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Research Article

Response of Dry Bean to Sulfentrazone Plus Imazethapyr

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Field studies were conducted in 2010 and 2011 at the Huron Research Station, Exeter, Ontario and from 2009 to 2011 at the University of Guelph Ridgetown Campus, Ridgetown, Ontario to evaluate the sensitivity of four market classes of dry bean to sulfentrazone applied preemergence at 105, 140, and 280 g ai/ha alone and in combination with imazethapyr at 37.5 g ai/ha. At 1 week after emergence (WAE), sulfentrazone alone or in combination with imazethapyr at all doses evaluated caused no significant visible injury in dry bean. At 2 WAE, sulfentrazone alone caused 1–11, 1–11, 1–5, and 3–19% visible injury, and sulfentrazone + imazethapyr caused 3–11, 2–10, 2–5, and 4–20% visible injury in black, cranberry, kidney, and white bean, respectively. At 4 WAE, sulfentrazone alone caused 1–7, 1–7, 0–4, and 1–16% visible injury and sulfentrazone + imazethapyr caused 1–8, 1–5, 1–3, and 2–14% visible injury in black, cranberry, kidney, and white bean, respectively. Sulfentrazone PRE caused slightly greater injury in black and white bean compared to cranberry and kidney bean. Generally, crop injury with sulfentrazone at rates up to 140 g ai/ha alone and in combination with imazethapyr at 37.5 g ai/ha was minimal with no adverse effect on plant height, shoot dry weight, seed moisture content, and yield. Based on these results, there is potential for preemergence application of sulfentrazone at rates up to 140 g ai/ha alone or in combination with imazethapyr at 37.5 g ai/ha in black, cranberry, kidney and white bean.

1. Introduction

Dry bean is an important crop grown in Ontario. In 2012, dry bean growers seeded 46,500 hectares and produced 129,000 MT of dry bean with a farm-gate value of approximately $90 million [1]. Major market classes of dry bean grown in Ontario include black, cranberry, kidney, and white (navy) bean. Dry bean is a short season crop with short physical stature and therefore is very sensitive to weed interference [2–6]. Weed interference has been shown to reduce seed yield of dry bean as much as 70% [7]. Presence of weeds at the harvest time can also cause seed staining and interfere with harvesting efficiency in dry bean [8–11]. More research is needed to develop innovative precision weed management options that have an adequate margin of crop safety, provide consistent broad spectrum weed control, and maximize dry bean yield and net returns. Each year Ontario dry bean producers face a dilemma in respect to annual broadleaf weed control. Research has clearly demonstrated that the use of a broad spectrum soil applied herbicide program is the optimal approach to protect the crop during the critical period of weed control. The dilemma is there is only one soil applied herbicide with predominantly broadleaf weed activity—imazethapyr. It is widely recognized that imazethapyr is a very efficacious soil applied broadleaf herbicide but it has a narrow margin of crop safety, especially in the small seeded market classes of dry beans, specifically white and black beans. White and black beans are two of the most widely grown market classes of dry beans in Ontario. More research is needed to identify new herbicide options or tankmix partners with imazethapyr that provide consistent broadleaf weed control and have an adequate margin of crop safety in different market classes of dry bean.

Sulfentrazone is a protoporphyrinogen oxidase (PPO) inhibitor herbicide for use in soybean (*Glycine max*) that can control many of the common annual broadleaf weeds that occur in Ontario such as common lambsquarters (*Chenopodium album* L.), redwood pigweed (*Amaranthus retroflexus* L.), velvetleaf (*Abutilon theophrasti* Medicus), common ragweed (*Ambrosia artemisiifolia* L.), common waterhemp (*Amaranthus tuberculatus* VAR. rudis), and eastern black nightshade (*Solanum ptycanthum* Dun. ex DC. pp.)

