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Sulfentrazone plus a Low Rate of Halosulfuron for Weed Control in White Bean (*Phaseolus vulgaris* L.)

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Abstract

Halosulfuron was recently registered as the second soil-applied herbicide for broadleaf weed control in Ontario dry beans, but does not provide an alternative mode of action. Sulfentrazone is used to control broadleaf weeds in soybean and other pulse crops, and its registration for Ontario dry beans would provide a different mode of action for broadleaf weed control. Five field studies were conducted over two years (2014, 2015) to determine if the spectrum of broadleaf weed control is improved by adding a half-rate of halosulfuron to sulfentrazone PRE, and to determine the tolerance of white bean to sulfentrazone (140 or 210 g ai ha^{-1}), s-metolachlor (1050 g ai ha^{-1}), and halosulfuron (17.5 g ai ha^{-1}) applied alone and in combination. Crop injury was assessed at 2 and 4 weeks after crop emergence. Weed control was assessed at 4 and 8 weeks after herbicide application (WAA), and weed density and biomass were determined at 8 WAA. Seed moisture and yield were determined at harvest. Halosulfuron added to sulfentrazone improved the control of *Ambrosia artemisiifolia* and *Sinapis arvensis*. Sulfentrazone + s-metolachlor + halosulfuron caused up to 23% crop injury. Therefore, this study concludes that sulfentrazone + s-metolachlor + halosulfuron provides broad spectrum weed control, but is too injurious to white bean for registration in Ontario.

Keywords

Biomass, Density, Injury, Height, Navy Bean, *Phaseolus vulgaris* L.

1. Introduction

Dry edible beans (*Phaseolus vulgaris* L.) are a staple food that fit well in a typical

Ontario crop rotation of corn, soybean and wheat. Several market classes of dry beans are grown in Ontario including cranberry, black, Dutch brown, kidney, small red Mexican, otebo, pinto, yellow eye and white (navy) bean. White bean is the predominant class of dry bean grown in Ontario, accounting for approximately 50% of production [1] [2].

One of the most critical aspects of crop management for dry bean producers is weed control, as dry beans are poor competitors [3]. In Ontario, weed interference has caused white bean yield losses of 68% to 77% [4] [5] [6]. Weeds can also affect bean quality at harvest by staining the seed coat, producing unwanted aromas, or contaminating the beans with foreign plant parts. When used in efficacious tank mix combinations that do not injure the crop, herbicides are effective tools for controlling weeds.

Sulfentrazone is a protoporphyrinogen oxidase IX (PPO) inhibitor herbicide in the aryl triazinone family and was recently registered Canada-wide for preemergence (PRE) application in chickpea (*Cicer arientinum* L.), soybean (*Glycine max* L.), sunflower (*Helianthus annuus* L.), flax (*Linum usitatissimum* L.) and field pea (*Pisum sativum* L.). Sulfentrazone is taken up by germinating weeds and is translocated to the shoot, where it inhibits the PPO enzyme and causes an excess of protoporphyrinogen IX. Various reactions occur in the cytoplasm resulting in the conversion of protoporphyrinogen IX to O^+ radicals, which disrupt the cell membranes and cause loss of cell function [7] [8]. Sulfentrazone primarily controls broadleaf species such as common lambsquarters (*Chenopodium album* L.), common waterhemp (*Amaranthus tuberculatus* var. *rudis*), and redroot pigweed (*Amaranthus retroflexus* L.), as well as annual grasses including *Digitaria* (crabgrass), *Panicum* and *Setaria* (foxtail) species [9] [10] [11].

In 2014, halosulfuron was available for the first time for use in Ontario. Halosulfuron is a sulfonyl urea herbicide, used in dry beans, corn (field, seed, sweet and popcorn-*Zea mays* L.) and various vegetable crops for broadleaf weed control. Halosulfuron controls common Ontario weed species such as common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters, wild mustard (*Sinapis arvensis* L.), redroot pigweed, flower-of-an-hour (*Hibiscus trionum* L.), and velvetleaf (*Abutilon theophrasti* L.) [12]. Several studies have shown that dry beans have excellent tolerance to halosulfuron applied PRE [4] [5].

S-metolachlor is a chloroacetamide herbicide and is currently the only grass herbicide registered for PRE application in dry bean. S-metolachlor controls grass species such as *Digitaria* spp. (crabgrass), *Echinochloa crusgalli* (L.) Beauv. (barnyard grass), *Panicum capilare* L. (witchgrass), *Panicum dichotomiflorum* (L.) Michx. (fall panicum), and *Setaria* spp. [13].

