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Halosulfuron Tank-Mixes Applied PRE in White Bean

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White bean tolerance and weed control were examined by applying halosulfuron alone or in combination with pendimethalin, dimethenamid-P, or *S*-metolachlor applied PRE. All herbicides applied alone or in combination caused less than 3% visible injury 1 and 4 wk after emergence (WAE). Halosulfuron applied PRE provided greater than 95% control of common lambsquarters, wild mustard, redroot pigweed, and common ragweed and less than 55% control of green foxtail at 4 and 8 WAE. Weed density and dry weight at 8 WAE paralleled the control ratings. Dry bean yields in halosulfuron plus a soil applied grass herbicide did not differ compared to the weed-free control. Green foxtail competition with halosulfuron PRE applied alone resulted in reduced white bean yield compared to the weed-free control.

Nomenclature: Dimethenamid-P; halosulfuron; pendimethalin; *S*-metolachlor; common lambsquarters, *Chenopodium album* L.; common ragweed, *Ambrosia artemisiifolia* L.; green foxtail, *Setaria viridis* (L.) Beauv.; redroot pigweed, *Amaranthus retroflexus* L.; wild mustard, *Sinapis arvensis* L.; white bean, *Phaseolus vulgaris* L.

Key words: Dry bean, injury, seed moisture content, weed control, weed emergence, yield.

La tolerancia del frijol blanco y el control de malezas fueron examinados para aplicaciones PRE de halosulfuron solo o en combinación con pendimethalin, dimethenamid-P, o *S*-metolachlor. Todos los herbicidas aplicados solos o en combinación causaron menos de 3% de daño visible, a 1 y 4 semanas después de la emergencia (WAE). Halosulfuron aplicado PRE brindó un control mayor a 95% de *Chenopodium album*, *Sinapis arvensis*, *Amaranthus retroflexus*, y *Ambrosia trifida*, y menor a 55% para el control de *Setaria viridis*, a 4 y 8 WAE. Las reducciones en la densidad y peso seco de las malezas a 8 WAE fueron proporcionales a las evaluaciones de control. Los rendimientos del frijol blanco con combinaciones de halosulfuron más otro herbicida no fueron diferentes al compararse con el testigo libre de malezas. La competencia causada por *S. viridis* en parcelas con halosulfuron PRE aplicado solo resultó en reducciones en el rendimiento del frijol blanco al compararse con el testigo libre de malezas.

White bean is the major dry edible bean produced in Ontario, with 58, 55, and 48% of total dry edible bean production in 2012, 2013, and 2014 in Ontario, respectively (Statistics Canada 2015). Ontario, as the largest white bean producer in Canada, produced 77% of Canadian white bean in 2014 (Statistics Canada 2015). White bean is susceptible to weed interference with 77, 58, 81, and 68% white bean yield loss due to weed interference in studies conducted by Malik et al. (1993), Chikoye et al. (1995), and Soltani et al. (2014b and 2014c), respectively.

There are only three herbicides registered in Ontario for broadleaf weed control in white bean: imazethapyr, bentazon, and fomesafen (HCPMRA 2010; OMAF 2012; Sikkema et al. 2004). Bentazon and fomesafen are applied POST (Sikkema et al. 2004) whereas imazethapyr was the only soil-applied broadleaf herbicide available for use on white bean when this study was initiated in 2013. Although, imazethapyr is an efficacious soil-applied herbicide with activity on both annual grass and broadleaf weeds, it has a narrow margin of crop safety on white bean (Arnold et al. 1993; Bauer et al. 1995; Blackshaw and Saindon 1996; Soltani et al. 2007; Wilson and Miller 1991). Halosulfuron, which was registered for use in Ontario in 2014, provides an additional herbicide option for the control of annual broadleaf weeds, including common lambsquarters, redroot pigweed, velvetleaf (*Abutilon theophrasti* Medik.), wild mustard, common cocklebur (*Xanthium pennsylvanicum* L.), jimsonweed (*Datura stramonium* L.), and lady's thumb (*Polygonum persicaria* L.) (Senseman 2007).

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In contrast, halosulfuron provides little to no control of annual grass weeds including green foxtail and barnyardgrass (*Echinochloa crus-galli* Beauv.) (Senseman 2007). For example, Soltani et al. (2014b) reported only 50% control of green foxtail with halosulfuron applied preplant incorporated (PPI). Halosulfuron soil adsorption is correlated with soil organic carbon content and inversely related to soil pH (Dermiyati and Yamamoto 1997). Halosulfuron is degraded by microbial degradation and through chemical hydrolysis. It will hydrolyze more rapidly when soil pH is less than 4.5 (Grey et al. 2007). Higher soil pH or lower soil organic matter will result in greater crop injury. A lower rate of halosulfuron (35 g ai ha^{-1}) was recommended for lighter textured soils with low organic matter (Senseman 2007).

