Glyphosate-Induced Weed Shifts in Glyphosate-Resistant Corn or a Rotation of Glyphosate-Resistant Corn, Sugarbeet, and Spring Wheat

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A field trial was conducted for 6 yr (1998 through 2003) at Scottsbluff, NE, to measure weed shifts following multiple applications of two rates of glyphosate or alternating glyphosate with nonglyphosate treatments in continuous corn or in a crop rotation of corn, sugarbeet, and spring wheat with all three crops resistant to glyphosate. After 6 yr, plant densities of common lambsquarters, redroot pigweed, hairy nightshade, and common purslane increased in the crop-rotation treatment compared with continuous corn. There were four weed control subplot treatments consisting of two in-crop applications of glyphosate at 0.4 or 0.8 kg ae/ha each spring, alternating two applications of glyphosate at 0.8 kg/ha one year with a nonglyphosate treatment the next year, or a nonglyphosate treatment each year. The composition of the weed population averaged across all four treatments shifted from kochia and wild proso millet to predominately common lambsquarters. After 3 yr of using glyphosate at 0.4 kg/ha twice each year, common lambsquarters density increased compared with that in the 0.8 kg/ha rate of glyphosate or alternating glyphosate treatments. By the sixth year, the density of common lambsquarters in the glyphosate at 0.4 kg/ha treatment had increased to the extent that corn grain yield was reduced 43% compared with corn grain yield in the 0.8 kg/ha glyphosate treatment. Using glyphosate at either rate for 6 yr decreased the densities of kochia, wild proso millet, and longspine sandbur, did not alter densities of redroot pigweed and green foxtail, and increased the density of hairy nightshade. In the low-rate treatment of glyphosate, the number of common lambsquarters seeds in the seed bank were 134 seeds/kg soil in 1998, declined to 15 seeds/kg by 2002, but began to increase in 2003 as the densities of plants not controlled by glyphosate increased.

Nomenclature: Glyphosate; common lambsquarters, *Chenopodium album* L. CHEAL; common purslane, *Portulaca oleracea* L. POROL; green foxtail, *Setaria viridis* (L.) P. Beauv. SETVI; hairy nightshade, *Solanum physalifolium* Rusby SOLSA; kochia, *Kochia scoparia* (L.) Schrad. KCHSC; longspine sandbur, *Cenchrus longispinus* (Hack.) Fern. CCHPA; redroot pigweed, *Amaranthus retroflexus* L. AMARE; wild proso millet, *Panicum miliaceum* L. PANMI; corn, *Zea mays* L.; spring wheat, *Triticum aestivum* L.; sugarbeet, *Beta vulgaris* L.

Key words: Alternating glyphosate, seed bank, weed shift.

The act of disturbing land for farming has led to shifts in plant species composition. Native plants have been replaced by crop plants and weedy annual, biennial, and perennial weeds (Harper 1957). Changing crops or tillage practices can also influence weed species diversity (Clements et al. 1994). Even the switch from horse-drawn equipment to tractor-drawn implements or the switch from manure to manufactured fertilizers has been shown to cause changes in weed species composition (Haas and Streibig 1982). The introduction of herbicides for selective weed control in crops added yet another way of selecting for different weed species. The repeated use of the same herbicide in the same crop for several years caused not only a shift in plant species but also reduced species diversity so that only one weed species competed with the crop (Fryer 1981). This problem was further compounded by weeds that developed resistance to herbicides (Harper 1957). Therefore, weed shifts caused by changing crops, cultural practices, or methods of weed control have been occurring since people started farming.

Two changes in North American agriculture in the past few years have dramatically influenced weed populations: (1) the conversion from preplant tillage to conservation tillage or no tillage (no-till) (Swanton et al. 1993), and (2) the use of glyphosate in glyphosate-resistant crops (Shaner 2000). The rapid adoption of glyphosate-resistant crops by U.S. farmers is one of the most dramatic changes ever seen in agricultural technology (Buttel 2002). The adoption of no-till or reduced tillage has apparently been enhanced by the use of glyphosate in glyphosate-resistant crops (Young 2006).

In the mid-1950s, Harper (1957) predicted that annual repeated use of any herbicide could lead to shifts in weed species composition within a crop–weed community. Bandeen et al. (1982) further suggested that a normal variability in response to herbicides exists among plant species and that tolerance can quickly increase with repeated use of a herbicide. Not all annual broadleaf weeds respond the same to glyphosate, and species vary in natural tolerance. Common ragweed (*Ambrosia artemisiifolia* L.), velvetleaf (*Abutilon theophrasti* Medik.), and morningglory (*Ipomoea* spp.) vary in their natural tolerance to glyphosate, which can result in weed shifts with increased use of glyphosate (Jordon et al. 1997).

The increased use of glyphosate in glyphosate-resistant soybean [*Glycine max* (L.) Merr.] in the United States has shifted weed populations to winter annuals, common

DOI: 10.1614/WT-06-199.1

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lambsquarters, and waterhemp (*Amaranthus* spp.) (Culpepper 2006). In a series of field studies conducted from Minnesota to Louisiana, it was shown that glyphosate rate and intensity of use in soybean influenced weed shifts (Scursoni et al. 2006). Increases from one to two annual applications of glyphosate reduced weed escapes and weed diversity. The frequency of escapes of common lambsquarters was 86% with only one in-crop application of glyphosate vs. 50% with two in-crop applications. The authors found common lambsquarters, eastern black nightshade (*Solanum ptycanthum* Dun.), pigweed (*Amaranthus* spp.), foxtail (*Setaria* spp.), smartweed (*Polygonum* spp.), and velvetleaf were the most common weed escapes from glyphosate in soybean.

After 4 yr of multiple glyphosate applications in glyphosate-resistant cotton (*Gossypium hirsutum* L.), weed populations shifted to Palmer amaranth (*Amaranthus palmeri* S. Wats) (Culpepper et al. 2006). Multiple applications of glyphosate had selected for a weed biotype that could tolerate glyphosate at eight times the normal use rate. Although weeds clearly can develop resistance to glyphosate, weed shifts because of differences in plant tolerance to glyphosate will probably occur more frequently than resistant weed biotypes (Shaner 2000).