[11–14]. Sulfentrazone can be soil applied as a preplant (PP), preplant incorporated (PPI), or preemergence (PRE) herbicide for broadleaf weed control [15, 16]. Sulfentrazone is taken up by both the roots and foliage; however, it is primarily taken up by the roots in treated soils [14]. Sulfentrazone is registered at a rate of 150 to 400 g ha^{-1} in soybean with the rate applied dependent on soil texture and organic matter. Susceptible plants in sulfentrazone treated soils show necrotic symptoms and die shortly after exposure to light [14].

There is little published data on the sensitivity of "Black Velvet" black bean, "T9905" white bean, "Etna" cranberry bean, and "Red Hawk" kidney bean to sulfentrazone alone or in combination with imazethapyr. Sulfentrazone alone or in combination with imazethapyr has the potential to provide acceptable control of troublesome annual broadleaf weeds with an acceptable margin of crop safety in dry bean. Tolerance of dry beans to various soil applied herbicides has been shown to be dependent by herbicide rate, market class, cultivar, and environmental conditions [2, 5, 17, 18].

The objective of this study was to evaluate the tolerance of black, cranberry, kidney, and white bean to sulfentrazone applied preemergence at 105, 140, and 280 g ai/ha alone and in combination with imazethapyr at 37.5 g ai/ha.

2. Materials and Methods

Field studies were conducted in 2010 and 2011 at the Huron Research Station, Exeter, Ontario, Canada and at 2009, 2010, and 2011 at the University of Guelph Ridgetown Campus, Ridgetown, Ontario, Canada. The soil at Exeter was a Brookston clay loam (Orthic Humic Gleysol, mixed, mesic, and poorly drained) with 32% sand, 42% silt, 26% clay, 3.7% organic matter, and pH of 7.8. The soil at Ridgetown was a Wattford (Grey-Brown Brunisolic, mixed, mesic, sandy, and imperfectly drained)-Brady (Gleyed Brunisolic Grey-Brown Luvisol, mixed, mesic, sandy, and imperfectly drained) sandy loam with 53% sand, 27% silt, 20% clay, 5.3% organic matter, and pH of 7.0. Seedbed preparation at all sites consisted of fall moldboard plowing followed by two passes with a field cultivator in the spring.

The experiments were established as a 2-way factorial design arranged in a completely randomized block with four replications. Factor 1 was dry bean market class ("Black Velvet" black bean, "T9905" white bean, "Etna" cranberry bean, and "Red Hawk" kidney bean) and Factor 2 was preemergence herbicide treatments. Preemergence herbicide treatments included an untreated weed-free control, sulfentrazone at 105, 140, and 280 g ai/ha, imazethapyr at 37.5 g ai/ha, and sulfentrazone plus imazethapyr at 105 + 37.5, 140 + 37.5, and 280 + 37.5 g ai/ha. Plots were 6 m wide (8 rows spaced 0.75 m apart) and 10 m long at Exeter and 8 m long at Ridgetown. Within each plot there were two rows of "Black Velvet" black bean, "T9905" white bean, "Etna" cranberry bean, and "Red Hawk" kidney bean. Beans were planted in late May to early June of each year.

Herbicide applications were made with a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} of spray solution at a pressure of 240 kPa using ultra low drift nozzles (ULD120-02, Hypro, New Brighton, MN). Treatments were applied at one day after seeding and were left undisturbed on the surface of soil. All plots were maintained weed-free during the season with hand hoeing and cultivation as required.

Dry bean injury was visually estimated on a scale of 0 (no injury) to 100% (complete plant death) at 1, 2, and 4 weeks after crop emergence (WAE). Bean shoot dry weight was evaluated 4 WAE by cutting plants at the soil surface from 1 m of row per plot. Plants were dried at 60°C to a constant moisture and then weighed. Dry bean height was measured for 10 plants in each plot 6 WAE and the average height was recorded. Dry bean was considered mature when 90% of the pods in the weed-free check had turned from green to a golden colour. Beans were harvested from each plot with a small plot combine, yield, and seed moisture content were recorded, and yields were adjusted to 18% moisture.

