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Glyphosate-Resistant Giant Ragweed (*Ambrosia trifida*) and Waterhemp (*Amaranthus rudis*) Management in Dicamba-Resistant Soybean (*Glycine max*)

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Field experiments were conducted across two locations during 2011 and 2012 to evaluate herbicide options for the control of glyphosate-resistant (GR) giant ragweed and GR waterhemp in dicamba-resistant (DR) soybean. All herbicide treatments provided 91 to 100% control of GR giant ragweed 3 wk after treatment (WAT). Flumioxazin plus dicamba plus glyphosate applied preplant provided greater control and density reduction of GR giant ragweed than flumioxazin plus 2,4-D plus glyphosate. When flumioxazin plus dicamba plus glyphosate were applied preplant, the addition of dicamba to glyphosate at either the early-postemergence (EPOST) or mid-postemergence (MPOST) timing provided greater control and density reduction of GR giant ragweed than glyphosate alone. Regardless of the preplant treatment, delay of EPOST dicamba to the MPOST timing did not influence GR giant ragweed control or density reduction. In the GR waterhemp experiment, dicamba plus glyphosate applied sequentially provided 88 to 89% control and 90% density reduction at the EPOST and MPOST timings compared to only 24% control and 42% density reduction in response to glyphosate applied sequentially. Control and GR waterhemp density reduction did not improve with the addition of acetochlor to either the EPOST or late-postemergence (LPOST) timings. Flumioxazin plus chlorimuron applied PRE followed by dicamba plus glyphosate or dicamba plus glyphosate plus acetochlor provided greater control of GR waterhemp than glyphosate plus fomesafen or glyphosate alone applied EPOST. Results from this research indicate that dicamba applied once or sequentially and when timed appropriately to match the biology of the weed species can be utilized as a component of an integrated program for the management of GR weeds like giant ragweed and waterhemp in DR soybean.

Nomenclature: 2,4-D; acetochlor; chlorimuron; dicamba; flumioxazin; fomesafen; glyphosate; giant ragweed, *Ambrosia trifida* L.; waterhemp, *Amaranthus rudis* Sauer; soybean, *Glycine max* (L.) Merr.

Key words: Conrol, density reduction, postemergence, preplant.

Se realizaron experimentos de campo en dos localidades durante 2011 y 2012 para evaluar las opciones de herbicidas para el control de *Ambrosia trifida* resistente a glyphosate (GR) y *Amaranthus rudis* GR, en soya resistente a dicamba (DR). Todos los tratamientos de herbicidas brindaron 91 a 100% de control de *A. trifida* GR, 3 semanas después del tratamiento (WAT). Flumioxazin más dicamba más glyphosate aplicados pre-siembra brindaron mayor control y una mayor reducción en la densidad de *A. trifida* GR que flumioxazin más 2,4-D más glyphosate. Cuando se aplicó flumioxazin más dicamba más glyphosate en pre-siembra, la adición de dicamba a glyphosate, ya sea en post-emergencia temprana (EPOST) o post-emergencia media (MPOST), brindó mayor control y mayor reducción de la densidad de *A. trifida* GR que glyphosate solo. Sin importar el tratamiento pre-siembra, el retrasar la aplicación de dicamba de EPOST a MPOST no influenció el control o la reducción en la densidad de *A. trifida* GR. En el experimento de *A. rudis* GR, las aplicaciones secuenciales de dicamba más glyphosate brindaron 88 a 89% de control y 90% de reducción en la densidad en EPOST y MPOST al compararse con solamente 24% de control y 42% en la reducción de la densidad en respuesta a glyphosate aplicado secuencialmente. El control y la reducción en la densidad de *A. rudis* GR no mejoró con la adición de acetochlor a las aplicaciones EPOST o post-emergencia tardía (LPOST). Flumioxazin más chlorimuron aplicados PRE seguidos de dicamba más glyphosate o dicamba más glyphosate más acetochlor brindaron mayor control de *A. rudis* GR que glyphosate más fomesafen o glyphosate solo aplicado EPOST. Los resultados de esta investigación indican que la aplicación sola o secuencial de dicamba en el momento apropiado según la biología de la especie de maleza puede ser utilizada como un componente del programa integrado para el manejo de malezas GR tales como *A. trifida* y *A. rudis* en soya DR.

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Waterhemp is a member of the *Amaranthaceae* family and is distributed from Texas to Maine and extends into parts of North Dakota (Bryson and DeFelice 2009). Waterhemp is one of the most problematic weeds Midwest farmers must contend with (Bradley 2013; Bradley et al. 2007; Waggoner and Bradley 2011). Season-long control can be difficult due to a discontinuous emergence pattern and rapid vegetative growth that ranges from 0.11- to 0.16-cm per growing degree day (Horak and Loughin 2000). In addition, waterhemp can produce as many as 309,000 to 2.3 million seeds plant^{-1} when emergence occurs with soybean (Hartzler et al. 2004). Waterhemp can also cause as much as a 43% soybean yield reduction (Hager et al. 2002).

In 2005, glyphosate resistant (GR) waterhemp was first discovered in a soybean field in Platte County, Missouri after consecutive glyphosate treatments had occurred for a period of at least seven years (Legleiter and Bradley 2008). Currently, there are waterhemp populations in a number of states throughout the Midwest with resistance to glyphosate, acetolactate synthase (ALS)-, protoporphyrinogen (PPO), photosystem II-, and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides (Heap 2013). Furthermore, some waterhemp populations in Illinois have evolved multiple resistances to as many as four modes of action (Hager 2011), while populations in Kansas, Iowa, and Missouri have evolved multiple resistances to two or more herbicide modes of action (Heap 2013).

