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Weed Control and Yield Comparisons of Glyphosate- and Glufosinate-Resistant Corn Grown in Rotation

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*Information on long-term glyphosate- and glufosinate-resistant corn (*Zea mays *L.) production on weed control and rotation benefits is lacking. A six-year field study was conducted from 2004 to 2009 at Stoneville, MS, to examine the effects of rotating glyphosate-resistant and glufosinate-resistant corn under reduced tillage conditions on weed control, soil weed seedbanks, and yield. The four rotation systems were glyphosate-resistant and glufosinate-resistant corn grown continuously and in rotation with two herbicide programs, post-emergence-only herbicides (POST) and preemergence herbicides followed by POST (PRE + POST). Control of 13 predominant weed species in glyphosate-resistant and glufosinate-resistant corn was >95%, regardless of herbicide program, with the exception of johnsongrass and yellow nutsedge, both perennial weeds. Johnsongrass and yellow nutsedge control was lower in the continuous glufosinate-resistant corn system compared with other rotation systems. Yellow nutsedge control was higher with the PRE + POST (89% to 99%) compared with the POST-only (72% to 86%) treatment. Corn yields were similar regardless of rotation when a corn cultivar stacked with both glyphosate-resistant and glufosinate-resistant traits was used. The PRE + POST program gave 5% to 10% higher yield than the POST-only program in four of six years. The seedbank for yellow nutsedge and predominant grass and broadleaf weeds was not significant among the four rotation systems. Seedbanks for*

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grasses and yellow nutsedge were higher in the POST-only program (20.5 and 1.8 per core of 678 cm^3, respectively) compared with the PRE + POST program (9.5 and 0.4 per core, respectively). These results indicate that johnsongrass and yellow nutsedge control could be reduced in continuous glufosinate-resistant corn and could be mitigated by rotating with glyphosate-resistant corn.

KEYWORDS *Conservation tillage, herbicide rotation, reduced tillage, transgenic crop, weed management*

INTRODUCTION

Transgenic corn (*Zea mays* L.) resistant to glufosinate and transgenic corn resistant to glyphosate were commercialized in the United States in the late 1990s (Duke 2005; Reddy & Koger 2006). Ability to apply glufosinate in glufosinate-resistant corn and glyphosate in glyphosate-resistant corn provides producers with simplicity and flexibility in controlling a broad spectrum of weeds without injuring corn (Reddy & Whiting 2000; Reddy 2001; Reddy 2003; Reddy & Chachalis 2004; Green & Castle 2010; Bayer CropScience 2011; Monsanto Company 2011). Glyphosate-resistant (Reddy 2003; Reddy & Chachalis 2004; Senseman 2007; Monsanto Company 2011), and glufosinate-resistant (Culpepper & York 1999; Ritter & Menbere 2001; Tharp & Kells 2001; Shrestha et al. 2001; Bayer CropScience 2011) corn weed-management systems have both advantages and limitations. Glufosinate controls a broad spectrum of weeds and is an alternative to glyphosate. Because glufosinate acts like a contact herbicide with limited translocation (Senseman 2007; Everman et al. 2009a, b), thorough spray coverage is required for complete kill of targeted weeds. Because of limited translocation, glufosinate is not as effective as glyphosate on perennials.

In the United States, area planted to glyphosate-resistant corn has increased from 7% in 2000 to 72% in 2011 (United States Department of Agriculture 2011). However, it should be noted that the area reported for corn includes all herbicide-resistant (single and stacked gene) hybrids. Currently, corn hybrids with the glyphosate-resistant trait alone or stacked with glufosinate-resistant trait are commercially available in the United States. Because of their remarkable success, glyphosate-resistant crops have dominated the U.S. seed market, and thus the area planted to glufosinate-resistant crops is negligible. Overreliance on single herbicide-based programs could lead to problems, such as weed species shifts and evolution of resistant weeds. The widespread adoption of glyphosate-resistant crops has not only caused weed species shifts in these crops, but has also resulted in evolution of glyphosate-resistant weed biotypes (Reddy & Norsworthy

2010). In a three-year rotation, continuous bromoxynil-resistant cotton (*Gossypium hirsutum* L.) system resulted in higher densities of common purslane (*Portulaca oleracea* L.), sicklepod (*Senna obtusifolia* [L.] H.S. Irwin & Barneby), and yellow nutsedge (*Cyperus esculentus* L.) compared with continuous glyphosate-resistant cotton (Reddy 2004). After six years, control of yellow nutsedge decreased in continuous non-glyphosate-resistant cotton compared with rotated non-glyphosate-resistant and glyphosate-resistant cotton (Reddy et al. 2006). To date, 21 weed species are reported to be resistant to glyphosate (Heap 2011), and until recently there were no reports of weed species resistant to glufosinate. In 2011, Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* [Lam.] Husnot) resistance to glufosinate was reported (Avila-Garcia & Mallory-Smith 2011). Glyphosate-resistant and glufosinate-resistant corn offers growers the advantages of rotating herbicides with different mechanisms of action. Alternating the sequence of herbicide use in a rotation has the potential to increase yields. When herbicides are rotated, control of problem weeds is improved and selection pressure toward the evolution of resistant weeds is reduced.

