,3,5	6.7	**	7.7	**	9.6	0.10	6.8	***	4.4	***	3.5	***
Spring preplant timing	2,4,6	1.2		0.4		4.0		0.1		0.8		0.1	
Fall preplant timing fb[a] gly POST vs.	1,3	6.0	0.15	11.2	***	11.2	0.08	10.1	***	5.0	*	5.3	***
Spring preplant timing fb gly POST	2,4	1.7		0.1		2.3		0.1		1.2		0.2	
Fall residual preplant timing vs.	3,5	4.0	*	0.8	0.57	3.2	0.77	0.5	0.41	1.7	*	0.2	0.49
Spring residual preplant timing	4,6	0.1		0.5		3.7		0.1		0.0		0.04	
Gly preplant fb gly POST vs.	1,2	7.7	***	10.9	**	13.5	***	9.6	***	6.1	***	5.2	***
Residual preplant fb gly POST	3,4	0.0		0.4		0.0		0.7		0.1		0.2	
Residual or WWCC fb gly POST vs.	3,4,7	4.2	0.16	0.3	0.37	4.1	0.95	0.8	*	2.6	0.13	0.2	0.17
Residual or WWCC fb nongly POST	5,6,8	3.1		0.8		4.6		0.0		1.1		0.0	
Residual fb gly POST vs.	3,4	0.0	**	0.4	0.49	0.0	0.08	0.7	0.11	0.1	0.09	0.2	0.27
Residual fb nongly POST	5,6	4.1		0.9		6.9		0.0		1.6		0.0	
Gly preplant fb gly POST vs.	1,2	7.7	**	10.9	**	13.5	**	9.6	***	6.1	***	5.2	***
No gly at preplant or POST	5,6,8	3.1		0.8		4.6		0.0		1.1		0.0	
Spring residual vs.	4,6	0.1	*	0.5	0.87	3.7	0.34	0.1	0.32	0.0	***	0.04	0.69
WWCC	7,8	6.8		0.3		6.1		0.5		3.8		0.1	
Fall residual vs.	3,5	4.0	0.81	0.8	0.46	3.2	0.51	0.5	0.85	1.7	0.10	0.2	0.77
WWCC	7,8	6.8		0.3		6.1		0.5		3.8		0.1	

[a] Abbreviations: fb, followed by; gly, glyphosate; Residual, residual herbicides are described in Table 2; WWCC, winter wheat cover crop; nongly, herbicides other than glyphosate; SYS, management system; MAP, months after postemergence.
[b] Symbols *, **, and *** designate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. All other P values are rounded to the nearest hundredth.

Table 7. Contrast means and P values for crop yield for 2006 and 2007. Contrasts are between weed management systems in no-tillage soybean–soybean and soybean–corn cropping systems. All plots were soybeans in 2006 (treatment $n = 10$) while soybean and corn were planted in 2007 (treatment $n = 5$).

Contrast	Management systems	2006		2007			
		Soybean		Soybean		Corn	
		kg ha^{-1}	P	kg ha^{-1}	P[b]	kg ha^{-1}	P
Fall preplant timing vs.	1,3,5 (3)	2970	0.30	3700	0.15	6870	*
Spring preplant timing	2,4,6 (−3)	3090		3970		8160	
Fall preplant timing fb[a] gly POST vs.	1,3 (2)	2950	0.48	3860	0.65	7220	0.29
Spring preplant timing fb gly POST	2,4 (−2)	3050		3960		8020	
Fall residual preplant timing vs.	3,5 (2)	2970	0.35	3690	*	6680	*
Spring residual preplant timing	4,6 (−2)	3100		4190		8270	
Gly preplant fb gly POST vs.	1,2 (2)	3030	0.61	3640	*	7590	0.94
Residual preplant fb gly POST	3,4 (−2)	2960		4180		7650	
Residual or WWCC fb gly POST vs.	3,4,7 (3)	3080	0.89	3950	*	7360	0.41
Residual or WWCC fb nongly POST	5,6,8 (−3)	3090		3500		6860	
Residual fb gly POST vs.	3,4 (2)	2960	0.30	4180	*	7650	0.65
Residual fb nongly POST	5,6 (−2)	3110		3700		7310	
Gly preplant fb gly POST vs.	1,2 (6)	3030	0.64	3640	0.51	7590	0.29
No gly at preplant or POST	5,6,8 (−6)	3090		3500		6860	
Spring residual vs.	4,6 (2)	3100	0.56	4190	***	8270	*
WWCC	7,8 (−2)	3180		3300		6380	
Fall residual vs.	3,5 (2)	2970	0.13	3690	0.09	6680	0.68
WWCC	7,8 (−2)	3180		3300		6380	

