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Using Pyroxasulfone for Downy Brome (*Bromus tectorum* L.) Control in Winter Wheat

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Abstract

Downy brome is one of the most troublesome weeds in no-till wheat production systems of the US Great Plains. Pyroxasulfone is a relatively new, soil-applied residual herbicide (root/shoot growth inhibitor) labeled for use in wheat. Multiple field experiments were conducted near Huntley, MT from 2012 through 2016 to determine the efficacy of pyroxasulfone to control downy brome in imidazolinone (IMI)-tolerant (Clearfield™) winter wheat. Pyroxasulfone did not cause any injury to wheat in any of the three studies. Downy brome injury with pyroxasulfone preemergence (PRE) only program did not differ between 89 or 178 g·ai (active ingredient)·ha^{-1} rates, and averaged 82% and 84% in 2 separate studies. In a preplant (PP) burndown program, the addition of pyroxasulfone (178 g·ai·ha^{-1}) to glyphosate improved downy brome end-season injury from 15% to 74%. In a separate study, the end-season injury with pyroxasulfone was greater when applied PRE (84%) compared to the delayed PRE (DPRE) timing (74%). In addition, the water dispersible granule (WDG) formulation of pyroxasulfone performed slightly better than the suspension concentrate (SC) formulation for downy brome injury. Pyroxasulfone applied PRE in the fall at a rate of 89 g·ai·ha^{-1} followed by (fb) imazamox (44 g·ai·ha^{-1} rate) applied postemergence (POST) in the spring effectively controlled downy brome (99% end-season injury). Furthermore, the injury was consistent with the standard program comprising of propoxycarbazone (29 g·ai·ha^{-1}) PRE fb imazamox POST in IMI-tolerant winter wheat. In conclusion, pyroxasulfone applied PRE in the fall can be effectively utilized in conjunction with a standard acetolactate synthase (ALS)-inhibitor-based POST herbicide program for a season-long downy brome management in winter wheat.

Keywords

Downy Brome, Pyroxasulfone, Soil-Applied Herbicide, Herbicide Rate, Application Timing, Formulation, Wheat

1. Introduction

Wheat (*Triticum aestivum* L.) is an important cereal grain crop well suited for dryland cropping systems of the northwestern United States, including Montana. In 2015, Montana ranked third among the wheat producing states, accounting for 9% of the total US wheat production [1]. About 75% of the total wheat grown in the United States is winter wheat [2], which is primarily grown in rotation with chemical fallow, pulse crops (dry pea, chickpea, or lentil), or canola in this region. Weed management is a major obstacle in successful winter wheat production [3], and a season-long weed infestation can cause severe reductions in yield and grain quality of winter wheat [4] [5].

Downy brome (commonly known as cheatgrass) is an invasive, self-pollinated, winter annual grass weed, widespread in rangeland and winter wheat production areas of this region [6]. It is a native of Mediterranean region of Europe, and was first identified in the United States in 1861 in New York and Pennsylvania [7]. Currently, downy brome infests 23 million hectares in 17 states in the northwestern United States [8]. The increased downy brome abundance in the semi-arid wheat production systems is attributed to the adoption of no-till practice, mainly for soil moisture conservation and soil erosion prevention, and limited selective herbicides for downy brome management [6]. Downy brome seeds are short-lived (1 to 2 years), best germinating at 20˚C, and seedlings emerge from shallow soil depths (1 to 5 cm) [9] [10]. Fall-emerging downy brome seedlings overwinter in a semi-dormant state and resume growth in the spring after winter vernalization. Those plants attain physiological maturity by mid-June in this region [11]. Downy brome is a prolific seed producer (up to 2.6 billion seeds ha^{-1}) [12].

Downy brome interference in winter wheat has been studied extensively, and moderate to severe grain yield reductions have been reported [9] [13] [14] [15]. Downy brome at densities of 24, 40, and 65 plants·m^{-2} reduced winter wheat yields by 10%, 15%, and 20%, respectively [15]. In a study conducted in Washington, a moderate infestation of downy brome at a density of 54 plants·m^{-2} reduced winter wheat yield by 28% [14]. High levels of downy brome infestation (>500 plants·m^{-2}) can cause near-total (>92%) yield loss in winter wheat [14].

