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Glyphosate-resistant downy brome (*Bromus tectorum*) control using alternative herbicides applied postemergence

Charles M. Geddes[1] and Mattea M. Pittman[2]

[1]Research Scientist, Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, AB, Canada and [2]Research Assistant, Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, AB, Canada

Note

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Author for correspondence:
Charles M. Geddes, Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, 5403 1st Avenue South, Lethbridge, AB T1J 4B1
Email: Charles.Geddes@agr.gc.ca

Abstract

Downy brome is a troublesome facultative winter-annual grass weed that invades agricultural and nonagricultural lands in western North America and can cause substantial crop yield losses particularly in no-till winter wheat. Glyphosate-resistant (GR) downy brome was identified in southern Alberta in 2021, representing the first confirmation of a GR grass weed in Canada. This study was designed to evaluate alternative herbicides and herbicide mixtures applied post-emergence (POST) for control of GR and glyphosate-susceptible (GS) downy brome populations at the seedling stage under a controlled environment. The GR downy brome did not exhibit cross-resistance to other herbicides applied POST. Quizalofop alone or in combination with imazamox, imazamox + bentazon, or imazamox/imazethapyr, and glufosinate mixed with either clethodim or tiafenacil resulted in ≥80% visible control, plant mortality, and reduction in biomass of both GR and GS downy brome populations 21 d after treatment. Diligent stewardship of these remaining herbicide options is warranted since downy brome populations with resistance to herbicides that inhibit acetyl-CoA carboxylase or acetolactate synthase have been reported in neighboring states.

Introduction

Downy brome is an invasive grass weed in the semiarid region of western North America. Native to Europe, this species was introduced to North America in the mid-1800s as an early-season forage grass used for livestock feed (Mack 1981). Multiple isolated introductions of the species, followed by rapid spread throughout western North America, resulted in significant infestations in cropland, rangeland, and nonagricultural areas (Mack 1981; Upadhyaya et al. 1986). A mid-season survey of annual crops in Alberta, Canada, found annual brome species [including downy brome and Japanese brome (*Bromus japonicus* Houtt.)] primarily in the southern ecoregions (Leeson et al. 2019). The species is considered winter-annual but can exhibit spring-annual or biennial growth if low precipitation limits fall seed germination (Thill et al. 1984). As a facultative winter-annual grass weed, this species can be problematic, particularly in winter wheat crops, where it can cause up to 92% yield loss at high densities (Blackshaw 1993; Rydrych and Muzik 1968).

Downy brome is a cleistogamous self-pollinating species that reproduces by seed (Evans and Young 1984; Mitich 1999; Upadhyaya et al. 1986). Seed set takes place typically in May or June (Ball et al. 2004), producing up to 7,500 seeds per plant (Ostlie and Howatt 2013) depending on plant density and the environment (Upadhyaya et al. 1986). The seed exhibits little to no primary dormancy and usually germinates within 1 yr after dispersal (Burnside et al. 1996). However, some seeds can persist for 2 to 5 yr in the soil seedbank (Upadhyaya et al. 1986).

In 2021, a population of glyphosate-resistant (GR) downy brome was confirmed in a GR canola (*Brassica napus* L.) field in Taber County, Alberta (Geddes and Pittman 2022). This followed the discovery of three GR downy brome populations in Washington State prior to 2020 (Zurger and Burke 2020). The Alberta population exhibited up to 11.9-fold resistance to glyphosate in dose-response bioassays, and all seedlings from the population survived glyphosate treatment at 900 g ae ha^{-1} under controlled environmental conditions. Estimated glyphosate rates required for 80% control of the population ranged from 2,795 to 4,511 g ha^{-1}, well above common field use rates. Since downy brome is primarily self-pollinated (Evans and Young 1984), seed contamination of equipment and grain represents the greatest risk of GR biotype spread (Geddes and Pittman 2022). The short-lived seedbank of downy brome suggests that adequate management for a few years in a row could effectively deplete downy brome populations (Sebastian et al. 2017). Therefore, the objectives of this research were to determine 1) which alternative postemergence (POST) herbicides and herbicide mixtures effectively manage GR downy brome at the seedling stage under controlled-environment, and 2) whether the response of GR downy brome to POST-applied herbicides was similar to that of a glyphosate-susceptible (GS) population.