[a] Abbreviations: fb, followed by; gly, glyphosate; Residual, residual herbicides are described in Table 2; WWCC, winter wheat cover crop; nongly, herbicides other than glyphosate.

[b] Symbols *, **, and *** designate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. All other P values are rounded to the nearest hundredth.

systems at the $P < 0.1$ level for every count timing in the continuous soybean systems in 2007.

Management systems in both crop rotations that did not use glyphosate at the preplant or postemergence application reduced in-field horseweed densities in both years at all count timings compared to systems that relied only on glyphosate at both application timings (Tables 5 and 6). Residual herbicide systems reduced in-field horseweed densities equal to or greater than WWCC systems at all count timings in both years (Table 5 and 6). Furthermore, spring-applied residual herbicides had lower densities than the WWCC systems in the continuous soybean rotation in both years at the postemergence and 4 MAP timings at the $P < 0.1$ level (Tables 5 and 6).

The results from the third and fourth yr of this study regarding the influence of application timing, herbicide selection, and WWCC systems are consistent with results from the first 2 yr (Davis et al. 2007). Preplant herbicides applied in the spring had lower horseweed densities because germination and emergence of horseweed in the region of this experiment occurs primarily in the spring (Davis and Johnson 2008). Selecting an effective herbicide can be a critical component of any integrated weed management system. Spring-applied herbicides that provided residual activity on horseweed provided the most consistent horseweed control.

One difference in the results of the third and fourth yr vs. the first and second was that non-glyphosate postemergence herbicide selection systems increased in-field horseweed densities. This data further supported Bruce and Kells (1990) and VanGessel et al. (2001) who have also shown that horseweed is difficult to control with non-glyphosate postemergence soybean herbicides. Several authors have previously emphasized the importance of controlling horseweed populations prior to soybean establishment (Bruce and Kells 1990; Davis et al. 2007; VanGessel et al. 2001). This data would suggest that in addition to controlling horseweed prior to crop establishment, an integrated approach of postemergence herbicides should also be utilized. Models used by Gressel and Segel (1990) and Neve (2007) also have shown that tank-mixing herbicides may reduce or delay the occurrence of herbicide-resistant weed biotypes. Although not directly examined, these results may conclude that tank-mixing glyphosate and non-glyphosate postemergence herbicides, or rotating postemergence glyphosate with non-glyphosate systems, may be a more beneficial strategy in the long-term dynamics of reducing in-field densities than eliminating glyphosate altogether.

Influence of Management Systems on Crop Yield. Soybean crop yield was not influenced by previous crop rotation or management systems in 2006. Rotation by management systems effects were not significant ($P = 0.3860$), crop rotation effects alone were not significant ($P = 0.1107$), and management system effects alone were not significant ($P = 0.5879$). Furthermore, systems were pooled over crop rotation and there were no significant differences in soybean crop yield using preplanned contrasts, with mean yields between 2,960 and 3,180 kg ha^{-1} (Table 7).

