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Tolerance of four dry bean market classes to flufenacet, acetochlor, and *S*-metolachlor applied preplant incorporated

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Research Article

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Flufenacet; acetochlor; *S*-metolachlor; Azuki bean; *Vigna angularis* (Willd.) Ohwi & H. Ohashi; kidney bean; *Phaseolus vulgaris* L.; small red bean; *Phaseolus vulgaris* L; white bean; *Phaseolus vulgaris* L.; common bean; *Phaseolus vulgaris* L.; soybean; *Glycine max* (L.) Merr.

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Abstract

Common bean and azuki bean are poor competitors with weeds and demonstrate sensitivity to herbicides used for weed control in soybean. *S*-metolachlor, flufenacet, and acetochlor are categorized as Group 15 herbicides and provide control of multiple annual grass and select small-seeded broadleaf weeds. By way of field trials near Exeter and Ridgetown, Ontario, in 2019, 2020, and 2021, four dry bean market classes (azuki, kidney, small red, and white bean) were evaluated for their tolerance to 1× established label rates and 2× rates of *S*-metolachlor (1,600 and 3,200 g ai ha^{-1}), flufenacet (750 and 1,500 g ai ha^{-1}) and acetochlor (1,700 and 3,400 g ai ha^{-1}) applied preplant incorporated (PPI). Injury was evaluated by assessing visible injury symptoms, density, shoot biomass, height, seed moisture content, and seed yield. Azuki bean was more sensitive to the Group 15 herbicides than other dry bean market classes; the Group 15 herbicides caused a 12% reduction in azuki bean growth at 2 wk after emergence; growth reduction was ≤2% in the other bean classes. Flufenacet (2× rate) was the most injurious treatment, causing a 27% reduction in azuki bean yield. This study concludes that kidney, small red, and white bean have a sufficient margin of crop safety to flufenacet, acetochlor, and *S*-metolachlor applied PPI. Azuki bean was sensitive to flufenacet; additional research is needed to investigate azuki bean tolerance to acetochlor and *S*-metolachlor applied PPI.

Introduction

Dry bean and azuki bean are important food crops. In 2020, the United States was the fourth largest producer of dry bean; the highest dry bean-producing states were North Dakota, Michigan, Minnesota, Nebraska, and Idaho (FAO 2021; Lucier and Davis 2020). Although production occurs on smaller hectarages in Canada, farm cash receipts from Canadian dry bean production totaled more than Can$315 million in 2020 (Government of Alberta 2021; Manitoba Agriculture 2021; OMAFRA 2021d). Ontario accounts for 38% of Canadian dry bean production with approximately 63,500 hectares seeded to dry bean in 2020 (OMAFRA FCT 2020). White (navy) bean accounts for 50% of Ontario dry bean production, the remaining hectares are seeded primarily with black, kidney, cranberry, and azuki bean market classes (OMAFRA FCT 2020; OMAFRA 2021a, 2021b). Dry bean demonstrates sensitivity to weeds, in part, resulting from its small stature (Ghamari and Ahmadvand 2012; Sikkema et al. 2007). A meta-analysis by Soltani et al. (2017a) concluded that 56% yield loss in Ontario dry bean would result when weeds are not controlled.

Although dry bean is sensitive to weed interference, far fewer herbicide options are available for weed management in Ontario dry beans relative to soybean. EPTC, dimethenamid-*P*, pendimethalin, *S*-metolachlor, and trifluralin are registered for soil application in Ontario and are used primarily for annual grass control; clethodim, fluazifop-p-butyl, quizalofop-p-ethyl, and sethoxydim are registered postemergence (POST) herbicides for grass weed control. For broadleaf weed control, halosulfuron and imazethapyr are the only two herbicides registered for soil application, and POST broadleaf herbicides in Ontario are limited to halosulfuron, fomesafen, and bentazon (OMAFRA 2021c). Dry beans are sensitive to many herbicides, which prevents the use of some herbicides that are used for soybean from being registered with dry bean crops (Cowan and Sikkema 2018; Shaner 2014).