The timing of downy brome emergence has a greater influence on wheat yield reductions than the plant density [8] [15]. The early-emerging cohorts of downy brome (that emerged between planting and 1 to 2 weeks after winter wheat emergence) were found to be more competitive than the late-emerging cohorts (that emerged after 3 weeks of winter wheat emergence) [13] [15]. For instance, downy brome at densities of 200 to 400 plants·m^{-2} that emerged in the fall with winter wheat, reduced winter wheat yields up to 68% [13]. Up to 40% winter wheat yield reductions were observed when fall-emerging downy brome at 132 plants·m^{-2} were not controlled by early spring; however, the yield loss was only 6% when those plants were removed by March [9].

Growers rely on selective herbicides for downy brome management in wheat. A majority of these herbicides belong to five different ALS-inhibiting herbicide families, including sulfonylureas (SU), imidazolinones (IMI), triazolopyrimidines (TP), pyrimidinylthiobenzoates (PTB), and sulfonylamino-carbonyl-triazolinones (SCT). However, the intensive use of these ALS-inhibiting herbicides has resulted in the evolution of ALS-resistant downy brome biotypes [16]. For instance, a downy brome biotype with cross-resistance to imazamox (IMI), propoxycarbazone-sodium (SCT), and pyroxsulam (TP) has recently been reported from an IMI-tolerant winter wheat field in Montana [17]. Similarly, downy brome biotypes with cross-resistance to primisulfuron, sulfosulfuron, imazamox, and propoxycarbazone have been documented from Kentucky bluegrass fields in Oregon [18] [19], suggesting the need to revisit effective weed control programs and investigate alternative herbicide chemistries for downy brome management.

Pyroxasulfone is a relatively new soil-applied premergence (PRE) herbicide that acts as a root/shoot growth inhibitor in germinating seedlings of both grassy and broadleaf weeds [20]. It is registered in several crops including wheat, corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], sunflower (*Helianthus annuus* L.), and dry bean [21] [22] [23]. Pyroxasulfone applied PRE in wheat controls grass weeds such as, Italian ryegrass (*Lolium perenne* ssp. multiflorum) and rigid ryegrass (*Loliumrigidum*) [21] [24] [25]. However, there is very little information available on the effectiveness of pyroxasulfone for downy brome management in wheat. The objectives of this research were: 1) to evaluate pyroxasulfone applied PRE standalone or followed by (fb) a standard POST herbicide program; 2) compare the effectiveness of pyroxasulfone with other standard preplant (PP) glyphosate-based herbicide programs (standalone) or fb a POST herbicide program; and 3) compare the efficacy of pyroxasulfone formulation, rate and application timing for crop safety and season-long downy brome injury and grain yields in IMI-tolerant (Clearfield®) winter wheat.

2. Materials and Methods

Three separate field experiments were conducted at the Montana State University Southern Agricultural Research Center (MSU-SARC) near Huntley, MT, during 2012 through 2016 to achieve the aforementioned objectives (1, 2, and 3). Soil was a Fort Collins clay loam (fine loamy, mixed, superactive, mesic Aridic Haplustalfs) with a pH of 7.8% and 2.1% organic matter. Monthly mean air temperature (˚C) and total precipitation (mm) were recorded at a weather station located approximately 1 km from the test site. Plots were 3 m wide by 9 m long. An IMI-tolerant winter wheat cultivar "Clearstone CL 2" was seeded 2.5 cm deep in 19-cm rows at a rate of 67 kg·ha^{-1} using a no-till drill in the first fortnight of October. Plots were fertilized with N-P-K using a gravity-fed broadcast spreader according to the MSU fertilizer guidelines for winter wheat production [26]. The test site for each experiment had a natural uniform infestation of downy brome at densities of 60 to 65 plants·m^{-2}. All herbicide treatments were applied with a CO_2-pressurized hand-held sprayer equipped with four flat-fan spray nozzles (TeeJetTP8001, TeeJet Technologies, Wheaton, IL 60189) calibrated to deliver 94 L·ha^{-1} at 276 kPa. Herbicides used in the three experiments are presented in Table 1. The herbicide application rates were selected based on the labeled rates in IMI-tolerant winter wheat. In all experiments, a nontreated check was included for comparison. The winter wheat crop was harvested using a small-plot combine (Wintersteiger Ag) and wheat grain samples were cleaned, and yields were adjusted to 13% moisture.