Materials and Methods

Collection of Plant Material

Collection of mature seed from the GR and GS downy brome populations followed the methods described by Geddes and Pittman (2022). In brief, mature seed was collected in 2021 by sampling about 100 downy brome plants at random from each field. The seed was air-dried at ambient room temperature, cleaned by hand, homogenized, and stored at 4 C prior to use. The GR downy brome population was collected from the field where it was confirmed in Taber County, Alberta, while the GS population was collected from a field in Lethbridge County, Alberta (Geddes and Pittman 2022).

Experimental Design and Treatment Structure

The experiment followed a two-way factorial randomized complete block design with four replications. The first factor was the downy brome population (GR vs. GS), and the second factor was the herbicide treatment, which included 20 herbicides or herbicide mixtures and an untreated control (Table 1). The POST herbicide treatments were selected by including those that were registered for control or suppression of downy brome or Japanese brome in Alberta (Anonymous 2022), in addition to consulting both private and public industry experts. The experiment was repeated in two separate greenhouses at the Agriculture and Agri-Food Canada Lethbridge Research and Development Centre.

Experimental Logistics and Data Collection

Seeds from each downy brome population were planted at a depth of 1 cm in 12 × 12 × 15 cm plastic greenhouse pots filled with modified Cornell soilless potting medium containing about 760, 960, and 510 mg N-P-K L^{-1} mixture (Sheldrake and Boodley 1966). The pots were placed in the greenhouse and watered daily to field capacity. The greenhouse used for the first run was equipped with MITRA light-emitting diode (LED) bulbs (Heliospectra Canada Inc., Toronto, ON) delivering 200 μmol m^{-2} s^{-1} supplemental light and followed an 18-h photoperiod with 22/11 C temperature regime. The greenhouse used for the second run was equipped with RAZR 3 LED bulbs (Fluence, Austin, TX) delivering 230 μmol m^{-2} s^{-1} supplemental light, and followed a 16-h photoperiod with 20/17 C temperature regime. The emerged seedlings were thinned to 15 plants per pot. The herbicide treatments were applied using a moving-nozzle cabinet sprayer when the downy brome plants reached the two-leaf stage. The sprayer was equipped with a flat-fan 8002VS TeeJet® nozzle (Spraying Systems Co., Wheaton, IL) delivering 200 L ha^{-1} spray solution at 275 kPa 50 cm above the midpoint of the plant canopy. The nozzle traveled at 2.4 km h^{-1}.

Visible control of the plants in each experimental unit (pot) was estimated at 7 and 21 d after treatment (DAT) following the methodology described by the Canadian Weed Science Society/Société Canadienne de Malherbologie (2018). Plant survival was determined 21 DAT by categorizing the health status of each plant in each pot as living (no injury or some injury with new regrowth) or dead (dead or nearly dead). Plant biomass fresh weight (FW) was determined 21 DAT for each pot by harvesting the plants down to the soil surface and weighing. The biomass samples were then dried at 60 C for 1 wk and biomass dry weight (DW) was determined.

Statistical Analysis

Visible control (7 and 21 DAT), plant survival, and biomass (FW and DW) data were analyzed using ANOVA in the MIXED procedure of SAS Studio software (version 3.81; SAS Institute Inc., Cary, NC). The initial model included downy brome population, herbicide treatment, experimental run, and their interactions as fixed factors, whereas experimental replication nested within run was a random factor. Variance component analyses (Littell et al. 2006) determined that all main and interaction factors including experimental run accounted for <5% of the total sums of squares for each response variable. Therefore, subsequent analyses pooled data across runs. Residual conformation to the Gaussian distribution was tested using the Shapiro-Wilk statistic, while heteroscedasticity was assessed by visual inspection of the residuals over the predicted values (Kozak and Piepho 2018). The square root transformation and arcsine square root transformation were used to meet the assumptions of ANOVA for biomass and plant survival data, respectively. Data were adjusted further for homogeneity of variance using the repeated group option based on minimization of the Akaike information criterion (Littell et al. 2006). Extreme outliers were removed using Lund's test (Lund 1975). Mean separation was determined based on Tukey's HSD ($\alpha = 0.05$). The CORR procedure with SAS software was used to determine correlations among visible control (7 and 21 DAT), plant survival, biomass FW, and biomass DW (21 DAT) in response to the herbicide treatments.