Currently, halosulfuron and imazethapyr are the only soil-applied herbicides registered for broadleaf weed control in Ontario dry beans, and are both ALS inhibitor herbicides. As there are currently ten ALS inhibitor-resistant weed species in Ontario, dry bean growers will have difficulty controlling these weeds without another mode of action [14]. This study aimed to determine the tolerance of white bean to tank mixes of sulfentrazone + s-metolachlor + halosulfuron and to determine if a low dose of halosulfuron added to sulfentrazone would improve the spectrum of broadleaf weed control.

2. Materials and Methods

2.1. Experimental Design

Five field studies were conducted over a two-year period (2014, 2015) at the University of Guelph Ridgetown Campus (Ridgetown) and Huron Research Station (Exeter) in Ontario, Canada. The 2014 site in Exeter was a clay loam soil of 31% sand, 42% silt and 27% clay, and had a pH of 7.8 and organic matter content of 4.3%. In 2015, the Exeter sites were both a loamy soil, with the first site consisting of 32% sand, 42% silt and 26% clay, pH of 7.7 and organic matter content of 3.2%, and the second site consisting of 35% sand, 43% silt, 22% clay, a pH of 7.6 and organic matter content of 3.6%. In Ridgetown, the soil at both sites was a sandy clay loam. The first site had a sand, silt, and clay content of 52%, 24%, and 24%, respectively, a pH of 7.3 and organic matter content of 4.3%. The second site had a sand, silt, and clay content of 46%, 27%, and 27%, respectively, a pH of 6.4 and an organic matter content of 3.7%. All sites were prepared by moldboard ploughing in the fall followed by two passes with an s-tine cultivator and rolling baskets in the spring. Plots were 3 m by 10 m in Exeter and 3 m by 8 m in Ridgetown. All plots were seeded with white bean variety "T9905" (obtained from Hensall District C0-operative, 1 Davidson Drive, Hensall, ON, N0M 1X0, Canada) at a rate of approximately 233,000 seeds ha^{-1}, 4 to 5 cm deep in rows spaced 75 cm apart. Plots were not irrigated and were fertilized according to Ontario Ministry of Agriculture, Food and Rural Affairs field crops guidelines [14].

Experiments were arranged in a randomized complete block design with four replicates of thirteen treatments. An untreated weedy control and a weed-free control (sprayed with s-metolachlor (1050 g ai ha^{-1}) + halosulfuron (35 g ai ha^{-1}) PRE and maintained weed-free by hand-hoeing) were included in each replicate. Herbicide treatments included PRE applications of sulfentrazone (140 and 210 g ai ha^{-1}), half the registered rate of halosulfuron (17.5 g ai ha^{-1}), and s-metolachlor (1050 g ai ha^{-1}) for grass control, used alone and in various combinations (**Table 1**). Herbicides were applied PRE one day after planting with a pressurized CO_2 backpack sprayer and 1.5 m handheld boom with four ULD 120-02 nozzles (Hypro, New Brighton, MN) spaced 50 cm apart, calibrated to deliver 200 $L{\cdot}ha^{-1}$ at 240 kPa.

Crop injury was visually assessed at 2 and 4 weeks after crop emergence (WAE) by comparing the herbicide treatments to the weed-free control, and weed control was visually assessed at 4 and 8 weeks after herbicide application (WAA) by comparing the herbicide treatments to the weedy control. Herbicide treatments were given a score between 0% (no injury or weed control) to 100% (complete plant death). At 8 WAA, weed density and biomass were determined by counting the number of plants by species in 1 m^2 per plot, followed by cutting

Table 1. Mean visible injury, seed moisture, and yield at harvest (adjusted to 18% moisture) of white bean treated with various tank mixes of sulfentrazone, s-metolachlor and halosulfuron applied PRE in five field studies at the University of Guelph Ridgetown Campus, Ridgetown, ON and Huron Research Station, Exeter, ON over a two-year period (2014, 2015)[a].