2.1. Pyroxasulfone Preemergence

Field experiments were conducted in 2012/2013 and 2013/2014 winter wheat growing seasons, and were set up in a randomized complete block design with four replications. The study included three fall-applied preemergence (PRE) standalone treatments, two spring-applied postemergence (POST) standalone treatments, and two PRE followed by (fb) POST treatments. PRE standalone treatments included pyroxasulfone at either 89 or 178 g·ai·ha^{-1} in comparison to propoxycarbazone at 29 g·ai·ha^{-1} (local standard), and were applied immediately after winter wheat planting on October 12 in 2012 and October 7 in 2013. POST treatments included imazamox at 44 g·ai·ha^{-1} or pyroxsulam at 18 g·ai·ha^{-1}, and were applied on May 10 in 2013 and May 14 in 2014 when winter wheat and downy brome had broken their winter dormancy and resumed growth (approximately 4- to 5-tiller stage of winter wheat). Injury data on crop and downy brome were visually assessed on a scale of 0 to 100%, with 0 representing no injury and 100 representing complete plant death at 2, 5, and 8 weeks after the POST (WAPOST) herbicide application.

Table 1. List of tested herbicides along with adjuvants.

Active ingredients	Trade name	Manufacturer	Adjuvant[a]	Adjuvant rate % v/v
Pyroxasulfone	Zidua®	BASF Corporation, Research Triangle Park, NC 27709		
Propoxycarbazone	Olympus® 70	Bayer CropScience, Research Triangle Park, NC 27709		
Saflufenacil	Sharpen®	BASF Corporation, Research Triangle Park, NC 27709	MSO + AMS	1 + 20 g/L
Imazamox	Beyond®	BASF Corporation, Research Triangle Park, NC 27709	MSO + UAN	1 + 9.2 L/ha
Pyroxsulam	PowerFlex® HL	Dow AgroScience LLC, Indianapolis, IN 46268	NIS + UAN	0.5 + 4.6 L/ha
Glyphosate	Roundup PowerMax®	Monsanto Company, Saint Louis, MO 63167	NIS + AMS	0.25 + 20 g/L

MSO, methylated seed oil, MSO concentrate, Loveland Products; AMS, ammonium sulfate, Thrust, Loveland Products; UAN, urea ammonium nitrate, Nortrace, Loveland Products; NIS, nonionic surfactant.

2.2. Pyroxasulfone Preplant

Ten preplant (PP) standalone or PP followed by (fb) standard POST herbicide treatments were evaluated for injury on crop and downy brome during the 2013/2014 and 2014/2015 winter wheat growing seasons. Treatments were arranged in a randomized complete block design, with four replications. Treatments included glyphosate applied preplant (PP) at 870 g·ai·ha^{-1} alone or in combination with pyroxasulfone at 89 or 178 g·ai·ha^{-1} or propoxycarbazone at 29 g·ai·ha^{-1} (local standard), in combination with pyroxasulfone at 89 g·ai·ha^{-1} plus saflufenacil at 25 g·ai·ha^{-1}; and glyphosate (870 g·ai·ha^{-1}) PP fb imazamox (44 g aiha^{-1}) POST or pyroxsulam (18 g·ai·ha^{-1}) POST. The PP treatments were applied a day before winter wheat planting on October 7 in 2013 and October 10 in 2014, while POST treatments were applied on May 5 in 2014 and May 10 in 2015. Treatments were visually assessed for injury on crop and downy brome at 21 weeks after the PP (WAPP) herbicide application, and 4 and 8 weeks after the POST (WAPOST) herbicide application, using the rating scale as previously described.