Management systems influenced corn and soybean crop yields in 2007. The timing of preplant herbicide applications influenced crop yields. Spring preplant systems provided greater soybean and corn yields than fall preplant systems at the $P < 0.15$ level (Table 7). However, this comparison was not observed when only glyphosate was used postemergence. In systems that used only residual preplant herbicides, spring applications also provided greater soybean and corn yields than fall applications (Table 7).

The selection of preplant and postemergence herbicides influenced soybean yield in 2007 but did not influence corn yields. Residual preplant herbicide systems provided greater soybean yields than glyphosate preplant systems (Table 7). Spring-applied residual preplant herbicide systems also provided greater soybean and corn yields than WWCC systems. Furthermore, fall-applied residual preplant herbicides provided greater soybean yields than WWCC systems at the $P < 0.10$ level. In contrast, glyphosate postemergence herbicide systems provided greater soybean yields than non-

Table 8. Contrast means and P values for 2006 and 2007 horseweed seedling densities kg^{-1} dry soil from October soil sample collections in a multi-year management study at Butlerville, IN. Contrasts are between weed management systems in no-tillage soybean–soybean (SSS) and soybean–corn (SCS) cropping systems.

Contrast	SYS	2006				2007			
		SSS		SCS		SSS		SCS	
		plant kg^{-1} dry soil	P[b]	plant kg^{-1} dry soil	P	plant kg^{-1} dry soil	P	plant kg^{-1} dry soil	P
Fall preplant timing vs.	1,3,5	4.5	**	3.7	***	46.8	***	24.4	**
Spring preplant timing	2,4,6	0.2		0.3		8.4		0.6	
Fall preplant timing fb[a] gly POST vs.	1,3	6.2	***	4.8	***	133.9	***	36.4	**
Spring preplant timing fb gly POST	2,4	0.1		0.4		12.4		0.9	
Fall residual preplant timing vs.	3,5	1.3	0.19	1.9	*	7.6	0.20	2.9	0.55
Spring residual preplant timing	4,6	0.1		0.4		0.8		0.4	
Gly preplant fb gly POST vs.	1,2	5.6	*	3.6	*	74.2	***	34.3	*
Residual preplant fb gly POST	3,4	0.8		1.5		5.1		3.0	
Residual or WWCC fb gly POST vs.	3,4,7	2.0	0.18	1.2	0.46	20.8	*	2.3	0.46
Residual or WWCC fb nongly POST	5,6,8	0.5		0.7		3.8		0.5	
Residual fb gly POST vs.	3,4	0.8	0.88	1.5	0.36	5.1	0.87	3.0	0.47
Residual fb nongly POST	5,6	0.6		0.8		3.5		0.2	
Gly preplant fb gly POST vs.	1,2	5.6	**	3.6	**	74.2	***	34.3	***
No gly at preplant or POST	5,6,8	0.5		0.7		3.8		0.5	
Spring residual vs.	4,6	0.1	0.11	0.4	0.69	0.8	**	0.4	0.98
WWCC	7,8	2.3		0.5		28.3		0.5	
Fall residual vs.	3,5	1.3	0.75	1.9	0.09	7.6	*	2.9	0.56
WWCC	7,8	2.3		0.5		28.3		0.5	

[a] Abbreviations: fb, followed by; gly, glyphosate; residual, residual herbicides are described in Table 2; WWCC, winter wheat cover crop; nongly, herbicides other than glyphosate; SYS, management system.
[b] Symbols *, **, and *** designate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. All other P values are rounded to the nearest hundredth.

glyphosate postemergence systems. There were no differences in soybean or corn yield between herbicide systems that used only glyphosate for weed control vs. systems that used no glyphosate for weed control (Table 7).

