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Control of acetolactate synthase–resistant Palmer amaranth in dry edible bean

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Abstract

Herbicide-resistant Palmer amaranth is a troublesome weed in several agronomic crops and is a relatively new challenge to dry bean production in western Nebraska. Objectives were to evaluate preemergence (PRE) and postemergence (POST) herbicides for control of acetolactate synthase–resistant Palmer amaranth and their effect on Palmer amaranth density and biomass as well as dry bean injury and yield in western Nebraska. Field experiments were conducted in 2017 and 2019 near Scottsbluff, NE. The experiments were arranged as a two-factor strip-plot design. The strip-plot factor consisted of no-PRE or pendimethalin (1,070 g ai ha^{-1}) + dimethenamid-P (790 g ai h^{-1}) applied PRE. The main-plot factor was POST herbicides, which consisted of various mixtures of imazamox, bentazon, or fomesafen applied in a single or sequential application at labeled rates, and reduced rates of imazamox (9 g ai ha^{-1}) + bentazon (314 g ai ha^{-1}) + fomesafen (70 g ai ha^{-1}) applied in single or sequential (two or three) applications. PRE herbicides reduced Palmer amaranth density and biomass during both years and increased dry bean yield in 2017. POST treatments containing fomesafen improved Palmer amaranth control compared with treatments containing imazamox and bentazon only. The sequential-application reduced-rate POST system did not improve Palmer amaranth control compared to one POST application containing fomesafen at a labeled rate in either year. Using pendimethalin + dimethenamid-P PRE followed by POST treatments containing imazamox + bentazon + fomesafen at a labeled rate provided 86% and 99% Palmer amaranth control in 2017 and 2019, respectively.

Introduction

Palmer amaranth is an annual broadleaf weed species that is present in crop production systems across many regions of the United States (Ward et al. 2013), including the Panhandle region of Nebraska (Sarangi and Jhala 2018). Palmer amaranth is a dioecious species, native to the southwestern United States and Mexico (Sauer 1957), and is highly competitive owing to its rapid growth rate (Jha et al. 2008). Horak and Loughin (2000) reported that Palmer amaranth can grow at a rate of 0.21 cm growing degree day $(GDD)^{-1}$ (base 10 C). Palmer amaranth has the ability to emerge for most of the growing season, achieving optimum germination at fluctuating soil temperatures near 30 C (Jha and Norsworthy 2009; Steckel et al. 2004), which favors late-season emergence. Palmer amaranth can produce up to 600,000 seeds female $plant^{-1}$ (Keeley et al. 1987). Palmer amaranth is becoming a widespread weed issue in the Panhandle of Nebraska (Sarangi and Jhala 2018) and is challenging to control because of resistance to glyphosate and acetolactate synthase (ALS)-inhibiting herbicides (Chahal et al. 2017; Sprague et al. 1997). Owing to its late-season emergence characteristics, Palmer amaranth can emerge during the entirety of the dry bean production season.

Dry bean is a leguminous crop commonly produced under irrigation in arid and semiarid climates of the Northern High Plains. In 2019, 537,625 ha of dry bean were planted in the United States, including 48,600 ha in Nebraska (USDA 2019). Dry bean is planted later in the season compared with other crops, such as corn (*Zea mays* L.) and sugarbeet (*Beta vulgaris* L.), to allow for optimum soil temperature for germination (Pearson et al. 2015). In the Northern High Plains region, dry bean is planted in late May to early June and harvested in September (Pearson et al. 2015). Weed control in dry bean is important to ensure high yields and bean quality (Nissen and Kniss 2015). Dry bean is not considered to be a competitive crop with weeds, compared with corn and soybean [*Glycine max* (L.) Merr.], because of its slow growth, poor canopy closure, and lower biomass accumulation. It is estimated that dry bean yield would be reduced by 71% in North America, or 59% in Nebraska, without effective weed control (Soltani et al. 2017b). By comparison, a 50% yield loss would be expected in corn and soybean without effective weed control (Soltani et al. 2016, 2017a). Beiermann et al. (2022b) found dry bean yield to be reduced by 82% to 97% in western Nebraska when weeds were allowed to compete with dry bean.