2.3. Pyroxasulfone Rate, Application Timing and Formulation

Field experiments were conducted in 2014/2015 and 2015/2016, and were set up in a randomized complete block design with a factorial arrangement of treatments, and four replications. Factors included pyroxasulfone formulation, rate, and application timing. Pyroxasulfone formulations tested were water-dispersible granule (WDG) and suspension concentrate (SC). Pyroxasulfone rates included 89 or 178 g·ai·ha^{-1}. The application timings tested were PRE (immediately after winter wheat planting) and delayed PRE (DPRE; when 80% of germinated wheat seeds had a shoot at least 1.2 cm long until wheat spiking). Data on crop and downy brome injury were visually assessed at 24 and 32 weeks after the PRE (WAPRE) application using the rating scale as previously described.

2.4. Statistical Analyses

All data were subjected to ANOVA using PROC MIXED in SAS 9.3 (SAS Institute, Inc., SAS Campus Dr., Cary, NC 27513) to test the significance of fixed effects, *i.e.*, year, treatment (herbicide treatment in experiment 1 and 2 and herbicide rate, formulation, or timing in experiment 3), and their interactions. Replication and interactions involving replication were random effects in the model. Downy brome percent injury data from the nontreated check plots were excluded from the analysis, while the wheat yield data from the nontreated check plots were included for comparison. Residual analyses were performed using PROC UNIVARIATE and the homogeneity of variance assumption was tested. All data met ANOVA requirements. Treatment means were separated using Fisher's protected LSD at $P \leq 0.05$.

3. Results and Discussion

The 2015/2016 growing season was wetter and warmer compared to 2012/2013 and 2014/2015 growing seasons (Table 2). However, the interaction of treatment by year was not significant on downy brome injury or winter wheat grain yield in any of the three experiments; hence, data were pooled over the two years.

3.1. Pyroxasulfone Preemergence

No winter wheat injury was observed with any of the PRE standalone, POST standalone, or PRE fb POST herbicide program. Among all treatments, pyroxasulfone (89 g·ha^{-1}) or propoxycarbazone (29 g·ai·ha^{-1}) PRE followed by imazamox (44 g·ai·ha^{-1}) POST were the most effective treatments (>97% injury) for managing downy brome in IMI-tolerant wheat at 2, 5, and 8 WAPOST (Table 3). Downy brome injury with pyroxasulfone (89 or 178 g·ai·ha^{-1}) PRE alone was greater than propoxycarbazone PRE alone, but comparable to imazamox (44 g·ha^{-1}) POST standalone treatment across all evaluation dates, and averaged 81% at 8 WAPOST. Although there is no published information on pyroxasulfone efficacy on downy brome, up to 94% control of Italian ryegrass has been reported with a PRE application of pyroxasulfone (150 g·ai·ha^{-1}) in winter wheat [21]. Similarly, pyroxasulfone at rates ≥150 g·ha^{-1} had up to 90% control of rigid ryegrass (*Loliumrigidum* Gaud.) in wheat [27]. Consistent with our results, up to 64% injury of downy brome has been reported with a fall application of propoxycarbazone PRE at a similar rate in winter wheat, in a study conducted in North Dakota, USA [28]. With imazamox POST, applied even at a lower rate of 35 g·ai·ha^{-1}, up to 82% injury of downy brome has been documented in spring

Table 2. Monthly mean air temperature (˚C) and total precipitation for the winter wheat growing periods in 2012-2016 at the MSU Southern Agricultural Research Center near Huntley, MT. The months of October–July represent the critical winter wheat growing season in southcentral Montana.