Reduced tillage is a general term describing several types of management practices, all of which exclude at least one major cultivation practice or minimize the intensity of tillage operations (Locke & Bryson 1997). Moreover, reduced tillage promotes accumulation of crop residues at the soil surface, thereby reducing the potential for soil erosion compared with conventional tillage (Locke & Bryson 1997). In the United States, about 36%, 40%, and 24% of corn area was planted under conventional tillage, conservation tillage, and reduced tillage system, respectively, in 2008 (Conservation Technology Information Center 2011).

Although weed control and yield responses in glyphosate- and glufosinate-resistant corn have been well documented, the information on weed control and yield comparisons of glyphosate-resistant and glufosinate-resistant corn grown continuously and in rotation is lacking. The objectives of this six-year field study were to assess weed control, soil weed seedbanks, and corn yield response in glyphosate-resistant and glufosinate-resistant corn rotation systems involving glyphosate POST and glufosinate POST applications either alone or following preemergence herbicides under a reduced tillage management system.

MATERIALS AND METHODS

Experimental Conditions

A six-year field study was conducted from 2004 through 2009 at the USDA-ARS Crop Production Systems Research Unit farm in Stoneville, MS. The soil was a Dundee silt loam (fine-silty, mixed, thermic Aeric Ochraqualf) with pH of 6.7, 1.1% organic matter, a cation exchange capacity (CEC) of

15 cmol/kg, and soil textural fractions of 26% sand, 55% silt, and 19% clay. Prior to this study, the experimental area was under soybean (*Glycine max* [L.] Merr.) production. Field preparation consisted of subsoiling, disking, and bedding in the fall of 2003. The land was not tilled in subsequent years, but the raised beds were refurbished each fall after harvest with no additional tillage operations to maintain as a reduced-tillage system. The experimental area was treated with paraquat at 1.1 kg ai/ha 2 to 5 d prior to planting corn to kill existing vegetation.

The four rotation systems were continuous glyphosate-resistant corn (RRRRRR), continuous glufosinate-resistant corn (LLLLLL), glyphosate-resistant corn rotated with glufosinate-resistant corn (RLRLRL), and glufosinate-resistant corn rotated with glyphosate-resistant corn (LRLRLR), and two herbicide programs were post-emergence-only herbicides (POST) and preemergence herbicides followed by POST (PRE + POST). The reverse rotation (RLRLRL and LRLRLR) sequences were included to make comparisons between rotation and continuous herbicide systems each year. Corn cultivars, planting dates, herbicides and application timing, and harvest dates used in the study are presented in Table 1. Corn was planted in rows spaced 102-cm apart using a MaxEmerge 2 planter. Cultivars were selected on the basis of regional use patterns of producers and seed availability. The POST-only treatment included two applications of glyphosate at 0.87 kg ae/ha in glyphosate-resistant corn and two applications of glufosinate at 0.41 kg ai/ha in glufosinate-resistant corn. The PRE + POST treatment included atrazine at 1.82 kg ai/ha plus *s*-metolachlor at 1.41 kg ai/ha followed by two applications of glyphosate at 0.87 kg/ha in glyphosate-resistant corn or two applications of glufosinate at 0.41 kg/ha in glufosinate-resistant corn. PRE herbicides were applied immediately after planting. First POST and second POST-directed treatments were applied at three to five and six to eight weeks after planting corn, respectively. All herbicide treatments, except POST-directed, were applied broadcast with a tractor-mounted sprayer with 8004 standard flat spray nozzles delivering 187 L/ha water. POST-directed treatments were applied broadcast using a hooded sprayer equipped with off-centered nozzles (OC-01 flat spray tips) for post-direct spraying and sprayer hoods with three nozzles (95002 even flat spray tips) for spraying between the rows. Fertilizer application was standard for corn production (Reddy & Bryson 2009), and corn was irrigated on an as-needed basis each year.