Early-emerging annual weed species in western Nebraska, such as kochia [*Bassia scoparia* (L.) A.J. Scott] and common lambsquarters (*Chenopodium album* L.), are less problematic in dry bean production because of the later planting timing (Werle et al. 2014). Late-season-emerging weeds, such as *Amaranthus* and *Solanum* species, are competitive with dry bean (Ogg and Dawson 1984). Historically, redroot pigweed (*Amaranthus retroflexus* L.) and hairy nightshade [*Solanum villosum* (L.) Mill.] have been competitive late-emerging species in dry bean growing regions and significantly reduce yield (Aguyoh and Masiunas 2003; Amini et al. 2014; Blackshaw 1991). Palmer amaranth is highly competitive with dry bean and can cause severe yield reduction (Miranda et al. 2021). Miranda et al. found Palmer amaranth to cause 5% yield reduction in dry bean at the equivalent density of 4 Palmer amaranth plants ($100\ m^{-2}$).

Residual herbicides applied preplant incorporated (PPI) or PRE are the basis of initial weed control in dry bean production (Beiermann et al. 2022a; Blackshaw et al. 2000; Wilson and Sbatella 2014). As PRE and PPI herbicides cannot provide season-long weed control, POST herbicides are usually applied between the first and fifth trifoliate dry bean growth stages, when the residual activity of PRE or PPI herbicides is no longer providing effective control (Beiermann et al. 2022a). Common POST herbicides in dry bean include imazamox and bentazon for the control of broadleaf weeds (Nissen and Kniss 2015; Wilson 2005).

In contrast to soybean production, for which numerous PRE residual herbicide options are available (Sarangi and Jhala 2019), dry bean growers in western Nebraska only have Group 3, 8, and 15 residual herbicides available (Knezevic et al. 2020). Furthermore, broadleaf herbicides applied POST in dry bean are limited to halosulfuron, imazamox, imazethapyr, bentazon, and fomesafen. Halosulfuron, imazamox, and imazethapyr are ALS-inhibiting herbicides and do not provide effective control of resistant Palmer amaranth, as resistance to ALS-inhibiting herbicides is widespread in Nebraska (Chahal et al. 2017; Heap 2020). Bentazon has little activity on Palmer amaranth and will not provide effective control if applied alone (Anonymous 2017). Fomesafen can control Palmer amaranth, when applied either PRE or POST in soybean (Bond et al. 2006; Whitaker et al. 2010), and can provide effective control of *Amaranthus* species applied POST in dry bean (Anonymous 2015; Wilson 2005). Further challenging weed control in dry bean, both imazamox and fomesafen are only labeled for one POST application in dry bean per growing season and cannot be used to control successive weed flushes.

A reduced-rate POST herbicide program has been developed by North Dakota State University that uses multiple POST application of imazamox, bentazon, and fomesafen, compared with a single full-rate POST application (Zollinger et al. 2010). The goal of making multiple POST applications is to potentially increase the control of late-emerging summer annual weed species. Reduced-rate herbicide programs were developed for POST weed control in sugarbeet (Dexter and Luecke 1998). The "microrate" POST herbicide program in sugarbeet involved making multiple applications of a mixture of herbicides at reduced rates, compared with a single application at a full rate (Dexter and Luecke 1998). Sugarbeet growers benefited from this program by reducing crop injury and herbicide cost, while increasing weed control (Dale et al. 2006; Dexter 1994). The concept of the program was to start the first POST application early season to target small, newly emerged weeds and then to follow up with two or more additional POST applications, made at timed intervals, to control later-emerging weeds (Dale et al. 2006).

Certain dry bean growers in the High Plains production region of Nebraska and Colorado are currently using reduced-rate POST herbicides. The efficacy of a reduced-rate herbicide program, compared with labeled POST applications, has not previously been evaluated in the High Plains for the control of ALS-inhibitor-resistant Palmer amaranth. The objective of this experiment was to evaluate PRE followed by POST herbicide programs for control of ALS-inhibitor-resistant Palmer amaranth in dry edible bean. To our knowledge, this is the first study to evaluate herbicide programs to control ALS-inhibitor-resistant Palmer amaranth in dry bean.

