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WEED SCIENCE

Evaluation of Postemergence Weed Control Programs in Cotton Without the Addition of Glyphosate

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ABSTRACT

Glyphosate has played an important role in agricultural production systems, especially after the release of glyphosate resistant crops. With increased usage and an overall reliance on chemical control, weed resistance to glyphosate has occurred and is now a major issue. The objective of this research was to investigate weed control levels provided by glufosinate, 2,4-D, and clethodim as an alternative to glyphosate. Multiple POST applications generally provided superior weed control in comparison to a single early-POST application. No programs provided greater than 80% warm-season grass control beginning 21 d after mid-POST application. Applications of glufosinate or glufosinate + 2,4-D fb clethodim + glufosinate, glufosinate + 2,4-D, or clethodim + glufosinate + 2,4-D provided adequate broadleaf weed control throughout the rating period. Although POST-only programs are an option, they are not a sustainable weed control practice. It remains important to incorporate residual herbicides into a weed control program as well as alternative weed control methods.

Glyphosate-resistant (GR) soybean (*Glycine max* [L.] Merr.), cotton (*Gossypium hirsutum* L.), and corn (*Zea mays* L.) were released in 1996, 1997, and 1998, respectively (Duke, 2005). Widespread adoption of GR crops occurred as glyphosate proved to be a simpler and more economical weed control option for producers (Culpepper, 2006; Owen and Zelaya, 2005). In 1995, prior to the release of GR crops, 12.5 million kg glyphosate were applied to agricultural areas in the U.S. and has increased continually (Benbrook, 2016). Estimated annual usage of glyphosate in agricultural settings has exceeded 113 million kg since 2010 (USGS, 2021).

Shaner (2000) observed a general decrease in the amount of soybean and cotton hectarage treated with chemical classes excluding glyphosate after the release of GR crops. The heavy reliance on glyphosate placed tremendous selection pressure on the chemistry, which led to the development of GR-weed species (Culpepper, 2006; Owen and Zelaya, 2005). A weed shift also occurred due to altered production practices that accompanied the adoption of GR crops (reduced tillage, reduced residual herbicide applications, and reduced rotation between modes of action) and producers encountered weed species that were naturally more tolerant to glyphosate (Culpepper, 2006; Shaner, 2000).

Of the weed species with developed resistance, Palmer amaranth (*Amaranthus palmeri* S. Wats) is one of the most troublesome weeds for row crop producers (Kruger et al., 2009; Van Wychen, 2016, 2017). Palmer amaranth in Tennessee has confirmed resistance to glyphosate, acetolactate synthase (ALS) inhibitors, and microtubule inhibitors as well as multiple resistance to glyphosate + ALS inhibitors, glyphosate + protoporphyrinogen oxidase inhibitors, and glyphosate + dicamba (Foster and Steckel, 2022; Giacomini et al., 2017; Heap, 2021; Steckel et al., 2008). Several grass species in Tennessee have developed resistance to glyphosate including goosegrass (*Elusine indica* L.), johnsongrass (*Sorghum halepense* L.), Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* [Lam.] Husnot), annual bluegrass (*Poa annua* L.), junglerice (*Echinochloa colona* [L.] Link) and barnyardgrass (*Echinochloa crus-galli* [L.] P. Beauv.) (Dickson et al., 2011; Heap, 2021; Nandula et al., 2018). Along with resistance development, there have been reports of reduced herbicidal activity on some grass species when combinations of postemergence herbicides are applied (Mueller et

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al., 1989; Perkins et al., 2021). Decreased herbicidal activity on grass weed species has been attributed to antagonistic effects between commonly used postemergence herbicides such as glyphosate and dicamba (Perkins et al., 2021).

With the increase in GR-weed species, there has been a shift in weed control strategies to integrated weed management practices, which include cover crop implementation, crop rotation, herbicide mode of action rotation, the use of residual herbicides, tillage, and the use of herbicide-resistant (HR) crops (Sosnoskie and Culpepper, 2014; Webster et al., 2013). From 2019 to 2021, approximately 94% of Tennessee cotton acreage was planted in cotton with resistance to glyphosate, glufosinate, and dicamba (XtendFlex™, Bayer Crop Science, St. Louis, MO) followed by approximately 5% of cotton acreage planted in cotton with resistance to glyphosate, glufosinate, and 2,4-D (Enlist™, Corteva Agriscience, Indianapolis, IN) (USDA-ARS, 2019, 2020). The remaining 1% of Tennessee cotton acreage was planted in cotton with resistance to glyphosate and glufosinate only (GlyTol® LibertyLink®, BASF Corporation, Research Triangle Park, NC).