There are three soil-applied PRE herbicides that have activity on annual grasses that may have an adequate margin of crop safety in white bean in Ontario: pendimethalin, dimethenamid-P, and *S*-metolachlor, with only *S*-metolachlor being currently registered for use on white bean. Pendimethalin, a group 3 dinitroaniline herbicide, controls many annual grass weeds including large crabgrass (*Digitaria sanguinalis* L.), barnyardgrass, and green foxtail (Senseman 2007; Soltani et al. 2012a). In addition, pendimethalin provides suppression of common lambsquarters (Betts and Morrison 1979; Ferrell et al. 2003; Soltani et al. 2013b). Dimethenamid-P and *S*-metolachlor are group 15 chloroacetamide herbicides that control emerging annual grass weeds and suppress some small-seeded broadleaf weeds including eastern black nightshade (*Solanum ptychanthum* Dunal), common lambsquarters, and pigweed species (*Amaranthus* spp.) (Senseman 2007; Soltani et al. 2012a). Soltani et al. (2012a), for example, reported that pendimethalin, dimethanamid-P, and *S*-metolachlor applied PPI provided greater than 95% control of green foxtail.

Halosulfuron in combination with pendimethalin, dimethanamid-P, or *S*-metolachlor applied PRE may provide control of common annual grass and broadleaf weeds in white bean in Ontario. The registration of these PRE tank-mixes would provide white bean producers with additional week management option that provide broad-spectrum weed control with a wide margin of crop safety. The objective of this research was to evaluate the level of crop injury, weed control, weed emergence timing, and white bean yield when halosulfuron was applied PRE alone or in combination with pendimethalin, dimethenamid-P, or *S*-metolachlor.

Materials and Methods

Six field experiments were conducted over a 2-yr period (2013, 2014), including four trials at the Huron Research Station near Exeter, Ontario, Canada (2013, 2014) and two trials at the Ridgetown Campus of the University of Guelph near Ridgetown, Ontario, Canada (2014).

The soils for the two trials near Exeter in 2013 were a Brookston clay loam with 29% sand, 44% silt, 27% clay, 3.6% organic matter, and pH of 7.7 at site 1 and 18% sand, 46% silt, 36% clay, 4.7% organic matter, and pH of 7.5 at site 2. The soils for the two trials near Exeter in 2014 were 31% sand, 42% silt, 27% clay, 3.8% organic matter, and pH of 7.7 at site 3 and 41% sand, 40% silt, 19% clay, 3.3% organic matter, and pH of 7.7 at site 4. The soils for the two trials near Ridgetown in 2014 were a Fox sandy loam with 50% sand, 25% silt, 25% clay, 2.9% organic matter, and pH of 7.1 for site 5 and 45% sand, 26% silt, 29% clay, 3.7% organic matter, and pH of 7.8 for site 6. Seedbed preparation consisted of fall moldboard plowing followed by two passes with a field cultivator with rolling basket harrows in the spring.

All six experiments were conducted as a randomized complete block design with four replications. Herbicides evaluated included halosulfuron (Gowan Canada, P.O. Box 248 Station T, Calgary, AB, Canada) alone or in combination with pendimethalin (BASF Canada Inc., 100 Milverton Drive, 5th Floor, Mississauga, ON, Canada), dimethenamid-P (BASF Canada Inc.) or *S*-metolachlor (Syngenta Canada Inc., 140 Research Lane, Guelph, ON, Canada), applied PRE as listed in Table 1. White bean ('T9905') was seeded at 250,000 seeds ha^{-1} to a depth of 4 cm in late May to early June of each year depending on weather conditions. Each plot was 3 m wide consisting of four rows (spaced 0.75 m apart) and 10 or 8 m in length at the Exeter and Ridgetown sites, respectively.

Herbicides were applied after seeding and before the white bean plants emerged. Depending on the weather, herbicides were applied on the same day as planting or within 6, 7, or 8 days after planting.