Results and Discussion

A downy brome population by herbicide treatment interaction ($P < 0.05$) was present for all response variables, which was caused by either very poor (visible control at 7 DAT) or no control (all other response variables) of the GR downy brome with glyphosate applied at 900 g ha^{-1} (Table 2). In contrast, glyphosate (900 g ha^{-1}), when visually assessed, controlled the GS downy brome by 54% at 7 DAT, which increased to excellent control (≥90%) based on all response variables measured 21 DAT. These data agree with previous reports from southern Alberta where glyphosate applied at 180 to 200 g ha^{-1} controlled herbicide-susceptible downy brome >80% (Blackshaw 1991). In the current study, the level of control in response to glyphosate differed ($P < 0.001$) between the GR and GS populations for all response variables (Table 2). No other differences were observed between the GR and GS populations for any other herbicide treatments with the exception of visible control 21 DAT in response to tiafenacil (50 g ai ha^{-1}). The GR population had 28% less visible control 21 DAT in response to tiafenacil than the GS population ($P < 0.001$). However, differences between the populations in response to this herbicide alone were absent for all other response variables. This suggests that overall, tiafenacil resulted in similar control of both GR and GS populations, because the quantitative data (i.e., plant biomass) did not support the qualitative estimate (visible control 21 DAT). Negligible differences in control of the GR and GS populations for all herbicide treatments, except for glyphosate alone, suggests that the GR population did not exhibit cross-resistance to other herbicides applied POST.

Table 1. Herbicide treatments evaluated for management of glyphosate-resistant and glyphosate-susceptible downy brome postemergence.

Herbicide common name	Herbicide trade name	Rate	Herbicide group	Formulation[a]	Surfactant	Manufacturer[b]
		g ai/ae ha^{-1}				
Glyphosate	Roundup WeatherMAX®	900		SN		Bayer
Imazamox/Imazapyr	Ares™ SN	20/9	2/2	SN	Surjet 0.5% vol/vol	Corteva
Quizalofop	Assure® II	48	1	EC	Merge 0.5% vol/vol	AMVAC
Flucarbazone	Everest® 70 WDG	24	2	WG	Agral 90 0.25% vol/vol	UPL
Clethodim	Centurion®	45	1	EC	Amigo 0.5% vol/vol	BASF
Glufosinate	Liberty® 150 SN	500	10	SN	Amigo 0.5% vol/vol	BASF
Glufosinate + Clethodim	Liberty® 150 SN + Centurion®	500 + 45	10 + 1	SN + EC	Amigo 0.5% vol/vol	BASF
Imazamox + Bentazon + Quizalofop	MPower® Anaconda™ [c]	20 + 430 + 48	2 + 6 + 1	EC	28% UAN @ 0.81 L/ac + Merge 0.25% vol/vol	NewAgco
Imazamox + Clethodim	MPower® Samurai® Master[d]	20 + 30	2 + 1	WG + EC	Merge 0.5% vol/vol	NewAgco
Pyroxsulam	Simplicity™	11	2	OD	Agral 90 0.25% vol/vol	Corteva
Pyroxsulam	Simplicity™	15	2	OD	Agral 90 0.25% vol/vol	Corteva
Imazamox	Solo® ADV	20	2	SN		BASF
Imazamox + Quizalofop	Solo® ADV + Assure® II	20 + 36	2 + 1	SN + EC		BASF + AMVAC
Imazamox/Bentazon	Viper® ADV	20 + 430	2/6	SN	28% UAN 0.81 L/ac	BASF
Metribuzin	Squadron® II	420	5	WG		ADAMA
Metribuzin	Squadron® II	560	5	WG		ADAMA
Imazamox/Imazethapyr + Quizalofop	Odyssey® WDG + Assure® II	15/15 + 36	2/2 + 1	WG + EC	Merge 0.5% vol/vol	BASF + AMVAC
Thiencarbazone	Varro™	5	2	SN	Agral 90 0.25% vol/vol	Bayer
Tiafenacil	Tiafenacil 70WG	50	14	WG	MSO 1% vol/vol	Gowan
Glufosinate + Tiafenacil	Liberty® 150 SN + Tiafenacil 70WG	500 + 50	10 + 14	SN + WG	MSO 1% vol/vol	BASF + Gowan