The increasing number of GR-weed species has encouraged the agricultural community to find alternative methods for weed control outside of chemical control. Although alternative methods can help reduce weed populations, chemical control options still provide efficacious control at a relatively low cost per unit (Merchant et al., 2013). Typical chemical weed control programs in cotton include burndown applications, at-planting applications, as well as single or multiple postemergence applications in-season, which can include both postemergence and residual herbicides. Glyphosate commonly is used in an herbicide weed control program, but due to the increase in GR species and the antagonistic nature of some postemergence herbicide combinations, it is necessary to investigate cotton herbicide programs that do not include glyphosate. Common postemergence herbicides used in cotton for control of weed species in 2,4-D-resistant cotton are glufosinate, 2,4-D, and clethodim.

The objective of this research was to investigate weed control levels provided by glufosinate, 2,4-D, and clethodim as alternatives to glyphosate. Researchers hypothesized that adequate weed control levels would be accomplished with two postemergence applications containing multiple modes of action. This experiment did not include residual herbicides in postemergence herbicide applications, although this is a recommended practice as control is typically increased (Gardner et al., 2006b; Meyer et al., 2015).

MATERIALS AND METHODS

Field experiments were conducted from 2019 to 2021 at University of Tennessee AgResearch and Education Centers in both Milan, TN (MREC) on a Collins silt loam (coarse-silty, mixed, active, acid, thermic Aquic Udifluvents) and Grand Junction, TN (Ames) on a Collins silt loam and Lexington silt loam (fine-silty, mixed, active, thermic Ultic Hapludalfs) to evaluate postemergence weed control programs in cotton without the use of glyphosate. Experimental units consisted of four, 97- and 102-cm wide rows that were 9 m in length at Ames and MREC, respectively. Treatments were arranged in a randomized complete block design and replicated four times at each location.

The Milan location had a uniform flush of weed species that emerged prior to planting the cotton crop. In 2019, the Ames site required overseeding with weed seed prior to trial establishment to build a weed seed bank, which was accomplished with the spreading of seed contaminants from seed cleaners in the area. Contained within the seed contaminants were a greater number of viable soybean seeds than expected, which required a blanket paraquat application to terminate the flush of soybeans that likely were glufosinate resistant. Except for the Ames location in 2019, cotton was seeded into emerged weeds and no burndown or preemergence herbicide application. Phytogen 400 W3FE (Corteva Agriscience, Indianapolis, IN) was seeded at a rate of 98,800 seeds ha^{-1} (Table 1). The selected variety was resistant to glyphosate, glufosinate, and 2,4-D. Apart from weed control, cotton was managed based on University of Tennessee Extension agronomic and pest management recommendations (Raper, 2016).

Two postemergence (POST) application timings were used for experiments including an early-POST and mid-POST. The early-POST application was made approximately 3 wk after planting or when cotton reached two to three true leaves and weeds were approximately 5 to 8 cm in height (Table 1). The mid-POST application was made 14 d after the early-POST (DAEP) application or when cotton reached four to six true leaves (Table 1). At the time of the mid-POST application, weeds were approxi-

Table 1. Cotton planting dates and herbicide application date

	Milan			Grand Junction		
	2019	2020	2021	2019	2020	2021
Cotton Planting Date	23 May	22 May	20 May	29 May	14 May	17 May
Early-POST Date	11 June	19 June	17 June	25 June	16 June	18 June
Mid-POST Date	25 June	30 June	02 July	12 July	29 June	02 July