Control of individual weed species in all plots was visually estimated on a scale of 0% (no weed control) to 100% (complete weed control) two weeks after POST-directed herbicide application. Corn was harvested from all eight rows with a combine, and grain yield was adjusted to 15% moisture. Overall effect of rotation systems on weed seedbank was assessed at the end of a six-year rotation. Nine soil cores (9.2 cm diameter and 10.2 cm deep) were collected randomly from each plot after corn harvest in 2009. The cores were collected on a diagonal line between second and seventh row, 6 m

TABLE 1 Production practices used in glufosinate-resistant and glyphosate-resistant corn grown continuously and in rotation at Stoneville, MS, 2004–2009[a,b]

Year	Production practice	Glufosinate-resistant corn	Glyphosate-resistant corn
2004	Variety	Garst 8347LL	DKC69–72 (RR2)
	Planting date	12 March	12 March
	PRE (at planting)	Atrazine + *S*-metolachlor	Atrazine + *S*-metolachlor
	EPOST (4 WAP)	Glufosinate	Glyphosate
	PD (6 WAP)	Glufosinate	Glyphosate
	Harvest date	13 August	13 August
2005	Variety	Garst 8347LL	DKC69–72 (RR2)
	Planting date	30 March	30 March
	PRE (at planting)	Atrazine + *S*-metolachlor	Atrazine + *S*-metolachlor
	EPOST (4 WAP)	Glufosinate	Glyphosate
	PD (6 WAP)	Glufosinate	Glyphosate
	Harvest date	22 August	22 August
2006	Variety	Pioneer P31G96 (LL/RR)	Pioneer P31G96 (LL/RR)
	Planting date	27 March	27 March
	PRE (at planting)	Atrazine + *S*-metolachlor	Atrazine + *S*-metolachlor
	EPOST (3 WAP)	Glufosinate	Glyphosate
	PD (6 WAP)	Glufosinate	Glyphosate
	Harvest date	15 August	15 August
2007	Variety	Pioneer P31G71 (LL/RR)	Pioneer P31G71 (LL/RR)
	Planting date	12 March	12 March
	PRE (at planting)	Atrazine + *S*-metolachlor	Atrazine + *S*-metolachlor
	EPOST (4 WAP)	Glufosinate	Glyphosate
	PD (7 WAP)	Glufosinate	Glyphosate
	Harvest date	14 August	14 August
2008	Variety	Pioneer P31G71 (LL/RR)	Pioneer P31G71 (LL/RR)
	Planting date	24 March	24 March
	PRE (at planting)	Atrazine + *S*-metolachlor	Atrazine + *S*-metolachlor
	EPOST (4 WAP)	Glufosinate	Glyphosate
	PD (7 WAP)	Glufosinate	Glyphosate
	Harvest date	18 August	18 August
2009	Variety	Pioneer P31G71 (LL/RR)	Pioneer P31G71 (LL/RR)
	Planting date	23 March	23 March
	PRE (at planting)	Atrazine + *S*-metolachlor	Atrazine + *S*-metolachlor
	EPOST (5 WAP)	Glufosinate	Glyphosate
	PD (8 WAP)	Glufosinate	Glyphosate
	Harvest date	26 August	26 August

[a]Abbreviations: (EPOST) early post-emergence; (PD) post-emergence directed to base of the corn plant; (PRE) preemergence; and (WAP) weeks after planting corn.

[b]Rates of herbicides g a.i. (a.e. for glyphosate)/ha: Atrazine, 1,820 + *S*-metolachlor; 1,410 as PRE; glufosinate, 410; and glyphosate, 870.

inside the plot from both ends. Soil from the nine cores was spread in two 0.5 m by 0.25 m plastic trays having porous bottoms, watered as needed, and kept in a greenhouse. The greenhouse was maintained at 15/20°C (± 3°C) temperature with a 12/12 h light/dark photoperiod during winter months and at 26/22°C (± 3°C) temperature with a 13/11 h light/dark photoperiod during summer months. Weed seedlings that emerged were counted and removed from each tray on a monthly basis for 12 months to quantify total viable soil seedbank.

Statistical Analysis

The experiment was conducted in a split-plot arrangement of treatments in a randomized complete-block design with rotation as main plot and herbicides as the subplot with four replications. Each subplot consisted of eight rows of corn spaced 102 cm apart and 39.6 m long.

The data were subjected to analysis of variance using PROC GLM (SAS software, release 8.2, SAS Institute, Cary, NC), and treatment means were separated using Fisher's protected LSD test (5% level of significance). Data were averaged across years (as main effect means) if the year by treatment interactions were not significant.