Giant ragweed is one of the most competitive weed species encountered in soybean production systems (Webster et al. 1994). Season-long competition of giant ragweed can cause severe reductions in soybean yield (Baysinger and Sims 1991,1992). Season-long giant ragweed competition reduced soybean yield 46 to 50% with a density of less than two plants per 9-m soybean row (Baysinger and Sims 1991). Webster et al. (1994) also reported a 45 to 77% yield reduction with giant ragweed competition of 1 plant per m^2. Giant ragweed exhibits a rapid growth rate, typically extending 0.3 to 1.5-m above a competing crop canopy and measuring up to 5.2-m in height (Johnson et al. 2007). In addition, giant ragweed typically emerges earlier than other summer annual weed species; emergence can begin in late March in western portions of the Corn Belt and extends much later into the growing season in eastern Corn Belt states (Harrison et al. 2001; Johnson et al. 2007; Stoller and Wax 1973). GR giant ragweed was first identified in Ohio in 2004 and since that time 10 additional states have identified GR giant ragweed populations (Heap 2013). There are also giant ragweed populations with resistance to ALS-inhibiting herbicides in Indiana, Illinois, Ohio, Minnesota, Missouri, and Iowa (Heap 2013; Johnson et al. 2007; Patzoldt and Tranel 2002).

Dicamba has been available for use in corn and wheat production for over 50 yrs for the control of broadleaf weed species (Cao et al. 2011). Dicamba is labeled for use in soybean, corn, cotton, small grains, and pasturelands, but certain PREPLANT intervals and timing restrictions are required to ensure crop safety (Anonymous 2013). In response to the increasing numbers of weed populations that have evolved resistance to glyphosate, a number of seed and agrochemical companies are developing crop cultivars with resistance to multiple herbicide modes of action (Green and Castle 2010).

Cotton and soybean cultivars with resistance to dicamba and glyphosate are under development and may provide growers with additional tools to combat GR broadleaf weeds like giant ragweed and waterhemp (Green and Castle 2010). Johnson et al. (2010) found that dicamba plus glyphosate compared to glyphosate alone resulted in an increase in the consistency of control of GR weed species. However, 0.28 kg ha^{-1} dicamba provided less than 58% control of problematic weeds including smooth pigweed (*Amaranthus hybridus* L.) Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] common waterhemp, and giant ragweed (Johnson et al. 2010). In a similar study, 0.9 kg ha^{-1} glyphosate plus 0.6 kg ha^{-1} dicamba provided 88% control of GR giant ragweed, reduced shoot dry weight by 6-fold, and increased soybean yield 910 kg ha^{-1} compared to 0.9 kg ha^{-1} glyphosate plus 0.3 kg ha^{-1} dicamba (Vink et al. 2012).

Little research has been conducted to evaluate the utility of PRE or preplant followed by POST or sequential POST glyphosate and dicamba combinations in dicamba resistant (DR) soybean. The objectives of this research were to compare and contrast the effects of a variety of herbicide programs that contain dicamba on the control and density reduction of GR waterhemp and GR giant ragweed, while also assessing DR soybean yield. The

Table 1. Source of materials used in the experiments.

Common name	Trade name	Treatment rate	Manufacturer
		(kg ai or ae ha^{-1})[a]	
Flumioxazin	Valor SX	0.071[b]	Valent USA Corporation, Walnut Creek, CA, www.valent.com
Flumioxazin + chlorimuron	Valor XLT	0.084	Valent USA Corporation, Walnut Creek, CA, www.valent.com
2,4-D	2,4-D Ester	0.56[c]	Universal Crop Protection Alliance, LLC, Eagan, MN, http://www.ucpallc.com
Glyphosate	Roundup WeatherMax	0.86	Monsanto Corporation, St. Louis, MO, www.monsanto.com
Acetochlor	Warrant	1.3	Monsanto Corporation, St. Louis, MO, www.monsanto.com
Dicamba	Clarity	0.14 to 0.56	BASF Corporation, Florham Park, NJ, www.basf.com
Fomesafen	Flexstar	0.34 to 0.39	Syngenta, Wilmington, DE, www.syngenta.com
Cloransulam	FirstRate	0.018	Dow AgroSciences, Indianapolis, IN, www.dowagro.com
Sulfentrazone + chlorimuron	Authority XL	0.20	FMC Corporation, Philadelphia, PA, www.fmc.com
Ammonium sulfate	N-Pak AMS	2.9	Winfield Solutions LLC, St. Paul, MN, www.winfield.com

[a] Abbreviations: ae, acid equivalent; ai, active ingredient.

[b] Active ingredient of acetochlor, chlorimuron, cloransulam, flumioxazin, fomesafen, glyphosate, sulfentrazone were used.

[c] Acid equivalent of 2,4-D and dicamba were used.

herbicide programs evaluated in this research consisted of preplant followed by (fb) POST, PRE fb POST, and sequential POST herbicide treatments in DR soybean.