Flufenacet is an oxyacetamide herbicide that belongs to the Group 15 herbicides (WSSA; Soltani et al. 2005). It is a very long-chain fatty acid elongases (VLCFAE) inhibitor. Absorption takes place through the roots and shoots of emerging weeds, providing control of many annual grass and select small-seeded broadleaf weeds (Gajbhiye and Gupta 2001;

Johnson et al. 2012; Soltani et al. 2005). Flufenacet is registered for the control of green foxtail [*Setaria viridis* (L.) P. Beauv.], yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], giant foxtail (*Setaria faberi* Herrm.), witchgrass (*Panicum capillare* L.), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], fall panicum (*Panicum dichotomiflorum* Michx.), proso millet (*Panicum miliaceum* L.), smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and yellow nutsedge (*Cyperus esculentus* L.). In addition, flufenacet is registered for the suppression of common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and Powell amaranth (*Amaranthus powellii* S. Wats.) (A Kaastra, Bayer Crop Science, personal communication, February 25, 2022).

Acetochlor is a WSSA Group 15 chloroacetanilide herbicide that is also a VLCFAE inhibitor (Shaner 2014). It is commonly used in U.S. corn, soybean, and cotton (*Gossypium hirsutum* L.) production but has not been registered for use in Canada (Cahoon et al. 2015; Murschell and Farmer 2019). Acetochlor provides effective control of broadleaf signalgrass [*Urochloa platyphlla* (Munro ex C. Wright) R. D. Webster], barnyardgrass, redroot pigweed, hairy nightshade (*Solanum physalifolium* Rusby), common lambsquarters, and Palmer amaranth (*Amaranthus palmeri* S. Watson; Cahoon et al. 2015; Jursik et al. 2013; Mueller and Steckel 2011). It exists as two different stand-alone formulations that include an emulsifiable concentrate (EC) and a micro-encapsulated (ME) product. The ME product, as used in this study, is a slow-release acetochlor via the use of a polymer coating that increases crop safety in certain crops (Cahoon et al. 2015; Fogleman et al. 2018). Although injury with ME acetochlor exceeds 20% in select nonregistered, sensitive crops such as pumpkin (*Curcurbita pepo*) and rice (*Oryza sativa*), less injury occurs than when the EC formulation is used (Ferebee et al. 2019; Fogleman et al. 2018).

S-metolachlor is a registered chloroacetanilide, WSSA Group 15 herbicide used for weed control in dry bean in Canada (Soltani et al. 2018). It primarily controls annual grasses with activity on select small-seeded annual broadleaf weeds (Osborne et al. 1995; Sikkema et al. 2009). Although visible dry bean injury has been documented with *S*-metolachlor; dry bean shoot biomass, height, density, seed moisture, and yield are rarely affected (Sikkema et al. 2009; Soltani et al. 2018).

Studies investigating the tolerance of dry bean to flufenacet and acetochlor applied preplant incorporated (PPI) have not been completed to our knowledge. Flufenacet and acetochlor have activity primarily on annual grasses, with select activity on small-seeded broadleaf weeds. Canadian dry bean growers would benefit from additional herbicide options for weed control, which may lead to improved weed control, lower yield losses from weeds, and increased net returns for producers, assuming that there is sufficient dry bean tolerance to these products, and registrations are permissible.

The research objective of this study was to evaluate azuki, kidney, small red, and white bean tolerance to PPI applications of three Group 15 herbicides (flufenacet, acetochlor, and *S*-metolachlor) at the 1× and 2× rates.

Materials and Methods

From 2019 to 2021, six field trials were conducted (two trials per year) in Ridgetown, ON, at the University of Guelph Ridgetown Campus, and near Exeter, ON, at the Huron Research Station. Soil characteristics for each site-year are summarized in Table 1. The cumulative rainfall received and the average daily temperature for 7 and 14 d following herbicide application at each site-year is listed in Table 2.

Table 1. Soil characteristics for the six field trials.[a]

Year	Location	Soil texture	Sand	Silt	Clay	OM[b]	pH
			%				
2019	Ridgetown	Loam	43	42	15	4.2	6.5
2019	Exeter	Clay loam	36	38	26	2.7	7.8
2020	Ridgetown	Loam	47	37	16	5.1	6.3
2020	Exeter	Clay loam	41	35	24	2.4	7.6
2021	Ridgetown	Sandy clay loam	51	28	21	3.9	6.3
2021	Exeter	Clay loam	35	43	22	4.4	8.0

[a]Soil analysis was performed by A&L Canada Laboratories Inc. (2136 Jetstream Road, London, Ontario, Canada, N5V 3P5) from soil cores taken to depths of 15 cm.
[b]Abbreviation: OM, organic matter.