mately 10 to 15 cm in height. Treatments included single applications early-POST of clethodim (Section® Three Herbicide; WinField United, Arden Hills, MN) at 0.17 kg ai ha^{-1} with a crop oil concentrate at 0.5 % volume per volume, clethodim + glufosinate (Liberty® 280 SL; BASF Corporation, Research Triangle Park, NC) at 0.66 kg ai ha^{-1}, clethodim + 2,4-D choline salt (Enlist One™ with Colex-D™ Technology; Corteva Agriscience, Indianapolis, IN) at 1.1 kg ae ha^{-1}, glufosinate + 2,4-D, and clethodim + glufosinate + 2,4-D. All treatments were applied at mid-POST timing following an early-POST application of either glufosinate alone or glufosinate + 2,4-D. A non-treated control was included to provide a total of 16 treatments. Postemergence applications were made with CO2-powered backpack sprayers calibrated to apply 140 L ha^{-1} at a pressure of 276 kPa. Applications were made with TTI 11002 (TeeJet Technologies, Springfield, IL) nozzles at a walking speed of 4.8 km hr^{-1}.

Estimates of visual weed control were conducted 7, 14, 21, and 28 DAEP and 7, 14, 21, and 28 d after mid-POST (DAMP) on a scale of 0 to 100% (0 = no control, 100 = complete control) for each weed species present at the time of application (Frans et al., 1986). Broadleaf weed species present across experimental locations included Amaranthus species (*Amaranthus* spp.), morningglory species (*Ipomoea* spp.), prickly sida (*Sida spinosa* L.), and common purslane (*Portulaca oleracea* L.). A mixture of warm-season grasses was present at each location, which included goosegrass, johnsongrass, and large crabgrass (*Digitaria sanguinalis* L.). No attempt was made to evaluate warm-season grass control by species as grass population was generally low at each location (data not shown; Byrd and York, 1987; Gardner et al., 2006b). At 28 DAMP application, aboveground weed biomass samples were collected from a 0.25 m^2 area and dried at 41 °C for 72 h to achieve a constant weight and expressed as percent reduction in biomass relative to the non-treated control.

Data were analyzed in SAS (v. 9.4, SAS Institute Inc., Cary, NC) using the PROC MIXED procedure. Treatments were considered fixed effects. Experimental location and replication were considered random effects to make inferences about herbicide program efficacy across multiple environments (Blouin et al., 2011; Gbur et al., 2012). Analysis of visual weed control estimates did not include the values from the non-treated control. Data were subjected to analysis of variance and means were separated using Fisher's Protected LSD at the $\alpha = 0.05$.

RESULTS

Broadleaf Weed Control. Visual broadleaf control was affected by herbicide treatment across all rating timings and weed species (Tables 2 to 7). Across all rating timings and broadleaf weeds observed, clethodim-only early-POST provided less weed control than all other herbicide treatments (Tables 2 to 7). This is to be expected as clethodim, a graminicide, has no activity on broadleaf weeds (Jordan et al., 1996). At 7 DAEP, clethodim + 2,4-D provided less control of *Amaranthus* species, prickly sida, and common purslane than other early-POST treatments (Table 2). These results are supported by Merchant et al. (2013) who found that broadleaf control from 2,4-D was often inadequate, but control was improved with the addition of glufosinate.

At 14 DAEP, the clethodim + 2,4-D early-POST treatment generally provided less control of Amaranthus species and prickly sida compared to other combinations of 2,4-D applied early-POST (Table 3). Morningglory species control 14 DAEP provided by clethodim + 2,4-D early-POST resulted in 93% control, which was greater than the clethodim + glufosinate + 2,4-D early-POST treatment (80%). Although the addition of glufosinate to this treatment did not improve morningglory species control, glufosinate is highly effective in controlling morningglories (Everman et al., 2009; Hoss et al., 2003). Differences observed amongst early-POST treatments of either glufosinate or glufosinate + 2,4-D both 7 and

14 DAEP can be attributed to natural differences in weed populations across field sites (Tables 2 and 3) that could have impacted herbicide efficacy by reducing coverage.

By 21 DAEP and 7 DAMP, all early-POST-only treatments (0-73%) and glufosinate followed by (fb) clethodim (65%) provided less prickly sida control than remaining treatments with multiple POST applications (84-97%) (Table 4). The same was true for common purslane control except following glufosinate + 2,4-D fb clethodim application, which provided control similar to that of early-POST-only treatments. Copes et al. (2021) observed variable effectiveness in prickly sida control with only POST applications compared to using both preemergence (PRE) and POST herbicides. *Amaranthus* species control was less following early-POST-only treatments (0-78%) and glufosinate fb clethodim (72%) than treatments with multiple POST applications (86-91%) (Table 4). Glufosinate fb clethodim + 2,4-D (86%) provided similar levels of control to early-POST-only treatments. Clethodim + 2,4-D (90%) and glufosinate + 2,4-D (88%) early-POST, provided morningglory species control similar to that of the two POST programs (86-99%).