Materials and Methods

Site Description

Field experiments were conducted during the 2017 and 2019 growing seasons at the University of Nebraska–Lincoln Panhandle Research and Extension Center near Scottsbluff, NE (41.89°N, 103.68°W). Soil type is a Glenberg sandy loam (Ustic Torrifluvents) with pH 8.2, 70% sand, 15% silt, 15% clay, and 1.5% organic matter in 2017 and pH 8.0, 66% sand, 17% silt, 17% clay, and 2% organic matter in 2019. Fertilizer was spread across the study area in both years prior to planting, providing 112 kg ha^{-1} nitrogen and 45 kg ha^{-1} phosphorus. The preceding crops in the study area were corn in 2016 and sugarbeet in 2018.

Experimental Design and Herbicide Treatments

This study was designed as a strip plot with four replications. The main-plot factor was POST herbicides, and the strip-plot factor was PRE herbicides; both factors were randomized. Strip plots (PRE herbicides) were oriented east to west and were 33 m wide (15 × 2.2 m POST treatments) by 3.8 m long. Main plots (POST herbicides) were oriented north to south and were 2.2 m wide by 7.6 m long. This design allowed POST herbicide treatments to be evaluated with and without PRE herbicides. POST treatments applied without a PRE ensured high weed pressure, whereas PRE followed by POST treatment is a representation of common grower practice.

The dry bean variety 'Sinaloa' (ADM Seedwest, Decatur, IL, USA) was used in 2017, and 'LaPaz' (ADM Seedwest) was used in 2019. Both varieties are an indeterminate pinto bean with upright plant architecture. Planting took place on June 1, 2017, and June 8, 2019. Dry bean was planted in a 56-cm row spacing at a population of 210,000 plants ha^{-1}. No tillage was performed prior to planting to help ensure that Palmer amaranth seed produced in the previous year remained near the soil surface.

The PRE herbicide treatments were pendimethalin + dimethenamid-P, referred to as PRE, and nontreated, referred to as no-PRE. PRE herbicide application rates are referenced in Table 1. PRE herbicides were applied on the day of planting in 2017 and 3 d after planting in 2019. PRE herbicides were incorporated with 1.3 cm of overhead irrigation within 24 h of application. Glyphosate was applied across the entire study

Table 1. Herbicide products and application rates for control of ALS inhibitor-resistant Palmer amaranth in field experiments conducted near Scottsbluff, NE, in 2017 and 2019.[a]

Common name	Trade name	WSSA SOA	Rate		Manufacturer
			Standard	Reduced	
			——— g ai ha^{-1} ———		
Pendimethalin	Prowl® H2O	3	1,070	—	BASF, Research Triangle Park, NC, USA
Dimethenamid-P	Outlook®	15	790	—	BASF
Imazamox[b]	Raptor®	2	35	9	BASF
Bentazon[b]	Basagran®	6	673	314	BASF
Fomesafen[b]	Reflex®	14	280	70	Syngenta, Greensboro, NC, USA

[a]Abbreviation: WSSA SOA, Weed Science Society of America Herbicide Site of Action.
[b]Herbicides applied POST included 18 g ammonium sulfate L^{-1} and 1.5% v/v methylated seed oil.

at a rate of 1,261 g ae ha^{-1}, on the same day as PRE herbicide application to ensure that any emerged weeds were controlled. Standard-rate POST herbicide treatments consisted of applications of imazamox, bentazon, and fomesafen (Table 1), and reduced-rate POST herbicide treatments consisted of a mixture of imazamox + bentazon + fomesafen applied one, two, or three times, referred to hereinafter as Reduced Rates 1, 2, and 3, corresponding to the number of sequential applications made.

The first application of all POST treatments was applied when dry bean reached the V1 growth stage. Palmer amaranth was 3 cm and 2 cm at the time of the first POST application in 2017 and 2019, respectively. The second POST herbicide application for standard-rate treatments followed by 10 d, when dry bean was at the V2 growth stage. Sequential reduced-rate POST treatments followed in 7-d intervals. Dry bean was at the V1 growth stage for the second and V2 for the third application of sequential reduced-rate treatments. Herbicides applied POST were mixed with 18 g ammonium sulfate L^{-1} and 1.5% v/v methylated seed oil. Herbicide applications were made with a CO_2-pressurized backpack sprayer equipped with TeeJet® 11002 AIXR nozzles (TeeJet® Technologies, Spraying Systems, Wheaton, IL, USA). Nozzle spacing was 51 cm, and nozzles were calibrated to deliver 140 L ha^{-1} of spray solution.