Table 2. Cumulative precipitation and average daily temperature during the six field trials conducted.[a]

		Cumulative precipitation		Average daily temperature	
Year	Location	7 DAA	14 DAA	7 DAA	14 DAA
		mm		C	
2019	Ridgetown	12.9	19.5	18.5	20.1
2019	Exeter	20.2	27.6	19.2	21.6
2020	Ridgetown	0	17.3	17.8	19.8
2020	Exeter	5.8	37.6	19.1	18.5
2021	Ridgetown	6.3	23.5	19.6	19.1
2021	Exeter	10.9	37.3	20.0	17.2

[a]Abbreviation: DAA, days after application.

The experimental design used for the study was a split-plot with four replications. Herbicide treatment was the main plot factor and was arranged in a randomized complete block design. A nontreated control, flufenacet (750 and 1,500 g ai ha^{-1}), acetochlor (1,700 and 3,400 g ai ha^{-1}), and *S*-metolachlor (1,600 and 3,200 g ai ha^{-1}) was included in each replicate. The rates used for *S*-metolachlor represent the manufacturer's recommended 1× label rate and 2× rate, while the rate structure for flufenacet and acetochlor were determined based on previously identified rate ranges. The 2× rates were included to imitate an application overlap in the field. Main plots differed slightly in size; plots measured 6 m wide by 8 m long in Ridgetown, ON, with plots being slightly longer in Exeter, ON, at 6 m wide by 10 m long. Subplot factor was dry bean market class, which included azuki, white, kidney, and small red beans represented by the cultivars 'Erimo', 'T9905', 'Dynasty', and 'Viper', respectively. Due to equipment limitations, dry bean was seeded in a continuous fashion and was not randomized within each main plot. Two rows of each market class were sown 4 cm deep in rows spaced 75 cm apart. Azuki, kidney, small red, and white bean were seeded at 230,000, 188,000, 207,000, and 254,000 seeds ha^{-1}, respectively, in Exeter; and 232,900, 175,500, 232,900, and 232,900 seeds ha^{-1}, respectively, in Ridgetown.

Site preparation began in the fall when sites were moldboard plowed. One pass of spring cultivation was conducted prior to herbicide application with an S-tine cultivator with rolling basket harrows. The entire experimental area was maintained weed-free with a cover spray of pendimethalin (1,000 g ai ha^{-1}) + imazethapyr (37.5 g ai ha^{-1}) applied preemergence (PRE). Fomesafen (240 g ai ha^{-1}) was applied POST when needed in addition to hand hoeing as necessary. Herbicides were applied using a CO_2-pressurized backpack sprayer that delivered 200 L ha^{-1} at 240 kPa with ultra-low drift 120-02 nozzles (ULD120-02; Hypro, Pentair Ltd., London, UK). Within 1 h of application, the herbicides were incorporated with an S-tine cultivator with rolling basket harrows. Two passes in opposite directions were used to incorporate the herbicides. All dry bean market classes emerged at similar times.

Visible dry bean injury assessments were completed at 1, 2, 4, and 8 wk after emergence (WAE) on a percent scale of 0 to 100 where 0% represented no injury and 100% indicated complete plant death. All injury symptoms that were present at a specific site-year were evaluated. Density and biomass assessments were completed at 3 WAE by counting and clipping bean plants in 1 m of row at the soil line; samples were placed in paper bags, kiln-dried at 60 C for 2 wk, and the biomass was recorded. Shoot dry weight per plant was determined by taking the weight of the biomass in 1 m of row and dividing it by the number of plants. Bean height measurements were taken at 6 WAE by averaging the height of 10 arbitrarily selected plants from both rows in each plot. Dry beans were straight-cut and threshed with a small-plot combine at harvest maturity; seed moisture content and seed yield weight were documented. Seed moisture content was adjusted to standard moistures of 13% for azuki bean and 18% for *Phaseolus vulgaris* classes prior to statistical analysis.