At both 28 and 35 DAEP, which coincide with 14 and 21 DAMP, respectively, control provided by two POST treatments was generally greater than glufosinate fb clethodim and early-POST-only treatments (Tables 5 and 6). Morningglory species control is an exception as only clethodim, clethodim + glufosinate, and clethodim + glufosinate + 2,4-D early-POST provided less control than all other treatments, with clethodim and clethodim + glufosinate + 2,4-D providing the least morningglory control beginning 35 DAEP (Table 6). Gardner et al. (2006b) observed morningglory species control of at least 94% when glufosinate was applied in comparison to preemergence herbicides alone (35-54%). Common purslane control 28 DAEP does not follow the general trend either, as all treatments besides glufosinate + 2,4-D fb clethodim (67%) and clethodim only (0%) provided control greater than 91% (Table 5).

At 28 DAMP, the following treatments provided greater than 80% control regardless of broadleaf species: glufosinate or glufosinate + 2,4-D fb clethodim + 2,4-D, glufosinate + 2,4-D, and clethodim + glufosinate + 2,4-D and glufosinate + 2,4-D fb clethodim + glufosinate (Table 7). Control of *Amaranthus* species was also greater than 80% following applications of glufosinate + 2,4-D fb clethodim. Riar et al. (2011) concluded that to achieve Palmer amaranth control similar to that of PRE fb POST programs, a POST-only program required an additional POST application between early-POST timing and layby. Morningglory species control was also greater than 80% following applications of glufosinate fb clethodim + glufosinate and clethodim + 2,4-D and glufosinate + 2,4-D early-POST (Table 7). Common purslane control greater than 80% was achieved with applications of clethodim + glufosinate and clethodim + glufosinate + 2,4-D at early-POST. Adequate levels of purslane control observed from early-POST-only treatments might be explained by the suppressive nature of other more upright growing weed species present in plots and crop shading as opposed to treatment effect.

Warm-Season Grass Control. Control of warm-season grasses was affected by herbicide treatment 7, 21, and 28 DAEP and 7, 14, 21, and 28 DAMP (Table 8). Annual grass weed control 7 DAEP was less with clethodim alone (47%) and clethodim + 2,4-D (48%) than any other treatment combination (80-90%) (Table 8). By 14 DAEP, warm-season grass control fell below 80% regardless of early-POST application and no differences were observed amongst treatments. Beginning at 21 DAEP and continuing throughout the rating period, warm-season grass control from a single early-POST application was greater when clethodim was applied (66-77%) compared to clethodim + glufosinate (40-52%) or clethodim + glufosinate + 2,4-D (38-50%). These results agree with Mueller et al. (1989) who observed reduced johnsongrass control when 2,4-D was tank mixed with fenoxaprop, haloxyfop, or sethoxydim.

The addition of glufosinate to graminicides, like clethodim, has been found to cause antagonism with respect to clethodim efficacy on grass weed control (Burke et al., 2005; Gardner et al., 2006a). Chalal and Jhala (2015) observed less control of GR volunteer corn when acetyl CoA carboxylase inhibitors were tank-mixed with glufosinate compared to those graminicides applied alone. Harre et al. (2020) observed clethodim antagonism when applied with glyphosate + 2,4-D, but combinations of clethodim + 2,4-D did not result in reduced control of GR corn compared to clethodim alone. When either glufosinate or glufosinate + 2,4-D was applied first, warm-season grass control was not reduced following mid-POST applications of clethodim or clethodim tank-mixes (Table 8).

Clethodim alone applied early-POST (77%), and all treatments that received two POST applications (68-87%) provided greater warm-season grass control than other early-POST-only treatments (42-54%) beginning 14 DAMP and continuing throughout the rating period (Table 8). In some cases, a mid-POST application was able to provide greater than 80% warm-season grass control, but by 21 DAMP, no herbicide treatment provided control of warm-season grass species greater than 80%.