Treatment	Rate	Dry bean injury (%)				Seed moisture (%)		Yield (T ha^{-1})	
	(g ai ha^{-1})	2 WAE		4 WAE					
Untreated Control		0	a	0	a	17.5	ab	1.2	g
Weed-free Control		0	a	0	a	16.8	a	2.7	a
S-metolachlor	1050	2	abc	3	abc	17.2	ab	1.5	defg
Sulfentrazone	140	5	abc	5	abc	17.3	ab	1.3	fg
Sulfentrazone	210	10	bcde	10	bcd	17.4	ab	1.5	efg
Halosulfuron	17.5	2	ab	1	ab	17.1	ab	1.8	cdefg
Sulfentrazone + s-metolachlor	140 + 1050	9	bcd	10	bcd	17.3	ab	1.6	defg
Sulfentrazone + s-metolachlor	210 + 1050	22	e	24	d	17.6	b	1.5	efg
Halosulfuron + s-metolachlor	17.5 + 1050	3	abc	2	ab	17.0	ab	2.5	ab
Sulfentrazone + halosulfuron	140 + 17.5	8	bcd	6	abc	17.0	ab	2.0	bcde
Sulfentrazone + halosulfuron	210 + 17.5	17	de	15	cd	17.0	ab	1.8	cdef
Sulfentrazone + s-metolachlor + halosulfuron	140 + 1050 + 17.5	12	cde	10	bcd	16.9	ab	2.3	abc
Sulfentrazone + s-metolachlor + halosulfuron	210 + 1050 + 17.5	23	e	22	d	16.9	ab	2.1	abcd
SE (±)		0.06		0.06		0.01		0.01	

[a]Abbreviations: PRE, pre-emergence; WAE, weeks after emergence. Means followed by the same letter within a column are not statistically different according to a Fisher's Protected LSD test at $\alpha = 0.05$. Data are averaged for years and locations.

the weeds at the soil surface, placing each species into a separate paper bag, drying in a kiln, and weighing the dry biomass. White bean seed moisture and yield (adjusted to 18% moisture) were determined at harvest.

2.2. Statistical Analysis

Statistical Analysis Software (SAS) version 9.4 (SAS Institute Inc., NC) was used for the analysis. Data were partitioned into fixed and random effects to account for error. Treatments were deemed as fixed effects and their significance determined by the F-test. Replicate, environment, replicate within environment, and environment by treatment interaction were the random effects and their significance was determined using the Z-test. Various transformations of the data were applied using the UNIVARIATE procedure to test the assumptions of normality and homogeneity of the residuals. All transformations met the assumptions for the crop injury, weed control, seed moisture and yield data, therefore the arcsine square root transformation was selected for the analysis as it produced the least amount of error. Weed density and biomass data were transformed using a logarithmic transformation to meet the assumptions. An analysis of variance was performed on all data using the MIXED procedure and Fisher's Protected LSD test ($\alpha = 0.05$). Values were converted back to the original scale for presentation.

3. Results and Discussion

3.1. Crop Injury

At 2 WAE, sulfentrazone (140 and 210 g ai ha^{-1}) caused 5% and 10% injury in white bean, respectively (**Table 1**). S-metolachlor and halosulfuron caused 2% injury, and halosulfuron + s-metolachlor caused 3% injury, but were equivalent to the control. The combination of sulfentrazone (140 g ai ha^{-1}) plus s-metolachlor or halosulfuron did not cause greater injury than each herbicide individually, but sulfentrazone (210 g ai ha^{-1}) plus s-metolachlor or halosulfuron caused up to 22% injury. Similarly, sulfentrazone (140 g ai ha^{-1}) + s-metolachlor + halosulfuron caused 12% injury, while sulfentrazone (210 g ai ha^{-1}) + s-metolachlor + halosulfuron caused 23% injury. All tank mixes containing sulfentrazone caused greater injury than the weed-free control. Injury levels at 4 WAE were similar to 2 WAE. The level of injury caused by sulfentrazone remained constant at 4 WAE, s-metolachlor caused 3% injury and halosulfuron caused 1% injury. Soltani *et al.* [5] also found that halosulfuron (17.5 g ai ha^{-1}) applied PRE produces very little injury in edible bean. Sulfentrazone + s-metolachlor caused up to 24% injury and sulfentrazone + halosulfuron caused up to 15% injury. Sulfentrazone (140 g ai ha^{-1}) + s-metolachlor + halosulfuron caused 10% injury and sulfentrazone (210 g ai ha^{-1}) + s-metolachlor + halosulfuron caused 22% injury. Halosulfuron + s-metolachlor and sulfentrazone (140 g ai ha^{-1}) + halosulfuron were the only tank mixes at 4 WAE that did not cause injury greater than the weed-free control.