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Table 1. White bean injury (visual rating) 1 and 4 wk after emergence (WAE) with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P, and *S*-metolachlor applied PRE at Exeter (2013 to 2014) and Ridgetown, ON, Canada (2014).[a]

		Injury	
Herbicide treatment	Rate	1 WAE	4 WAE
	g ai ha^{-1}	%	
Weedy control		0 a	0
Weed-free control		0 a	0
Pendimethalin	1,080	0 a	0
Dimethenamid-P	544	3 b	1
S-metolachlor	1,050	2 b	0
Halosulfuron	35	0 a	0
Pendimethalin + halosulfuron	1,080 + 35	0 a	0
Dimethenamid-P + halosulfuron	544 + 35	3 b	1
S-metolachlor + halosulfuron	1,050 + 35	2 ab	0
P value		0.01	0.24

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

Beans were planted on May 27 and June 6, 2013, for sites 1 and 2 in Exeter, respectively. Herbicides were sprayed on June 4 and June 14 for sites 1 and 2, respectively. In 2014, beans were planted on June 2, 9, 6, and 18 for sites 3 to 6 in Exeter and Ridgetown. Herbicides were sprayed on June 10, 16, 13, and 24 for sites 3 to 6, respectively. Herbicides were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha−1 of spray solution at a pressure of 200 kPa using ULD 120-02 (Hypro, New Brighton, MN) ultralow drift nozzles. The spray boom was 1.5 m in length with four nozzles spaced 50 cm apart.

White bean injury was visually estimated on a scale of 0 (no injury) to 100% (complete plant death) at 1 and 4 WAE. Weed control was visually estimated on a scale of 0 (no control) to 100% (complete control) at 4 and 8 WAE. Weed density and dry weight were determined 8 WAE by cutting the weeds at the soil surface in two 0.5-m^2 quadrats per plot and separating and counting by species. Data from the two quadrats in each plot were combined for analysis. Weeds were dried at 60 C to a constant moisture and then weighed. White bean plants from the center two rows of each plot were harvested using a plot combine harvester when 90% of the pods in the weed-free control were golden in color. White bean weight and moisture content were recorded per plot and yields were adjusted to 18% seed moisture content.

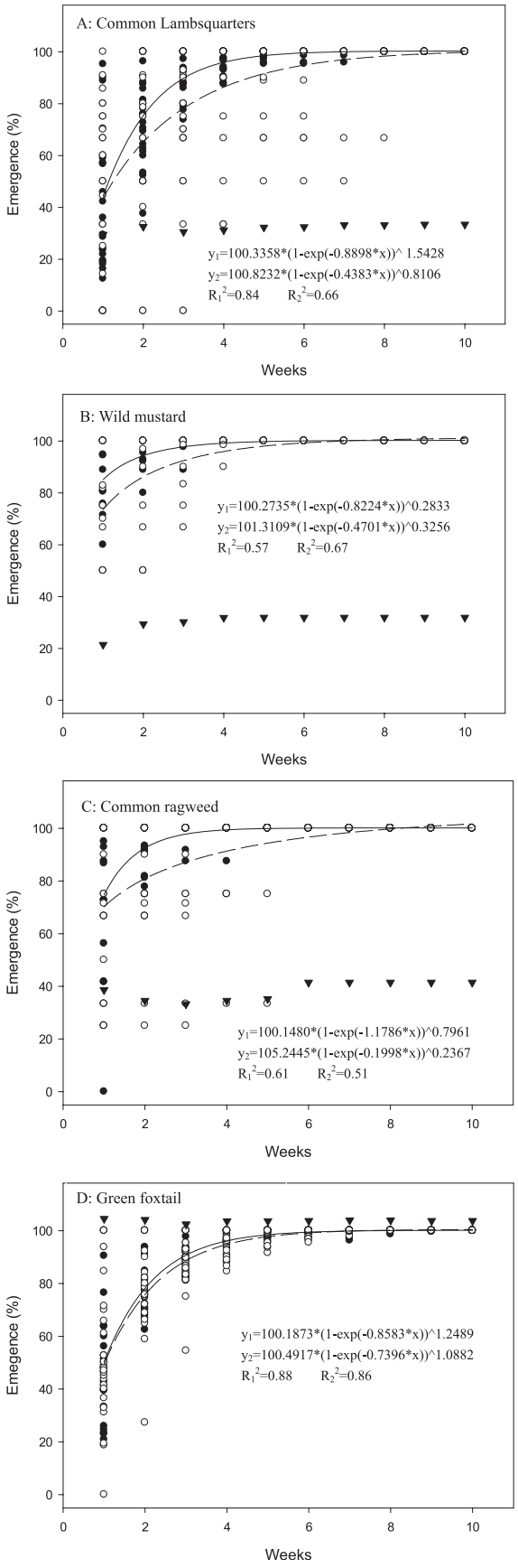
Data were subjected to an analysis of variance using the PROC MIXED procedures of SAS version 9.3 (SAS Institute Inc., Cary, NC). Herbicide treatment was considered a fixed effect, while location, block within location, and their interactions were considered random effects. Significances of fixed effects were tested using *F* tests and random effects were tested using a *Z* test of the variance estimate. The UNIVARIATE procedure was used to test data for normality and homogeneity of variance. Any treatment assigned a value of zero was excluded from the analysis, including the weedy and weed-free controls for injury and the weed-free control for weed control, weed density, and weed dry weight. Significant differences among treatments evaluated was determined using the Tukey adjusted means comparison with differences considered significant at $P < 0.05$.