[a]Abbreviations: EC, emulsifiable concentrate; SC, suspension concentrate; SN, solution; WG, water dispersible granules; OD, oil dispersion.
[b]Manufacturer full names: ADAMA Agricultural Solutions Canada, Ltd.; AMVAC Canada; BASF Canada Inc.; Bayer CropScience Inc.; Corteva Agriscience Canada Company; Gowan Canada; NewAgco Inc.; UPL AgroSolutions.
[c]Mixture of MPower Samurai® + MPower Boa® + MPower Quiz®
[d]Mixture of MPower Samurai® + MPower Independence®

Table 2. Visible control 7 DAT, and visible control, plant survival, biomass fresh weight and biomass dry weight 21 DAT of glyphosate-resistant and glyphosate-susceptible downy brome populations with a range of postemergence herbicides and herbicide mixtures under controlled-environment.[a,b]

Herbicide treatment	Rate	Visible control 7 DAT			Visible control 21 DAT			Plant survival[c] 21 DAT			Biomass FW[d] 21 DAT			Biomass DW[d] 21DAT		
		GR	GS	GR vs. GS[e]	GR	GS	GR vs. GS	GR	GS	GR vs. GS	GR	GS	GR vs. GS	GR	GS	GR vs. GS
	g ai/ae ha^{-1}	%	%		%	%		%	%		g pot^{-1}	g pot^{-1}		g pot^{-1}	g pot^{-1}	
Untreated								100^{a}	100^{a}		13.7^{a}	18.4^{a}		1.8^{ab}	2.0^{a}	
Glyphosate	900	25^{gh}	54^{b-e}	***	6^{f}	97^{a}	***	100^{ab}	0^{f}	***	10.2^{ab}	0.4^{gh}	***	1.4^{a-c}	0.2^{f}	***
Imazamox/ Imazapyr	20/9	39^{e-g}	44^{d-f}		76^{bc}	78^{bc}		41^{de}	22^{c-f}		1.3^{fg}	0.9^{f-h}		0.4^{f-h}	0.3^{ef}	
Quizalofop	48	61^{cd}	72^{b}		97^{a}	99^{a}		0^{f}	0^{f}		0.5^{gh}	0.4^{gh}		0.3^{gh}	0.2^{ef}	
Flucarbazone	24	14^{hi}	26^{gh}		52^{de}	46^{e}		100^{ab}	100^{a}		6.0^{b-e}	6.8^{cd}		0.8^{c-f}	0.8^{c-e}	
Clethodim	45	41^{e-g}	49^{c-f}		54^{de}	53^{de}		96^{a-c}	84^{ab}		4.0^{c-f}	4.3^{c-e}		0.7^{d-g}	0.6^{c-f}	
Glufosinate	500	35^{fg}	38^{e-g}		43^{e}	45^{e}		99^{a-c}	88^{ab}		7.6^{a-d}	7.6^{b-d}		1.1^{a-d}	1.0^{b-d}	
Glufosinate + Clethodim	500+45	66^{bc}	63^{bc}		88^{ab}	85^{ab}		4^{ef}	4^{d-f}		0.4^{h}	0.4^{gh}		0.2^{h}	0.2^{f}	
Imazamox + Bentazon + Quizalofop	20+430+48	40^{e-g}	48^{c-f}		94^{ab}	97^{a}		0^{f}	0^{f}		0.6^{gh}	0.5^{gh}		0.3^{f-h}	0.3^{ef}	
Imazamox + Clethodim	20+30	46^{d-f}	51^{c-e}		63^{c-e}	78^{bc}		72^{b-d}	34^{cd}		2.0^{fh}	1.3^{e-h}		0.5^{f-h}	0.4^{d-f}	
Pyroxsulam	11.1	14^{hi}	23^{gh}		52^{de}	54^{de}		99^{a-c}	92^{ab}		2.4^{d-h}	2.4^{d-h}		0.4^{f-h}	0.4^{d-f}	
Pyroxsulam	14.8	28^{f-h}	32^{fg}		63^{c-e}	58^{de}		96^{a-c}	99^{ab}		1.8^{f-h}	2.1^{e-g}		0.4^{f-h}	0.4^{d-f}	
Imazamox	20	17^{hi}	24^{gh}		67^{cd}	64^{cd}		78^{a-d}	70^{bc}		2.0^{f-i}	2.4^{ef}		0.5^{e-h}	0.5^{c-f}	
Imazamox + Quizalofop	20+36	43^{e-g}	44^{d-f}		93^{ab}	96^{ab}		1^{f}	0^{f}		0.9^{gh}	0.5^{gh}		0.4^{f-h}	0.3^{ef}	
Imazamox/ Bentazon	20+430	4^{i}	3^{i}		4^{f}	3^{f}		100^{a}	100^{a}		14.4^{a}	16.9^{a}		1.8^{a}	1.8^{ab}	
Metribuzin	420	5^{i}	4^{i}		11^{f}	12^{f}		98^{a-c}	94^{ab}		7.6^{a-d}	10.1^{a-c}		1.0^{b-e}	1.2^{a-c}	
Metribuzin	560	1^{i}	3^{i}		16^{f}	13^{f}		99^{a-c}	99^{ab}		8.8^{a-d}	8.9^{a-d}		1.1^{a-d}	1.1^{a-c}	
Imazamox/ Imazethapyr + Quizalofop	15/15+36	54^{c-e}	60^{b-d}		93^{ab}	94^{ab}		1^{f}	2^{d-f}		0.8^{gh}	0.6^{gh}		0.4^{f-h}	0.3^{ef}	
Thiencarbazone	5	7^{i}	13^{hi}		18^{f}	6^{f}		99^{a}	100^{a}		11.4^{a-c}	16.3^{ab}		1.3^{a-c}	1.8^{ab}	
Tiafenacil	50	82^{ab}	90^{a}		54^{de}	82^{a-c}		66^{cd}	29^{c-e}	***	2.3^{e-h}	0.9^{e-h}		0.5^{f-h}	0.2^{ef}	
Glufosinate + Tiafenacil	500+50	96^{a}	96^{a}		98^{a}	97^{a}		0^{f}	1^{ef}		0.4^{hi}	0.3^{h}		0.2^{h}	0.2^{f}	