The selection of preplant or preemergence herbicides is critical for an effective weed management system to achieve greatest yield potential. Crop yield results from the third and fourth years of this experiment suggest that postemergence glyphosate systems can also consistently achieve equal or greater yields than non-glyphosate postemergence herbicide systems. This was also apparent in years one and two when postemergence glyphosate increased corn yields due to better postemergence fall panicum control (Davis et al. 2007). In 2007, lower soybean yields in non-glyphosate postemergence systems were likely due to horseweed competition (Table 7) and poor control of fall panicum, large crabgrass, and barnyardgrass (data not presented), which required an extra postemergence application of clethodim at the R1 soybean growth stage. Like years one and two, there was no yield advantage in WWCC systems vs. preplant residual herbicide systems in years three and four (Davis et al. 2007). Furthermore, there was a soybean and corn yield reduction in WWCC systems vs. spring-applied preplant residual herbicides in 2007 and a reduction in soybean yield vs. fall-applied preplant residual herbicide systems. Davis et al. (2007) suggested WWCC systems could be challenging, and the third and fourth yr of this experiment would conclude that WWCC do not provide a yield advantage over preplant residual herbicide systems.

Influence of Management Systems on Horseweed Seedbank Densities. Herbicide application timing influenced horseweed seedbank densities. Spring preplant applications reduced horseweed seedbank densities vs. fall preplant applications over all postemergence herbicide selections and postemergence glyphosate only (Table 8). However, the magnitude of differences between fall and spring was less when residual herbicides were used.

Selection of preplant herbicides also influenced annual horseweed seedbank densities, but little differences were observed between postemergence herbicide selections. Residual herbicide use reduced seedbank densities more than preplant glyphosate systems (Table 8). Overall, management systems using no glyphosate for preplant or postemergence applications reduced seedbank densities more than systems using only glyphosate for preplant and postemergence applications for both years and both crop rotations. Fall and spring preplant residual systems also reduced seedbank densities more than WWCC systems in the continuous soybean rotation in 2007.

In-field horseweed densities were influenced by management systems. In-field horseweed densities were notably higher in 2007 than in previous years of the study (Table 6; Davis et al. 2007). This trend was also reflected in changes in soil seedbank densities at the conclusion of 4 yr. The initial seedbank densities ranged from 2.8 to 4.0 seedlings kg^{-1} dry soil in October 2003 (Davis et al. 2007). However, in October 2007, seedbank densities of crop management systems ranged from 0.8 seedlings kg^{-1} dry soil in systems that utilized preplant residual herbicides, to 134 seedlings kg^{-1} dry soil in fall-applied systems that utilized preplant herbicides followed by glyphosate postemergence (Table 8). Therefore, in this experiment, repeated preplant herbicide applications in the fall followed by repeated applications of postemergence glyphosate increased densities of horseweed in the seedbank by 33- to 47-fold over the course of 4 yr, whereas spring-applied preplant herbicides reduced or maintained lower horseweed densities. As we stated in our earlier paper, integrated weed management practices that aim to reduce in-field densities and prevent annual seed rain events should be used to lower or maintain low horseweed soil seedbank densities (Davis et al. 2007).

Table 9. Glyphosate-resistant (GR) and -susceptible (GS) horseweed plants grown from soil samples collected in October 2006 and 2007 following 3 and 4 yr, respectively, of management systems in a multi-year no-till field study at Butlerville, IN. Contrasts are between weed management systems in no-tillage soybean–soybean (SSS) and soybean–corn (SCS) cropping systems and chi-square values indicate significance. Average GR : GS horseweed ratio was 3 : 1 from soil samples collected from entire study area in October 2003.