Weed Biomass Reduction. Herbicide treatment impacted weed biomass reduction relative to the non-treated control 28 DAMP (Table 9). In general, greater biomass reduction was achieved with two POST applications in comparison to a single early-POST application (Table 9). However, exceptions were observed. Glufosinate + 2,4-D fb clethodim (74%) resulted in greater biomass reduction than applications of glufosinate fb clethodim (25%) and early-POST applications of clethodim (20%) (Table 9). Glufosinate or glufosinate + 2,4-D fb clethodim + glufosinate (56-63%) reduced weed biomass more than clethodim + glufosinate early-POST (21%). Similar weed biomass reduction levels were observed when clethodim + 2,4-D was applied early-POST (53%) and mid-POST following either glufosinate (65%) or glufosinate + 2,4-D (74%). Two applications of glufosinate + 2,4-D (75%) reduced weed biomass more than a single early-POST application of glufosinate + 2,4-D (35%). Glufosinate or glufosinate + 2,4-D fb clethodim + glufosinate + 2,4-D (78%) resulted in greater biomass reduction than clethodim + glufosinate + 2,4-D early-POST (38%).

Table 2. Effect of herbicide program combination on weed control 7 d after early-POST application

Herbicide Program		Visual Weed Control Estimates (%)			
Early-POST	Mid-POST	AMASS[z]	IPOSS	SIDSP	POROL
Clethodim	--	0 C[y]	0 D	0 C	0 D
Clethodim + Glufosinate	--	93 A	93 A	89 A	90 A
Clethodim + 2,4-D	--	67 B	54 C	59 B	74 C
Glufosinate + 2,4-D	--	94 A	91 AB	94 A	92 A
Clethodim + Gluf. + 2,4-D	--	91 A	70 BC	89 A	93 A
Glufosinate	Clethodim	94 A	89 AB	93 A	84 ABC
	Clethodim + Glufosinate	93 A	85 AB	92 A	88 AB
	Clethodim + 2,4-D	94 A	93 A	93 A	91 A
	Glufosinate + 2,4-D	90 A	84 AB	92 A	77 BC
	Clethodim + Gluf. + 2,4-D	92 A	78 AB	90 A	89 A
Glufosinate + 2,4-D	Clethodim	94 A	89 AB	93 A	94 A
	Clethodim + Glufosinate	93 A	89 AB	88 A	91 A
	Clethodim + 2,4-D	95 A	91 AB	94 A	91 A
	Glufosinate + 2,4-D	95 A	95 A	95 A	94 A
	Clethodim + Gluf. + 2,4-D	94 A	89 AB	92 A	91 A
p-value		<.0001	<.0001	<.0001	<.0001
Standard Error		2.9	8.3	4.0	5.9

[z] **Abbreviations: *Amaranthus* spp. (AMASS); *Ipomoea* spp. (IPOSS); prickly sida (SIDSP); common purslane (POROL); glufosinate (Gluf.)**

[y] **Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.**

Table 3. Effect of herbicide program combination on weed control 14 d after early-POST application

Herbicide Program		Visual Weed Control Estimates (%)			
Early-POST	Mid-POST	AMASS[z]	IPOSS	SIDSP	POROL
Clethodim	--	0 E[y]	0 C	0 F	0 E
Clethodim + Glufosinate	--	82 CD	89 AB	80 CDE	81 A-D
Clethodim + 2,4-D	--	77 D	93 A	71 E	74 D
Glufosinate + 2,4-D	--	89 ABC	93 A	88 ABC	86 A-D
Clethodim + Gluf. + 2,4-D	--	86 ABC	80 B	85 BCD	93 AB
Glufosinate	Clethodim	88 ABC	86 AB	84 BCD	83 A-D
	Clethodim + Glufosinate	84 BCD	89 AB	78 DE	80 BCD
	Clethodim + 2,4-D	82 BCD	88 AB	79 DE	93 AB
	Glufosinate + 2,4-D	82 BCD	84 AB	83 BCD	76 CD
	Clethodim + Gluf. + 2,4-D	87 ABC	85 AB	86 A-D	92 AB
Glufosinate + 2,4-D	Clethodim	87 ABC	94 A	90 AB	95 A
	Clethodim + Glufosinate	86 ABC	88 AB	89 AB	91 ABC
	Clethodim + 2,4-D	91 AB	92 A	85 BCD	93 AB
	Glufosinate + 2,4-D	94 A	90 AB	94 A	92 AB
	Clethodim + Gluf. + 2,4-D	94 A	85 AB	92 AB	84 A-D
p-value		<.0001	<.0001	<.0001	<.0001
Standard Error		4.3	3.8	4.8	7.8