[a]Abbreviations: DAT, days after treatment; DW, dry weight; FW, fresh weight; GR, glyphosate-resistant population; GS, glyphosate-susceptible population.

[b]Within columns, different letters indicate significant difference based on Tukey's HSD ($\alpha = 0.05$).

[c]Data are back-transformed arcsine square root means.

[d]Data are back-transformed square root means.

[e]For each treatment, *** indicates a significant difference between GR and GS populations at $P < 0.001$; no other differences were observed ($P > 0.05$).

Table 3. Pearson correlation coefficients showing the correlation among downy brome visible control at 7 and 21 DAT, and plant survival, biomass fresh weight, and biomass dry weight at 21 DAT in response to a range of herbicides applied postemergence.[a,b]

		7 DAT	21 DAT			
		Visible control	Visible control	Plant survival	Biomass FW	Biomass DW
7 DAT	Visible control		0.76***	−0.69***	−0.66***	−0.64***
21 DAT	Visible control	0.76***		−0.86***	−0.86***	−0.83***
	Plant survival	−0.69***	−0.86***		0.68***	0.66***
	Biomass FW	−0.66***	−0.86***	0.68***		0.98***
	Biomass DW	−0.64***	−0.83***	0.66***	0.98***	

[a]Abbreviations: DAT, days after treatment; DW, dry weight; FW, fresh weight.
[b]Numbers indicate Pearson *R* values; *** indicates a significant correlation at $P < 0.001$.