Data were analyzed as a 2-way factorial using PROC MIXED in SAS 9.2. The two treatment factors, dry bean type and herbicide treatment, as well as their interaction were considered fixed effects, while environment (year-location combinations), interactions between environment and the fixed effects, and replicate nested within environment were considered random effects. Significance of fixed effects were tested using F-tests and random effects were tested using a Z-test of the variance estimate. Environments were combined for a given variable if the environment by bean type by herbicide interaction was not significant. The UNIVARIATE procedure was used to test data for normality and homogeneity of variance. For all injury ratings, the untreated check (assigned a value of zero) was excluded from the analysis. However, all values were compared independently to zero to evaluate treatment differences with the untreated check. To satisfy the assumptions of the variance analyses, injury 1 WAE and seed moisture content were log transformed, and injury 2 and 4 WAE were square root transformed. Treatment comparisons were made using Fisher's Protected LSD at a level of $P < 0.05$. Additionally, contrasts were performed for each variable comparing (a) sulfentrazone versus sulfentrazone plus imazethapyr and (b) imazethapyr versus sulfentrazone plus imazethapyr. Data compared on the transformed scale were converted back to the original scale for presentation of results.

3. Results and Discussion

Environment by bean type by herbicide interaction was not significant for injury 1 and 4 WAE, shoot dry weight, height, seed moisture, and yield and all five datasets were analyzed together. Environment by bean type by herbicide interaction was significant for injury 2 WAE: Ridgetown 2010 was all zero (not shown in Table 1) and was separated from the rest. For main effects, bean Type was significant for yield; bean Type and Herbicide were significant for injury 2 and 4 WAE and height. Bean Type × Herbicide interaction was also significant for injury 2 and 4 WAE and height.

Table 1: Significance of main effects and interactions for percent visual injury, dry weight, height, seed moisture content, and yield of dry bean treated with PRE applications of sulfentrazone, imazethapyr, or sulfentrazone plus imazethapyr. Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD at $P < 0.05$. Means for a main effect were separated only if there was no significant interaction involving that main effect[a].

Main effects[b]	Dry bean injury			Dry weight (g)	Height (cm)	Moisture (%)	Yield (T/ha)
	1 WAE	2 WAE[c] (%)	4 WAE				
Type of dry bean	NS	*	*	NS	**	NS	**
Black	1	4	3	71	59	16.3	3.5[a]
Cranberry	1	4	2	72	51	18.0	1.7[b]
Kidney	1	2	1	73	53	18.7	1.9[b]
White	1	7	5	61	54	17.6	3.5[a]
SE	0	0	0	2	1	0.1	0.1
Herbicide treatment (rate in g ai/ha)	NS	**	**	NS	**	NS	NS
Untreated	0	0	0	77	56	17.5	2.8
Sulfentrazone (105)	0	2	1	72	55	17.9	2.7
Sulfentrazone (140)	1	3	2	72	56	17.7	2.6
Sulfentrazone (280)	2	11	8	63	53	18.0	2.6
Imazethapyr (37.5)	0	1	1	66	55	17.3	2.7
Sulfentrazone + imazethapyr (105 + 37.5)	1	3	2	70	54	17.6	2.7
Sulfentrazone + imazethapyr (140 + 37.5)	1	4	3	70	54	17.4	2.6
Sulfentrazone + imazethapyr (280 + 3 7.5)	2	11	7	64	51	17.6	2.6
SE	0	0	0	2	1	0.1	0.1
Interaction							
T × H	NS	*	**	NS	*	NS	NS
Contrasts							
Sulfentrazone versus sulfentrazone + imazethapyr	4 versus 4	7 versus 7	6 versus 6	69 versus 68	54 versus 53	18.1 versus 17.8*	2.6 versus 2.6
Imazethapyr versus sulfentrazone + imazethapyr	1 versus 4*	2 versus 7**	1 versus 6*	66 versus 68	55 versus 53	17.6 versus 17.8	2.7 versus 2.6

[a]Abbreviations: WAE: week after crop emergence; H: herbicide treatment; NS: not significant at $P = 0.05$ level; PRE: preemergence; T: type of dry bean.
[b]Significance at $P < 0.05$ and $P < 0.01$ levels denoted by * and **, respectively.
[c]Ridgetown 2010 values not included (all values zero, could not be combined with other environments).