Materials and Methods

Site Description. Two experiments were conducted at separate locations with dense infestations of either GR giant ragweed (160 to 280 plants m^{-2}) or GR waterhemp (70 to 170 plants m^{-2}) during 2011 and 2012. The experiment to investigate the management of GR giant ragweed in DR soybean was conducted in Mt. Airy, Missouri (39.23°N, 92.37°W) in 2011 and 2012. The second experiment to investigate the management of GR waterhemp in DR soybean was conducted near Mokane, Missouri (38.39°N, 91.52°W) in 2011 and near Moberly, Missouri (39.18°N, 92.22°W) in 2012. At the 2012 Moberly research site, the waterhemp population exhibited resistance to PPO-inhibiting herbicides and glyphosate. The soil type at the Mokane research site was a Blenco silty clay loam (clayey over loamy, smectitic over mixed, superactive, mesic Aquertic Hapludolls) with 1.4% organic matter and pH of 6.8. At the Moberly research site, the soil type was a Putnam silt loam (fine, smetitic, mesic Vertic Albaqualfs) with 2.2% organic matter and pH of 6.3. At the Mt. Airy site, the soil type was a Keswick silt loam (fine, smectitic, mesic Aquertic Chromic Hapludalfs) with 2.2% organic matter and pH of 5.1 in 2011 and 2.1% organic matter and pH of 5.1 in 2012. At each location, maturity group 3.5 soybean containing glyphosate and dicamba-resistance traits (Monsanto Company, 800 North Lindbergh Boulevard St. Louis, MO. 63167) were planted at 346,000 to 383,000 seeds ha^{-1} in rows spaced 76 cm apart. Sources of materials and herbicide rates used in both experiments are listed in Table 1. Dates of major field operations for each experiment are provided in Table 2. At both GR waterhemp sites, DR soybean were planted into a conventionally-tilled seedbed (Mokane and Moberly site) while at both GR giant ragweed sites, DR soybean were no-till planted directly into the previous year's soybean residue. Monthly rainfall totals and average monthly temperatures at each location are presented in Table 3.

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Table 2. Dates of major field operations and weed sizes at the time of the herbicide treatments at the Mt. Airy, Moberly, and Mokane research locations in 2011 and 2012.

	Research location			
	Mt. Airy		Mokane	Moberly
	2011	2012	2011	2012
Seeding date	May 10	May 14	Jun 21	May 16
Dates of herbicide treatment				
Preplant[a] fb EPOST	Apr 18 fb May 6 to 20	Mar 26 fb May 25 to Jun 7	—	—
Preplant fb MPOST	Apr 18 fb May 28	Mar 26 fb May 12 to 14	—	—
PRE fb EPOST	—	—	Jun 6[b] fb Jul 12	May 16 fb Jun 14
EPOST fb LPOST	—	—	Jul 5 fb Jul 15 to 25	Jun 12 fb Jun 22 to Jul 16
MPOST fb LPOST	—	—	Jul 8 fb Jul 18 to 21	Jun 14 fb Jun 28 to Jul 16
Soybean growth stage at treatment				
Preplant fb EPOST	— fb V2 – V5	— fb 1st true leaf–V2	—	—
Preplant fb MPOST	— fb R1	— fb V3–V4	—	—
PRE fb EPOST	—	—	— fb V4	— fb V3
EPOST fb LPOST	—	—	V3 fb V5–R1	V2 fb V6–R2
MPOST fb LPOST	—	—	V3 fb R1	V3 fb R1–R2
Average weed size (cm) at treatment				
Preplant fb EPOST	2 fb 10	2 fb 10	—	—
Preplant fb MPOST	2 fb 23	2 fb 20	—	—
PRE fb EPOST	—	—	— fb 10	— fb 10
EPOST fb LPOST	—	—	10 fb 20 to 25	10 fb 20 to 30
MPOST fb LPOST	—	—	20 fb 30	20 fb 30

[a] Abbreviations: fb, followed by; EPOST, early postemergence; MPOST, mid postemergence; LPOST, late postemergence.

[b] Due to wet conditions at the Mokane site in 2011, soybean were not able to be planted until 15 d after the initial PRE application.

All experiments were arranged in a randomized complete block design with 18 treatments and 6 replications. The herbicide treatments, timings, and rates evaluated for the GR giant ragweed experiment are listed in Tables 4 and 5 while herbicide treatments, timings, and rates for the GR waterhemp experiment are listed in Tables 6 and 7. Individual plots measured 3 m by 7 m in size. In all experiments, treatments were applied with a CO_2-pressurized backpack sprayer equipped with XR8002 flat-fan nozzle tips (TeeJet®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL. 60187) calibrated to deliver 140 L ha^{-1} at 103 to 152 kPa, while maintaining a constant speed of 5 km hr^{-1}. Spray tarps measuring 1 m by 2 m were utilized on each side and in front of the spray boom to prevent plot to plot spray drift. All trials included a nontreated control for comparison.

Preplant treatments in the giant ragweed experiment were applied to plants 2 cm in height. Following the preplant treatment, POST herbicide treatments were applied to GR giant ragweed at either the 10- (EPOST) or 20-cm (MPOST) treatment timing to determine the effect of weed height on subsequent herbicide treatments. Likewise, GR waterhemp were initially treated PRE or when plants reached either the EPOST or MPOST treatment timing. A late-season, sequential POST treatment occurred when GR waterhemp regrowth measured an additional 10 cm (LPOST) beyond the PRE, EPOST, or MPOST treatment timing. Following PRE herbicide treatments, waterhemp plants that emerged after this treatment were treated with an EPOST herbicide treatment once they reached 10 cm in height.

Treatment Evaluation and Data Collection. Weed control and crop injury was visually assed at regular intervals after treatment on a scale of 0 to 100, where 0 represents no plant death or crop injury and 100 was equal to complete plant death. Waterhemp or giant ragweed plants surviving herbicide treatment were determined by counting individual plants between the center two soybean rows within each plot 3 WAA of the MPOST or LPOST regrowth treatment. Due to human error, density reduction in the GR waterhemp experiment

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Table 3. Monthly rainfall (mm) and average monthly temperatures (C) in comparison to the 30-yr averages from April through October in 2011 and 2012 at Mt. Airy and Moberly, and in 2011 at Mokane, Missouri.