Weed emergence data were collected weekly from 1 to 10 WAE from two 0.25-m^2 permanent quadrats in the weedy control and halosulfuron treatment plots. Data from the two quadrats were analyzed by PROC MIXED to tell the difference and then they were combined for analysis. The percentage of accumulated weed emergence in weedy control and halosulfuron treatments was based on the total weed emergence in the weedy control and halosulfuron treatments, respectively. Weed emergence curves were obtained by nonlinear regression using the sigmoidal equation:

$$y = a(1 - e^{-bx})^c$$

where y represents the percentage of total accumulated weed emergence at weeks after white bean emergence x, e is the base of the natural logarithm, and a, b, and c are the parameters. The curves were plotted in SigmaPlot v. 12.1 (Systat Software Inc., Chicago, IL). The difference in weed emergence in the weedy control compared to halosulfuron treatments was analyzed by a two-sample *t* test in SAS version 9.3. The mean comparison of two treatments was also tested. The percentage of emergence of weeds in halosulfuron based on final accumulative weeds in the weedy control is also presented in Figure 1. However, the model we used could not fit those data due to very high weed emergence in the first week.

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Results and Discussion

Crop Injury. White bean injury caused by the herbicides evaluated is presented in Table 1. Data were pooled across environments. Pendimethalin, halosulfuron, and pendimethalin + halosulfuron caused no visible injury in white bean at 1 and 4 WAE. Dimethenamid-P and *S*-metolachlor caused 3 and 2% white bean injury at 1 WAE and 1 and 0% injury at 4 WAE, respectively. The level of white bean injury with dimethenamid-P and *S*-metolachlor did not increase with the addition of halosulfuron. At 1 WAE, dimethenamid-P and dimethenamid-P + halosulfuron caused the greatest injury to white bean (Table 1). At 4 WAE, herbicides evaluated caused 1% or less injury in white bean and there was no difference among the herbicides evaluated (Table 1). Dimethenamid-P (440 g ai ha^{-1}) applied PRE caused 2, 1, and 0% dry bean injury at 1, 2, and 4 WAE, respectively (Soltani et al. 2014a). In another study, in sandy soil (86% sand) and low organic matter (1%), dimethenamid-P (1300 g ai ha^{-1}) and *S*-metolachlor (2800 g ai ha^{-1}) applied PRE damaged white bean cultivars without any yield reduction (Poling et al. 2009). The level of injury from halosulfuron in this study is similar to a study by Soltani et al. (2014c) who reported no white bean injury with halosulfuron applied PRE at 35 g ai ha^{-1}. In addition, Soltani et al. (2014c) reported that halosulfuron applied PPI or PRE resulted in less white bean injury than when it was applied POST. In another study, *S*-metolachlor at 1,600 and 3,200 g ai ha^{-1} applied PRE did not cause any white bean injury or white bean plant height reduction (Soltani et al. 2004). However, in that same study, the addition of clomazone (1,680 g ai ha^{-1}) to *S*-metolachlor (3,200 g ai ha^{-1}) caused a decrease in white bean height of 18%. Soltani et al. (2013a) reported pendimethalin applied PRE caused more injury than when it was applied PPI at 4 WAE to

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Figure 1. Emergence periodicity of annual weed species in white bean with and without influence of halosulfuron. •, —, and y_1 represent the percentage of emergence of weeds in weedy control based on final accumulative weeds in weedy control; ○, — —, and y_2 represent the percentage of emergence of weeds in halosulfuron treatment based on final accumulative weeds in halosulfuron treatment; ▼ represents the percentage of emergence of weeds in halosulfuron based on final accumulative weeds in weedy control.

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Table 2. Percentage of control (based on visual rating), density, and dry weight of common lambsquarters in white bean treated with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P, and *S*-metolachlor applied PRE at Exeter (2013 to 2014) and Ridgetown, ON, Canada (2014).[a]

Herbicide treatment	Rate	Control		Density	Dry weight
		4 WAE	8WAE		
	g ai ha^{-1}	%		no. m^{-2}	g m^{-2}
Weedy control		0 e	0 d	19.5 e	24.0 c
Weed-free control		100 a	100 a	0.0 a	0.0 a
Pendimethalin	1,080	95 b	98 a	0.7 bc	0.3 a
Dimethenamid-P	544	52 c	30 b	3.0 d	8.0 b
S-metolachlor	1,050	17 d	9 c	4.5 d	10.7 bc
Halosulfuron	35	98 ab	96 a	0.8 c	0.2 a
Pendimethalin + halosulfuron	1,080 + 35	100 ab	100 a	0.2 abc	0.1 a
Dimethenamid-P + halosulfuron	544 + 35	99 ab	99 a	0.2 ab	0.2 a
S-metolachlor + halosulfuron	1,050 + 35	99 ab	98 a	0.3 abc	0.3 a
P value		< 0.001	< 0.001	< 0.001	< 0.001