Scientists have recommended four ways to manage glyphosate-induced weed shifts: (1) combine glyphosate with other herbicides with different modes of action, (2) rotate glyphosate-resistant crops with nonglyphosate-resistant crops, (3) rotate glyphosate with herbicides with a different mode of action, and (4) use a soil-applied herbicide at planting (Culpepper 2006). Weed shifts have been reported from glyphosate use in glyphosate-resistant soybean and cotton but not in corn, sugarbeet, or wheat. This research was initiated to explore the weed community response that could occur with multiple applications of different rates of glyphosate in continuous glyphosate-resistant corn or a crop rotation of corn, sugarbeet, and wheat with all three crops resistant to glyphosate. The study also was designed to explore the efficacy of several methods for managing glyphosate-induced weed shifts.

Methods and Materials

This article reports on an experiment conducted at Scottsbluff, NE, from 1998 through 2003. The experiment was part of a larger series of studies also conducted at Colby, KS; Fort Collins, CO; North Platte, NE; and Torrington, WY (Westra et al. 2004). Three of the sites—Fort Collins, Scottsbluff, and Torrington—were irrigated to supplement natural rainfall, and two of the sites, Colby and North Platte, used only natural precipitation for crop growth. Trends in the data from the three irrigated sites have been reported by Westra et al. (2004).

The experiment was a two-factorial split-plot set in a randomized complete-block design. The two main plots were continuous glyphosate-resistant corn or a crop rotation of glyphosate-resistant corn (1998), sugarbeet (1999), corn (2000), sugarbeet (2001), spring wheat (2002), and corn (2003) (Table 1). Hereafter, the two main plot treatments are referred to as continuous corn and crop rotation, respectively. There were four subplots that consisted of glyphosate at 0.4 ae kg/ha applied twice (low-rate glyphosate), glyphosate at 0.8 kg/ha applied twice (standard-rate glyphosate), a nonglyphosate treatment designed to control a minimum of 95% of the weed population in each crop (nonglyphosate), or an alternating treatment of glyphosate at 0.8 kg/ha applied twice followed the next year by a nonglyphosate treatment (alternating) (Table 1). POST herbicides were applied when weed height averaged 10 cm. In-crop glyphosate treatments were applied twice with the second application occurring approximately 2 wk after the first treatment. Each subplot was 9.1 by 30.5 m, which included 12 crop rows spaced 76 cm apart. All treatments were replicated four times and fixed in space for 6 yr to allow for a repeated-measures analysis.

The intentionally selected plot area had a diverse and dense weed population. Corn had been grown in the plot area from 1995 through 1997, and the plot was treated at planting with alachlor and treated POST with 2,4-D plus dicamba. In 1997, the year before initiation of the study, the weed population consisted of kochia, common lambsquarters, wild proso millet, longspine sandbur, common purslane, green foxtail, and redroot pigweed at densities of 276, 196, 139, 43, 23, 5, and 3 plants/m^2, respectively. The dense and diverse weed population was expected to enhance the probability of measuring weed shifts when weeds were exposed to different cropping systems and to glyphosate in following years. Weeds in the experimental area had not previously been exposed to glyphosate before initiating the study.

Soil was a Glenberg loamy sand (Ustic Torrifluvents) with pH 8.1 and 0.9% organic matter. In mid-April of each year, corn stalks were shredded, and the plot area was prepared for planting corn and sugarbeet by rototilling the soil to a depth of 10 to 15 cm. A second rototilling was conducted several days before planting followed by packing with a roller harrow to ensure no weeds were growing before planting (Table 2). During the 2002 growing season, glyphosate-resistant spring wheat was included in the crop-rotation treatment. Preplant tillage occurred in mid-March in 2002 in this section of the experiment to prepare a seedbed for wheat seeding on April 1. Tillage was conducted in the same direction as crop rows and weed-control treatments to minimize the movement of soil between different treatments.

Commercial fertilizer was applied before planting and side-dressed after crop emergence to supply the crops with needed nutrients according to soil test results and University of Nebraska recommendations for optimum crop production. Crops were irrigated using an overhead sprinkler with 25 mm of water within 2 d of planting to enhance crop seed germination and to incorporate herbicides applied PRE after planting. Adapted glyphosate-resistant crop varieties were seeded according to University of Nebraska recommendations (Table 2). At the time of planting, corn was treated with a band of terbufos at 200 g/300 m of corn row. Irrigation continued throughout the growing season to meet the water demands of the crops and 19 mm of water was applied 1 to 2 d before each POST herbicide application to enhance weed and crop growth before treatment. Crops were harvested at maturity, and grain was removed from the plot area. Sugarbeet roots were returned to respective plots following

Table 1. Description of crops, herbicide treatments, and application dates for different cropping systems at Scottsbluff, NE, from 1998 through 2003.