RESULTS AND DISCUSSION

Thirteen predominant weed species were present in the experimental area. The grass weeds were: browntop millet, *Urochloa ramosa* (L.) Nguyen; johnsongrass, *Sorghum halepense* (L.) Pers.; junglerice, *Echinochloa colona* (L.) Link; and large crabgrass, *Digitaria sanguinalis* (L.) Scop. The broadleaf weeds were: carpetweed, *Mollugo verticillata* L.; common purslane; eclipta, *Eclipta prostrata* (L.) L.; ivyleaf morningglory, *Ipomoea hederacea* Jacq.; pitted morningglory, *Ipomoea lacunosa* L.; prickly sida, *Sida spinosa* L.; prostrate spurge, *Chamaesyce humistrata* (Engelm. ex Gray) Small; and velevetleaf, *Abutilon theophrasti* Medik. Yellow nutsedge was the dominant sedge. Control of most weed species in glyphosate-resistant and glufosinate-resistant corn was >95% (data not shown) regardless of the herbicide program, with the exception of johnsongrass and yellow nutsedge. Control of johnsongrass (71% to 100%) and yellow nutsedge (66% to 85%) was lower in the continuous glufosinate-resistant system compared with the LRLRLR, RLRLRL, and RRRRRR rotation systems (Tables 2 and 3). Yellow nutsedge control was higher with the PRE + POST (89% to 99%) compared with the POST-only (72% to 86%) treatment. Overall, in all six years yellow nutsedge control was lower with POST only in continuous LLLLLL corn (35%–75%) compared with continuous RRRRRR corn (83%–93%) (data not shown). Reduction in yellow nutsedge control in glufosinate-resistant corn could have been partly because of limited translocation of glufosinate to underground tubers and rhizomes compared with higher levels of translocation of glyphosate. As a result, yellow nutsedge reestablished by regrowth of partially controlled plants and by resprouting of tubers that were not killed by glufosinate because of limited translocation. In contrast, glyphosate had considerable activity on yellow nutsedge and effectively reduced

TABLE 2 Johnsongrass control at two weeks after second post-emergence application in glyphosate-resistant and glufosinate-resistant corn grown continuously and in rotation at Stoneville, MS, 2004–2009

	Johnsongrass[b]					
	2004	2005	2006	2007	2008	2009
Rotation/Herbicide[a]	%					
Rotation						
LLLLLL	95a	89a	76b	71b	94a	100a
LRLRLR	95a	100a	95a	99a	98a	100a
RLRLRL	99a	100a	100a	99a	100a	100a
RRRRRR	99a	100a	99a	100a	99a	100a
Herbicide						
POST	98a	97a	90a	89a	98a	100a
PRE + POST	96a	98a	95a	96a	98a	100a

[a]Abbreviations: (LL) glufosinate-resistant; (RR) glyphosate-resistant; (LR) glufosinate-resistant/glyphosate-resistant; (RL) glyphosate-resistant/glufosinate-resistant; (PRE) pre-emergence; and (POST) post-emergence.

[b]Means within a column for each main effect followed by same letter are not significantly different at the 5% level as determined by Fisher's LSD test.

TABLE 3 Yellow nutsedge control at two weeks after second post-emergence application in glyphosate-resistant and glufosinate-resistant corn grown continuously and in rotation at Stoneville, MS, 2004–2009

	Yellow nutsedge[b]					
	2004	2005	2006	2007	2008	2009
Rotation/herbicide[a]	%					
Rotation						
LLLLLL	79a	85a	80b	69b	70b	66b
LRLRLR	89a	96a	90ab	85a	93a	94a
RLRLRL	90a	94a	93a	84a	90a	86a
RRRRRR	90a	89a	94a	90a	95a	96a
Herbicide						
POST	84a	86b	81b	74b	77b	72b
PRE + POST	89a	96a	97a	89a	97a	99a

[a]Abbreviations: (LL) glufosinate-resistant; (RR) glyphosate-resistant; (LR) glufosinate-resistant/glyphosate-resistant; (RL) glyphosate-resistant/glufosinate-resistant; (PRE) pre-emergence; and (POST) post-emergence.

[b]Means within a column for each main effect followed by same letter are not significantly different at the 5% level as determined by Fisher's LSD test.

populations in the various cropping systems. In a three-year study, glyphosate POST only controlled over 92% yellow nutsedge in glyphosate-resistant cotton (Reddy 2004). In a six-year study, glyphosate POST only controlled over 95% yellow nutsedge in both glyphosate-resistant corn and glyphosate-resistant cotton (Reddy et al. 2006).