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

selected dry bean market classes including white bean, but the injury to white bean was as low as 1%. Overall, the above studies concluded that pendimethalin, dimethenamid-P, *S*-metolachlor, and halosulfuron, applied alone, or in combination resulted in little, to no, white bean injury, which was similar to the results observed in this study.

Weed Control. The dominant weed species at the experimental sites were common lambsquarters, wild mustard, redroot pigweed, common ragweed, and green foxtail. Data were pooled across environments. The results are presented in Tables 2–6.

Common Lambsquarters. Halosulfuron (35 g ai ha^{-1}) or pendimethalin (1,080 g ai ha^{-1}) applied alone PRE provided excellent common lambsquarters control (Table 2). Dimethenamid-P and *S*-metolachlor provided poor control of common lambsquarters (Table 2). Common lambsquarters density and dry weight at 8 WAE followed a similar pattern. Halosulfuron reduced common lambsquarters density and dry weight 96 and 99%, respectively (Table 2). There was no decrease in common lambsquarters dry weight when pendimethalin, dimethenamid-P, or *S*-metolachlor was added to halosulfuron (Table 2).

Table 3. Percentage of control (based on visual ratings), density, and dry weight of wild mustard in white bean with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P, and *S*-metolachlor applied PRE at Exeter (2013 to 2014) and Ridgetown, ON, Canada (2014).[a]

Herbicide treatment	Rate	Control		Density	Dry weight
		4 WAE	8WAE		
	g ai ha^{-1}	%		no. m^{-2}	g m^{-2}
Weedy control		0 c	0 c	6.6 b	34.0 b
Weed-free control		100 a	100 a	0.0 a	0.0 a
Pendimethalin	1,080	48 b	7 c	4.6 b	30.6 b
Dimethenamid-P	544	57 b	39 b	2.1 b	21.7 b
S-metolachlor	1,050	50 b	35 b	2.7 b	22.7 b
Halosulfuron	35	98 a	100 a	0.0 a	0.0 a
Pendimethalin + halosulfuron	1,080 + 35	100 a	100 a	0.0 a	0.0 a
Dimethenamid-P + halosulfuron	544 + 35	100 a	100 a	0.0 a	0.0 a
S-metolachlor + halosulfuron	1,050 + 35	100 a	100 a	0.0 a	0.0 a
P value		< 0.001	< 0.001	< 0.001	< 0.001

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

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Table 4. Percentage of control (based on visual ratings), density, and dry weight of redroot pigweed in white bean with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P, and *S*-metolachlor applied PRE at Exeter (2013 to 2014) and Ridgetown, ON, Canada (2014).[a]

Herbicide treatment	Rate	Control		Density	Dry weight
		4 WAE	8WAE		
	g ai ha^{-1}	%		no. m^{-2}	g m^{-2}
Weedy control		0 d	0 c	7.2 c	33.1 b
Weed-free control		100 a	100 a	0.0 a	0.0 a
Pendimethalin	1,080	69 b	67 b	2.6 b	7.6 b
Dimethenamid-P	544	100 a	100 a	0.3 a	0.1 a
S-metolachlor	1,050	99 a	100 a	0.1 a	0.0 a
Halosulfuron	35	100 a	100 a	0.0 a	0.0 a
Pendimethalin + halosulfuron	1,080 + 35	100 a	100 a	0.0 a	0.0 a
Dimethenamid-P + halosulfuron	544 + 35	100 a	100 a	0.0 a	0.0 a
S-metolachlor + halosulfuron	1,050 + 35	100 a	100 a	0.0 a	0.0 a
P value		< 0.001	< 0.001	< 0.001	< 0.001