3.1. Crop Injury. Injury symptoms evaluated visually included stunted growth, wrinkling of leaf tissue, leaf necrosis, leaf chlorosis, and leaf veinal discoloration. At 1 WAE, sulfentrazone alone or in combination with imazethapyr at doses evaluated caused no significant injury in black, cranberry, kidney, and white bean (Table 1). However, at 2 and 4 WAE, there was significant injury in dry bean with sulfentrazone alone or in combination with imazethapyr. At 2 WAE, sulfentrazone alone caused 1–11, 1–11, 1–5, and 3–19% injury, and sulfentrazone + imazethapyr caused 3–11, 2–10, 2–5, and 4–20% injury in black, cranberry, kidney, and white bean, respectively (Table 2). At 4 WAE, sulfentrazone alone caused 1–7, 1–7, 0–4, and 1–16% injury, and sulfentrazone + imazethapyr caused 1–8, 1–5, 1–3, and 2–14% injury in black, cranberry, kidney, and white bean, respectively (Table 2). Imazethapyr alone at 37.5 g ai/ha did not cause any significant injury in black, cranberry, kidney and white bean at 2 and 4 WAE (Table 2). Contrasts indicated that adding imazethapyr to sulfentrazone did not increase injury in dry bean at 1, 2, and 4 WAE (Table 1). However, adding sulfentrazone to imazethapyr increased injury 3, 5, and 5% at 1, 2, and 4 WAE, respectively (Table 1). In other studies, sulfentrazone applied PRE at higher rates (420 to 840 g ai/ha) caused up to 30% visible injury in black, brown, cranberry, kidney, otebo, pinto, white, and yellow eye bean [19]. The levels of injury in this study is similar to those seen with other PPO inhibitors such as fomesafen in dry bean [17, 20–22]. Sikkema et al. [20] also reported only 1% or less visible injury in dry bean with fomesafen applied preemergence. However, other PPO inhibitor herbicides such as flumioxazin caused as much as 34% visible injury in black, cranberry, kidney, and white bean [21]. Saflufenacil applied PRE caused 51 to 99% visible injury in adzuki, cranberry, lima, snap, and white bean [23].

Differential sensitivity was seen between market classes of dry beans with some treatments. White bean was more sensitive than cranberry or black bean which were most sensitive than kidney bean to sulfentrazone alone at 280 g ai/ha or in combination with imazethapyr at 37.5 g ai/ha at 2 and 4 WAE (Table 2). Other studies have also shown differential sensitivity with soil applied herbicides in dry bean [2, 5, 24]. Market classes of dry beans have different geographic origins and consequently have different gene pool which affects their

Table 2: Percent visual injury 2 and 4 WAE and height for four dry bean types treated with PRE applications of sulfentrazone, imazethapyr, or sulfentrazone plus imazethapyr. Means followed by the same letter within a column (a–d) or row (X–Z) in each section are not significantly different according to Fisher's Protected LSD at $P < 0.05$[a].