3.2. Weed Control, Density and Biomass

3.2.1. Pigweed Species

Redroot pigweed and green pigweed (*Amaranthus powelli* S. Wats.) were the dominant pigweed species at the Exeter and Ridgetown locations, respectively, but were combined for analysis. All herbicides and herbicide combinations provided ≥89% control of pigweeds throughout the season (**Table 2**). Sulfentrazone (140 and 210 g ai ha^{-1}) provided 100% control at 4 and 8 WAA, s-metolachlor provided 89% control at 4 WAA and 99% control at 8 WAA, and halosulfuron provided 91% control at 4 WAA and 90% control at 8 WAA. Soltani *et al.* [4] [5] also found 83% to 93% control of redroot pigweed with halosulfuron (17.5 g ai ha^{-1}) applied PRE. Sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor provided 99 to 100% control, while sulfentrazone (140 g ai ha^{-1}) + halosulfuron provided 99% control at 4 and 8 WAA and sulfentrazone (210 g ai ha^{-1}) + halosulfuron provided 100% control throughout the season. Sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor + halosulfuron provided 98% to 100% control. All herbicides and herbicide combinations reduced pigweed density and biomass relative to the weedy control. This level of control is consistent with other studies that used similar rates of sulfentrazone [15] [16].

3.2.2. Common Ragweed

At 4 WAA, sulfentrazone at 140 and 210 g ai ha^{-1} provided 19% and 24% control of common ragweed, respectively (**Table 3**). S-metolachlor provided 27% control, while halosulfuron provided 94% control and was the only herbicide that provided control equivalent to the weed-free control. Trader *et al.* [17] reported

Table 2. Mean visible control, density, and dry biomass of pigweed species (*Amaranthus powelli* and *A. retroflexus*) after a PRE application of sulfentrazone, s-metolachlor, halosulfuron, or combination for five field studies conducted near Ridgetown, ON and Exeter, ON, Canada over a two-year period (2014, 2015)[a].

Treatment	Rate	Control (%)				Density 8 WAA		Biomass 8 WAA	
	(g ai ha^{-1})	4 WAA		8 WAA		(plants m^{-2})		(g·m^{-2})	
Untreated Control		0	b	0	b	7.0	b	4.5	b
Weed-free Control		100	a	100	a	0.0	a	0.0	a
S-metolachlor	1050	89	a	99	a	0.4	a	0.5	a
Sulfentrazone	140	100	a	100	a	0.3	a	0.3	a
Sulfentrazone	210	100	a	100	a	0.0	a	0.0	a
Halosulfuron	17.5	91	a	90	a	0.6	a	0.4	a
Sulfentrazone + s-metolachlor	140 + 1050	100	a	99	a	0.1	a	0.2	a
Sulfentrazone + s-metolachlor	210 + 1050	100	a	100	a	0.0	a	0.0	a
Halosulfuron + s-metolachlor	17.5 + 1050	98	a	98	a	0.3	a	0.5	a
Sulfentrazone + halosulfuron	140 + 17.5	99	a	99	a	0.1	a	0.1	a
Sulfentrazone + halosulfuron	210 + 17.5	100	a	100	a	0.2	a	0.2	a
Sulfentrazone + s-metolachlor + halosulfuron	140 + 1050 + 17.5	100	a	98	a	0.0	a	0.0	a
Sulfentrazone + s-metolachlor + halosulfuron	210 + 1050 + 17.5	100	a	100	a	0.0	a	0.0	a
SE (±)		0.09		0.09		0.17		0.23	

[a]Abbreviations: PRE, pre-emergence; WAA, weeks after application. Means followed by the same letter within a column are not statistically different according to a Fisher's Protected LSD test at $\alpha = 0.05$. Data are averaged for years and locations.

Table 3. Mean visible control, density, and dry biomass of common ragweed (*Ambrosia artemisiifolia*) after a PRE application of sulfentrazone, s-metolachlor, halosulfuron, or combination for five field studies conducted near Ridgetown, ON and Exeter, ON, Canada over a two-year period (2014, 2015)[a].