[z] Abbreviations: *Amaranthus* spp. (AMASS); *Ipomoea* spp. (IPOSS); prickly sida (SIDSP); common purslane (POROL); glufosinate (Gluf.)

[y] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 4. Effect of herbicide program combination on weed control 21 d after early-POST and 7 d after mid-POST application

Herbicide Program		Visual Weed Control Estimates (%)			
Early-POST	Mid-POST	AMASS[z]	IPOSS	SIDSP	POROL
Clethodim	--	0 F[y]	0 E	0 E	0 C
Clethodim + Glufosinate	--	62 E	78 CD	55 D	60 B
Clethodim + 2,4-D	--	78 CD	90 AB	73 C	63 B
Glufosinate + 2,4-D	--	74 D	88 ABC	68 C	64 B
Clethodim + Gluf. + 2,4-D	--	71 DE	69 D	65 CD	67 B
Glufosinate	Clethodim	72 D	86 BC	65 CD	60 B
	Clethodim + Glufosinate	91 AB	99 A	91 AB	93 A
	Clethodim + 2,4-D	86 BC	95 AB	84 B	89 A
	Glufosinate + 2,4-D	93 AB	99 A	92 AB	95 A
	Clethodim + Gluf. + 2,4-D	96 A	98 AB	95 A	96 A
Glufosinate + 2,4-D	Clethodim	91 AB	94 AB	88 AB	71 B
	Clethodim + Glufosinate	97 A	99 A	97 A	96 A
	Clethodim + 2,4-D	95 AB	98 AB	93 AB	96 A
	Glufosinate + 2,4-D	98 A	99 A	98 A	97 A
	Clethodim + Gluf. + 2,4-D	98 A	99 A	97 A	96 A
p-value		<.0001	<.0001	<.0001	<.0001
Standard Error		6.4	4.2	7.1	15.2

[z] Abbreviations: *Amaranthus* spp. (AMASS); *Ipomoea* spp. (IPOSS); prickly sida (SIDSP); common purslane (POROL); glufosinate (Gluf.)

[y] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 5. Effect of herbicide program combination on weed control 28 d after early-POST and 14 d after mid-POST application

Herbicide Program		Visual Weed Control Estimates (%)			
Early-POST	Mid-POST	AMASS[z]	IPOSS	SIDSP	POROL
Clethodim	--	0 H[y]	0 C	0 G	0 C
Clethodim + Glufosinate	--	55 G	55 B	45 F	93 A
Clethodim + 2,4-D	--	68 EF	88 A	61 DE	96 A
Glufosinate + 2,4-D	--	72 DE	84 A	67 D	94 A
Clethodim + Gluf. + 2,4-D	--	62 FG	40 B	54 EF	93 A
Glufosinate	Clethodim	62 FG	84 A	54 EF	91 A
	Clethodim + Glufosinate	86 BC	98 A	85 BC	96 A
	Clethodim + 2,4-D	86 BC	98 A	83 BC	97 A
	Glufosinate + 2,4-D	91 AB	98 A	90 BC	95 A
	Clethodim + Gluf. + 2,4-D	94 AB	97 A	93 ABC	98 A
Glufosinate + 2,4-D	Clethodim	80 CD	81 A	81 AB	67 B
	Clethodim + Glufosinate	94 AB	96 A	93 C	97 A
	Clethodim + 2,4-D	92 AB	97 A	91 ABC	96 A
	Glufosinate + 2,4-D	96 A	95 A	96 A	95 A
	Clethodim + Gluf. + 2,4-D	96 A	97 A	96 A	96 A
p-value		<.0001	<.0001	<.0001	<.0001
Standard Error		7.1	7.2	7.3	4.5

[z] Abbreviations: *Amaranthus* spp. (AMASS); *Ipomoea* spp. (IPOSS); prickly sida (SIDSP); common purslane (POROL); glufosinate (Gluf.)