		Rainfall			Temperature		
Location	Month	2011	2012	30-yr average[a]	2011	2012	30-yr average[a]
		mm			C		
Mt. Airy & Moberly[b]	April	104	126	103	12.4	13.1	13.0
	May	115	77	126	16.4	20.0	18.2
	June	128	57	126	23.1	23.4	22.9
	July	45	36	113	27.4	28.1	25.5
	August	34	4	109	24.5	23.9	24.6
	September	22	125	109	17.9	19.7	19.9
	October	25	78	81	13.5	12.5	13.7
Mokane	April	89	—	111	12.9	—	12.6
	May	104	—	121	15.5	—	17.2
	June	90	—	113	22.8	—	22.1
	July	127	—	110	27.2	—	24.7
	August	47	—	107	24.6	—	24.0
	September	83	—	110	17.6	—	19.2
	October	26	—	89	13.1	—	13.0

[a] 30-yr averages (1982–2011) obtained from National Climatic Data Center (2012).

[b] Weather data were recorded in Moberly, MO., Mt. Airy site: located 15.25 km W of the weather station, Moberly site: located 11.25 km SSE of the weather station.

was not recorded correctly in response to PRE fb POST herbicide programs and therefore this data will not be presented. At each location, soybean were harvested from the center two rows in each plot with a small plot combine and yield was adjusted to 13% moisture content.

Statistical Analysis. Control, weed density reduction, and yield data were analyzed using the PROC MIX procedure in SAS (SAS 9.2, SAS® Institute Inc. Cary, NC). Each year was considered an environment sampled at random; year as a random effect in the model allows inferences about treatments over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Herbicide treatments were considered fixed effects in the model while environment and replications (nested within environments) were considered random. Control and density reduction were combined over years but yield comparisons were separated by year (Table 5 and 7), primarily due to the drought and the much lower yields experienced in 2012 than 2011. Individual treatment differences were separated using Fisher's protected LSD at $P \leq 0.05$.

Results and Discussion

Glyphosate-Resistant Giant Ragweed. Greater than 91% GR giant ragweed control and 98% density reduction occurred in response to the treatments evaluated in this experiment (Table 4). Flumioxazin plus dicamba plus glyphosate preplant followed by glyphosate EPOST compared to flumioxazin plus 2,4-D plus glyphosate preplant followed by glyphosate EPOST provided greater control and density reduction of GR giant ragweed. When flumioxazin plus dicamba plus glyphosate was applied preplant, the addition of dicamba to glyphosate at either the EPOST or MPOST timing increased control and density reduction of GR giant ragweed compared to glyphosate alone. The addition of fomesafen or cloransulam to glyphosate applied EPOST also increased control of GR giant ragweed compared to glyphosate alone, but similar levels of density reduction were observed with these combinations compared to glyphosate alone applied EPOST. For treatments that contained flumioxazin plus chlorimuron plus dicamba plus glyphosate applied preplant, the addition of dicamba or fomesafen to glyphosate POST resulted in greater control and density reduction of GR giant ragweed compared to glyphosate alone applied EPOST. Conversely, cloransulam plus glyphosate applied EPOST provided similar levels of GR giant ragweed control and density reduction as compared to glyphosate alone. Johnson et al. (2010) also observed 70% control of giant ragweed 3 WAA with

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Table 4. Control and density reduction of glyphosate-resistant giant ragweed 3 weeks after the final POST herbicide treatments across two site-years in Missouri.

Treatment[a]	Treatment timing[b]	Treatment rate[c]	Control	Density reduction[d]
		kg ai or ae ha^{-1}	——%——	
Flumioxazin + 2,4-D + glyphosate	Preplant[e]	0.07 + 0.56 + 0.86	91	98
Glyphosate	EPOST	0.86		
Flumioxazin + dicamba + glyphosate	Preplant	0.07 + 0.56 + 0.86	95	99
Glyphosate	EPOST	0.86		
Flumioxazin + dicamba + glyphosate	Preplant	0.07 + 0.56 + 0.86	100	100
Dicamba + glyphosate	EPOST	0.56 + 0.86		
Flumioxazin + dicamba + glyphosate	Preplant	0.07 + 0.56 + 0.86	99	100
Dicamba + glyphosate	MPOST	0.56 + 0.86		
Flumioxazin + dicamba + glyphosate	Preplant	0.07 + 0.56 + 0.86	98	99
Fomesafen + glyphosate	EPOST	0.34 + 0.86		
Flumioxazin + dicamba + glyphosate	Preplant	0.07 + 0.56 + 0.86	98	99
Cloransulam + glyphosate	EPOST	0.02 + 0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	96	99
Glyphosate	EPOST	0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	100	100
Dicamba + glyphosate	EPOST	0.56 + 0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	100	100
Dicamba + glyphosate	MPOST	0.56 + 0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	99	100
Fomesafen + glyphosate	EPOST	0.39 + 0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	95	99
Cloransulam + glyphosate	EPOST	0.02 + 0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	97	100
Glyphosate	EPOST	0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	100	100
Dicamba + glyphosate	EPOST	0.56 + 0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	100	100
Dicamba + glyphosate	MPOST	0.56 + 0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	99	100
Fomesafen + glyphosate	EPOST	0.39 + 0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	97	100
Cloransulam + glyphosate	EPOST	0.02 + 0.86		
LSD (0.05)			2	1

[a] All treatments included ammonium sulfate at 2.9 kg ha^{-1}.

[b] Treatment timing: PREPLANT, 14 d prior to planting; EPOST, 10-cm giant ragweed regrowth; MPOST, 20-cm giant ragweed regrowth.

[c] Active ingredient rate used for acetochlor, chlorimuron, cloransulam, flumioxazin, fomesafen, glyphosate, and sulfentrazone. Acid equivalent rate used for 2,4-D and dicamba.

[d] Initial GR giant ragweed density at the two experimental locations ranged from 160 to 280 plants m^{-2}.