Treatment	Rate	Control (%)				Density 8 WAA		Biomass 8 WAA	
	(g ai ha^{-1})	4 WAA		8 WAA		(plants m^{-2})		(g·m^{-2})	
Untreated Control		0	b	0	c	7.5	d	11.1	bcd
Weed-free Control		100	a	100	a	0.2	a	0.3	a
S-metolachlor	1050	27	b	7	c	4.5	bcd	10.6	bcd
Sulfentrazone	140	19	b	11	c	6.3	cd	15.9	cd
Sulfentrazone	210	24	b	16	c	5.4	bcd	15.0	cd
Halosulfuron	17.5	94	a	83	a	1.5	abcd	2.3	abc
Sulfentrazone + s-metolachlor	140 + 1050	12	b	7	c	6.0	cd	15.4	cd
Sulfentrazone + s-metolachlor	210 + 1050	26	b	18	bc	5.6	bcd	19.5	d
Halosulfuron + s-metolachlor	17.5 + 1050	98	a	90	a	1.2	abcd	1.6	ab
Sulfentrazone + halosulfuron	140 + 17.5	86	a	75	ab	1.3	abcd	2.9	abcd
Sulfentrazone + halosulfuron	210 + 17.5	90	a	77	a	1.7	abcd	1.8	abc
Sulfentrazone + s-metolachlor + halosulfuron	140 + 1050 + 17.5	94	a	90	a	0.7	ab	0.7	a
Sulfentrazone + s-metolachlor + halosulfuron	210 + 1050 + 17.5	98	a	94	a	0.8	abc	1.4	ab
SE (±)		0.16		0.18		0.54		0.65	

[a]Abbreviations: PRE, pre-emergence; WAA, weeks after application. Means followed by the same letter within a column are not statistically different according to a Fisher's Protected LSD test at $\alpha = 0.05$. Data are averaged for years and locations.

up to 97% control of common ragweed in pumpkin with 18 g ai ha^{-1} halosulfuron. Sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor provided up to 26% control, and was not improved compared to either herbicide applied alone. In contrast, sulfentrazone (140 and 210 g ai ha^{-1}) + halosulfuron provided 86% and 90% control, respectively, which was equivalent to the weed-free control and an improvement compared to sulfentrazone applied alone. Similarly, sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor + halosulfuron provided 94% to 98% control and were equivalent to the weed-free control. Soltani *et al.* [8] also found good control of common ragweed with halosulfuron tank mixes applied preplant incorporated. At 8 WAA, control decreased with all herbicides and herbicide combinations. Sulfentrazone (140 and 210 g ai ha^{-1}), s-metolachlor and sulfentrazone + s-metolachlor provided up to 18% control and were not different from the weedy control. In contrast, halosulfuron provided 83% control, sulfentrazone + halosulfuron provided 75% to 77% control, and sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor + halosulfuron provided 90% to 94% control, and were equivalent to the weed-free control. Sulfentrazone (140 and 210g ai ha^{-1}) reduced ragweed density by 16% and 28%, respectively, and sulfentrazone + s-metolachlor reduced density by up to 25%. Sulfentrazone + halosulfuron tank mixes reduced density by up to 83%, but were not statistically different from the weedy control. Sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor + halosulfuron reduced ragweed density by 89 and 91%, respectively, and were the only herbicide treatments that reduced density relative to the weedy control. None of the herbicides applied on their own reduced ragweed biomass relative to the weedy control. Sulfentrazone + s-metolachlor did not provide any biomass reduction, while sulfentrazone (140 and 210 g ai ha^{-1}) + halosulfuron reduced ragweed biomass by 74% and 84%, respectively, but was not an improvement compared to the weedy control. Sulfentrazone (210 g ai ha^{-1}) + s-metolachlor + halosulfuron also reduced biomass by 87%, but was not different from the weedy control. Sulfentrazone (140 g ai ha^{-1}) + s-metolachlor + halosulfuron was the only herbicide treatment that reduced ragweed biomass relative to the weedy control, providing a 94% reduction.

3.2.3. Common Lambsquarters

Sulfentrazone (140 and 210 g ai ha^{-1}) provided 100% control of common lambsquarters at 4 and 8 WAA (**Table 4**). S-metolachlor provided 7% control at 4 WAA and 16% control at 8 WAA, while halosulfuron provided 87% to 97% control. This is consistent with another study which found 83% to 96% control of common lambsquarters with the same rate of halosulfuron [5]. Sulfentrazone + s-metolachlor and sulfentrazone + halosulfuron provided 99% to 100% control at 4 and 8 WAA, while the three-way tank mixes provided 100% control. Sulfentrazone (140 and 210 g ai ha^{-1}) reduced lambsquarters density by 100%, s-metolachlor reduced density by 67%, and halosulfuron reduced density by 82%. Sulfentrazone + s-metolachlor reduced density by 100%, and sulfentrazone + halosulfuron reduced density by 99% to 100%. Both three-way tank mixes reduced density by 100%. Sulfentrazone applied alone and in a co-application reduced lambsquarters density to an equivalent level as the weed-free control. Similarly, sulfentrazone (140 and 210 g ai ha^{-1}), s-metolachlor and halosulfuron

Table 4. Mean visible control, density, and dry biomass of common lambsquarters (*Chenopodium album*) after a PRE application of sulfentrazone, s-metolachlor, halosulfuron, or combination for five field studies conducted near Ridgetown, ON and Exeter, ON, Canada over a two-year period (2014, 2015)[a].