	Year	Glyphosate-resistant crop	Herbicide	Rate		Application dates			
				ae	ai	PRE	POST 1	POST 2	POST 3
				kg/ha					
Low	1998	Corn	Glyphosate	0.4		—	May 27	June 11	—
	1999	Corn	Glyphosate	0.4		—	May 26	June 8	—
	2000	Corn	Glyphosate	0.4		—	May 22	June 8	—
	2001	Corn	Glyphosate	0.4		—	June 5	June 22	—
	2002	Corn	Glyphosate	0.4		—	June 5	June 21	—
	2003	Corn	Glyphosate	0.4		—	May 29	June 11	—
Low	1998	Corn	Glyphosate	0.4		—	May 27	June 11	—
	1999	Sugarbeet	Glyphosate	0.4		—	May 20	June 1	—
	2000	Corn	Glyphosate	0.4		—	May 22	June 8	—
	2001	Sugarbeet	Glyphosate	0.4		—	May 24	June12	—
	2002	Spring wheat	Glyphosate	0.4		—	May 15	June 5	—
	2003	Corn	Glyphosate	0.4		—	May 29	June 11	—
Standard	1998	Corn	Glyphosate	0.8		—	May 27	June 11	—
	1999	Corn	Glyphosate	0.8		—	May 26	June 8	—
	2000	Corn	Glyphosate	0.8		—	May 22	June 8	—
	2001	Corn	Glyphosate	0.8		—	June 5	June 22	—
	2002	Corn	Glyphosate	0.8		—	June 5	June 21	—
	2003	Corn	Glyphosate	0.8		—	May 29	June 11	—
Standard	1998	Corn	Glyphosate	0.8		—	May 27	June 11	—
	1999	Sugarbeet	Glyphosate	0.8		—	May 20	June 1	—
	2000	Corn	Glyphosate	0.8		—	May 22	June 8	—
	2001	Sugarbeet	Glyphosate	0.8		—	May 24	June 12	—
	2002	Spring wheat	Glyphosate	0.8		—	May 15	June 5	—
	2003	Corn	Glyphosate	0.8		—	May 29	June 11	—
Alternating	1998	Corn	Glyphosate	0.8		—	May 27	June 11	—
	1999	Corn	Acetochlor + isoxaflutole		1.7 + 0.05	May 12	—	—	—
	2000	Corn	Glyphosate	0.8		—	May 22	June 8	—
	2001	Corn	Acetochlor + isoxaflutole		1.7 + 0.05	May 10			
			Dicamba + diflufenzopyr		0.14 + 0.06		June 5	—	—
	2002	Corn	Glyphosate	0.8		—	June 5	June 21	—
	2003	Corn	Acetochlor + isoxaflutole		1.7 + 0.04	May 2	—	—	—
Alternating	1998	Corn	Glyphosate	0.8		—			
	1999	Sugarbeet	Phenmedipham + desmedipham + triflusulfuron + clopyralid + clethodim		0.18 + 0.18 + 0.02 + 0.1 + 0.1	—	May 20	June 1	June 16
	2000	Corn	Glyphosate	0.8		—	May 22	June 8	—
	2001	Sugarbeet	Phenmedipham + desmedipham + triflusulfuron + clopyralid + clethodim		0.18 + 0.18 + 0.02 + 0.1 + 0.1	—	May 24	June 1	June 12
	2002	Spring wheat	Glyphosate	0.8		—	May 15	June 5	—
	2003	Corn	Acetochlor + isoxaflutole		1.7 + 0.04	May 2	—	—	—
Nonglyphosate	1998	Corn	Rimsulfuron + thifensulfuron + dicamba		0.011 + 0.006 + 0.14	—	May 27	—	—
	1999	Corn	Acetochlor + isoxaflutole		1.7 + 0.05	May 12	—	—	—
	2000	Corn	Acetochlor + isoxaflutole		1.7 + 0.05	May 9	—	—	—
	2001	Corn	Acetochlor + isoxaflutole		1.7 + 0.05	May 10			
			Dicamba + diflufenzopyr		0.14 + 0.06		June 5	—	—
	2002	Corn	Acetochlor + isoxaflutole		1.7 + 0.05	May 7			
			Dicamba + diflufenzopyr		0.14 + 0.06		June 5	—	—
	2003	Corn	acetochlor + isoxaflutole		1.7 + 0.04	May 2	—	—	—
Nonglyphosate	1998	Corn	Rimsulfuron + thifensulfuron + dicamba		0.011 + 0.006 + 0.14	—	May 27	—	—
	1999	Sugarbeet	Phenmedipham + desmedipham + triflusulfuron + clopyralid + clethodim		0.18 + 0.18 + 0.02 + 0.1 + 0.1	—	May 20	June 1	June 16
	2000	Corn	Acetochlor + isoxaflutole		1.7 + 0.05	May 10	—	—	—
	2001	Sugarbeet	Phenmedipham + desmedipham + triflusulfuron + clopyralid + clethodim		0.18 + 0.18 + 0.02 + 0.1 + 0.1	—	May 24	June 1	June 12
	2002	Spring wheat	Bromoxynil + MCPA + fluroxpyr		0.42 + 0.42 + 0.21	—	May 15	—	—
	2003	Corn	Acetochlor + isoxaflutole		1.7 + 0.04	May 2	—	—	—

Table 2. Planting, data collection, and harvest dates from 1998 through 2003 at Scottsbluff, NE.

Year	Crop	Variety	Planting date	Seed bank sample	Weed and crop density 1	2	3	Harvest date
1998	Corn	DeKalb 493RR	May 4	May 6	—	June 23	August 27	October 29
1999	Corn	Asgrow RX 448RR	May 7		—	June 25	September 22	November 3
	Sugarbeet	Hilleshög 1605RR	April 27	May 8	—	June 25	September 22	October 1
2000	Corn	Asgrow 493RR	May 2	May 5	—	June 21	August 10	November 7
2001	Corn	DeKalb 440RR YG	May 9	May 9	May 24	June 27	September 17	October 24
	Sugarbeet	Hilleshög 1605RR	April 30	May 7	May 24	June 27	September 17	September 25
2002	Corn	DeKalb 46-28RR	May 6	May 6	May 31	July 1	September 12	November1
	Spring wheat	SD 99	April 1	May 1	May 13	July 1	July 25	July 24
2003	Corn	DeKalb 47-10RR	May 1	May 1	May 23	June 23	August 21	November 10

harvest, allowed to freeze over the winter, and were then rototilled into the soil the following spring.

Soil seed-bank samples were collected in the same location each year after crop planting (Table 2). Nine core samples, 5.7 cm in diam and 16 cm deep, were collected from each subplot (Figure 1). Soil cores were kept separate, weighed, and frozen until weed seeds were extracted with a semi-automatic elutriator, identified, and counted by species using a dissecting microscope. Seed-bank density was expressed as seeds per kilogram of dry soil. Weed counts were taken twice each year: 2 wk following the final POST herbicide application and at crop harvest. Weed counts were taken a third time in 2001 through 2003 before applying the first POST herbicide. Weed counts were taken in the same location each year by counting plant species in three 76-cm-wide by 6-m-long quadrats in each subplot (Figure 1). Crop density and yield were determined in the same area each year by counting plants 2 wk following the final POST herbicide application and harvesting grain or roots from a 66-m^2 area in the center of each plot, respectively. Weed densities reported in this article are from counts taken 2 wk following the final POST herbicide application.

Herbicides were applied at a water volume of 197 L/ha and at a pressure of 248 kPa through 11002 VS nozzle tips with a tractor-mounted sprayer. Spray additives were combined with the spray solution according to manufacture's suggestions for herbicides applied POST: glyphosate, dicamba plus diflufenzopyr, rimsulfuron plus thifensulfuron, and clethodim.

Data were analyzed with the Mixed procedure of SAS (2004) as a repeated-measures split-plot design. Fixed effects in the model included year, main-plot treatment factor corn and crop rotation, and subplot treatment factor herbicide treatment along with their interactions. Random effects included replicate and replicate-by-main-plot treatment with separate effects for each year. Correlations across years for the random effects and residuals were modeled using a compound-symmetry covariance structure. The compound-symmetry correlation structure was selected after examining a number of correlation structures using Akaike's information criteria. Mean comparisons were performed using the general t statistic.