Data analysis was performed using SAS software v. 9.4 (SAS Institute Inc., Cary, NC) and the GLIMMIX procedure. Fixed effects included herbicide treatment, dry bean market class, and the interaction between herbicide treatment and dry bean market class, while environment (site-year combination), block nested within the environment, the interaction of dry bean market class, herbicide treatment, and environment, and the interaction of herbicide treatment by block nested within environment were the random effects. The *F*-test and *Z*-test were used to assess the significance of the fixed and random effects, respectively. Studentized residual plots were analyzed, the Shapiro-Wilk test statistic was verified, and a check for overdispersion was conducted to satisfy the assumptions of homogeneity and normality using the UNIVARIATE procedure. Injury assessments were transformed to normalize data using the arcsine square root transformation. Dry bean density, shoot biomass, height, seed moisture, and seed yield were analyzed as a percentage of the nontreated control to allow market classes to be compared. Dry bean density, shoot biomass, height, and seed yield were transformed using the square root function, while seed moisture content used a lognormal distribution. All transformed data were back-transformed to the original scale for the presentation of results. Comparisons between herbicide treatments were made using a Tukey-Kramer grouping test with a significance of $P < 0.05$.

Results and Discussion

Visible dry bean leaf deformation, growth reduction, stand reduction, chlorosis and necrosis, delayed emergence, and bleaching were evaluated at 1, 2, 4, and 8 WAE, though for clarity of discussion only, the prevalent symptoms of leaf deformation, growth reduction, stand reduction, and chlorosis and necrosis at 2 WAE are presented. Injury symptoms were evaluated only when present; not all symptoms were present at each site-year, thus explaining why not all injury symptoms were evaluated at all six site-years. Main effects are presented when there was no interaction between dry bean market class and herbicide treatment. Where a significant interaction was detected, simple effects are presented. No injury was observed from the PRE cover spray of pendimethalin (1,000 g ai ha^{-1}) + imazethapyr (37.5 g ai ha^{-1}). Some injury from the POST application of fomesafen did occur in Exeter in 2021, however, the timing of application allowed for recovery. Additionally, the remaining injury in the nontreated control was considered when injury assessments were performed.

Leaf Deformation

Visible leaf deformation was evaluated at all six site-years, and the main effects are presented (Table 3). Leaf deformation included cupped, crinkled, or curled leaves and leaves with a shortened midrib. The main effect of dry bean market class was significant at 2 WAE. Azuki bean was more sensitive to the Group 15 herbicides than the other dry bean market classes. The Group 15 herbicides caused 4% azuki bean leaf deformation, but there was no leaf deformation in kidney, small red, or white bean at 2 WAE. Leaf deformation decreased with time; the Group 15 herbicides caused 10%, 4%, 1%, and 0% azuki bean leaf deformation at 1, 2, 4, and 8 WAE, respectively (data not presented). At 1 WAE, Group 15 herbicides caused ≤4% injury, and ≤1% injury at 2, 4, and 8 WAE in kidney, small red, and white bean. Similarly, Soltani et al. (2018) reported that azuki bean was the most sensitive dry bean market class to other PPI Group 15 herbicides such as pethoxamid, *S*-metolachlor, dimethenamid-*P*, and pyroxasulfone.

Growth Reduction

Visible growth reduction was evaluated at all six site-years, and the main effects are presented (Table 3). The most sensitive dry bean market class to the Group 15 herbicides was azuki bean, with a 12% visible growth reduction at 2 WAE. Azuki bean growth reduction decreased with time, there was 8% and 3% growth reduction at 4 and 8 WAE, respectively (data not presented). At 2 WAE, Group 15 herbicides caused ≤2% visible growth reduction in kidney, small red, and white beans; there was no difference among *P. vulgaris* (L.) classes. There was no difference in dry bean growth reduction with acetochlor and *S*-metolachlor at the 1× and 2× rates; in contrast, the 2× rate of flufenacet caused greater dry bean growth reduction relative to the 1× rate. Sikkema et al. (2009) reported limited injury with *S*-metolachlor applied PPI at 2,746 g ai ha^{-1} in kidney, black, cranberry, and white bean; however, the rate was lower than the 2× rate of 3,200 g ai ha^{-1} used in this study. Additionally, very little injury with *S*-metolachlor at 1,600 and 3,200 g ai ha^{-1} was reported in pinto and azuki beans, though other studies have indicated that azuki bean is more sensitive to *S*-metolachlor (Li et al. 2016; Soltani et al. 2008a; 2017b).