Data Collection

Weed control and crop injury were visually estimated on a scale of 0 to 100. Weed density was assessed 3 wk after the first POST application and at harvest. A 1.0-m^2 quadrat was randomly placed in each plot, and the total number of Palmer amaranth plants was counted for density. Palmer amaranth plants in the quadrat were clipped at ground level and oven-dried to collect aboveground weed biomass at harvest time.

Dry bean plants were collected on September 17, 2017, by handpulling beans from 6 m of the two center rows in each plot to determine yield. Plants were air-dried in paper bags until they were at a moisture level to allow threshing by a stationary combine. Yields are adjusted to a standard moisture of 15%. Yield data were not collected in 2019 as a result of severe hail damage that took place on August 15. Harvest weed control ratings, weed density, and biomass were collected on September 10, 2019.

Statistical Analysis

Data were analyzed using R software (R Core Team 2019). Analysis of variance (ANOVA) was performed on weed control, crop injury ratings, and yield data. Post hoc testing was performed with Tukey's honestly significant difference (HSD) using the ExpDes package (Ferreira et al. 2014). Weed density and biomass were analyzed with a generalized linear mixed model with a quasi-Poisson error distribution using the LME4 package (Bates et al. 2019). Post hoc mean separation of POST herbicide treatment was performed with Tukey's HSD using the MULTCOMP package (Hothorn et al. 2019). If an interaction was present between PRE and POST treatment factors, mean separation was performed within the PRE and no-PRE treatments individually. The mean response of each POST treatment is presented separately for PRE and no-PRE treatments regardless of interaction to better represent the performance of each POST treatment with and without a PRE herbicide applied.

Results and Discussion

Palmer amaranth Control

Pendimethalin + dimethenamid-P applied PRE resulted in greater Palmer amaranth control across all POST treatments in both study years (Table 2). There was an interaction between PRE and POST herbicide treatment 3 wk after first POST application and at harvest in 2017 and 2019. The application of pendimethalin + dimethenamid-P provided 48% and 74% control 3 wk after first POST application in 2017 and 2019, respectively. The level of control provided by a PRE-only treatment was reduced to 14% and 55% control at harvest time in 2017 and 2019, respectively (Table 2). Sequential applications of soil-active herbicides POST may extend Palmer amaranth control later into the growing season and could be an option to manage herbicide-resistant populations (Miranda et al. 2022). In 2017, POST treatments provided generally low levels of Palmer amaranth control 3 wk after first POST application when applied with no PRE herbicide. Palmer amaranth control from POST treatments was improved with the addition of a PRE application in 2017. All POST treatments applied following the PRE treatment provided greater than 90% Palmer amaranth control 3 wk after first POST application, except for the treatments imazamox + bentazon, fomesafen, fomesafen + bentazon, imazamox + bentazon + fomesafen followed by (fb) bentazon, and Reduced Rate 1 in 2017 (Table 2).

In 2019, Palmer amaranth control 3 wk after first POST application, within no PRE, was 93% or greater with all POST treatments containing fomesafen, as well as the Reduced Rate 2 and Reduced Rate 3 (Table 2). Within the PRE treatment, there was no difference in Palmer amaranth control among POST treatments 3 wk after first POST application, and all POST treatments provided greater than 94% control (Table 2).

Table 2. Ratings of PRE and POST herbicide programs for control of ALS inhibitor-resistant Palmer amaranth in field experiments conducted near Scottsbluff, NE, in 2017 and 2019.[a,b,c]