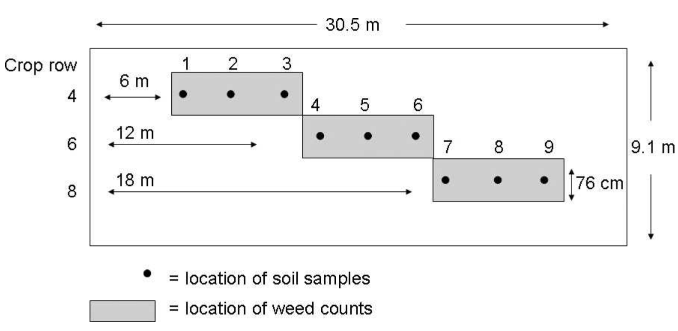

Figure 1. Subplot sampling arrangement used from 1998 to 2003.

Results and Discussion

At the initiation of the experiment, seed from eight weed species were found in the soil seed bank: common lambsquarters, hairy nightshade, redroot pigweed, kochia, wild proso millet, common purslane, longspine sandbur, and green foxtail at average densities of 106, 18, 13, 13, 11, 7, 2, and 2 seeds/kg of soil, respectively.

Crop Rotation. Growing glyphosate-resistant corn continuously for 6 yr vs. a rotation of three glyphosate-resistant crops (corn, sugarbeet, and spring wheat) influenced the plant density of four of eight weed species (Table 3). During the 1998 growing season, corn was grown in both main plots, and weed densities did not differ between them. In 1999, sugarbeet succeeded corn in the cropping rotation (Table 1), and the densities of both green foxtail and common purslane were lower in sugarbeet compared with corn (Table 3). Corn followed sugarbeet in 2000, and weed densities were again similar between continuous corn and the crop rotation. In 2001, sugarbeet was again grown in the crop rotation, and the densities of common lambsquarters and kochia increased in sugarbeet compared with continuous corn. Some sugarbeet plants in all plots were infected with *Rhizoctonia solani* root and crown rot. To slow the development of *Rhizoctonia solani*, spring wheat was inserted in the rotation to extend the time interval between sugarbeet crops to 3 yr. To maintain a rotation of glyphosate-resistant crops, glyphosate-resistant spring wheat was grown in the crop rotation in 2002, and glyphosate-resistant corn was grown in 2003.

Compared with initial densities recorded in 1998, after 6 yr, the densities of common lambsquarters, redroot pigweed, hairy nightshade, and common purslane had increased in the crop rotation (Table 3). During this same period, the densities of kochia, wild proso millet, and

Table 3. Effect of crop rotations averaged over weed control treatments on weed and soil seed-bank density at Scottsbluff, NE, from 1998 through 2003.

Year	Weed density[a]		Seed bank[a]		Weed density[a]		Seed bank[a]	
	Continuous corn	Corn Sugarbeet Wheat	Continuous corn	Corn Sugarbeet Wheat	Continuous corn	Corn Sugarbeet Wheat	Continuous corn	Corn Sugarbeet Wheat
	plants/10 m^2		seeds/kg soil		plants/10 m^2		seeds/kg soil	
	CHEAL[b]				POROL[b]			
1998	123	108	97	114	73	31	2	2
1999	29	9	33	35	13	0.2*	0	0.2
2000	53	44	75	48	7	20	0.9	0.4
2001	24	108*[c]	26	35	0.7	7	0	0
2002	37	37	7	11	2	0.4	0	0
2003	156	244*†[c]	11†	29†	7†	66*†	0†	0.2
	KCHSC[b]				PANMI[b]			
1998	211	198	9	15	370	502	13	7
1999	26	35	0	0.2	9	0.7	0	0
2000	2	4	0	0	4	7	0	0
2001	4	57*	0.7	.4	0.2	0.9	0	0
2002	2	0.7	0	0	0	0.2	0	0
2003	4†	2†	0†	0†	2†	2†	0†	0†
	AMARE[b]				CCHPA[b]			
1998	15	22	13	13	178	121	2	2
1999	0.4	0.7	4	4	0.9	0.9	0	0
2000	18	11	9	4	24	2	0	0
2001	2	2	7	4	57	7	0.2	0
2002	0.2	0.7	0.9	2	4	0	0	0
2003	13	64*†	0.9†	4†	37†	15†	0†	0†
	SOLSA[b]				SETVI[b]			
1998	0	2	22	13	4	7	0.2	0.9
1999	11	4	22	15	11	2*	0.2	0.2
2000	22	15	11	4	2	2	0.4	0.2
2001	2	4	22	15	0.4	0.2	0	0.2
2002	0	0	4	4	0	0	0	0
2003	2	13*†	2†	2†	1	2	0	0.2†

[a] Weed density recorded approximately 2 wk after the last POST herbicide treatment.

[b] AMARE, redroot pigweed; CCHPA, longspine sandbur; CHEAL, common lambsquarters; KCHSC, kochia; PANMI, wild proso millet; POROL, common purslane; SETVI, green foxtail; SOLSA, hairy nightshade.

[c] *, difference ($P = 0.05$) in weed and seed-bank density between crop rotations within a specific year; †, difference ($P = 0.05$) in weed and seed-bank density between a crop rotation in the first year and the same rotation 6 yr later.

longspine sandbur declined in the crop rotation. Where corn was grown for 6 yr, the 2003 densities of kochia, common purslane, wild proso millet, and longspine sandbur declined from densities observed in 1998, whereas the densities of common lambsquarters, redroot pigweed, hairy nightshade, and green foxtail were similar in 1998 and 2003.

The number of seeds in the seed bank did not differ between continuous corn or crop rotation for any of the eight weed species in any of the 6 yr. However, in both main plots, the densities of common lambsquarters, kochia, redroot pigweed, hairy nightshade, wild proso millet, and longspine sandbur seed decreased from 1998 to 2003. Averaged over the two cropping systems, the total number of seed per kilogram of soil was 163 in 1998 compared with 24 in 2003, an 85% decline in the seed bank.

Weed-Control Treatments. The four weed control treatments influenced weed density and the number of seeds in the seed bank over the 6 yr of the study (Table 4). As noted earlier, kochia was the predominant broadleaf weed present in the study area the year before initiating the experiment. This dominance was evident in 1998, with kochia density, measured 2 wk after the last POST herbicide treatment, averaging 490 plants/10 m^2 where the low rate of glyphosate was applied. Also present in the low-rate glyphosate treatment plot were common lambsquarters, common purslane, and redroot pigweed at densities of 136, 48, and 20 plants/10 m^2, respectively. Increasing glyphosate rate from 0.4 to 0.8 kg/ha reduced kochia density in 1998 by 86% to 70 plants/10 m^2. By 2003, kochia density had declined from 490 to 4 plants/10 m^2 in subplots treated with glyphosate at 0.4 kg/ha and from 70 to 2 plants/10 m^2 in subplots treated with glyphosate at 0.8 kg/ha. The alternating glyphosate and nonglyphosate treatments were also effective in controlling kochia as both treatments reduced kochia density.