Stand Reduction

Visible stand reduction was evaluated at five site-years. The simple effects are presented (Table 4) as an interaction was detected (Table 3). The Group 15 herbicides did not cause stand reductions in kidney, small red, or white bean at 2 WAE. Flufenacet (1× rate), acetochlor (1× and 2× rate), and *S*-metolachlor (1× rate) reduced azuki bean stand 1% to 3% at 2 WAE, whereas flufenacet (2× rate) and *S*-metolachlor (2× rate) caused a stand reduction of 18% and 5%, respectively. At the 1× rate, flufenacet, acetochlor, and *S*-metolachlor reduced azuki bean stand similarly. At the 2× rate, *S*-metolachlor caused a greater stand reduction than acetochlor; flufenacet (2× rate) reduced azuki bean stand by 18% at 2

Table 3. Mean values of main effects and their interaction.[a,c,d]

Main effects	Rate	Leaf deformation[e] 2 WAE	Growth reduction[e] 2 WAE	Stand reduction[e] 2 WAE	Chlorosis and necrosis[e] 2 WAE
	—g ai ha^{-1}—	—% injury—			
Dry bean market class		**	**	**	NS
Azuki		4 b	12 b	3	0
Kidney		0 a	1 a	0	0
Small Red		0 a	2 a	0	0
White		0 a	1 a	0	0
Herbicide treatment		NS	**	**	NS
Nontreated control		0	0 a	0	0
Flufenacet	750	0	2 bc	1	0
Flufenacet	1,500	1	8 d	2	0
Acetochlor	1,700	1	1 b	0	0
Acetochlor	3,400	1	3 bc	0	0
S-metolachlor	1,600	1	1 bc	0	0
S-metolachlor	3,200	1	3 c	0	1
Interaction					
B × H[b]		NS	NS	**	NS

[a]Abbreviation: WAE, weeks after crop emergence.
[b]B, dry bean market class; H, herbicide.
[c]Small letters (a–d) within main effects, means followed by the same letter (a–d) within a column are not significantly different according to Tukey-Kramer grouping at P < 0.05.
[d]Asterisks (* and **) denote significance at P < 0.05 and P < 0.01, respectively; NS, not significant at P = 0.05.
[e]Leaf deformation and growth reduction are based on six site-years: Exeter and Ridgetown locations in 2019, 2020, and 2021; stand reduction was based on five site-years: Ridgetown location in 2019 and 2020, and Exeter location in 2019, 2020, and 2021; chlorosis and necrosis are based on four site years: Ridgetown location in 2019 and 2020, and Exeter location in 2020 and 2021.

Table 4. Percent visible stand reduction.[a,b]

Herbicide treatment	Rate	Stand reduction Azuki	Kidney	Small Red	White
	—g ai ha^{-1}—	—%—			
2 WAE					
Nontreated control		0	0	0	0
Flufenacet	750	3 abY	0 ZY	0 Z	0 ZY
Flufenacet	1,500	18 cY	0 Z	0 Z	0 Z
Acetochlor	1,700	1 ab	0	0	0
Acetochlor	3,400	1 a	0	0	0
S-metolachlor	1,600	1 ab	0	0	0
S-metolachlor	3,200	5 bY	0 Z	0 Z	0 Z

[a]Abbreviation: WAE, weeks after crop emergence.
[b]Means followed by the same letter (a–d) within a column or (Y–Z) within a row are not significantly different according to Tukey-Kramer grouping at P < 0.05.

WAE, which was greater than all other herbicide treatments evaluated. At 2 WAE, flufenacet (1× rate) caused a greater stand reduction in azuki bean than small red bean; stand reduction in kidney and white bean was intermediary and similar to that of the other dry bean market classes. There was a greater stand reduction in azuki bean than kidney, small red, and white bean with flufenacet (2× rate) and *S*-metolachlor (2× rate) at 2 WAE.

Chlorosis and Necrosis

Visible chlorosis and necrosis were evaluated at four site-years, and the main effects are presented (Table 3). Neither main effect was significant at 2 WAE.