[e] Abbreviations: EPOST, early postemergence; MPOST, mid postemergence; ae, acid equivalent; ai, active ingredient.

flumioxazin plus chlorimuron applied PRE. Therefore the results from this research indicate that the addition of dicamba plus glyphosate to flumioxazin plus chlorimuron will likely increase the control of GR giant ragweed substantially. For treatments that contained sulfentrazone plus chlorimuron plus dicamba plus glyphosate applied preplant, a POST treatment of dicamba resulted in higher control of GR giant ragweed compared to an EPOST treatment of glyphosate alone, however GR giant ragweed density reduction was the same with all POST herbicide combinations. Johnson et al. (2010) also observed greater than 95% control of giant ragweed with sulfentrazone plus cloransulam applied PRE.

Regardless of the preplant treatment, delaying a dicamba treatment until MPOST compared to

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Table 5. Influence of PREPLANT followed by POST herbicides on soybean yield when in competition with glyphosate-resistant giant ragweed across two site-years in Missouri.

Treatment[a]	Treatment timing[b]	Treatment rate[c]	Soybean yield 2011	Soybean yield 2012
		kg ai or ae ha^{-1}	kg ha^{-1}	
Flumioxazin + 2,4-D + glyphosate	Preplant[d]	0.07 + 0.56 + 0.86	2985	911
Glyphosate	EPOST	0.86		
Flumioxazin + dicamba + glyphosate	Preplant	0.07 + 0.56 + 0.86	2960	1356
Glyphosate	EPOST	0.86		
Preplant	Preplant	0.07 + 0.56 + 0.86	2960	2303
Dicamba + glyphosate	EPOST	0.56 + 0.86		
Preplant	Preplant	0.07 + 0.56 + 0.86	2842	2220
Dicamba + glyphosate	MPOST	0.56 + 0.86		
Flumioxazin + dicamba + glyphosate	Preplant	0.07 + 0.56 + 0.86	3138	1333
Fomesafen + glyphosate	EPOST	0.34 + 0.86		
Flumioxazin + dicamba + glyphosate	Preplant	0.07 + 0.56 + 0.86	2766	1446
Cloransulam + glyphosate	EPOST	0.02 + 0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	3182	1611
Glyphosate	EPOST	0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	2758	2521
Dicamba + glyphosate	EPOST	0.56 + 0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	2933	2564
Dicamba + glyphosate	MPOST	0.56 + 0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	2964	1930
Fomesafen + glyphosate	EPOST	0.39 + 0.86		
Flumioxazin + chlorimuron + dicamba + glyphosate	Preplant	0.06 + 0.02 + 0.56 + 0.86	3117	1988
Cloransulam + glyphosate	EPOST	0.02 + 0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	2953	2011
Glyphosate	EPOST	0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	3456	2792
Dicamba + glyphosate	EPOST	0.56 + 0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	2749	2379
Dicamba + glyphosate	MPOST	0.56 + 0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	2958	2941
Fomesafen + glyphosate	EPOST	0.39 + 0.86		
Sulfentrazone + chlorimuron + dicamba + glyphosate	Preplant	0.17 + 0.03 + 0.56 + 0.86	3254	2308
Cloransulam + glyphosate	EPOST	0.02 + 0.86		
Non-treated control			931	34
LSD (0.05)			616	728

[a] All treatments included ammonium sulfate at 2.9 kg ha^{-1}.

[b] Treatment timing: PREPLANT, 14 day prior to planting; EPOST, 10-cm giant ragweed regrowth; MPOST, 20-cm giant ragweed regrowth.

[c] Active ingredient rate used for acetochlor, chlorimuron, cloransulam, flumioxazin, fomesafen, glyphosate, and sulfentrazone. Acid equivalent rate used for 2,4-D and dicamba.

[d] Abbreviations: EPOST, early postemergence; MPOST, mid postemergence; ae, acid equivalent; ai, active ingredient.

EPOST did not affect control or density reduction of GR giant ragweed (Table 4). This response may be due to the greater percentage of GR giant ragweed eliminated early in the season with a preplant herbicide treatment, and because additional germination of GR giant ragweed seedlings through the remainder of the season did not occur. Therefore, in areas with early and uniform giant ragweed emergence such as what typically occurs in Missouri and western portions of the Corn Belt, season-long control of GR giant ragweed is attainable with effective early-season preplant herbicide treatments to small plants.

No greater than 2% soybean injury was observed in response to dicamba at any time interval after treatment and no greater than 26% soybean injury

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Table 6. Control and density reduction of glyphosate-resistant waterhemp 3 weeks after final POST herbicide treatment across two site-years in Missouri.