Kochia presence in the seed bank followed the same trend as plant counts, and by 2003, kochia was not detected in the seed bank, and the kochia plant population was only 2 to 4 plants/10 m^2 (Table 4). All herbicide treatments dramatically reduced kochia density to the extent that kochia was no longer a predominant species in the experimental area by 2002.

Glyphosate rate did not influence common lambsquarters density in 1998 or 1999, but after 3 consecutive yr of glyphosate use, more common lambsquarters plants were present in the low-rate glyphosate treatment compared with the standard-rate glyphosate treatment (Table 4). The improvement in common lambsquarters control with the increased rate of glyphosate was evident in 2001, 2002, and 2003. In 2003, common lambsquarters density had increased over 300%, from 136 plants/10 m^2 in 1998 to 449 plants/10 m^2 in plots treated with the low-rate of glyphosate. However, common lambsquarters density did not increase in plots treated with glyphosate at 0.8 kg/ha each year or when glyphosate was alternated with a nonglyphosate treatment. The nonglyphosate treatment provided better common lambsquarters control in 1998, 2001, and 2003 than the standard rate of glyphosate.

The density of common lambsquarters seed in the seed bank tended to reach a low point with all herbicide treatments in 2002 and then started to increase in 2003 (Table 4). In 2003, the seed-bank density of common lambsquarters was greater in plots treated with the low rate of glyphosate compared with plots treated with the standard rate of glyphosate. Compared with that observed in 1998, common lambsquarters seed-bank density had declined in all herbicide treatments after 6 yr. In 2003, seed-bank density was similar among glyphosate at the standard rate, alternating glyphosate, and nonglyphosate treatments. The seed-bank density of common lambsquarters did not increase as rapidly as in-crop plant density in the low-rate glyphosate treatment.

Redroot pigweed density varied over the 6-yr period (Table 4). In 1998, the density of redroot pigweed was lower in the nonglyphosate-treated plots compared with the standard-rate treatment of glyphosate. However, after 6 yr, redroot pigweed density in the nonglyphosate treatment had increased from 0 to 55 plants/10 m^2. Redroot pigweed density did not change from 1998 to 2003 in glyphosate treatments. The seed-bank density of redroot pigweed after 6 yr had declined in all herbicide treatments and did not differ among treatments.

In 1998, hairy nightshade density in the four herbicide treatments ranged from 0 to 4 plants/10 m^2 (Table 4). Fewer hairy nightshade plants were in the nonglyphosate-treated plots compared with the standard-rate treatment of glyphosate in 1998. In 2001, more hairy nightshade plants remained in plots treated with the low rate of glyphosate compared with the standard rate. Over the 6 yr period, the density of hairy nightshade increased in glyphosate-treated plots and remained at a similar level in the nonglyphosate treatment. The seed-bank density of hairy nightshade declined in response to all weed-control treatments.

The final broadleaf weed observed in the experiment was common purslane. In 1998, common purslane density was influenced by all herbicide treatments and was lower in the nonglyphosate-treated plots compared with plots treated with the standard rate of glyphosate (Table 4). The difference in common purslane density between plots treated with the standard rate of glyphosate and the nonglyphosate treatment was also evident in 2003. In 2003, more common purslane plants were present in plots treated with the standard rate of glyphosate than in plots treated with the low rate or alternating use of glyphosate. Common purslane's prostrate growth habit restricts the ability of the plant to compete in tall crops, like corn, more than in shorter-statured crops, such as sugarbeet and spring wheat (Table 3). Because the standard rate of glyphosate reduced the density of common lambsquarters more than the low rate of glyphosate, the reduction probably allowed more space for common purslane to become established. The seed-bank density of common purslane was low throughout the study.

Initially, the study area was infested with wild proso millet. Even after the final POST herbicide treatment in 1998, the density of wild proso millet remained high (Table 4). The nonglyphosate treatment provided better wild proso millet control in 1998 than the standard rate of glyphosate. The density of wild proso millet dropped dramatically after 1998 in all treatments; by 2003, the density had declined from 458 to 1 plant/10 m^2 where the standard rate of glyphosate was used and from 273 to 7 plants/10 m^2 in the nonglyphosate treatment. Wild proso millet seed was not detected in the seed bank after 1998.

The nonglyphosate treatment was not as effective as the standard rate of glyphosate in controlling longspine sandbur in 1998, 2000, 2001, or 2003 (Table 4). The density of longspine sandbur declined from 57 to 0.2 plants/10 m^2 from 1998 to 2003 in plots treated with the standard rate of glyphosate. Longspine sandbur density declined from 431 to 86 plants/10 m^2 from 1998 to 2003 in nonglyphosate treated areas. However, the density of longspine sandbur was lowest in 2003 where the low and standard rates of glyphosate were used. Longspine sandbur seed was not detected in the seed bank after the first year of study.

During the first year, the standard rate of glyphosate was more effective than the nonglyphosate treatment in controlling green foxtail (Table 4). However, after 6 yr of use, the density of green foxtail remained at a similar level in glyphosate and alternating-glyphosate treatments. Green foxtail declined from 31 to 2 plants/10 m^2 over this period in the nonglyphosate treatment. The seed bank initially contained very few green foxtail seed; after 6 yr, the density of seed had not changed.

Practical Implications. During the 6 yr of this study, composition of the weed population shifted from kochia and wild proso millet to predominately common lambsquarters (Table 4). Using the low rate of glyphosate twice each year for 3 yr allowed common lambsquarters density to increase, whereas using the standard- and alternating-glyphosate treatments did not allow common lambsquarters density to increase. Common lambsquarters density also increased in the nonglyphosate treatment over the 6-yr period.

Weed-control treatments suppressed weeds during the first 5 yr of the experiment to the extent that weed escapes did not influence corn grain yields (Table 5). However, by the sixth year of the study, corn yields were 43% lower where the low rate of glyphosate was used for weed control compared with plots treated with the standard rate of glyphosate. This was the result of poor common lambsquarters control and severe competition where the low rate of glyphosate was used (Table 4). Corn yields in areas treated with the standard- or alternating-glyphosate treatment were similar to that of the nonglyphosate treatment.

Table 4. Effect of weed control treatments averaged over crop rotations on in-crop weed and seed-bank density at Scottsbluff, Nebraska, from 1998 through 2003.