Herbicide treatment (rate in g ai/ha) by variable	Dry bean type								
	Black		Cranberry		Kidney		White		SE
Injury 2 WAEb[b]									
Untreated	0^{a}	Z	0^{a}	Z	0^{a}	Z	0^{a}	Z	0
Sulfentrazone (105)	1^{ab}	Z	1^{ab}	Z	1^{ab}	Z	3^{bc}	Z	0
Sulfentrazone (140)	3^{b}	YZ	2^{b}	YZ	2^{bc}	Z	6^{c}	Y	1
Sulfentrazone (280)	11^{c}	Y	11^{c}	Y	5^{c}	Z	19^{d}	X	2
Imazethapyr (37.5)	1^{ab}	Z	1^{ab}	Z	1^{ab}	Z	1^{ab}	Z	1
Sulfentrazone + imazethapyr (105 + 37.5)	3^{b}	Z	2^{b}	Z	2^{bc}	Z	4^{bc}	Z	1
Sulfentrazone + imazethapyr (140 + 37.5)	3^{b}	Z	3^{b}	Z	2^{bc}	Z	6^{c}	Z	1
Sulfentrazone + imazethapyr (280 + 37.5)	11^{c}	Y	10^{c}	YZ	5^{c}	Z	20^{d}	X	2
SE	1		1		0		1		
Injury 4 WAE									
Untreated	0^{a}	Z	0^{a}	Z	0^{a}	Z	0^{a}	Z	0
Sulfentrazone (105)	1^{ab}	Z	1^{ab}	Z	0^{a}	Z	1^{ab}	Z	0
Sulfentrazone (140)	2^{b}	YZ	2^{bc}	YZ	1^{ab}	Z	4^{b}	Y	1
Sulfentrazone (280)	7^{c}	Y	7^{d}	YZ	4^{b}	Z	16^{c}	X	2
Imazethapyr (37.5)	1^{ab}	Z	1^{ab}	Z	0^{a}	Z	1^{ab}	Z	0
Sulfentrazone + imazethapyr (105 + 37.5)	1^{ab}	Z	1^{ab}	Z	1^{ab}	Z	2^{b}	Z	0
Sulfentrazone + imazethapyr (140 + 37.5)	3^{b}	Z	2^{bc}	Z	2^{b}	Z	4^{b}	Z	1
Sulfentrazone + imazethapyr (280 + 37.5)	8^{c}	Y	5^{cd}	YZ	3^{b}	Z	14^{c}	X	2
SE	1		1		0		1		
Height									
Untreated	61^{a}	Z	52^{a}	Y	53^{a}	Y	58^{a}	Z	1
Sulfentrazone (105)	59^{abc}	Z	51^{ab}	X	54^{a}	XY	55^{a}	Y	1
Sulfentrazone (140)	60^{ab}	Z	52^{a}	Y	55^{a}	Y	56^{a}	YZ	1
Sulfentrazone (280)	57^{bc}	Z	50^{ab}	XY	54^{a}	YZ	50^{b}	X	2
Imazethapyr (37.5)	59^{abc}	Z	51^{ab}	X	53^{a}	XY	55^{a}	YZ	1
Sulfentrazone + imazethapyr (105 + 37.5)	59^{abc}	Z	50^{ab}	X	53^{a}	XY	55^{a}	YZ	1
Sulfentrazone + imazethapyr (140 + 37.5)	59^{abc}	Z	50^{ab}	X	53^{a}	XY	55^{a}	Y	1
Sulfentrazone + imazethapyr (280 + 37.5)	56^{c}	Z	49^{b}	Y	52^{a}	Y	48^{b}	Y	1
SE	1		1		1		1		

[a]WAE: week after crop emergence; PRE: preemergence.

[b]Ridgetown 2010 values not included (all values zero, could not be combined with other environments).

tolerance to herbicides [25–27]. Singh et al. [25–27]. studied more than 300 landraces of dry beans from various geographical and ecological regions of domestication of dry bean in America (Mexico, Nicaragua, El Salvador, Honduras, Costa Rica, Dominican Republic, Columbia, Argentina and Brazil) and concluded that origin determines distinctive agronomic traits, morphology, adaptation and disease resistance in dry bean.