Treatment	Rate	Control (%)				Density 8 WAA		Biomass 8 WAA	
	(g ai ha^{-1})	4 WAA		8 WAA		(plants m^{-2})		(g·m^{-2})	
Untreated Control		0	b	0	c	13.9	d	7.1	b
Weed-free Control		100	a	100	a	0.2	a	0.2	a
S-metolachlor	1050	7	b	16	c	4.6	c	5.8	b
Sulfentrazone	140	100	a	100	a	0.0	a	0.0	a
Sulfentrazone	210	100	a	100	a	0.0	a	0.0	a
Halosulfuron	17.5	87	a	97	ab	2.5	bc	0.4	a
Sulfentrazone + s-metolachlor	140 + 1050	100	a	99	ab	0.0	a	0.0	a
Sulfentrazone + s-metolachlor	210 + 1050	100	a	100	a	0.0	a	0.0	a
Halosulfuron + s-metolachlor	17.5 + 1050	91	a	76	b	1.0	ab	0.6	a
Sulfentrazone + halosulfuron	140 + 17.5	99	a	99	ab	0.1	a	0.2	a
Sulfentrazone + halosulfuron	210 + 17.5	100	a	99	ab	0.0	a	0.0	a
Sulfentrazone + s-metolachlor + halosulfuron	140 + 1050 + 17.5	100	a	100	ab	0.0	a	0.0	a
Sulfentrazone + s-metolachlor + halosulfuron	210 + 1050 + 17.5	100	a	100	a	0.0	a	0.0	a
SE (±)		0.09		0.11		0.17		0.17	

[a]Abbreviations: PRE, pre-emergence; WAA, weeks after application. Means followed by the same letter within a column are not statistically different according to a Fisher's Protected LSD test at $\alpha = 0.05$. Data are averaged for years and locations.

reduced lambsquarters biomass by 100%, 100%, 18% and 94%, respectively. Sulfentrazone + s-metolachlor provided a 100% reduction, sulfentrazone + halosulfuron provided 97 to 100% reduction in biomass, and sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor + halosulfuron reduced biomass by 100%. Sulfentrazone has shown excellent control of common lambsquarters when used alone and in a tank mix [18] [19].

3.2.4. Wild Mustard

Sulfentrazone (140 and 210 g ai ha^{-1}), s-metolachlor, and halosulfuron provided 50%, 48%, 20% and 100% control of wild mustard, respectively, at 4 WAA (Table 5). Excellent control of wild mustard with halosulfuron has been noted in other studies [4] [5]. Control decreased to 5%, 12%, and 2% for sulfentrazone (140 and 210 g ai ha^{-1}) and s-metolachlor, respectively, at 8 WAA but remained constant for halosulfuron. Sulfentrazone (140 g ai ha^{-1}) + s-metolachlor provided 54% control at 4 WAA, which was not an improvement compared to sulfentrazone alone, and decreased to 1% control by 8 WAA. In contrast, sulfentrazone (210 g ai ha^{-1}) + s-metolachlor provided 87% control at 4 WAA and was an improvement compared to sulfentrazone, but decreased to 20% control at 8 WAA. Sulfentrazone + halosulfuron and sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor + halosulfuron provided 100% control at both 4 and 8 WAA. Sulfentrazone alone reduced wild mustard density by 67%, and s-metolachlor reduced density by 49%, but neither herbicide reduced density relative to the

Table 5. Mean visible control, density, and dry biomass of wild mustard (*Sinapis arvensis*) after a PRE application of sulfentrazone, s-metolachlor, halosulfuron, or combination for five field studies conducted near Ridgetown, ON and Exeter, ON, Canada over a two-year period (2014, 2015)[a].