TABLE 4 Glyphosate-resistant and glufosinate-resistant corn grain yield as affected by rotation and herbicide treatments

	Corn yield[b]					
	2004	2005	2006	2007	2008	2009
Rotation/herbicide[a]	kg/ha					
Rotation						
LLLLLL	8,881b	7,970b	10,344a	9,816a	9,343a	8,520a
LRLRLR	9,355b	10,542a	10,602a	1,0308a	9,402a	8,351a
RLRLRL	12,219a	8,627b	10,218a	10,488a	9,299a	8,481a
RRRRRR	12,422a	10,482a	10,457a	10,356a	9,390a	8,477a
Herbicide						
POST	10,662a	9,126b	10,160b	9,702b	9,290a	8,117b
PRE + POST	10,776a	9,685a	10,651a	10,783a	9,427a	8,797a

[a]Abbreviations: (LL) glufosinate-resistant; (RR) glyphosate-resistant; (LR) glufosinate-resistant/glyphosate-resistant; (RL) glyphosate-resistant/glufosinate-resistant; (PRE) preemergence; and (POST) post-emergence.
[b]Means within a column for each main effect followed by same letter are not significantly different at the 5% level as determined by Fisher's LSD test.

In 2004 and 2005, corn yields were 27%–35% higher in glyphosate-resistant corn compared with glufosinate-resistant corn regardless of rotation system, mainly because of differences in yield potential of the two cultivars with different traits (Table 4). In the latter four years of the study (2006–2009), a glyphosate-resistant and glufosinate-resistant stacked gene cultivar was used instead of two separate genetic lines. Use of one cultivar eliminated genetic differences in yield potential, which enabled us to separate the effect of glyphosate- and glufosinate-based herbicide programs on yield. When a glyphosate-resistant and glufosinate-resistant stacked cultivar was used in 2006–2009, corn yields were similar regardless of rotation system (Table 4). Between herbicide programs, PRE + POST program gave 5% to 10% higher yield than POST only program in four of the six years. PRE herbicides reduce detrimental early-season weed interference with corn. The increased yield in the PRE + POST program was likely the result of improved weed control with soil-applied herbicides compared with the POST-only program.

Weed seedbank and the reserve of viable weed seeds present in the soil profile can serve as a physical history of the past successes or failures of weed-management systems. The size and species composition of the weed seedbank can help producers develop suitable weed-management strategies. The seedbank for yellow nutsedge and dominant grass and broadleaf weeds was not significant among the four rotation systems (Table 5). Seedbank for broadleaves was similar in the POST-only and the PRE + POST treatments. Seedbanks for grasses and yellow nutsedge were higher in the POST-only program (20.5 and 1.8 per core, respectively) compared with the

TABLE 5 Grasses, broadleaves, and yellow nutsedge soil seedbank as affected by rotation and herbicides at termination of a six-year study in 2009 in Stoneville, MS

	Soil seedbank[b]		
Rotation/herbicide[a]	Grasses	Broad leaves	Yellow nutsedge
Rotation		#/nine cores	
LLLLLL	118a	408a	13a
LRLRLR	129a	414a	8a
RLRLRL	147a	514a	12a
RRRRRR	145a	496a	8a
Herbicide			
POST	184a	492a	16a
PRE + POST	85b	424a	4b

[a]Abbreviations: (LL) glufosinate-resistant; (RR) glyphosate-resistant; (LR) glufosinate-resistant/glyphosate-resistant; (RL) glyphosate-resistant/glufosinate-resistant; (PRE) preemergence; and (POST) post-emergence.

[b]Means within a column for each main effect followed by same letter are not significantly different at the 5% level as determined by Fisher's LSD test.

PRE + POST program (9.5 and 0.4 per core, respectively). These results indicated that johnsongrass and yellow nutsedge control could be reduced in a continuous LLLLLL corn system and could be mitigated by rotating glufosinate-resistant corn with glyphosate-resistant corn.

In summary, continuous glufosinate-resistant corn production resulted in reduced control of johnsongrass and yellow nutsedge; however, corn yields were similar regardless of rotation system. Additional PRE or POST herbicide options (or both) are required to manage johnsongrass and yellow nutsedge in continuous glufosinate-resistant corn. Rotating glufosinate-resistant corn with glyphosate-resistant corn could also improve johnsongrass and yellow nutsedge control. Currently, glyphosate-resistant and glufosinate-resistant stacked corn hybrids are available for producers. By planting a stacked gene corn hybrid, both glyphosate and glufosinate could be used alternatively on the same corn crop to manage these weeds.

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