3.2. Shoot Dry Weight and Plant Height. Sulfentrazone and imazethapyr alone or in combination with each other at doses evaluated had no adverse effect on shoot dry weight of black, cranberry, kidney, and white bean (Table 1). In other studies, sulfentrazone applied PRE at 420 g ha^{-1} did not have any effect on the shoot dry weight of black, brown, cranberry, kidney, otebo, pinto, white, and yellow eye beans but, at 840 g ha^{-1}, decreased shoot dry weight 30 to 40% [19]. Other PPO inhibitor herbicides such as saflufenacil applied PRE have been shown to reduce shoot dry weight 92 to 99% in adzuki, cranberry, lima, snap, and white bean [23].

Plant height is important in dry bean production as shorter plants can have greater seed loss at the cutter bar of the combine during harvest. Sulfentrazone at 105 and 140 g ai/ha and imazethapyr at 37.5 g ai/ha alone or in combination with each other had no adverse effect on height of black, cranberry, kidney, and white bean (Table 2). Sulfentrazone at 280 g ai/ha decreased height of black bean 7% and white bean 14% but had no adverse effect on the height of cranberry and kidney bean compared to the untreated weed free control. Sulfentrazone at 280 g ai/ha plus imazethapyr at 37.5 g ai/ha decreased height of black bean 8%, cranberry bean 6%, and white bean 14% but had no adverse effect on the height of kidney

bean compared to the untreated weed free control (Table 2). Differential sensitivity was seen between market classes of dry beans with some treatments. Black and white bean were generally more sensitive to sulfentrazone than cranberry and kidney bean; however, results were not always statistically significant (Table 2).

In other studies, sulfentrazone applied PRE at 420 and 840 g ha^{-1} had no adverse effect on the height of black, brown, cranberry, kidney, otebo, pinto, white, and yellow eye bean. Imazethapyr applied PRE caused no adverse effect on the height of cranberry and kidney beans but reduced height of black and white beans as much as 40% [28–30]. PPO inhibitor herbicides such as flumioxazin PRE reduced the height of black bean 23% and white beans 28% but had no effect on the height of cranberry and kidney beans [21]. Saflufenacil applied PRE reduced plant height 25 to 93% in adzuki, cranberry, lima, snap, and white bean [23].

3.3. Seed Moisture Content and Yield. Sulfentrazone at 105, 140, and 280 g ai/ha, applied alone or in combination with imazethapyr at 37.5 g ai/ha, caused no adverse effect on the seed moisture content and yield of black, cranberry, kidney, and white bean (Table 1). In other studies sulfentrazone applied preemergence at 420 to 840 g ai/ha caused 26 to 52% seed yield reduction in black, cranberry, otebo, and white bean [19]. Other PPO inhibitor herbicides such as flumioxazin reduced seed yield of black and white bean 20 to 30% but had no adverse effect on yield of cranberry and kidney bean [21]. Saflufenacil applied PRE decreased seed yield 56 to 99% in adzuki, cranberry, lima, snap, and white beans [23]. Other PPO inhibitor herbicides such as fomesafen had little effect on the seed yield of dry bean [5, 20, 22].

4. Conclusions

Based on this research, sulfentrazone applied PRE at the rates up to 140 g ai/ha alone or in combination with imazethapyr at 37.5 g ai/ha has potential to be used in black, cranberry, kidney, and white bean under Ontario environmental condition. There is a slight differential sensitivity between dry bean market classes to sulfentrazone. Sulfentrazone PRE caused slightly greater injury in black and white bean compared to cranberry and kidney bean but crop injury at rates up to 140 g ai/ha was minimal with no adverse effect on plant height, shoot dry weight, seed moisture content, and yield under the environmental condition in this study. Availability of sulfentrazone alone or in combination with imazethapyr for weed management in dry bean production would provide growers with a new herbicide option for the control of troublesome weeds such as common ragweed, common lambsquarters, common pigweed, and other annual broadleaf weeds.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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