Year	Treatment no.	Weed control treatment	Weed density[a]	Comparison	Seed bank	Comparison	Weed density[a]	Comparison	Seed bank	Comparison
			plants/10 m^2		seeds/kg soil		plants/10 m^2		seeds/kg soil	
				CHEAL[b]				KCHSC[b]		
1998	1	Low	136	1 vs. 2	134	1 vs. 2*	490	1 vs. 2*	15	1 vs. 2
	2	Standard	114	2 vs. 3*[c]	62	2 vs. 3*	70	2 vs. 3	11	2 vs. 3
	3	Alternating	200	3 vs. 4*	95	3 vs. 4	66	3 vs. 4*	9	3 vs. 4
	4	Nonglyphosate	11	4 vs. 2*	134	4 vs. 2*	187	4 vs. 2*	13	4 vs. 2*
1999	1	Low	40	1 vs. 2	44	1 vs. 2	50	1 vs. 2*	0	1 vs. 2
	2	Standard	18	2 vs. 3	31	2 vs. 3	11	2 vs. 3	0	2 vs. 3
	3	Alternating	9	3 vs. 4	33	3 vs. 4	13	3 vs. 4	0.2	3 vs. 4
	4	Nonglyphosate	7	4 vs. 2	26	4 vs. 2	48	4 vs. 2	0	4 vs. 2
2000	1	Low	86	1 vs. 2*	55	1 vs. 2	4	1 vs. 2	0	
	2	Standard	37	2 vs. 3	59	2 vs. 3	2	2 vs. 3	0	
	3	Alternating	55	3 vs. 4*	64	3 vs. 4	2	3 vs. 4	0	
	4	Nonglyphosate	15	4 vs. 2	66	4 vs. 2	7	4 vs. 2	0	
2001	1	Low	222	1 vs. 2*	66	1 vs. 2*	35	1 vs. 2*	0.2	1 vs. 2
	2	Standard	26	2 vs. 3	18	2 vs. 3	9	2 vs. 3	0	2 vs. 3
	3	Alternating	13	3 vs. 4	29	3 vs. 4	31	3 vs. 4	0	3 vs. 4*
	4	Nonglyphosate	7	4 vs. 2*	26	4 vs. 2	48	4 vs. 2	2	4 vs. 2*
2002	1	Low	106	1 vs. 2*	15	1 vs. 2	4	1 vs. 2	0	
	2	Standard	9	2 vs. 3	4	2 vs. 3	1	2 vs. 3	0	
	3	Alternating	29	3 vs. 4	7	3 vs. 4	2	3 vs. 4	0	
	4	Nonglyphosate	2	4 vs. 2	7	4 vs. 2	0	4 vs. 2	0	
2003	1	Low	449	1 vs. 2 *†[c]	37	1 vs. 2*†	4	1 vs. 2†	0	†
	2	Standard	141	2 vs. 3	11	2 vs. 3†	2	2 vs. 3†	0	†
	3	Alternating	123	3 vs. 4†	18	3 vs. 4†	2	3 vs. 4†	0	†
	4	Nonglyphosate	84	4 vs. 2*†	11	4 vs. 2†	4	4 vs. 2†	0	†
				AMARE[b]				SOLSA[b]		
1998	1	Low	20	1 vs. 2	18	1 vs. 2	0	1 vs. 2	18	1 vs. 2
	2	Standard	35	2 vs. 3	11	2 vs. 3	0	2 vs. 3	14	2 vs. 3
	3	Alternating	18	3 vs. 4*	9	3 vs. 4*	1	3 vs. 4	17	3 vs. 4
	4	Nonglyphosate	0	4 vs. 2*	18	4 vs. 2	4	4 vs. 2	21	4 vs. 2
1999	1	Low	2	1 vs. 2	7	1 vs. 2	11	1 vs. 2	14	1 vs. 2
	2	Standard	0.2	2 vs. 3	4	2 vs. 3	10	2 vs. 3	17	2 vs. 3
	3	Alternating	0.2	3 vs. 4	4	3 vs. 4	6	3 vs. 4	21	3 vs. 4
	4	Nonglyphosate	0	4 vs. 2	2	4 vs. 2	1	4 vs. 2*	19	4 vs. 2
2000	1	Low	22	1 vs. 2	7	1 vs. 2	23	1 vs. 2	7	1 vs. 2
	2	Standard	15	2 vs. 3	9	2 vs. 3	20	2 vs. 3	6	2 vs. 3
	3	Alternating	18	3 vs. 4*	9	3 vs. 4	22	3 vs. 4	7	3 vs. 4
	4	Nonglyphosate	7	4 vs. 2	4	4 vs. 2	12	4 vs. 2	11	4 vs. 2
2001	1	Low	4	1 vs. 2	7	1 vs. 2	10	1 vs. 2*	17	1 vs. 2
	2	Standard	0.7	2 vs. 3	7	2 vs. 3	0.7	2 vs. 3	18	2 vs. 3
	3	Alternating	0.2	3 vs. 4	4	3 vs. 4	2	3 vs. 4	22	3 vs. 4
	4	Nonglyphosate	0.2	4 vs. 2	4	4 vs. 2	0.7	4 vs. 2	22	4 vs. 2
2002	1	Low	0.7	1 vs. 2	2	1 vs. 2	0	1 vs. 2	3	1 vs. 2
	2	Standard	0	2 vs. 3	2	2 vs. 3	0	2 vs. 3	4	2 vs. 3
	3	Alternating	0	3 vs. 4	2	3 vs. 4	0	3 vs. 4	5	3 vs. 4
	4	Nonglyphosate	2	4 vs. 2	0.7	4 vs. 2	0	4 vs. 2	6	4 vs. 2
2003	1	Low	20	1 vs. 2	2	1 vs. 2†	5	1 vs. 2†	2	1 vs. 2†
	2	Standard	33	2 vs. 3	2	2 vs. 3†	6	2 vs. 3†	2	2 vs. 3†
	3	Alternating	44	3 vs. 4	2	3 vs. 4†	10	3 vs. 4†	2	3 vs. 4†
	4	Nonglyphosate	55	4 vs. 2†	4	4 vs. 2†	11	4 vs. 2	9	4 vs. 2†
				POROL[b]				PANMI[b]		
1998	1	Low	48	1 vs. 2*	1		458	1 vs. 2	9	1 vs. 2
	2	Standard	28	2 vs. 3*	0.3		458	2 vs. 3	7	2 vs. 3

Table 4. Continued.