Treatment[a]	Treatment timing[b]	Treatment rate[c]	Control	Density reduction[d]
		kg ai or ae ha^{-1}	%	
Flumioxazin + chlorimuron	PRE[e]	0.06 + 0.02	50	—
Glyphosate	EPOST	0.86		
Flumioxazin + chlorimuron	PRE	0.06 + 0.02	89	—
Dicamba + glyphosate	EPOST	0.56 + 0.86		
Flumioxazin + chlorimuron	PRE	0.06 + 0.02	90	—
Dicamba + glyphosate + acetochlor	EPOST	0.56 + 0.86 + 1.3		
Flumioxazin + chlorimuron	PRE	0.06 + 0.02	55	—
Glyphosate + fomesafen	EPOST	0.86 + 0.39		
Glyphosate	EPOST	0.86	24	42
Glyphosate	LPOST	0.86		
Glyphosate + fomesafen	EPOST	0.86 + 0.34	44	75
Glyphosate	LPOST	0.86		
Glyphosate + fomesafen	MPOST	0.86 + 0.34	24	7
Glyphosate	LPOST	0.86		
Dicamba + glyphosate	EPOST	0.56 + 0.86	85	83
Glyphosate	LPOST	0.86		
Dicamba + glyphosate	MPOST	0.56 + 0.86	72	64
Glyphosate	LPOST	0.86		
Dicamba + glyphosate + acetochlor	EPOST	0.56 + 0.86 + 1.3	85	85
Glyphosate	LPOST	0.86		
Dicamba + glyphosate + acetochlor	EPOST	0.56 + 0.86 + 1.3	92	89
Dicamba + glyphosate	LPOST	0.56 + 0.86		
Dicamba + glyphosate	EPOST	0.56 + 0.86	89	91
Dicamba + glyphosate + acetochlor	LPOST	0.56 + 0.86 + 1.3		
Dicamba + glyphosate	EPOST	0.56 + 0.86	89	90
Dicamba + glyphosate	LPOST	0.56 + 0.86		
Dicamba + glyphosate	MPOST	0.56 + 0.86	88	90
Dicamba + glyphosate	LPOST	0.56 + 0.86		
Dicamba + glyphosate + acetochlor	EPOST	0.56 + 0.86 + 1.3	94	93
Dicamba + glyphosate + acetochlor	LPOST	0.56 + 0.86 + 1.3		
Dicamba + glyphosate	EPOST	0.56 + 0.86	90	91
Glyphosate + fomesafen	LPOST	0.86 + 0.34		
LSD (0.05)			16	38

[a] All POST treatments included ammonium sulfate at 2.9 kg ha^{-1}.

[b] Treatment timing: PRE, at planting; EPOST, 10-cm waterhemp or 10-cm waterhemp regrowth; MPOST, 20-cm waterhemp; LPOST, 10-cm waterhemp regrowth.

[c] Active ingredient rate used for acetochlor, chlorimuron, cloransulam, flumioxazin, fomesafen, glyphosate, and sulfentrazone. Acid equivalent rate used for 2,4-D and dicamba.

[d] Initial GR waterhemp density at the two experimental locations ranged from 70–170 plants m^{-2}.

[e] Abbreviations: EPOST, early postemergence; MPOST, mid postemergence; LPOST, late postemergence; ae, acid equivalent; ai, active ingredient.

was documented in response to fomesafen plus glyphosate 1 WAA (data not shown). By 2 WAA, soybean had recovered from the initial fomesafen injury, and no signs of soybean injury could be observed thereafter. In 2011, soybean yield ranged from 2749 to 3456 kg ha^{-1} and there were very few trends observed between herbicide treatments (Table 5). The similarity in soybean yield among treatments is likely related to the high levels of GR giant ragweed control and density reduction observed in the 2011 experiment (Table 4). In 2012, soybean yields were more variable and lower than in 2011, likely due to the drought that occurred at the Mt. Airy location in 2012 (Table 3). Soybean yield differences were not observed in either year in response to a PREPLANT treatment

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Table 7. Influence of PRE followed POST or sequential POST herbicide programs on soybean yield when in competition with glyphosate-resistant waterhemp across two site-years in Missouri.

Treatment[a]	Treatment timing[b]	Treatment rate[c]	Soybean yield 2011	Soybean yield 2012
		kg ai or ae ha^{-1}	kg ha^{-1}	
Flumioxazin + chlorimuron	PRE[d]	0.06 + 0.02	3,641	1,651
glyphosate	EPOST	0.86		
Flumioxazin + chlorimuron	PRE	0.06 + 0.02	3,766	1,604
Dicamba + glyphosate	EPOST	0.56[e] + 0.86		
Flumioxazin + chlorimuron	PRE	0.06 + 0.02	3,682	1,594
Dicamba + glyphosate + acetochlor	EPOST	0.56 + 0.86 + 1.3		
Flumioxazin + chlorimuron	PRE	0.06 + 0.02	3,929	1,410
Glyphosate + fomesafen	EPOST	0.86 + 0.39		
Glyphosate	EPOST	0.86	3,676	1,250
Glyphosate	LPOST	0.86		
Glyphosate + fomesafen	EPOST	0.86 + 0.34	3,682	1,523
Glyphosate	LPOST	0.86		
Glyphosate + fomesafen	MPOST	0.86 + 0.34	3,709	1,464
Glyphosate	LPOST	0.86		
Dicamba + glyphosate	EPOST	0.56 + 0.86	3,925	1,534
Glyphosate	LPOST	0.86		
Dicamba + glyphosate	MPOST	0.56 + 0.86	3,792	1,558
Glyphosate	LPOST	0.86		
Dicamba + glyphosate + acetochlor	EPOST	0.56 + 0.86 + 1.3	3,890	1,720
Glyphosate	LPOST	0.86		
Dicamba + glyphosate + acetochlor	EPOST	0.56 + 0.86 + 1.3	3,910	1,440
Dicamba + glyphosate	LPOST	0.56 + 0.86		
Dicamba + glyphosate	EPOST	0.56 + 0.86	3690	1560
Dicamba + glyphosate + acetochlor	LPOST	0.56 + 0.86 + 1.3		
Dicamba + glyphosate	EPOST	0.56 + 0.86	4000	1570
Dicamba + glyphosate	LPOST	0.56 + 0.86		
Dicamba + glyphosate	MPOST	0.56 + 0.86	3640	1780
Dicamba + glyphosate	LPOST	0.56 + 0.86		
Dicamba + glyphosate + acetochlor	EPOST	0.56 + 0.86 + 1.3	4040	1420
Dicamba + glyphosate + acetochlor	LPOST	0.56 + 0.86 + 1.3		
Dicamba + glyphosate	EPOST	0.56 + 0.86	3880	1430
Glyphosate + fomesafen	LPOST	0.86 + 0.34		
Non-treated control			2330	860
LSD (0.05)			530	370

[a] All POST treatments included ammonium sulfate at 2.9 kg ha^{-1}.