Several POST-applied herbicides or herbicide mixtures resulted in either good or excellent control of both the GR and GS downy brome populations. The Pest Management Regulatory Agency (2016) defines weed control as ≥80% efficacy, whereas weed suppression is considered ≥60% but <80% efficacy. Based on all response variables collected 21 DAT, quizalofop alone (48 g ai ha^{-1}), imazamox + quizalofop (20 + 36 g ai ha^{-1}), imazamox + bentazon + quizalofop (20 + 430 + 48 g ai ha^{-1}), imazamox/imazethapyr + quizalofop (15/15 + 36 g ai ha^{-1}), glufosinate + clethodim (500 + 45 g ai ha^{-1}), or glufosinate + tiafenacil (500 + 50 g ai ha^{-1}) controlled both the GR and GS downy brome populations ≥80% (Table 2). Glufosinate + tiafenacil (500 + 50 g ha^{-1}) (a glutamine synthetase inhibitor, categorized as a Group 10 herbicide by the Herbicide Resistance Action Committee [HRAC], mixed with a protoporphyrinogen oxidase inhibitor, HRAC Group 14) was the only herbicide treatment to result in excellent (≥90%) control of both populations based on all response variables, which was evident by 7 DAT and extended to 21 DAT (the latest measurement timing). While this herbicide mixture was effective, it has not been registered for use in western Canada to date (Anonymous 2022). Imaxamox/imazapyr (20/9 g ai ha^{-1}) and both low and high rates of pyroxsulam (11 and 15 g ai ha^{-1}) (two herbicides that inhibit acetolactate synthase [ALS; HRAC Group 2]) controlled both downy brome populations based on a ≥80% reduction in biomass FW and DW, but not visible control or plant survival. Therefore, these herbicides sufficiently stunted downy brome growth and development but did not result in complete plant death.

Downy brome visible control 21 DAT was highly correlated with plant survival, biomass FW, and biomass DW (Pearson $R = -0.86$, -0.86, and -0.83, respectively; $P < 0.001$) across the herbicide treatments (Table 3). Collinearity of these response variables was expected because the visible control rating scale is a subjective composite assessment designed to estimate weed growth reduction in response to herbicide treatment as a function of weed density, biomass, and height, among other growth-related factors (Canadian Weed Science Society/Société Canadienne de Malherbologie 2018). It is important to note, however, that visible control 7 DAT and plant survival 21 DAT were correlated with biomass FW and DW to a lesser (albeit significant; $P < 0.001$) degree than visible control 21 DAT (Table 3). These results suggest that despite minor differences among qualitative and quantitative estimates of herbicide treatments achieving the ≥80% management threshold labeled control (Table 2), visible control 21 DAT was a suitable estimator of growth reduction as a composite function of plant density and biomass.

The current study identified several options for managing GR and GS downy brome POST in canola, pulses, and many other lower-acreage crops that are grown in western Canada (Anonymous 2022). Most of these options relied on either quizalofop (a herbicide that inhibits acetyl-CoA carboxylase [ACCase; HRAC Group 1]), imazamox (a HRAC Group 2 herbicide that inhibits ALS), or both active ingredients to achieve adequate control (Table 2). An exception was glufosinate + clethodim (a glutamine synthetase inhibitor and an ACCase inhibitor), which is registered for use POST in glufosinate-resistant canola. However, the cereal phase of crop rotations represents a weak link in managing GR downy brome POST. This is because pyroxsulam or imazamox (two ALS-inhibiting herbicides) were the only herbicides registered for use in cereal crops in Alberta (Anonymous 2022) that controlled downy brome ≥80% based on biomass FW (Table 2); but not visible control or plant survival. Pyroxsulam is registered for use POST in spring wheat, durum wheat (*Triticum durum* Desf.) and winter wheat in western Canada, while imazamox is the grass component of Altitude FX® 3 (BASF Canada Inc., Mississauga, ON) registered for use in imidazolinone-resistant wheat. However, these active ingredients are not registered for use in other cereal crops grown in this region (Anonymous 2022). In western Canada, both fall- and spring-applied pyroxsulam in winter wheat controlled herbicide-susceptible downy brome >70% in the spring, and reduced biomass and seed-producing culms by about 85% and 70%, respectively (Johnson et al. 2018). However, both fall- and spring-applied thiencarbazone or flucarbazone suppressed downy brome at best. Similarly, fall- or spring-applied pyroxsulam managed downy brome in winter wheat better than or similar to a range of other ALS-inhibiting herbicides in Kansas, although none of the herbicides tested controlled downy brome >78% (Reddy et al. 2013). Across three locations in North Dakota, imazamox controlled downy brome the most (averaging 73% control) and had numerically lower biomass, seed, and stem number in spring wheat compared with other POST herbicides (Ostlie and Howatt 2013). Therefore, limited herbicide options for effective downy brome management POST in wheat risks selection for ALS inhibitor resistance in downy brome populations. Diligent stewardship of the alternative herbicides identified to manage GR downy brome is necessary to prevent further selection of resistance to other herbicide modes of action.