Treatment	Rate (g ai ha^{-1})	Control (%) 4 WAA		Control (%) 8 WAA		Density 8 WAA (plants m^{-2})		Biomass 8 WAA (g·m^{-2})	
Untreated Control		0	e	0	c	31.0	c	93.6	b
Weed-free Control		100	a	100	a	0.0	a	0.0	a
S-metolachlor	1050	20	d	2	bc	15.9	bc	51.8	b
Sulfentrazone	140	50	cd	5	bc	10.3	bc	37.1	b
Sulfentrazone	210	48	cd	12	bc	10.3	bc	32.1	b
Halosulfuron	17.5	100	ab	100	a	0.0	a	0.0	a
Sulfentrazone + s-metolachlor	140 + 1050	54	c	1	bc	10.5	bc	51.7	b
Sulfentrazone + s-metolachlor	210 + 1050	87	b	20	b	5.3	b	14.8	b
Halosulfuron + s-metolachlor	17.5 + 1050	100	a	100	a	0.0	a	0.0	a
Sulfentrazone + halosulfuron	140 + 17.5	100	a	100	a	0.0	a	0.0	a
Sulfentrazone + halosulfuron	210 + 17.5	100	a	100	a	0.1	a	0.0	a
Sulfentrazone + s-metolachlor + halosulfuron	140 + 1050 + 17.5	100	a	100	a	0.0	a	0.0	a
Sulfentrazone + s-metolachlor + halosulfuron	210 + 1050 + 17.5	100	a	100	a	0.0	a	0.0	a
SE (±)		0.07		0.09		0.28		0.45	

[a]Abbreviations: PRE, pre-emergence; WAA, weeks after application. Means followed by the same letter within a column are not statistically different according to a Fisher's Protected LSD test at $\alpha = 0.05$. Data are averaged for years and locations.

weedy control. Sulfentrazone (140 g ai ha^{-1}) + s-metolachlor also did not reduce density relative to the control, but sulfentrazone (210 g ai ha^{-1}) + s-metolachlor significantly reduced density by 83%. Similarly, sulfentrazone reduced wild mustard biomass by up to 66%, s-metolachlor reduced biomass by 45%, and sulfentrazone + s-metolachlor reduced biomass by up to 84%, but none were different from the weedy control. In contrast, halosulfuron and all co-applications containing halosulfuron reduced density and biomass equivalent to the weed-free control.

3.2.5. Green Foxtail

At 4 WAA, sulfentrazone (140 and 210 g ai ha^{-1}) provided 68% and 84% control of green foxtail (*Setaria viridis* (L.) Beauv), respectively, s-metolachlor provided 99% control and halosulfuron provided 31% control (Table 6). Sulfentrazone at either rate combined with s-metolachlor provided 99% control. Sulfentrazone (140 and 210 g ai ha^{-1}) plus halosulfuron provided 67% and 85% control, respectively, and were not an improvement compared to sulfentrazone applied alone. Sulfentrazone + s-metolachlor + halosulfuron provided 98% to 99% control. At 8 WAA, green foxtail control with sulfentrazone (140 and 210 g ai ha^{-1}) decreased to 45% and 80% control, respectively, control with s-metolachlor remained constant, and control with halosulfuron decreased to 11% and was not different from the weedy control. Sulfentrazone + s-metolachlor provided 98 to 99% control, while sulfentrazone + halosulfuron provided 42% to 63% control. The co-application of sulfentrazone + halosulfuron was not an improvement

Table 6. Mean visible control, density, and dry biomass of green foxtail (*Setaria viridis*) after a PRE application of sulfentrazone, s-metolachlor, halosulfuron, or combination, for five field studies conducted near Ridgetown, ON and Exeter, ON, Canada over a two-year period (2014, 2015)[a].

Treatment	Rate	Control (%)				Density 8 WAA		Biomass 8 WAA	
	($g\ ai\ ha^{-1}$)	4 WAA		8 WAA		($plants\ m^{-2}$)		($g \cdot m^{-2}$)	
Untreated Control		0	d	0	f	87.3	f	42.4	g
Weed-free Control		100	a	100	a	0.0	a	0.0	a
S-metolachlor	1050	99	a	99	ab	1.8	abc	0.7	ab
Sulfentrazone	140	68	b	45	de	20.1	def	7.8	def
Sulfentrazone	210	84	b	80	bcd	8.3	bcde	4.4	bcde
Halosulfuron	17.5	31	c	11	ef	48.7	ef	20.3	fg
Sulfentrazone + s-metolachlor	140 + 1050	99	a	98	ab	1.6	abc	0.6	ab
Sulfentrazone + s-metolachlor	210 + 1050	99	a	99	ab	0.8	ab	0.4	a
Halosulfuron + s-metolachlor	17.5 + 1050	98	a	96	ab	3.5	abcd	1.5	abcd
Sulfentrazone + halosulfuron	140 + 17.5	67	b	42	de	26.3	def	10.8	efg
Sulfentrazone + halosulfuron	210 + 17.5	85	b	63	cd	11.9	cde	5.7	cdef
Sulfentrazone + s-metolachlor + halosulfuron	140 + 1050 + 17.5	98	a	95	abc	1.1	abc	0.8	ab
Sulfentrazone + s-metolachlor + halosulfuron	210 + 1050 + 17.5	99	a	98	ab	1.3	abc	0.8	abc
SE (±)		0.07		0.12		0.56		0.49	