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

Excellent control of common lambsquarters with halosulfuron and pendimethalin applied PRE has been reported in other studies. Brown and Masiunas (2002) reported that halosulfuron applied PRE provided 90 to 98% control of common lambsquarters in a study conducted in pumpkin (*Cucurbita* spp.). In previous white bean field studies, halosulfuron provided 95 to 100%, 83 to 99%, and 36 to 51% common lambsquarters control when halosulfuron was applied PPI, PRE, and POST, respectively (Soltani et al. 2013c, 2014b,c). Chomas and Kells (2004) found that pendimethalin applied PRE provided almost 100% control of triazine-resistant lambsquarters. In that same study, metolachlor provided 66% control of triazine-resistant lambsquarters. Dimethenamid-P applied PRE provided 80% common lambsquarters control in a study conducted in potato (*Solanum tuberosum*) (Hutchinson et al. 2005). Although dimethenamid-P and *S*-metolachlor provided good common lambsquarters control in other studies, in this study, dimethenamid-P and *S*-metolachlor reduced common lambsquarters dry weight by only 67 and 55%, respectively (Table 2). Common lambsquarters dry weight with *S*-metolachlor applied PRE was equivalent to the weedy control (Table 2). In a greenhouse study, Isaacs et al. (2006) reported less

Table 5. Percentage of control (based on visual ratings), density, and dry weight of common ragweed in white bean with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P, and *S*-metolachlor applied PRE at Exeter (2013 to 2014) and Ridgetown, ON, Canada (2014).[a]

Herbicide treatment	Rate	Control		Density	Dry weight
		4 WAE	8WAE		
	g ai ha^{-1}	%		no. m^{-2}	g m^{-2}
Weedy control		0 d	0 e	9.0 d	35.2 c
Weed-free control		100 a	100 a	0.0 a	0.0 a
Pendimethalin	1,080	9 c	2 e	5.2 cd	22.9 bc
Dimethenamid-P	544	41 b	19 c	2.2 b	11.1 b
S-metolachlor	1,050	11 c	3 d	3.6 bc	20.4 bc
Halosulfuron	35	96 a	96 ab	0.4 a	0.7 a
Pendimethalin + halosulfuron	1,080 + 35	97 a	90 b	0.5 a	1.1 a
Dimethenamid-P + halosulfuron	544 + 35	99 a	97 ab	0.1 a	0.6 a
S-metolachlor + halosulfuron	1,050 + 35	97 a	97 ab	0.3 a	0.7 a
P value		< 0.001	< 0.001	< 0.001	< 0.001

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

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Table 6. Percentage of control (based on visual ratings), density, and dry weight of green foxtail in white bean with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P, and *S*-metolachlor applied PRE at Exeter (2013 to 2014) and Ridgetown, ON, Canada (2014).[a]

Herbicide treatment	Rate	Control		Density	Dry weight
		4 WAE	8WAE		
	g ai ha^{-1}	%		no. m^{-2}	g m^{-2}
Weedy control		0 f	0 e	50.9 e	84.3 f
Weed-free control		100 a	100 a	0.0 a	0.0 a
Pendimethalin	1,080	92 cd	88 c	5.5 c	5.8 d
Dimethenamid-P	544	99 ab	92 bc	1.5 ab	1.0 ab
S-metolachlor	1,050	99 ab	93 bc	2.0 ab	1.7 abc
Halosulfuron	35	53 e	44 d	25.9 d	23.8 e
Pendimethalin + halosulfuron	1,080 + 35	90 d	89 bc	4.8 c	3.8 cd
Dimethenamid-P + halosulfuron	544 + 35	98 b	94 b	2.3 ab	1.6 abc
S-metolachlor + halosulfuron	1,050 + 35	97 bc	92 bc	3.1 bc	2.8 bcd
P value		< 0.001	< 0.001	< 0.001	< 0.001

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

than 1% control of common lambsquarters with POST applications of halosulfuron.

Wild Mustard. Halosulfuron (35 g ai ha^{-1}) applied PRE provided excellent control of wild mustard. Halosulfuron, applied alone or in combination with pendimethalin, dimethenamid-P, or *S*-metolachlor provided greater than 97% wild mustard control at 4 and 8 WAE and a 100% reduction in wild mustard density and dry weight (Table 3). Lack of control was shown when pendimethalin, dimethenamid-P, or *S*-metolachlor were applied alone. They provided 48, 57, and 50% control of wild mustard at 4 WAE, respectively. Wild mustard control decreased over time with only 7 to 39% control at 8 WAE (Table 3). Wild mustard density and dry weight with pendimethalin, dimethenamid-P, and *S*-metolachlor was equivalent to the weedy control.

In other studies, *S*-metolachlor, applied PPI, provided 12% wild mustard control at 8 WAE, and no decrease in wild mustard dry weight and density compared to the weedy control (Soltani et al. 2014b). Pendimethalin provided poor control of broadleaf weeds including wild mustard (Senseman 2007). Soltani et al. (2014c) have shown that halosulfuron (35 g ai ha^{-1}) applied PPI, PRE, or POST provided 99 to 100% wild mustard control. Soltani et al. (2014b) also reported that halosulfuron + *S*-metolachlor, applied PPI, provided 100% wild mustard control, which is identical to what we observed in this study.