	3 WAT				Harvest			
	2017		2019		2017		2019	
POST herbicide	No-PRE	PRE	No-PRE	PRE	No-PRE	PRE	No-PRE	PRE
	%							
Nontreated control[d]	0 e	48 b	0 c	74 b	0 c	14 c	0 e	55 b
Imazamox + bentazon	51 bcd	83 a	84 ab	94 a	15 c	33 bc	53 cd	82 ab
Imazamox + bentazon fb bentazon	50 bcd	90 a	74 b	95 a	9 c	61 ab	49 d	84 ab
Imazamox + bentazon fb fomesafen	71 ab	95 a	97 a	99 a	26 c	82 a	84 abc	95 a
Imazamox + bentazon fb fomesafen + bentazon	68 abc	93 a	95 a	99 a	14 c	76 ab	69 abcd	93 a
Fomesafen	25 de	86 a	94 a	98 a	4 c	69 ab	73 abcd	96 a
Fomesafen fb imazamox + bentazon	69 abc	97 a	96 a	99 a	16 c	73 ab	89 ab	99 a
Fomesafen + bentazon	43 cd	81 a	93 a	99 a	8 c	59 abc	85 ab	99 a
Fomesafen + bentazon fb imazamox + bentazon	76 ab	99 a	98 a	99 a	25 c	98 a	97 a	99 a
Imazamox + bentazon + fomesafen	58 bc	92 a	94 a	99 a	7 c	86 a	88 ab	99 a
Imazamox + bentazon + fomesafen fb bentazon	68 abc	89 a	94 a	98 a	8 c	62 ab	82 abc	99 a
Reduced Rate 1	26 de	85 a	73 b	92 a	3 c	65 ab	60 bcd	93 a
Reduced Rate 2	75 ab	95 a	95 a	99 a	21 c	85 a	92 ab	98 a
Reduced Rate 3	89 a	98 a	99 a	99 a	40 c	94 a	96 a	99 a

[a]Abbreviations: fb, followed by, indicating a later application; WAT, weeks after first POST treatment.
[b]Means followed by the same letter are nonstatistically different at an alpha of 0.05.
[c]Reduced-rate treatments contain imazamox + bentazon + fomesafen at the rates 9, 314, and 70 g ai ha^{-1}, respectively; number indicates the number of sequential POST applications made.
[d]Weed-free control was removed from all presented analyses because of lack of variance.

Table 3. Effect of PRE and POST herbicide programs on ALS inhibitor-resistant Palmer amaranth density in dry bean field experiments conducted near Scottsbluff, NE, in 2017 and 2019.[a,b,c]

	3 WAT				Harvest			
	2017		2019		2017		2019	
POST herbicide	No-PRE	PRE	No-PRE	PRE	No-PRE	PRE	No-PRE	PRE
	plants m^{-2}							
Nontreated control[d]	49 CD	29 cd	31 E	16 e	89 AB	55 ab	43 c	8 ab
Imazamox + bentazon	50 D	40 d	12 CDE	6 cde	137 B	74 b	9 ab	6 ab
Imazamox + bentazon fb bentazon	43 ABCD	30 abcd	34 DE	5 de	92 AB	44 ab	11 b	2 ab
Imazamox + bentazon fb fomesafen	22 AB	1 ab	2 ABC	1 abc	44 AB	24 ab	2 ab	1 ab
Imazamox + bentazon fb fomesafen + bentazon	25 ABC	1 abc	9 ABCD	1 abcd	49 A	8 a	9 ab	3 ab
Fomesafen	57 BCD	18 bcd	4 ABC	0 abc	59 AB	23 ab	6 ab	1 ab
Fomesafen fb imazamox + bentazon	34 ABCD	2 abcd	2 A	0 a	63 AB	17 ab	2 ab	0 a
Fomesafen + bentazon	37 ABCD	8 abcd	6 ABC	1 abc	60 AB	29 ab	6 ab	0 a
Fomesafen + bentazon fb imazamox + bentazon	22 AB	0 ab	1 A	0 a	21 A	1 a	2 ab	1 ab
Imazamox + bentazon + fomesafen	31 ABCD	4 abcd	3 AB	1 ab	44 AB	14 ab	4 ab	0 a
Imazamox + bentazon + fomesafen fb bentazon	46 ABCD	16 abcd	4 A	0 a	64 AB	29 ab	10 ab	2 ab
Reduced Rate 1	37 ABCD	7 abcd	12 BCDE	8 bcde	81 AB	31 ab	6 ab	3 ab
Reduced Rate 2	22 AB	1 ab	3 ABC	0 abc	19 A	8 a	2 ab	1 ab
Reduced Rate 3	14 A	0 a	2 A	0 a	36 A	3 a	0 a	1 ab

[a]Abbreviations: fb, followed by, indicating a later application; WAT, weeks after first POST treatment.
[b]Means followed by the same letter are nonstatistically different at an alpha of 0.05. If no interaction occurred between PRE and POST treatment, both lowercase and uppercase letters are used in a column, and columns should not be compared.
[c]Reduced-rate treatments contain imazamox + bentazon + fomesafen at the rates 9, 314, and 70 g ai ha^{-1}, respectively; number indicates the number of sequential POST applications made.
[d]Weed-free control was removed from all presented analyses because of lack of variance.