	2012-2013		2013-2014		2014-2015		2015-2016	
	Temperature (˚C)	Precipitation (mm)	Temperature (˚C)	Precipitation (mm)	Temperature (˚C)	Precipitation (mm)	Temperature (˚C)	Precipitation (mm)
Oct.	7.1	29.9	6.6	63.8	10.1	6.4	10.9	57.4
Nov.	2.3	11.1	0.9	5.1	−1.5	12.5	1.3	14.3
Dec.	−3.6	2	−6.6	23.7	−2.3	8.9	−3.3	8.4
Jan.	−3.2	5.4	−1.5	3.6	−1.1	5.1	−2.9	7.4
Feb.	0.4	4.8	−7.9	7.4	−0.2	51.9	4.2	4.6
Mar.	2.5	5.9	0.4	40.7	6.8	3.6	5.4	43.7
Apr.	5.7	29.8	8.3	29.8	8.9	29.0	9.7	45.3
May	14.3	154.2	13.7	62.8	12.6	79.1	13.4	75.0
Jun.	17.6	34.1	16.7	70.7	20.8	50.9	21.0	99.1
Jul.	22.9	15.5	22.8	11.2	22.2	26.4	22.7	12.0
Total		**249.7**		**318.8**		**273.7**		**367.2**

Table 3. Comparison of pyroxasulfone preemergence with standard herbicide treatments for downy brome injury and grain yield in imidazolinone-tolerant (IMI-tolerant) winter wheat near Huntley, MT in 2012 and 2013[a,b].

			Downy brome injury[c,d]							
Herbicide(s)	Rate	Timing	2 WAPOST		5 WAPOST		8 WAPOST		Yield	
	(g·ai·ha^{-1})				%				kg·ha^{-1}	
Pyroxasulfone	89	PRE	85	b	83	b	80	b	2092	b
Pyroxasulfone	178	PRE	88	b	86	b	84	b	2049	b
Propoxycarbazone	29	PRE	78	c	76	c	71	c	1942	b
Imazamox	44	POST	87	b	85	b	80	b	2003	b
Pyroxsulam	18	POST	74	c	69	d	61	d	1700	c
Pyroxasulfone fb imazamox	89 fb 44	PRE fb POST	98	a	98	a	99	a	2635	a
Propoxycarbazone by imazamox	29 fb 44	PRE fb POST	97	a	98	a	98	a	2712	a
Nontreated check	-	-	-		-		-		884	d

[a]Year-by-treatment interactions for downy brome injury and wheat grain yield were not significant; therefore, data were combined across the two years; [b]Abbreviations: PRE, preemergence; POST, postemergence; WAPOST, weeks after POST herbicide application; fb, followed by; g·ai·ha^{-1}, gram active ingredient per hectare; [c]Means within a column followed by same letters are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$.

wheat [28]. However, the POST standalone treatment of pyroxsulam at 18 g·ai·ha^{-1} was the least effective treatment (61%) for downy brome injury in our study conducted in winter wheat.

Consistent with an excellent downy brome injury, winter wheat yield with pyroxasulfone or propoxycarbazone PRE followed by imazamox POST was higher (averaged 2673 kg·ha^{-1}) than all other treatments. The season-long infestation of downy brome reduced winter wheat yield by an average of 67% in the non treated check plots compared to the PRE fb POST programs. Winter wheat yield with pyroxasulfone (89 or 178 g·ai·ha^{-1}) or propoxycarbazone (29 g·ai·ha^{-1}) PRE standalone program was comparable to imazamox POST standalone program, averaging 2021 kg·ha^{-1}, but was higher than the yield obtained from pyroxsulam POST standalone program.

3.2. Pyroxasulfone Preplant

Pyroxasulfone applied PP did not cause any visual injury to winter wheat, irrespective of the rate. The glyphosate (870 g·ai·ha^{-1}) PP fb imazamox (44 g·ai·ha^{-1}) POST program caused 93% injury to downy brome at 8 WAPOST. There was no additional advantage of tank mixing pyroxasulfone (89 g·ai·ha^{-1}) or propoxycarbazone (29 g·ai·ha^{-1}) with glyphosate PP when fb imazamox POST for downy brome injury (Table 4). Similarly, there was no additional benefit of adding pyroxasulfone (89 g·ai·ha^{-1}) to glyphosate PP when fb pyroxsulam (18 g·ai·ha^{-1}), with injury averaging 85%. However, the end-season downy brome injury did not exceed 15% with glyphosate PP standalone treatment, which was most likely because of downy brome cohorts that emerged after the burndown glyphosate application in winter wheat. Similarly, a poor downy brome injury (30%) was