Density

Dry bean density was evaluated at all six site-years, and the main effects are presented (Table 5). The Group 15 herbicides reduced azuki bean density by 15%; there was no decrease in small red and white bean density. There was an increase in kidney bean density. Soltani et al. (2018) showed that of four dry bean classes, kidney bean density was reduced when treated with Group 15 herbicides, contrary to the findings in this study; however different Group 15 herbicides were used in this study. Herbicide treatment had no impact on plant density.

Shoot Biomass

Dry bean shoot biomass per meter was evaluated at all six site-years, and the main effects are presented (Table 5). The Group 15 herbicides reduced azuki and white bean shoot biomass per meter by 36% and 8%, respectively. Acetochlor and *S*-metolachlor (1× and 2× rates) applied PPI did not reduce dry bean shoot biomass per meter. Flufenacet applied PPI at the 1× and 2× rates reduced dry bean shoot biomass per meter by 15% and 29%, respectively. These results corroborate those presented by Stewart et al. (2010) when biomass reductions reached 50% in azuki bean treated with pyroxasulfone PPI (250 g ai ha^{-1}); however, flufenacet caused azuki bean reductions in this study, as pyroxasulfone was not evaluated.

Dry bean shoot biomass per plant was evaluated at all six site-years, and the main effects are presented (Table 5). The Group 15 herbicides reduced azuki bean shoot biomass per plant by 28%, whereas kidney, small red, and white bean shoot biomass per plant was reduced by 5% to 11%. Dry beans treated with flufenacet (2× rate) applied PPI incurred a 29% shoot biomass per plant reduction. Dry beans treated with acetochlor (1× and 2× rate), *S*-metolachlor (1× and 2× rate), and flufenacet (1× rate) had shoot biomass per plant that was similar to that of the nontreated control.

Plant Height

Dry bean height was evaluated at all six site-years. The simple effects are presented (Table 6); there was a significant interaction (Table 5). Flufenacet, acetochlor, and *S*-metolachlor (1× and 2× rates) did not cause a decrease in kidney, small red,

Table 5. Mean values of main effects of herbicides on dry beans as a percentage of the nontreated control and their interaction.[a,b]

Main effects	Rate	Density	Shoot biomass m^{-1}	Shoot biomass plant^{-1}	Height	Moisture	Yield
	—g ai ha^{-1}—	—% of the nontreated—					
Dry bean market class		**	**	**	**	**	**
Azuki		85 c	64 c	72 b	88	102 ab	91
Kidney		112 a	105 a	95 a	100	100 a	104
Small Red		111 ab	98 ab	89 a	98	101 a	103
White		102 b	92 b	90 a	97	103 b	99
Herbicide treatment		NS	**	**	**	**	*
Nontreated control		100	100	100	100	100	100
Flufenacet	750	98	85 bc	85 a	96	102 ab	99
Flufenacet	1,500	96	71 c	71 b	90	104 b	92
Acetochlor	1,700	109	103 a	95 a	99	101 a	102
Acetochlor	3,400	101	86 ab	88 a	97	101 a	98
S-metolachlor	1,600	107	100 ab	94 a	99	101 ab	104
S-metolachlor	3,200	102	88 ab	86 a	95	101 a	100
Interaction							
B × H[c]		NS	NS	NS	*	NS	*

[a]Small letters (a–c) within main effects, and means followed by the same letter (a–c) within a column are not significantly different according to Tukey-Kramer grouping at $P < 0.05$.
[b]Asterisks (* and **) denote significance at $P < 0.05$ and $P < 0.01$, respectively; NS, not significant at $P = 0.05$.
[c]B, dry bean market class; H, herbicide.

Table 6. Height and yield of dry beans as a percentage of the nontreated control.[a]

Herbicide treatment	Rate	Azuki	Kidney	Small red	White
	—g ai ha^{-1}—	—% of the nontreated—			
Height					
Nontreated control		100	100	100	100
Flufenacet	750	90 abY	100 Z	98 Z	96 Z
Flufenacet	1,500	77 cY	96 Z	94 Z	94 Z
Acetochlor	1,700	94 aY	103 Z	102 Z	98 ZY
Acetochlor	3,400	88 abY	102 Z	99 Z	98 Z
S-metolachlor	1,600	95 aY	102 Z	98 ZY	100 ZY
S-metolachlor	3,200	84 bcY	99 Z	100 Z	96 Z
Yield					
Nontreated control		100	100	100	100
Flufenacet	750	94 a	102	100	98
Flufenacet	1,500	73 bY	98 Z	103 Z	95 Z
Acetochlor	1,700	100 a	104	104	99
Acetochlor	3,400	91 aY	105 Z	101 Y	97 Y
S-metolachlor	1,600	101 a	112	101	100
S-metolachlor	3,200	88 abY	103 Z	106 Z	103 Z