The only treatments that provided greater than 90% Palmer amaranth control at harvest in 2017 were fomesafen + bentazon fb imazamox + bentazon and the Reduced Rate 3 POST treatments when applied following pendimethalin + dimethenamid-P applied PRE (Table 2). In 2019, Palmer amaranth control at harvest was among the lowest in POST treatments that did not contain fomesafen. All POST treatments containing fomesafen applied with a PRE treatment resulted in greater than 90% weed control, including all reduced-rate treatments (Table 2).

POST treatments appeared to provide a greater level of Palmer amaranth control in 2019 than in 2017, which is likely attributed to greater Palmer amaranth emergence in 2017 (Table 3). During the 2017 growing season, there was a high amount of Palmer amaranth emergence in early June, followed by a prolific late-season emergence. In the 2019 growing season, Palmer amaranth emergence appeared to be delayed in comparison to 2017 owing to cooler spring temperatures, and late-season emergence was not as evident. This is also supported by higher Palmer amaranth density in nontreated control plots in 2017 (Table 3).

Table 4. Effect of PRE and POST herbicide programs on ALS inhibitor-resistant Palmer amaranth biomass in dry bean field experiments conducted near Scottsbluff, NE, in 2017 and 2019.[a,b,c]

POST herbicide	2017 No-PRE	2017 PRE	2019 No-PRE	2019 PRE
	g m^{-2}			
Nontreated control[d]	1,060 b	630 b	502 B	157 b
Imazamox + bentazon	340 b	209 ab	212 AB	69 ab
Imazamox + bentazon fb bentazon	575 b	68 a	457 AB	23 ab
Imazamox + bentazon fb fomesafen	273 b	45 a	41 A	9 a
Imazamox + bentazon fb fomesafen + bentazon	335 b	73 a	257 AB	28 ab
Fomesafen	564 b	100 a	247 AB	0 ab
Fomesafen fb imazamox + bentazon	229 b	47 a	26 A	0 a
Fomesafen + bentazon	428 b	92 a	117 AB	0 ab
Fomesafen + bentazon fb imazamox + bentazon	582 b	2 a	25 A	2 a
Imazamox + bentazon + fomesafen	575 b	49 a	91 A	0 a
Imazamox + bentazon + fomesafen fb bentazon	409 b	94 a	118 AB	1 ab
Reduced Rate 1	920 b	107 ab	242 AB	40 ab
Reduced Rate 2	332 b	46 a	41 A	17 a
Reduced Rate 3	218 b	5 a	0 A	1 a

[a]Abbreviation: fb, followed by, indicating a later application.
[b]Means followed by the same letter are nonstatistically different at an alpha of 0.05. If no interaction occurred between PRE and POST treatment, both lowercase and uppercase letters are used in a column, and columns should not be compared.
[c]Reduced-rate treatments contain imazamox + bentazon + fomesafen at the rates 9, 314, and 70 g ai ha^{-1}, respectively; number indicates the number of sequential POST applications made.
[d]Weed-free control was removed from all presented analyses because of lack of variance.

Table 5. Effect of POST herbicides on dry bean injury in field experiment conducted in 2019 near Scottsbluff, NE.[a,b,c]

POST herbicide	Dry bean injury 3 WAT
	%
Imazamox + bentazon[d]	0 c
Imazamox + bentazon fb bentazon	11 bc
Imazamox + bentazon fb fomesafen	16 ab
Imazamox + bentazon fb fomesafen + bentazon	28 a
Fomesafen	0 c
Fomesafen fb imazamox + bentazon	13 bc
Fomesafen + bentazon	0 c
Fomesafen + bentazon fb imazamox + bentazon	13 bc
Imazamox + bentazon + fomesafen	1 c
Imazamox + bentazon + fomesafen fb bentazon	13 bc
Reduced Rate 1	0 c
Reduced Rate 2	5 bc
Reduced Rate 3	13 bc

[a]Abbreviations: fb, followed by, indicating a later application; WAT, weeks after first POST treatment.
[b]Means followed by the same letter are nonstatistically different at an alpha of 0.05.
[c]Reduced-rate treatments contain imazamox + bentazon + fomesafen at the rates 9, 314, and 70 g ai ha^{-1}, respectively; number indicates the number of sequential POST applications made.
[d]Nontreated control and weed-free control were removed from all presented analyses because of lack of variance.