[a]Abbreviations: PRE, pre-emergence; WAA, weeks after application. Means followed by the same letter within a column are not statistically different according to a Fisher's Protected LSD test at $\alpha = 0.05$. Data are averaged for years and locations.

relative to sulfentrazone on its own, but did provide control relative to the weedy control. Sulfentrazone (140 and 210 g ai ha^{-1}) + s-metolachlor + halosulfuron provided 95% to 98% control and were equivalent to the weed-free control. Other studies have shown improved control of foxtail species when either sulfentrazone or halosulfuron were tank mixed with a grass herbicide [4] [10]. Sulfentrazone (140 g ai ha^{-1}) reduced green foxtail density by 77%, which was not different from the weedy control, while sulfentrazone (210 g ai ha^{-1}) reduced density by 90%. S-metolachlor reduced density by 98% and halosulfuron reduced density by 44%. Sulfentrazone at either rate plus s-metolachlor reduced foxtail density by up to 99%, and was equivalent to the weed-free control. In contrast, sulfentrazone (140 g ai ha^{-1}) + halosulfuron provided only a 70% reduction and was not an improvement relative to the weedy control. Sulfentrazone (210 g ai ha^{-1}) reduced density relative to the weedy control, but was not an improvement compared to either herbicide on its own. Sulfentrazone + s-metolachlor + halosulfuron provided up to 99% density reduction. Sulfentrazone (140 and 210 g ai ha^{-1}) reduced green foxtail biomass by up to 90%, s-metolachlor reduced biomass by 98%, and halosulfuron reduced biomass by 52% but not relative to the weedy control. Sulfentrazone + s-metolachlor and sulfentrazone + s-metolachlor + halosulfuron reduced green foxtail biomass by 99% and 98%, respectively, and were equivalent to the weed-free control. Sulfentrazone (140 g ai ha^{-1}) + halosulfuron did not reduce green foxtail biomass relative to the weedy control, while sulfentrazone (210 g ai ha^{-1}) + halosulfuron reduced biomass by 87%.

3.3. Seed Moisture Content and Yield

Seed moisture at harvest ranged between 16.8% and 17.6% (Table 1). Sulfentrazone (210 g ai ha^{-1}) + s-metolachlor had a higher moisture content than the weed-free control, which could be due to the high level of injury produced by this tank mix causing delayed maturity. All other herbicide treatments had a moisture content equivalent to the weed-free control. White bean yield ranged from 1.2 to 2.7 T ha^{-1}. Comparing the two controls, weed interference in this study caused a 56% yield loss. Sulfentrazone (140 and 210 g ai ha^{-1}), s-metolachlor, and halosulfuron produced yields that were 52%, 44%, 44%, and 33% lower than the weed-free control, respectively, and were not different from the weedy control. This yield loss is likely attributed to weed interference rather than crop injury, as injury levels for these treatments were relatively low. Sulfentrazone + s-metolachlor did not improve yield relative to either herbicide on its own or to the weedy control. In contrast, sulfentrazone (140 and 210 g ai ha^{-1}) + halosulfuron produced yields greater than the weedy control, at 2.0 T ha^{-1} and 1.8 T ha^{-1}, respectively. Sulfentrazone (140 g ai ha^{-1}) + halosulfuron improved yield compared to sulfentrazone alone, but sulfentrazone (210 g ai ha^{-1}) + halosulfuron did not. Sulfentrazone + s-metolachlor + halosulfuron produced yields that were equivalent to the weed-free control, likely attributed to better weed control as crop injury was as high as 23%.

4. Conclusion

In this study, sulfentrazone applied PRE provided excellent control of redroot/green pigweed and common lambsquarters. When a low rate of halosulfuron was added to sulfentrazone, the spectrum of broadleaf weed control was improved. Sulfentrazone + halosulfuron provided good to excellent control of pigweeds, common lambsquarters, common ragweed, and wild mustard. Sulfentrazone + s-metolachlor + halosulfuron also provided excellent control of these species as well as green foxtail, but did not have an adequate margin of crop safety, therefore this study does not support the use of a tank mix of sulfentrazone + s-metolachlor + halosulfuron in Ontario white bean. However, this tank mix does provide broad spectrum weed control, and should be examined in other market classes of dry bean to determine their tolerance to the co-application of these three herbicides.

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