[a]Means followed by the same letter (a–c) within a column or (Y–Z) within a row in each section are not significantly different according to Tukey-Kramer grouping at $P < 0.05$.

or white bean height. Acetochlor and *S*-metolachlor at the 1× rate did not reduce azuki bean height; flufenacet at the 1× rate reduced azuki bean height by 10%. Acetochlor, *S*-metolachlor, and flufenacet at the 2× rate reduced plant height of azuki bean by 12%, 16%, and 23%, respectively. Similarly, Soltani et al. (2018) concluded that relative to *P. vulgaris* market classes, azuki bean height was much lower when treated with Group 15 herbicides such as pethoxamid, *S*-metolachlor, dimethenamid-P, and pyroxasulfone at 1× and 2× rates.

Seed Moisture Content

Higher seed moisture is an indication of a delay in maturity and is frequently associated with herbicide injury (Soltani et al. 2008b). Higher seed moisture content may increase drying costs and reduce dry bean quality, which may result in decreased net returns to the grower. Dry bean seed moisture content was recorded at all six site-years, and the main effects are presented (Table 5). Averaged over all herbicide treatments, white bean was the only dry bean market class that demonstrated an increase in seed moisture, and was greater by 3 percentage points. Flufenacet (1× rate), acetochlor (1× and 2× rates), and *S*-metolachlor (1× and 2× rates) applied PPI did not cause delayed maturity, indicated by seed moisture content that was similar to that of the nontreated control; in contrast, flufenacet (2× rate) caused an increase in seed moisture content by 4 percentage points relative to the nontreated control.

Yield

Dry bean yield was recorded at all six site-years. The simple effects are presented (Table 6) as there was a significant interaction (Table 5). Yield was calculated from the harvested area only where beans were present, and did not include the 1 m of row from where bean shoot biomass was retrieved. Herbicide treatment had no effect on kidney, small red, or white bean yield. Flufenacet (1× rate), acetochlor (1× and 2× rates), and *S*-metolachlor (1× and 2× rates) applied PPI did not reduce azuki bean yield; in contrast, flufenacet (2× rate) decreased azuki bean yield by 27%. Similarly, Soltani et al. (2020) reported no azuki bean yield reduction from the use of *S*-metolachlor at 1,200 g ai ha^{-1} applied PPI. A numerical drop in yield from 2,722 to 2,540 kg ha^{-1} occurred when *S*-metolachlor was applied at 3,200 vs. 1,600 g ai ha^{-1} (Soltani et al. 2018). Azuki bean was more sensitive than kidney, small red, or white bean to flufenacet (2× rate) and *S*-metolachlor (2× rate). Kidney bean was most tolerant to acetochlor (2× rate) applied PPI.

In conclusion, kidney, small red, and white bean are tolerant to flufenacet, acetochlor, and *S*-metolachlor at both the 1× and 2× rates when applied PPI. The Group 15 herbicides caused little to no visible symptomology on the *P. vulgaris* L. dry bean market classes, and there were negligible differences in density, height, and yield. For some parameters, the Group 15 herbicides caused a low-level response in white bean with no decrease in yield. In contrast, azuki bean was sensitive to the Group 15 herbicides applied PPI. Generally, azuki bean was more sensitive to flufenacet than acetochlor and *S*-metolachlor, and there was greater azuki bean injury with flufenacet at the 2× rate relative to the 1× rate. Visible leaf deformation and growth reduction were the most prevalent visible injury symptoms across all dry bean market classes.

This research concludes that there is a sufficient margin of crop safety to support the registration of flufenacet and a capsule suspension formulation of acetochlor applied PPI for weed management in *P. vulgaris* classes, similar to the current registration of *S*-metolachlor. Further studies are needed to determine whether a sufficient margin of crop safety exists in azuki bean to support the use of acetochlor in dry bean. In addition, the results indicate that a sufficient margin of crop safety does not exist in azuki bean to support the use of flufenacet applied PPI.

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