Contrast	SYS	2006 GR	2006 GS	2006 Chi-square	2007 GR	2007 GS	2007 Chi-square
		#	#	P[b]	#	#	P
Soybean-soybean vs.	—	54	7	0.26	522	251	0.40
Soybean–corn	—	19	5		161	88	
Fall preplant timing vs.	1,3,5	58	7	0.39	548	221	***
Spring preplant timing	2,4,6	3	1		33	42	
Fall preplant timing fb[a] gly POST vs.	1,3	55	6	0.34	545	198	***
Spring preplant timing fb gly POST	2,4	3	1		33	42	
Fall residual preplant timing vs.	3,5	3	1	—	34	43	0.78
Spring residual preplant timing	4,6	2	0		3	3	
Gly preplant fb gly POST vs.	1,2	52	7	0.37	544	217	0.06
Residual preplant fb gly POST	3,4	6	0		34	23	
Residual or WWCC fb gly POST vs.	3,4,7	17	4	—	128	88	***
Residual or WWCC fb nongly POST	5,6,8	4	1		11	34	
Residual fb gly POST vs.	3,4	6	0	—	34	23	***
Residual fb nongly POST	5,6	3	1		4	24	
Gly preplant fb gly POST vs.	1,2	52	7	0.60	544	217	***
No gly at preplant or POST	5,6,8	4	1		11	34	
Spring residual vs.	4,6	2	0	—	4	4	0.68
WWCC	7,8	12	4		101	75	
Fall residual vs.	3,5	7	1	0.48	34	43	*
WWCC	7,8	12	4		101	75	

[a] Abbreviations: fb, followed by; gly, glyphosate; residual, residual herbicides are described in Table 2; WWCC, winter wheat cover crop; nongly, herbicides other than glyphosate; SYS, management system.
[b] Symbols *, **, and *** designate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. All other P values are rounded to the nearest hundredth. Chi-square values are not presented where greater than 50% of data comparison cells have an expected value of less than 5.

Influence of Management Systems on the GR : GS Ratios of Horseweed Biotypes. Soil samples were collected in October 2003 at the beginning of this experiment. The initial ratio of GR : GS plants was 3 : 1 from 435 horseweed plants transplanted and screened for glyphosate resistance (Davis et al. 2007). Management systems were not compared by GR : GS ratios in the first 2 yr because too few horseweed plants were recovered and screened from the soil sample collections (Davis et al. 2007). However, in-field and seedbank densities had increased in several management systems by the fourth yr of this study, and GR : GS ratios were influenced by management systems but not crop rotation (Table 9). Differences in GR : GS ratios as influenced by crop management systems were not observed in 2006 (Table 9). The continuous soybean rotation had 2.5- and 3-fold greater horseweed seedbank seedling densities than the soybean–corn rotation in 2006 and 2007, respectively (Table 9). There were too few horseweed plants transplanted and screened for glyphosate resistance in several 2006 systems for proper statistical comparisons. This was similar to the results of the first and second yr of the experiment as we previously reported (Davis et al. 2007).

GR : GS ratios were approximately 2 : 1 for both rotations in 2007. In 2007, there were many more horseweed plants transplanted from soil sample collections than in the previous years of the study, because in-field and soil seedbank densities had greatly increased in many systems as previously described. Preplant application timing influenced GR : GS ratios except where only residual preplant herbicides were used. GR : GS ratios for fall application timing systems were 5 : 2 vs. 3 : 4 in spring application timings (Table 9).

Herbicide selection, particularly for postemergence applications, also influenced GR : GS population ratios of horseweed biotypes. GR : GS ratios were 3 : 2 for preplant residual herbicides or WWCC systems, followed by postemergence glyphosate vs. 1 : 3 and 1 : 6 for preplant residual herbicides or WWCC systems followed by postemergence non-glyphosate herbicides (Table 9). Furthermore, systems that used only glyphosate for preplant and postemergence weed control had 17-fold higher total horseweed densities with a 5 : 2 GR : GS plant ratio vs. 1 : 3 in systems that did not use glyphosate at either herbicide application timing. The WWCC system also contributed to larger GR : GS ratios than fall-applied preplant residual herbicides, but there was no difference between WWCC and spring-applied preplant residuals in 2007. The GR : GS plant ratio for fall preplant residual herbicides were approximately 3 : 4 vs. 4 : 3 for the WWCC system (Table 9).