Table 4. Comparison of pyroxasulfone with standard glyphosate-based burn down (preplant) programs for downy brome injury and grain yield in imidazolinone-tolerant (IMI-tolerant) winter wheat near Huntley, MT in 2013 and 2014.[a,b,c]

			Downy brome injury							
Herbicide(s)	Rate	Timing	21 WAPRE		4 WAPOST		8 WAPOST		Yield	
	($g \cdot ai \cdot ha^{-1}$)		%						$kg \cdot ha^{-1}$	
Glyphosate	870	PP	39	e	26	f	15	e	1270	d
Glyphosate + pyroxasulfone	870 + 89	PP	78	c	69	e	65	d	1467	c
Glyphosate + pyroxasulfone	870 + 178	PP	88	ab	81	d	74	c	1597	bc
Glyphosate + propoxycarbazone	870 + 29	PP	89	ab	78	d	73	c	1501	c
Glyphosate + pyroxasulfone + saflufenacil	870 + 89 + 25	PP	87	ab	83	d	77	c	1568	bc
Glyphosate + pyroxasulfone fbpyroxsulam	870 + 89 fb 18	PP fb POST	82	bc	90	c	85	b	1683	ab
Glyphosate + propoxycarbazone fbimazamox	870 + 29 fb 44	PP fb POST	91	a	99	a	94	a	1734	a
Glyphosate + pyroxasulfone fbimazamox	870 + 89 fb 44	PP fb POST	80	c	95	abc	94	a	1766	a
Glyphosate fb imazamox	870 fb 44	PP fb POST	39	e	97	ab	93	a	1769	a
Glyphosate fb pyroxsulam	870 fb 18	PP fb POST	42	e	91	bc	85	b	1671	ab
Nontreated check	-	-	-		-		-		1200	de

[a]Year-by-treatment interactions for downy brome injury and wheat grain yield were not significant; therefore, data were combined across the two years. [b]Abbreviations: PP, preplant; POST, postemergence; WAPP, weeks after PP application; WAPOST, weeks after POST application; fb, followed by; $g \cdot ai \cdot ha^{-1}$, gram active ingredient per hectare. [c]Means within a column followed by same letters are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$.

reported when glyphosate was applied alone PP in spring wheat [28]. In our study, tank mixing pyroxasulfone (178 $g \cdot ai \cdot ha^{-1}$) with or without saflufenacil (25 $g \cdot ai \cdot ha^{-1}$) or propoxycarbazone (29 $g \cdot ai \cdot ha^{-1}$) with glyphosate applied PP (standalone program), improved the end-season downy brome injury (averaged 73% injury) in winter wheat, indicating the excellent residual activity of those soil-applied herbicides on downy brome.

Wheat grain yields ranged from 1671 to 1769 $kg \cdot ha^{-1}$ when glyphosate with or without pyroxasulfone (89 $g \cdot ai \cdot ha^{-1}$) or propoxycarbazone (29 $g \cdot ai \cdot ha^{-1}$) PP was followed by imazamox or pyroxsulam POST (**Table 4**). In contrast to these glyphosate-based PP fb POST programs, grain yield with a glyphosate-based PP standalone program comprising of pyroxasulfone (89 or 178 $g \cdot ai \cdot ha^{-1}$), propoxycarbazone (29 $g \cdot ai \cdot ha^{-1}$), or pyroxasulfone + saflufenacil (25 $g \cdot ai \cdot ha^{-1}$) averaged 1533 $kg \cdot ha^{-1}$. This indicates that a follow up POST herbicide program was needed to prevent wheat yield reductions from downy brome interference, irrespective of the addition of pyroxasulfone or propoxycarbazone with glyphosate applied PP. However, a poor downy brome injury in the absence of pyroxasulfone or propoxycarbazone in the glyphosate PP standalone program resulted in the lowest yield (1270 $kg \cdot ha^{-1}$), which did not differ from the nontreated check plots.