[b] Treatment timing: PRE, at planting; EPOST, 10-cm waterhemp or 10-cm waterhemp regrowth; MPOST, 20-cm waterhemp; LPOST, 10-cm waterhemp regrowth.

[c] Active ingredient rate used for acetochlor, chlorimuron, cloransulam, flumioxazin, fomesafen, glyphosate, and sulfentrazone. Acid equivalent rate used for 2,4-D and dicamba.

[d] Abbreviations: EPOST, early postemergence; MPOST, mid postemergence; LPOST, late postemergence; ae, acid equivalent; ai, active ingredient.

that contained 2,4-D compared to dicamba. Regardless of the preplant treatment, soybean yield was lower with an EPOST treatment of glyphosate alone compared to glyphosate plus dicamba in 2012 but not 2011. As with the control and density reduction data, GR giant ragweed height at the time of the POST treatment had little influence on soybean yield due to the large percentage of GR giant ragweed eliminated by the preplant treatment (Table 5). Across both years, sulfentrazone plus chlorimuron plus dicamba plus glyphosate followed by glyphosate plus dicamba reduced soybean yield in 2011 only in response to MPOST compared to the EPOST timing. In both years, all herbicide

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treatments resulted in soybean yield greater than the non-treated control. Soybean yield in the non-treated control was reduced from 66 to 99% compared to the yield from herbicide treatments evaluated in this experiment. These results confirm the highly competitive nature of giant ragweed and are consistent with other research (Baysinger and Sims 1991; Vink et al. 2012; Webster et al. 1994).

Glyphosate-Resistant Waterhemp. Control of GR waterhemp ranged from 24 to 94% with the treatments evaluated in this experiment, while GR waterhemp density reduction in response to the POST treatments ranged from 7 to 93% (Table 6). Flumioxazin plus chlorimuron applied PRE followed by dicamba plus glyphosate or dicamba plus glyphosate plus acetochlor applied EPOST resulted in greater control of GR waterhemp than when this PRE treatment was followed by glyphosate plus fomesafen or glyphosate alone applied EPOST. Sequential EPOST treatments that included dicamba provided greater control and density reduction of GR waterhemp than glyphosate alone when applied sequentially (Table 6). When compared to glyphosate plus dicamba applied EPOST, glyphosate plus fomesafen applied at the same timing resulted in less control of GR waterhemp, but similar reduction in GR waterhemp density.

Delaying the glyphosate plus fomesafen treatment from EPOST to MPOST reduced control by 20% and density reduction by 68%. These results indicate that plant height at the time of application is critical for adequate control of GR waterhemp with PPO-inhibiting herbicides like fomesafen. Similarly, Legleiter and Bradley (2008) reported 99% survival of 15-cm GR waterhemp following 0.86 kg ha^{-1} glyphosate plus 0.19 kg ha^{-1} fomesafen. Additionally, the poor control of waterhemp with fomesafen can be attributed to some portion of the population exhibiting resistance to PPO-inhibiting herbicides at the Moberly location in 2012. Currently, waterhemp populations exhibiting multiple herbicide resistance to PPO-inhibiting herbicides and glyphosate have been documented in Missouri (Legleiter and Bradley 2008). Likewise waterhemp with multiple resistances to PPO-inhibiting herbicides and glyphosate exist in Illinois, Iowa, and Kansas (Heap 2013).

In this experiment, the smallest reduction in waterhemp density occurred with glyphosate and glyphosate plus fomesafen applied sequentially at the MPOST timing (Table 6). In an experiment conducted across 11 states, Johnson et al. (2010) found that glyphosate applied sequentially provided only 30% control of GR waterhemp. In this experiment, dicamba plus glyphosate applied sequentially provided 88 to 89% GR waterhemp control and 90% density reduction, regardless of application timing. Although the addition of acetochlor to dicamba plus glyphosate did not improve waterhemp control or density reduction compared to dicamba plus glyphosate (Table 6), the addition of acetochlor can reduce late-season germination and provide an additional herbicide mode of action for control of GR waterhemp. For example, Clewis et al. (2006) reported that *S*-metolachlor applied late-season provided additional residual control of Palmer amaranth compared to glyphosate alone applied at the same timing.

There was no soybean injury in response to dicamba in this experiment. The greatest soybean injury occurred in response to fomesafen plus glyphosate applied POST and ranged from 5 to 15% 1 WAA (data not shown). Soybean yield ranged from 3638 to 4041 kg ha^{-1} in 2011 and 1250 to 1779 kg ha^{-1} in 2012 (Table 7). In 2011, no differences in soybean yield were observed among herbicide treatments (Table 7). In 2012 dicamba plus glyphosate applied sequentially, dicamba plus glyphosate plus acetochlor followed by glyphosate, or flumioxazin plus chlorimuron followed by glyphosate yielded greater than glyphosate applied sequentially (Table 7). In both years all treatments resulted in yield greater than the non-treated control. These results suggest that the waterhemp population at the Moberly location contained a higher frequency of GR waterhemp than that at the Mokane location. Similar to the yield response in the GR giant ragweed experiment, soybean yield was greater in 2011 compared to 2012, presumably due to the reduced frequency of GR in the waterhemp population, increased precipitation (Table 3), and more favorable soil properties at the Mokane compared to the Moberly research location. Although there were some slight differences in soybean yield between herbicide treatments in 2012, the reason for the observed differences is not clear and could not be correlated with the level of GR waterhemp control or density reduction observed. Compared to the highest-yielding treatments in each year, season-long water-

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hemp competition reduced soybean yield by 42 (2011) to 51% (2012). These results are similar to Hager et al. (2002), where a 43% reduction in soybean yield occurred in response to season-long waterhemp competition.