Boerboom (1999) suggested integrated weed management (IWM) systems can be developed to delay herbicide resistance by reducing herbicide selection pressure or by limiting growth of resistant populations. Maxwell et al. (1990) also suggested predictive models could show the influence that management systems have on the ratios of herbicide-resistant and -susceptible biotypes in the soil seedbank. Unfortunately, the study of population dynamics in populations with herbicide-resistant and -susceptible biotypes is limited, and for the model proposed by Maxwell et al. (1990) to work, a great deal of understanding about the differences in phenotypic fitness characteristics of both resistant (R) and susceptible (S) biotypes is required. In this study, the differences in the total magnitude, for both GR and GS biotypes, of horseweed transplanted from soil seedbank collections supported the conclusions drawn from total in-field and seedbank densities previously discussed. However, analyzing the change in population structure of GR and GS biotypes revealed that ratios of GR and GS biotypes can be markedly shifted under different management systems. The most dramatic shift was from the initial GR : GS ratio of 3 : 1 to a ratio of 1 : 6 after

4 yr of residual preplant herbicide use followed by non-glyphosate postemergence herbicides (Table 9). This experiment clearly demonstrated, as proposed by Boerboom (1999), Maxwell et al. (1990), and Neve (2007), that IWM systems can reduce or limit herbicide-resistant population growth and shift ratios of resistant and susceptible population structure.

Management Implications for Horseweed Populations with GR Biotypes in No-Till Soybean Production. This research evaluated horseweed populations that emerge primarily in the spring and can be particularly troublesome to manage in GR crops due to GR biotypes. No previous research has examined IWM options such as WWCC systems, fall vs. spring preplant timings, and residual vs. non-residual herbicide selection in systems through multiple crop rotation cycles with GR horseweed as the predominant summer annual weed. Tillage is an important tool for IWM systems for agriculture production (Buhler 1995), 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, though, for no-till soybean producers in this region with infestations of GR horseweed because of the higher potential for soil erosion.

This research demonstrated advantages to rotating corn with soybean vs. continuous soybean production to reduce horseweed densities; however, the benefits are not realized until years three and four. Our results from years one and two concluded no advantage to crop rotation after 2 yr (one crop rotation cycle). These results indicate soybean–soybean rotations may be a viable crop production option, but should be continued for no more than 2 yr before horseweed population dynamics are influenced.

This experiment also empirically demonstrated that the population structure of GR : GS horseweed ratios can change in response to different management systems. The most dramatic shift was from the initial GR : GS ratio of 3 : 1 to a ratio of 1 : 6 after 4 yr of residual preplant herbicide use, followed by non-glyphosate postemergence herbicides. On the other hand, spring-applied preplant residuals averaged over both glyphosate and non-glyphosate postemergence herbicides had a GR : GS ratio of 1 : 1. Furthermore, those systems maintained the lowest total in-field and seedbank densities and provided better crop yield protection. We conclude from these results that shifting the population structure to strongly favor either GR or GS biotypes should not be desired. Once GR biotypes are in a local horseweed population, management systems that control both GR and GS biotypes should be implemented, as previously suggested by Davis et al. (2007). Spring-applied residual preplant herbicide use was the most effective management option for horseweed population control and optimal crop yields. Therefore, using herbicides with residual horseweed activity in the spring prior to crop establishment should be considered as the most consistent weed management approach for reducing total horseweed densities, and can be implemented by soybean producers with minimal cost and effort.

Sources of Materials

[1] Pioneer soybean variety 93M95, Pioneer Hi-Bred International, Inc., Resource Connection, P.O. Box 1000, Johnston, IA 50131-0184.

[2] Dekalb corn hybrid DKC54-46, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[3] Pioneer wheat variety P25R37 in 2005 and P25R54 in 2006, 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, Statistical Analysis Systems Institute Inc. Cary, NC 27513.

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