3.3. Pyroxasulfone Rate, Application Timing and Formulation

There was no visible crop injury observed with any of the pyroxasulfone formulations, rates, and application timings tested. Only the main effects of application timing and formulation were significant for downy brome injury. Averaged across pyroxasulfone formulations and application rates, downy brome injury was higher with the PRE compared to the DPRE application timing at both the evaluation dates (Table 5). For instance, at 24 and 32 WAPRE, the PRE application of pyroxasulfone provided 84 and 79% injury to downy brome, respectively, compared with the DPRE treatment with 74% and 70% injury, respectively (Table 5). Although downy brome injury did not differ between WDG and SC formulations at 24 WAPRE, the WDG formulation performed slightly better (78% vs 71%) than the SC formulation for end-season (32 WAPRE) downy brome injury. There were no significant effects of pyroxasulfone formulation, rate, application timing, and their interactions on winter wheat grain yield (data not shown).

It is worth emphasizing that the recent evolution of downy brome biotypes with >100-fold level of resistance to imazamox and cross-resistance to SCT and TP families of ALS inhibitor soriginating in IMI-tolerant (Clearfield®) winter wheat system in Montana, is a concern for wheat producers [17]. Therefore, the use of pyroxasulfone as an alternative, effective site-of-action herbicide for downy brome management may aid in reducing the selection pressure for resistance development from repeated applications (fall and spring) of ALS-inhibitors in winter wheat. Based on the results from this research, pyroxasulfone when applied PP or PRE in the fall had extended residual activity on downy brome; however, a follow up POST application of pyroxsulam or imazamox (in IMI-tolerant wheat) in the spring was needed to achieve a season-long downy brome management

Table 5. Effect of pyroxasulfone application timing and formulation on downy brome injury in imidazolinone-tolerant (IMI-tolerant) winter wheat near Huntley, MT in 2015 and 2016.[a,b,c]

	Downy brome injury	
	24 WAPRE	32 WAPRE
Application timing	%	
PRE	84 a	79 a
DPRE	74 b	70 b
Formulation		
WDG	82 a	78 a
SC	77 a	71 b

[a]The year-by-treatment interaction for downy brome injury was not significant; therefore, data were combined across the two years. [b]Abbreviations: WDG, water-dispersible granules; SC, suspension concentrate; PRE, preemergence; DPRE, delayed preemergence (when 80% of germinated wheat seeds had a shoot at least 1.2 cm long until wheat spiking); WAPRE, weeks after PRE herbicide application. [c]Means within a column followed by same letters are not significantly different according to Fisher's protected LSD test at $P \leq 0.05$.

in winter wheat. This PRE/PP fb POST program can potentially prevent downy brome seed additions to the soil seed bank (Jha, personal observation) in winter wheat, which is an important consideration for herbicide resistance management. Pyroxasulfone would potentially be a good fit in the current weed control programs in cereal-based cropping systems of the NGP where pulse crops (dry pea, chickpea, and lentil) have increasingly become common in rotation with winter wheat. Although only wild oat (*Avena fatua* L.) with resistance to pyroxasulfone has been documented so far (Heap 2017), there is a potential risk of evolving resistance to pyroxasulfone in other weed species including downy brome, if not used proactively. Therefore, appropriate product stewardship and diverse weed control tactics should be implemented to maintain the long-term utility of pyroxasulfone for downy brome injury in winter wheat.

4. Conclusion

Results from this study highlight that pyroxasulfone applied PP or PRE at use rates of 89 or 178 g·ai·ha^{-1} in the fall followed by a POST treatment of imazamox at 44 g·ai·ha^{-1} in the spring can be safely used in Clearfield® winter wheat to effectively manage downy brome. The WDG formulation of pyroxasulfone may be slightly superior to the SC formulation, and the PRE timing can potentially provide better early-season downy brome management than the DPRE application timing. Utilizing this relatively new PRE herbicide would add diversity (multiple sites of action) to downy brome management programs in winter wheat.

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