Redroot Pigweed. Dimethenamid-P (544 g ai ha^{-1}), *S*-metolachlor (1,050 g ai ha^{-1}), or halosulfuron (35 g ai ha^{-1}), applied PRE alone or in combination, provided almost 100% control of redroot pigweed at 4 and 8 WAE (Table 4). These same treatments reduced redroot pigweed density and dry weight 99 to 100%. Pendimethalin (1,080 g ai ha^{-1}) applied PRE provided 69 and 67% control of redroot pigweed at 4 and 8 WAE, respectively. Pendimethalin, applied PRE, reduced redroot pigweed density and dry weight 64 and 77%, respectively (Table 4).

Soltani et al. (2012b) reported 73 to 76% redroot pigweed control with pendimethalin, which was similar to the findings in this study (Table 4). In subsequent studies they found that halosulfuron applied PPI and PRE provided 97% redroot pigweed control at 8 WAE, but it was reduced to 80% when applied POST (Soltani et al. 2013c; Soltani et al. 2014b). *S*-metolachlor applied PRE provided 87 to 91% control of redroot pigweed in a field study in kidney bean (*Phaseolus vulgaris*) (Soltani et al. 2014d). Soltani et al (2014b) also found that *S*-metolachlor + halosulfuron applied PPI provided 100% redroot pigweed control at 8 WAE, which is similar to what we found in our study.

Common Ragweed. Pendimethalin (1,080 g ai ha^{-1}) and *S*-metolachlor (1,050 g ai ha^{-1}) applied PRE provided 9 to 11% and 2 to 3% control of common ragweed at 4 and 8 WAE, respectively (Table 5). Pendimethalin reduced common ragweed density

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and dry weight 42 and 35%, respectively, whereas *S*-metolachlor reduced common ragweed density and dry weight 60 and 42%, respectively. Dimethenamid-P (544 g ai ha^{-1}) applied PRE provided 41 and 19% control at 4 and 8 WAE, respectively, and reduced common ragweed density and dry weight by 76 and 68%, respectively (Table 5). Halosulfuron, applied alone PRE, provided 96% control of common ragweed, and reduced common ragweed density and dry weight 96 and 98%, respectively. Addition of pendimethalin, dimethenamid-P, or *S*-metolachlor to halosulfuron did not improve the control of common ragweed.

Soltani et al. (2014b) reported 30 to 40% common ragweed control with *S*-metolachlor and 97 to 99% control with halosulfuron when they were applied PPI. Halosulfuron, applied POST, provided 91 to 94% common ragweed control (Soltani et al. 2013c). The excellent control of common ragweed with halosulfuron applied PRE in this study is consistent with previous studies.

Green Foxtail. Pendimethalin (1,080 g ai ha^{-1}), dimethenamid-P (544 g ai ha^{-1}), or *S*-metolachlor (1,050 g ai ha^{-1}) applied PRE alone or in combination with halosulfuron provided 90 to 99% and 88 to 94% green foxtail control at 4 and 8 WAE, respectively. In addition, these treatments reduced green foxtail density and dry weight by 89 to 97% and 93 to 99%, respectively (Table 6). Halosulfuron (35 g ai ha^{-1}), applied PRE did not provide adequate green foxtail control. Halosulfuron provided 35 and 53% control at 4 and 8 WAE, respectively, and reduced green foxtail density and dry weight 49 and 72%, respectively (Table 6). The addition of halosulfuron to pendimethalin, dimethenamid-P, or *S*-metolachlor did not decrease the efficacy of these herbicides on green foxtail. Soltani et al. (2014b) reported, in a study conducted in white beans, 56% green foxtail control with halosulfuron applied PPI and no decrease in green foxtail density and dry weight. In that same study, *S*-metolachlor provided 95 and 97% green foxtail control at 4 and 8 WAE, with a 93 and 96% density and dry weight reduction, respectively.

Weed Emergence. There were no differences between the two quadrats' samples: common lambsquarters ($P = 0.7552$), wild mustard ($P = 0.2732$), common ragweed ($P = 0.3509$), and green foxtail ($P = 0.6087$). Thus, the two quadrats' samples were combined for further analysis. Halosulfuron (35 g ai ha^{-1}) applied PRE delayed common lambsquarters emergence compared to weedy control (Figure 1A) ($P = 0.001$). In the weedy control, approximately 90% of the common lambsquarters emerged by 3 WAE of white bean, while in the halosulfuron treatment, 90% common lambsquarters emergence did not occur until 5 WAE. Cumulative common lambsquarters emergence in the weedy control and the halosulfuron treatment was on average 22 and 4 plants m^{-2}, respectively, which was significantly different ($P < 0.0001$) between these two treatments.