Year	Treatment no.	Weed control treatment	Weed density[a]	Comparison	Seed bank	Comparison	Weed density[a]	Comparison	Seed bank	Comparison
			plants/10 m^2		seeds/kg soil		plants/10 m^2		seeds/kg soil	
	3	Alternating	129	3 vs. 4*	1		554	3 vs. 4*	7	3 vs. 4
	4	Nonglyphosate	2	4 vs. 2*	1		273	4 vs. 2*	13	4 vs. 2
1999	1	Low	18	1 vs. 2	0		4	1 vs. 2	0	
	2	Standard	8	2 vs. 3	0		7	2 vs. 3	0	
	3	Alternating	1	3 vs. 4	0.2		4	3 vs. 4	0	
	4	Nonglyphosate	0	4 vs. 2*	0		4	4 vs. 2	0	
2000	1	Low	24	1 vs. 2	0.9		9	1 vs. 2	0	
	2	Standard	12	2 vs. 3	0.7		4	2 vs. 3	0	
	3	Alternating	14	3 vs. 4*	0.7		4	3 vs. 4	0	
	4	Nonglyphosate	0.2	4 vs. 2*	0.7		4	4 vs. 2	0	
2001	1	Low	9	1 vs. 2	0		0.2	1 vs. 2	0	
	2	Standard	6	2 vs. 3	0		0.2	2 vs. 3	0	
	3	Alternating	0	3 vs. 4	0		0.2	3 vs. 4	0	
	4	Nonglyphosate	0	4 vs. 2	0		0	4 vs. 2	0	
2002	1	Low	6	1 vs. 2	0		0	1 vs. 2	0	
	2	Standard	0.2	2 vs. 3	0		0	2 vs. 3	0	
	3	Alternating	0.2	3 vs. 4	0		0	3 vs. 4	0	
	4	Nonglyphosate	1	4 vs. 2	0		0.2	4 vs. 2	0	
2003	1	Low	20	1 vs. 2*	0.2		0.2	1 vs. 2†	0	
	2	Standard	93	2 vs. 3*†	2		1	2 vs. 3†	0	
	3	Alternating	21	3 vs. 4†	0.2		2	3 vs. 4†	0	
	4	Nonglyphosate	14	4 vs. 2*†	0		7	4 vs. 2†	0	
				CCHPA[b]				SETVI[b]		
1998	1	Low	73	1 vs. 2	2	1 vs. 2	1	1 vs. 2	0	1 vs. 2*
	2	Standard	57	2 vs. 3	2	2 vs. 3	4	2 vs. 3	1	2 vs. 3
	3	Alternating	37	3 vs. 4*	2	3 vs. 4	0	3 vs. 4*	1	3 vs. 4
	4	Nonglyphosate	431	4 vs. 2*	1	4 vs. 2*	31	4 vs. 2*	1	4 vs. 2
1999	1	Low	0.7	1 vs. 2	0		2	1 vs. 2	0.7	1 vs. 2
	2	Standard	0.7	2 vs. 3	0		4	2 vs. 3	0	2 vs. 3
	3	Alternating	2	3 vs. 4	0		4	3 vs. 4	0	3 vs. 4
	4	Nonglyphosate	2	4 vs. 2	0		11	4 vs. 2	0	4 vs. 2
2000	1	Low	2	1 vs. 2	0		1	1 vs. 2	0.2	1 vs. 2
	2	Standard	0	2 vs. 3	0		1	2 vs. 3	0.7	2 vs. 3
	3	Alternating	0.7	3 vs. 4*	0		1	3 vs. 4	0	3 vs. 4
	4	Nonglyphosate	48	4 vs. 2*	0		1	4 vs. 2	0.7	4 vs. 2
2001	1	Low	4	1 vs. 2	0		0.2	1 vs. 2	0	1 vs. 2
	2	Standard	4	2 vs. 3	0		0	2 vs. 3	0.2	2 vs. 3
	3	Alternating	15	3 vs. 4*	0		0.7	3 vs. 4	0	3 vs. 4
	4	Nonglyphosate	101	4 vs. 2*	0.2		0.7	4 vs. 2	0.2	4 vs. 2
2002	1	Low	0	1 vs. 2	0		0		0	
	2	Standard	0	2 vs. 3	0		0		0	
	3	Alternating	0.2	3 vs. 4	0		0		0	
	4	Nonglyphosate	9	4 vs. 2	0		0		0	
2003	1	Low	0	1 vs. 2†	0	†	0	1 vs. 2	0	1 vs. 2
	2	Standard	0.2	2 vs. 3†	0	†	2	2 vs. 3	0	2 vs. 3
	3	Alternating	18	3 vs. 4*	0	†	2	3 vs. 4	0	3 vs. 4
	4	Nonglyphosate	86	4 vs. 2*†	0		2	4 vs. 2†	0.2	4 vs. 2

[a] Weed density recorded approximately 2 wk after the last POST herbicide treatment.

[b] AMARE, redroot pigweed; CCHPA, longspine sandbur; CHEAL, common lambsquarters; KCHSC, kochia; PANMI, wild proso millet; POROL, common purslane; SETVI, green foxtail; SOLSA, hairy nightshade.

[c] *, difference (P = 0.05) in weed and seed-bank density between weed control treatments within a specific year; †, difference (P = 0.05) in weed and seed-bank density between a specific treatment in the first year and the same treatment 6 yr later.

Table 5. Effect of weed control treatments on continuous corn grain yields at Scottsbluff, NE, from 1998 through 2003.

Year	Treatment no.	Glyphosate treatment	Corn grain yield	Comparison
			kg/ha	
1998	1	Low	10,700	1 vs 2
	2	Standard	11,300	2 vs 3
	3	Alternating	11,800	3 vs 4
	4	Nonglyphosate	11,400	4 vs 2
1999	1	Low	9,500	1 vs 2
	2	Standard	9,000	2 vs 3
	3	Alternating	9,300	3 vs 4
	4	Nonglyphosate	9,700	4 vs 2
2000	1	Low	11,300	1 vs 2
	2	Standard	13,100	2 vs 3
	3	Alternating	12,200	3 vs 4
	4	Nonglyphosate	11,500	4 vs 2
2001	1	Low	10,500	1 vs 2
	2	Standard	10,000	2 vs 3
	3	Alternating	10,400	3 vs 4
	4	Nonglyphosate	10,000	4 vs 2
2002	1	Low	11,500	1 vs 2
	2	Standard	10,500	2 vs 3
	3	Alternating	11,600	3 vs 4*[a]
	4	Nonglyphosate	9,500	4 vs 2
2003	1	Low	5,800	1 vs 2*†
	2	Standard	10,100	2 vs 3†
	3	Alternating	10,000	3 vs 4*†
	4	Nonglyphosate	10,700	4 vs 2†

[a] *, difference (P = 0.05) in grain yield between treatments with in a specific year; †, difference (P = 0.05) in grain yield between a specific treatment in the first year and the same treatment 6 yr later.