Dicamba has been available for use in corn and wheat production for over 50 years for the selective control of broadleaf weed species (Cao et al. 2011). The results from this research indicate that DR soybean allows dicamba to be applied POST for the selective control of GR broadleaf weed species like giant ragweed and waterhemp. However, it is important to recognize that multiple POST treatments of dicamba plus glyphosate will provide only one effective mode of action on a GR broadleaf weed like waterhemp and may eventually lead to the evolution of DR in these species, and also to the evolution of glyphosate resistance in grass weeds, as only one effective mode of action is being applied to grasses. Therefore, in order to delay the selection of DR weed species, the use of multiple effective herbicide modes of action applied PRE, preplant, and/or POST will be required.

Literature Cited

Anonymous (2013) Clarity® herbicide product label. EPA Reg. No. 7969-137. Research Triangle Park, NC: BASF Corporation. Pp. 10–21

Baysinger JA, Sims BD (1991) Giant ragweed (*Ambrosia trifida* L.) interference in soybeans (*Glycine max*). Weed Sci 39:358–362

Baysinger JA, Sims BD (1992) Giant ragweed (*Ambrosia trifida* L.) control in soybean (*Glycine max*). Weed Technol 6:13–18

Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. Weed Technol 25:165–169

Bradley KW (2013) Herbicide-resistance in the Midwest: current status and impacts. Weed Sci Soc Am Abstr 271. http://www.wssaabstracts.com/publis/17/proceedings.html. Accessed April, 24 2013

Bradley KW, Legleiter T, Hunter L, Nichols C, Foresman C (2007) The status of glyphosate-resistant waterhemp in Missouri. North Central Weed Sci Soc Abstr 192. http://www.ncwss.org/pubs.php. Accessed December, 12 2012

Bryson CT, DeFelice MS (2009) Weeds of the South. Athens: University of Georgia. Pp 37–53.

Cao M, Sato SJ, Behrens M, Jiang WZ, Clemente TE, Weeks DP (2011) Genetic engineering of maize (*Zea mays*) for high-level tolerance to treatment with the herbicide dicamba. J Agric Food Chem 59:5830–5834

Carmer SG, Nyquist WE, Walker, WM (1989) Least significant differences for combined analysis of experiments with two or three-factor treatments designs. Agron J 81:665–672

Clewis SB, Wilcut JW, Porterfield D (2006) Weed management with *S*-metolachlor and glyphosate mixtures in glyphosate-resistant strip- and conventional-tillage cotton (*Gossypium hirsutum* L.) Weed Technol 20:232–241

Green JM, Castle LA (2010) Transitioning from single to multiple herbicide-resistant crops. Pages 67–91 *in* Nandula VK, ed. Glyphosate Resistance in Crops and Weeds: History, Development, and Management. Hoboken, JN: J Wiley

Hager A (2011) Herbicide-Resistant Weeds in Illinois: A cause for concern. University of Illinois Extension Bulletin No 3 Article Apr. 6, 2011 http://bulletin.ipm.illinois.edu/print.php?id=1466 Accessed: Mar. 21, 2012

Hager AG, Wax LM, Stoller EW, Bollero GA (2002) Common waterhemp (*Amaranthus rudis*) interference in soybean. Weed Sci 50:607–610

Harrison SK, Regnier EE, Schmoll JT, Webb JE (2001) Competition and fecundity of giant ragweed in corn. Weed Sci 49:224–229

Hartzler RG, Battles BA, Nordby D (2004) Effect of common waterhemp (*Amaranthus rudis*) emergence date on growth and fecundity in soybean. Weed Sci 52:242–245

Heap IM (2013) The international survey of herbicide resistant weeds. http://www.weedscience.org. Accessed: April 17, 2013

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347–355

Johnson B, Loux M, Nordby D, Sprague C, Nice G, Westhoven A, Stachler J (2007) The Glyphosate, Weeds, and Crops Series: Biology and Management of Giant Ragweed (GWC-12). West Lafayette, IN: University of Purdue Extension. 14 p

Johnson B, Young B, Matthews J, Marquardt P, Slack C, Bradley K, York A, Culpepper S, Hager A, Al-Khatib K, Steckel L, Moechnig M, Loux M, Bernards M, Smeda R (2010) Weed control in dicamba-resistant soybeans. Online. Crop Manag doi: 10.1094/CM-2010-0920-01-RS

Legleiter TR, Bradley KW (2008) Glyphosate and multiple herbicide resistance in common waterhemp (*Amaranthus rudis*) populations from Missouri. Weed Sci 56:582–587

Patzoldt WL, Tranel PJ (2002) Molecular analysis of cloransulam resistance in a population of giant ragweed. Weed Sci 50:299–305

Stoller EW, Wax LM (1973) Periodicity of germination and emergence of some annual weeds. Weed Sci 21:574–580

Vink JP, Soltani N, Robinson DE, Tardif FJ, Lawton MB, Sikkema PH (2012) Glyphosate-resistant giant ragweed (*Ambrosia trifida*) control in dicamba-tolerant soybean. Weed Technol 26:422–428

Waggoner BS, Bradley KW (2011) A survey of weed incidence and severity in response to management practices in Missouri soybean production fields. North Central Weed Sci Soc Abstr 80. http://www.ncwss.org/pubs.pht. Accessed January 25, 2013

Webster TM, Loux MM, Regnier EE, Harrison SK (1994) Giant ragweed (*Ambrosia trifida*) canopy architecture and interference studies in soybean (*Glycine max*). Weed Technol 8:559–564

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