Halosulfuron (35 g ai ha^{-1}) applied PRE delayed wild mustard emergence relative to the weedy control (Figure 1B) ($P = 0.0063$). The cumulative wild mustard emergence in the weedy control and the halosulfuron-treated plots was 22 and 3 plants m^{-2}, respectively, and this difference was significant ($P < 0.0001$).

Halosulfuron (35 g ai ha^{-1}) applied PRE delayed common ragweed emergence relative to the weedy control (Figure 1C) ($P = 0.001$). Ninety percent common ragweed emergence occurred at 2 and 5 WAE in the weedy control and halosulfuron-treated plots, respectively (Figure 1C). The cumulative common ragweed emergence in the weedy control and the halosulfuron-treated plots was 8 and 2 plants m^{-2}, respectively ($P < 0.0001$).

Halosulfuron (35 g ai ha^{-1}) applied PRE had no effect on green foxtail emergence timing (Figure 1D) ($P = 0.40$). The cumulative green foxtail emergence in the weedy control and in the halosulfuron treated plots was 104 and 88 plants m^{-2}, respectively, and that difference was not statistically significant ($P = 0.08$).

Halosulfuron applied PRE resulted in a delay in broadleaf weed emergence relative to the weedy control. However, halosulfuron did not have an impact on green foxtail emergence timing. These data parallel the weed control, weed density, and dry weight results, indicating that halosulfuron provides control of common annual broadleaf weeds (common lambsquarters, wild mustard, redroot pigweed, and common ragweed) but has little to no activity on green foxtail. These results demonstrate the direct (reduced weed density) and indirect (delayed emergence timing) effect of halosulfuron on these common broadleaf weeds.

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Table 7. White bean seed moisture content and yield after treatments with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P, and *S*-metolachlor applied PRE at Exeter (2013 to 2014) and Ridgetown, ON, Canada (2014).[a]

Herbicide treatment	Rate	Moisture	Yield
	g ai ha^{-1}	%	t ha^{-1}
Weedy control		20.7 c	1.2 d
Weed-free control		19.0 a	2.9 a
Pendimethalin	1,080	20.4 c	1.9 c
Dimethenamid-P	544	20.2 c	2.1 bc
S-metolachlor	1,050	20.4 c	1.8 c
Halosulfuron	35	19.6 b	2.3 b
Pendimethalin + halosulfuron	1,080 + 35	19.2 ab	2.7 a
Dimethenamid-P + halosulfuron	544 + 35	19.2 ab	2.8 a
S-metolachlor + halosulfuron	1,050 + 35	19.3 ab	2.7 a
P value		< 0.001	< 0.001

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

The indirect effect can be important for crops such as white bean, which have a long delay in canopy closure (Van Acker et al. 2000).

White Bean Seed Moisture Content and Yield. The presence of weeds delayed white bean maturity as indicated by the increased seed moisture content in the weedy control relative to the weed-free control (Table 7). There was no advancement in white bean maturity with the application of pendimethalin, dimethenamid-P, or *S*-metolachlor. Halosulfuron, applied PRE, advanced the maturity of white bean compared to the weedy control (as measured by seed moisture content at harvest), but maturity was still delayed compared to the weed-free control (Table 7). The application of pendimethalin + halosulfuron, dimethenamid-P + halosulfuron, or *S*-metolachlor + halosulfuron resulted in no effect on white bean maturity relative to the weed-free control (Table 7).

Weed interference reduced white bean yield 59% in this study (Table 7). Due to incomplete weed control with pendimethalin, dimethenamid-P, *S*-metolachlor, or halosulfuron when applied alone, there was a decrease in white bean yield of 66, 72, 62, and 21%, respectively. The application of pendimethalin + halosulfuron, dimethenamid-P + halosulfuron, or *S*-metolachlor + halosulfuron resulted in no white bean yield loss relative to the weed-free control (Table 7).

Based on the results of this study, halosulfuron applied PRE at 35 g ai ha^{-1} is safe to use on white bean for annual broadleaf weed control. It is also safe to apply halosulfuron on white bean in combination with the soil-applied grass herbicides tested in this study: pendimethalin, dimethenamid-P, or *S*-metolachlor. Pendimethalin, dimethenamid-P, or *S*-metolachlor in combination with halosulfuron provided full-season control of common lambsquarters, wild mustard, redroot pigweed, common ragweed, and green foxtail. These herbicide tank mixes resulted in sufficient weed control to prevent significant white bean yield loss. The results of this study suggest that halosulfuron in combination with pendimethalin, dimethenamid-P, or *S*-metolachlor would be effective options for broad-spectrum weed control in white bean.

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