[y] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 6. Effect of herbicide program combination on weed control 35 d after early-POST and 21 d after mid-POST application

Herbicide Program		Visual Weed Control Estimates (%)			
Early-POST	Mid-POST	AMASS[z]	IPOSS	SIDSP	POROL
Clethodim	--	0 E[y]	0 D	0 G	0 E
Clethodim + Glufosinate	--	55 D	72 AB	47 F	64 BCD
Clethodim + 2,4-D	--	68 C	90 A	60 E	61 D
Glufosinate + 2,4-D	--	66 C	85 AB	66 DE	63 CD
Clethodim + Gluf. + 2,4-D	--	62 CD	28 C	54 EF	77 ABC
Glufosinate	Clethodim	62 CD	76 AB	57 EF	74 A-D
	Clethodim + Glufosinate	78 B	96 A	77 BCD	81 A
	Clethodim + 2,4-D	85 AB	96 A	83 ABC	79 A
	Glufosinate + 2,4-D	88 AB	90 A	86 AB	86 A
	Clethodim + Gluf. + 2,4-D	88 AB	96 A	88 AB	83 A
Glufosinate + 2,4-D	Clethodim	78 B	62 B	74 CD	76 ABC
	Clethodim + Glufosinate	88 AB	85 AB	85 ABC	83 A
	Clethodim + 2,4-D	89 A	94 A	86 AB	79 AB
	Glufosinate + 2,4-D	90 A	92 A	91 A	86 A
	Clethodim + Gluf. + 2,4-D	92 A	90 A	90 A	84 A
p-value		<.0001	<.0001	<.0001	<.0001
Standard Error		7.2	10.0	7.5	9.7

[z] Abbreviations: *Amaranthus* spp. (AMASS); *Ipomoea* spp. (IPOSS); prickly sida (SIDSP); common purslane (POROL); glufosinate (Gluf.)

[y] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 7. Effect of herbicide program combination on weed control 42 d after early-POST and 28 d after mid-POST application

Herbicide Program		Visual Weed Control Estimates (%)			
Early-POST	Mid-POST	AMASS[z]	IPOSS	SIDSP	POROL
Clethodim	--	0 G[y]	0 D	0 H	0 E
Clethodim + Glufosinate	--	59 F	72 AB	57 FG	83 A-D
Clethodim + 2,4-D	--	72 DE	90 A	67 DEF	76 CD
Glufosinate + 2,4-D	--	66 EF	85 AB	64 EFG	73 D
Clethodim + Gluf. + 2,4-D	--	65 EF	28 C	59 FG	88 ABC
Glufosinate	Clethodim	62 EF	76 AB	52 G	77 BCD
	Clethodim + Glufosinate	79 CD	96 A	76 BCD	79 A-D
	Clethodim + 2,4-D	87 ABC	96 A	86 ABC	88 ABC
	Glufosinate + 2,4-D	86 ABC	90 A	84 ABC	90 AB
	Clethodim + Gluf. + 2,4-D	88 ABC	96 A	87 AB	91 A
Glufosinate + 2,4-D	Clethodim	80 BCD	62 B	74 CDE	78 A-D
	Clethodim + Glufosinate	89 AB	85 AB	87 AB	89 ABC
	Clethodim + 2,4-D	88 ABC	94 A	86 AB	86 ABC
	Glufosinate + 2,4-D	92 A	92 A	90 A	91 A
	Clethodim + Gluf. + 2,4-D	93 A	90 A	90 A	90 AB
	p-value	<.0001	<.0001	<.0001	<.0001
	Standard Error	5.9	10.0	6.3	10.0

[z] Abbreviations: *Amaranthus* spp. (AMASS); *Ipomoea* spp. (IPOSS); prickly sida (SIDSP); common purslane (POROL); glufosinate (Gluf.)