Palmer amaranth Density and Biomass

Pendimethalin + dimethenamid-P reduced Palmer amaranth density 3 wk after first POST application and at harvest and also reduced Palmer amaranth biomass in both 2017 and 2019 (Tables 3 and 4). In 2017, 3 wk after first POST application, Palmer amaranth density was among the highest in the nontreated, imazamox + bentazon, and fomesafen treatments (Table 3). In 2019, 3 wk after first POST application, the treatments imazamox + bentazon, imazamox + bentazon fb bentazon, and Reduced Rate 1 resulted in higher Palmer amaranth density than other POST treatments (Table 3). In both years, treatments containing full rates of fomesafen resulted in lower Palmer amaranth density, with the exception of the fomesafen-only treatment in 2017 (Table 3).

At harvest in 2017, the only POST treatment with increased Palmer amaranth density was the imazamox + bentazon treatment (Table 3). In 2019, there was an interaction between PRE and POST treatments affecting Palmer amaranth density at harvest. Within the no-PRE treatment, all POST treatments reduced Palmer amaranth density compared to the nontreated. The best-performing POST treatment, Reduced Rate 3, reduced density in comparison to the poorest-performing treatment imazamox + bentazon fb bentazon (Table 3). Within the PRE treatment, there was no separation in the performance of POST treatments.

There was an interaction between PRE and POST herbicide treatments for 2017 Palmer amaranth biomass. Within the no-PRE treatment, there was no significant separation of POST treatments owing to excessive variance. Within the PRE treatment, all POST treatments, excluding imazamox + bentazon and Reduced Rate 1, reduced biomass in comparison to the PRE-alone treatment (Table 4). In 2019, the POST treatments imazamox + bentazon fb fomesafen, fomesafen fb imazamox + bentazon, fomesafen + bentazon fb imazamox + bentazon, imazamox + bentazon + fomesafen, and Reduced Rates 2 and 3 reduced Palmer amaranth density compared to the nontreated (Table 3).

In both study years, the best-performing POST treatments in Palmer amaranth density and biomass reduction were POST treatments containing a full rate of fomesafen and Reduced Rates 2 and 3 when applied with a PRE. The fomesafen-only and fomesafen + bentazon POST treatments provided poorer control in 2017, most likely because of excessive late-season Palmer amaranth emergence. Regardless of the amount of ALS-resistant Palmer amaranth, it would be common for a grower to apply imazamox and bentazon POST, because these herbicides increase the spectrum of weed control compared to fomesafen alone (Wilson 2005).

Dry Bean Injury

No dry bean injury was detected in the 2017 field season. In 2019, there was injury present in the form of spotting and crinkling of dry

Table 6. Effect of PRE and POST herbicides on dry bean yield in a field experiment conducted in 2017 near Scottsbluff, NE.[a,b,c]

POST herbicide	Dry bean yield
	kg ha^{-1}
No-PRE	
Nontreated control	1,020 C
Imazamox + bentazon	1,690 ABC
Imazamox + bentazon fb bentazon	1,510 ABC
Imazamox + bentazon fb fomesafen	2,150 A
Imazamox + bentazon fb fomesafen + bentazon	1,660 ABC
Fomesafen	1,160 ABC
Fomesafen fb imazamox + bentazon	2,220 AB
Fomesafen + bentazon	1,780 ABC
Fomesafen + bentazon fb imazamox + bentazon	2,150 AB
Imazamox + bentazon + fomesafen	1,840 AB
Imazamox + bentazon + fomesafen fb bentazon	1,890 ABC
Reduced Rate 1	950 BC
Reduced Rate 2	2,100 ABC
Reduced Rate 3	2,350 AB
Weed-free control	2,360 A
PRE	
Nontreated control	1,900 c
Imazamox + bentazon	2,150 abc
Imazamox + bentazon fb bentazon	2,560 abc
Imazamox + bentazon fb fomesafen	3,100 a
Imazamox + bentazon fb fomesafen + bentazon	2,760 abc
Fomesafen	2,500 abc
Fomesafen fb imazamox + bentazon	2,840 ab
Fomesafen + bentazon	2,320 abc
Fomesafen + bentazon fb imazamox + bentazon	2,840 ab
Imazamox + bentazon + fomesafen	3,120 ab
Imazamox + bentazon + fomesafen fb bentazon	2,860 abc
Reduced Rate 1	2,240 bc
Reduced Rate 2	2,650 abc
Reduced Rate 3	2,620 ab
Weed-free control	3,050 a