While ACCase or ALS inhibitor-resistant downy brome has not been documented in Canada, these biotypes have been reported in nearby U.S. states. For example, 52% of the downy brome populations tested from Washington State between 2013 and 2020 were cross-resistant to multiple chemical families of ALS-inhibiting herbicides, while 20% were resistant to a single ALS inhibitor, 2% were both ACCase and ALS inhibitor-resistant, and 6% were glyphosate-resistant (Zurger and Burke 2020). In addition, ACCase inhibitor-resistant downy brome was reported in Oregon (Ball et al. 2007), while ALS inhibitor-resistant biotypes have been reported in Oregon and Montana

(Kumar and Jha 2017; Park and Mallory-Smith 2004). Two of these three states where ACCase and/or ALS inhibitor-resistant downy brome was reported border Alberta to the south, suggesting that in addition to the risk of in situ selection due to recurrent herbicide application, there is also a risk of these biotypes entering Alberta across the Canada/United States border.

Practical Implications

The current study identified several POST herbicide options that may be used to control GR and GS downy brome populations at the seedling stage. It should be noted, however, that while controlled-environment studies can help remove the confounding effects of variable weather during or after herbicide treatment, this can sometimes also result in different efficacy from that observed under field conditions. In addition, our study evaluated herbicide efficacy when applied at the two-leaf stage of downy brome, but not at later stages of growth and development. Reduced herbicidal control of downy brome has been observed on occasion when the plants were at more advanced stages of growth and development (Geier et al. 2011; Metier et al. 2020). For example, glyphosate and four graminicides managed downy brome more effectively under controlled environment when the plants were <11 cm in height and had <12 leaves (Metier et al. 2020). Among four graminicides, Metier et al. (2020) found that quizalofop or fluazifop controlled downy brome better than clethodim or sethoxydim when the plants were ≥8.5 cm in height. In the field, improved control of downy brome using ALS-inhibiting herbicides applied in the fall compared with the spring was observed by Geier et al. (2011) but not by Johnson et al. (2018). Since GR downy brome has been documented in only a single field in Alberta to date, we did not have the option to repeat this work under field conditions. Nevertheless, results from the current study should be used by farmers and agronomists to support herbicide decisions and to develop comprehensive herbicide programs to help mitigate the evolution and manage the spread of GR downy brome. Further research is warranted to determine which preemergence (PRE) herbicides could contribute to an effective herbicide layering strategy targeting GR downy brome. In Montana, for example, layering propoxycarbazone (an ALS-inhibiting herbicide) or pyroxasulfone (a very-long-chain fatty acid–inhibiting herbicide [HRAC Group 15]) applied PRE with imazamox POST controlled herbicide-susceptible downy brome >97% in imidazolinone-resistant winter wheat (Kumar et al. 2017). In addition, the herbicide options identified by the current research should comprise one part of a more comprehensive integrated weed management program including nonchemical weed management practices. Such practices may include growing competitive cultivars (Blackshaw 1994a), crop rotations including diverse crop life cycles (Blackshaw 1994b), strategic nitrogen fertilization (Anderson 1991), judicious and occasional tillage (Blackshaw et al. 2001), and cleaning of equipment before entering and leaving fields (Geddes and Pittman 2022). Since the spread of GR downy brome is seed-limited, and the soil seedbank persists for only 2 to 5 yr (Upadhyaya et al. 1986), diligent efforts to mitigate downy brome seed production and return to the soil seedbank could go a long way to preventing the spread of GR downy brome beyond the fields where it was initially confirmed.

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