[y] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

DISCUSSION

When glyphosate is excluded from in-season weed control programs due to loss of efficacy or other restrictions, there are alternative methods for controlling troublesome and problematic weeds. Alternative POST-applied herbicides, like glufosinate and 2,4-D, can provide adequate levels of weed control in the absence of glyphosate (Craigmyle et al., 2013; Hoss et al., 2003; Merchant et al., 2013). Glufosinate, in general, is less efficacious on warm-season grasses and Amaranthus spp. than other commonly used POST products but control can be improved with the use of residual herbicides and timely applications (Chahal and Jhala, 2015; Gardner et al., 2006b). The addition of 2,4-D to a glufosinate application resulted in either no or minimal differences in control throughout the rating period regardless of weed species. In contrast, Merchant et al. (2013) observed improvements in weed control when glufosinate and 2,4-D were applied together versus either herbicide alone. Differences in weed size and density at the time of application could have contributed to this difference.

Within this experiment, programs that included two POST applications on average provided 85% broadleaf weed control 28 d after the final application without the use of residuals. Unfortunately, control of warm-season grass weeds was less than ideal across all environments, but control was generally greater with multiple POST applications. However, the addition of preemergence herbicides to the programs could provide greater control as well as reduce selection pressure on the already slim number of POST herbicide modes of actions currently available for use in-season (Gardner et al., 2006b; Riar et al., 2011). There is also the potential that an effective PRE fb POST herbicide program could reduce the chances of needing multiple POST applications (Riar et al., 2011).

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Table 8. Effect of herbicide program combination on warm-season grass visual control 7, 14, 21, and 28 d after early-POST (DAEP) and mid-POST (DAMP) applications

Herbicide Program		Warm-season grasses Visual Control Estimates					
		DAEP					
		7	14	21	28	35	42
				DAMP			
				7	14	21	28
Early-POST	Mid-POST	---------------------------- % ----------------------------					
Clethodim	--	47 Cz	70	66 DE	77 BC	72 A	70 A
Clethodim + Glufosinate	--	90 A	79	52 FG	46 DE	40 C	41 C
Clethodim + 2,4-D	--	48 C	65	60 EF	54 D	42 C	42 C
Glufosinate + 2,4-D	--	85 AB	71	45 G	42 E	37 C	32 C
Clethodim + Gluf.y + 2,4-D	--	87 AB	76	50 FG	45 DE	38 C	39 C
Glufosinate	Clethodim	80 B	65	73 CD	81 AB	76 A	74 A
	Clethodim + Gluf.	85 AB	71	90 A	81 AB	71 A	70 A
	Clethodim + 2,4-D	86 AB	66	76 B-D	79 AB	73 A	72 A
	Glufosinate + 2,4-D	81 B	67	85 AB	68 C	59 B	57 B
	Clethodim + Gluf. + 2,4-D	83 AB	66	92 A	79 AB	68 AB	69 A
Glufosinate + 2,4-D	Clethodim	86 AB	69	75 B-D	87 A	76 A	75 A
	Clethodim + Gluf.	84 AB	67	93 A	82 AB	71 A	67 AB
	Clethodim + 2,4-D	88 A	70	82 A-C	80 AB	73 A	70 A
	Glufosinate + 2,4-D	87 AB	68	89 A	72 BC	66 AB	67 AB
	Clethodim + Gluf. + 2,4-D	87 AB	65	93 A	80 AB	71 A	71 A
p-value		<.0001	0.1505	<.0001	<.0001	<.0001	<.0001
Standard Error		5.5	7.6	11.0	10.1	12.2	11.6

Table 9. Effect of herbicide program on percent weed biomass reduction relative to non-treated control at 28 d after mid-POST application

Herbicide Program		Biomass Reduction
Early-POST	Mid-POST	% of NTCz
Clethodim	--	20 Dy
Clethodim + Glufosinate	--	21 D
Clethodim + 2,4-D	--	53 ABCD
Glufosinate + 2,4-D	--	35 BCD
Clethodim + Glufosinate + 2,4-D	--	38 BCD
Glufosinate	Clethodim	25 CD
	Clethodim + Glufosinate	57 ABC
	Clethodim + 2,4-D	65 AB
	Glufosinate + 2,4-D	65 AB
	Clethodim + Glufosinate + 2,4-D	78 A
Glufosinate + 2,4-D	Clethodim	74 A
	Clethodim + Glufosinate	63 AB
	Clethodim + 2,4-D	74 A
	Glufosinate + 2,4-D	75 A
	Clethodim + Glufosinate + 2,4-D	78 A
p-value		0.0002
Standard Error		20.3

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