[a]Abbreviation: fb, followed by, indicating a later application.
[b]Means followed by the same letter are nonstatistically different at an alpha of 0.05. If no interaction occurred between PRE and POST treatments, both lowercase and uppercase letters are used in a column.
[c]Reduced-rate treatments contain imazamox + bentazon + fomesafen at the rates 9, 314, and 70 g ai ha^{-1}, respectively; number indicates the number of sequential POST applications made.

bean leaves 3 wk after first POST application. The treatments imazamox + bentazon fb fomesafen + bentazon and imazamox + bentazon fb fomesafen resulted in 28% and 16% injury, respectively, the highest levels observed (Table 5). These are the only two POST treatments in the study that contained a full rate of fomesafen in the second POST application. The second POST application, for full-rate POST treatments, was made 11 d before injury ratings were taken. Other studies have shown that fomesafen can cause injury to dry bean when applied POST, but reduction in yield is not expected (Soltani et al. 2006; Wilson 2005). Wilson reported that fomesafen injury was higher when applied as a mixture with imazamox. This agrees with the limited injury observed in the two treatments that contained fomesafen without imazamox (Table 5).

Dry Bean Yield

Pendimethalin + dimethenamid-P PRE resulted in higher yield in 2017, the only year for which yield data were collected. The POST herbicide treatments imazamox + bentazon fb fomesafen, fomesafen fb imazamox + bentazon, fomesafen + bentazon fb imazamox + bentazon, imazamox + bentazon + fomesafen, and Reduced Rate 3 resulted in increased yield compared to the nontreated (Table 6). All POST treatments, excluding Reduced Rate 1, had yields within the uppermost yielding group (Table 6). The Reduced Rate 2 treatment did not yield significantly higher than the nontreated, indicating that three POST applications of the reduced-rate system are necessary to reach the same level of yield as a single POST application of imazamox + bentazon + fomesafen.

The widespread adoption of reduced-rate POST herbicide programs in sugarbeet production was due to the high amount of crop injury caused by full-rate applications (Dexter 1994) and also the high cost and poor control from available PRE herbicide options (Dale et al. 2006). Similar to sugarbeet producers, dry bean growers do not have a plethora of herbicide options. However, dry bean growers have effective soil-active herbicide options that work to suppress Palmer amaranth emergence, so there is not complete reliance on a POST herbicide program as there is in sugarbeet production. Also, fomesafen can achieve a high level of control of *Amaranthus* species with a single application and has not been shown to cause yield-reducing levels of crop injury (Wilson 2005).

Additionally, using full rates for POST application is less likely to promote the evolution of resistant weed biotypes (Norsworthy et al. 2012). If the reduced-rate POST treatments provide a sublethal dose to the emerged weeds, this herbicide program could increase the rate of resistance development (Busi and Powles 2009; Manalil et al. 2011). Therefore a dry bean reduced-rate herbicide program may not provide the same benefits as the successfully adopted sugarbeet reduced-rate program.

There was no advantage to the reduced-rate POST system in controlling Palmer amaranth in the Panhandle of Nebraska compared to labeled treatments containing fomesafen. High levels of Palmer amaranth control were achieved with the use of a PRE herbicide followed by a full-rate POST application of fomesafen (Table 2). The benefits of the reduced-rate program in sugarbeet, including increased weed control and reduced crop injury, are not realized in dry bean. Dry bean growers can achieve the same level of yield and weed control with a one-pass POST system compared to a two-pass or three-pass POST system, resulting in considerable time and cost savings. A one-pass system also reduces the risk of inclement weather preventing timely sequential applications.

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