Controlling weeds in glyphosate-resistant corn with two applications of the standard rate of glyphosate provided weed control and corn grain yields similar to the nonglyphosate treatment (Tables 4 and 5). This finding is similar to that of Scursoni et al. (2006), who showed that the frequency and rate of glyphosate use in soybean was an important factor in regulating weed shifts and limiting weed escapes. These researchers also found that common lambsquarters was responsive to the intensity of glyphosate use, with weed density increasing as glyphosate frequency and rate decreased.

Researchers have predicated that weed shifts would occur as the intensity of herbicide use increased (Bandeen et al. 1982; Harper 1957). As expected, weed shifts have been observed as the frequency and rate of glyphosate use in glyphosate-resistant crops has increased (Culpepper 2006; Scursoni et al. 2006; Shaner 2000). Trying to prevent weed shifts from occurring with the use of glyphosate in glyphosate-resistant crops may not be practical. However, managing weed shifts is important. The use of a crop rotation of corn, sugarbeet, and spring wheat caused common lambsquarters density to increase compared with continuous corn. This increase likely occurred because sugarbeet and spring wheat are less competitive with weeds than is corn. The use of crop rotation to manage weed shifts will depend on the competitiveness of the crops in the rotation. If rotational crops are not as competitive as corn, growing continuous corn would be more effective than a crop rotation in managing common lambsquarters. The use of the standard rate of glyphosate in managing weed shifts was also critical. The density of common lambsquarters was greater following two applications of glyphosate at 0.4 kg/ha per year compared with two applications of glyphosate at 0.8 kg/ha. Common lambsquarters density remained similar over 6 yr when the standard rate of glyphosate was used twice each year for early season weed control.

Differential tolerance of annual broadleaf weeds to glyphosate has been reported in common ragweed, velvetleaf (Kapusta et al. 1994), and morningglory (Jordan et al. 1997). The normal variability in response of weeds to a herbicide can allow populations of weeds with enhanced tolerance to increase with increased use of the herbicide even though the weed can still be controlled at a higher rate (Bandeen et al. 1982). Increases in common lambsquarters with repeated use of glyphosate at 0.4 kg/ha was probably because of differential tolerance of common lambsquarters to glyphosate. Over time, tolerant common lambsquarters biotypes increased with the low-rate glyphosate treatment, but development of tolerant biotypes was slowed by the use of glyphosate at 0.8 kg/ha.

Alternating two applications of glyphosate with a nonglyphosate treatment the next year was similar to using two applications of glyphosate at 0.8 kg/ha every year for managing common lambsquarters. If glyphosate was never used for weed control over the 6-yr period, common lambsquarters density was lower compared with continuous use of glyphosate at 0.8 kg/ha. Even in the nonglyphosate treatment, a weed shift to common lambsquarters occurred and over time, the density of common lambsquarters and redroot pigweed increased. The results of this experiment indicated that important factors in managing a weed population that was shifting to common lambsquarters were using a competitive crop such as corn and use of the standard rate of glyphosate.

Acknowledgments

This study was supported, in part, by funds provided through Hatch Act, USDA. Additional support was provided by Monsanto.

Literature Cited

Bandeen, J. D., G. R. Stephenson, and E. R. Cowett. 1982. Discovery and distribution of herbicide-resistant weeds in North America. Pages 9–30 *in* H. M. LeBaron and J. Gressel, eds. Herbicide Resistance in Plants. New York: J. Wiley.

Buttel, F. H. 2002. The Adoption and Diffusion of GM Crop Varieties: The "Genetic Revolution" in Global Perspective. 1996–2001. Madison, WI: University of Wisconsin PTAS Staff Paper Series 6.

Clements, D. R., S. F. Weise, and C. J. Swanton. 1994. Integrated weed management and weed species diversity. Phytoprotection 75:1–18.

Culpepper, A. S. 2006. Glyphosate-induced weed shifts. Weed Technol. 20:277–281.

Culpepper, A. S., T. L. Grey, W. K. Vencill, J. M. Kichler, T. M. Webster, S. M. Brown, A. C. York, J. W. Davis, and W. W. Hanna. 2006. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci. 54:620–626.

Fryer, J. D. 1981. Weed management: fact or fable? Phil. Trans. R. Soc. Lond. B295 185197.

Haas, H. and J. C. Streibig. 1982. Changing patterns of weed distribution as a result of herbicide use and other agronomic factors. Pages 57–80 *in* H. M. Le Baron and J. Gessel, eds. Herbicide Resistance in Plants. New York: J. Wiley.

Harper, J. L. 1957. Ecological aspects of weed control. Outlook Agric. 1:197–205.
Jordan, D. L., A. C. York, J. L. Griffin, P. A. Clay, P. R. Vidrine, and D. B. Reynolds. 1997. Influence of application variables on efficacy of glyphosate. Weed Technol. 11:354–362.
Kapusta, G. L., R. F. Krausz, and J. L. Matthews. 1994. Soybean tolerance and summer annual weed control with glufosinate and glyphosate in resistant soybeans. Proc. North Cent. Weed Control Conf. 49:120.
SAS. 2004. SAS Online Doc. 9.1.3. Cary, NC: SAS Institute Inc.
Scursoni, J., F. Forcella, J. Gunsolus, M. Owen, R. Oliver, R. Smeda, and R. Vidrine. 2006. Weed diversity and soybean yield with glyphosate management along a north-south transect in the United States. Weed Sci. 54:713–179.
Shaner, D. L. 2000. The impact of glyphosate tolerant crops on the use of other herbicides and on resistance management. Pest Manag. Sci. 56:320–326.
Swanton, C. J., D. R. Clements, and D. A. Derksen. 1993. Weed succession under conservation tillage: a hierarchical framework for research and management. Weed Technol. 7:286–297.
Westra, P., R. Wilson, P. Stahlman, S. Miller, G. Wicks, S. Nissen, P. Chapman, and J. Withrow. 2004. Results of six years of weed shift studies in Central Great Plains Roundup Ready irrigated and dryland crops. Weed Sci. Soc. Am. Abstr. 42:92.
Young, B. 2006. Changes in herbicide use patterns and production practices resulting from glyphosate resistant crops. Weed Technol. 20:301–307.

Received December 7, 2006, and approved May 17, 2007.