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Source: Weed Technology, 18(4):1043-1048.
Published By: Weed Science Society of America
DOI: http://dx.doi.org/10.1614/WT-03-216R1
URL: http://www.bioone.org/doi/full/10.1614/WT-03-216R1

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Weed Technology. 2004. Volume 18:1043–1048

Downy Brome (*Bromus tectorum*) Response to Imazamox Rate and Application Timing in Herbicide-Resistant Winter Wheat[1]

ROBERT N. STOUGAARD, CAROL A. MALLORY-SMITH, and JAMES A. MICKELSON[2]

Abstract: Field experiments were conducted at Kalispell, MT, and Corvallis, OR, to determine the optimum rate and application timing of imazamox for downy brome control in winter wheat. Crop injury occurred as a reduction in plant height and was minimal at Kalispell, never exceeding 10%. Crop injury at Corvallis was more severe and was dependant on application timing. No injury was observed with spring applications, but fall applications resulted in as much as 33% injury at the highest rate of imazamox. Fall applications generally provided more consistent control of downy brome, as evidenced by the lower dosage required to reduce downy brome dry weight by 50% (lower I_{50} values). Nonetheless, spring applications generally provided control comparable with that of fall applications when imazamox was applied at the highest rate. The one exception was at Corvallis during 1997 to 1998, where spring applications failed to provide adequate control of downy brome even at the highest rate applied. Although imazamox generally provided excellent control of downy brome, wheat yield response to downy brome interference was negligible, declining by less than 10% in the absence of imazamox. The absence of a yield response to downy brome interference was attributed to the lack of competition for soil moisture from downy brome under the high-rainfall conditions of the experiment.

Nomenclature: Imazamox; downy brome, *Bromus tectorum* L. #[3] BROTE; winter wheat, *Triticum aestivum* L.

Additional index words: Dose–response, reduced rates.

INTRODUCTION

Downy brome is one of the most serious weed problems associated with winter wheat–based cropping systems. Downy brome is common throughout much of the Western United States, where it initially became established on overgrazed rangelands and then spread to adjacent winter wheat production fields (Morrow and Stahlman 1984; Mosley et al. 1999). Downy brome populations have since increased because of a shift from spring wheat to winter wheat production, the widespread adoption of conservation tillage practices, and the use of selective herbicides for the control of wild oat (*Avena fatua* L.) and annual ryegrass (*Lolium multifloram*) in winter wheat (Morrow and Stahlman 1984; Peeper 1984).

The spread of downy brome in winter wheat also has been accentuated by the general lack of effective herbicides. Although winter wheat and downy brome are taxonomically distinct, both species have similar life histories and biochemical pathways. As a result, the identification of herbicides for selective control of downy brome in winter wheat has been impeded. Although some herbicides are available, the use of these materials has been limited because of the associated expense, crop injury potential, or erratic control (Geier and Stahlman 1996; Geier et al. 1998).

At present, sulfosulfuron is one of the most effective herbicides for the control of downy brome in winter wheat. The best downy brome control is obtained with fall treatments applied to two- to three-leaf downy brome. But when applied in the spring, sulfosulfuron only provides suppression of downy brome (Blackshaw and Hamman 1998; Geier et al. 1998). Sulfosulfuron usage also is limited because of rotational restrictions (Shinn et al. 1998).

The recent development of imidazolinone-resistant winter wheat may provide an opportunity to effectively control downy brome over an extended period of time with minimal crop injury. An imidazolinone-resistant

[1] Received for publication September 15, 2003, and in revised form February 6, 2004.

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[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds,* Revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

Table 1. Planting, application, and demographic variables for downy brome control in winter wheat with imazamox.[a]

	Kalispell		Corvallis	
Variables	1997–1998	1999–2000	1997–1998	1998–1999
Seeding date	September 24, 1997	September 24, 1999	October 21, 1997	October 19, 1998
Fall treatments				
Application date	October 20, 1997	November 3, 1999	November 25, 1997	November 17, 1998
Downy brome stage	1.5–2 L	1 L	2–3 L	2 L
Wheat stage	2–3 L	2 L	3–4 L	2 L
Spring treatments				
Application date	April 10, 1998	April 18, 2000	January 23, 1998	February 9, 1999
Downy brome stage	4 L–2 T	3 T	3–5 T	2–5 T
Wheat stage	4 L–2 T	3 T	3–4 T	3–4 T
Downy brome demographics[b]				
Plants (number/m^2)	93	325	637	71
Biomass (g/m^2)	106	153	605	161

[a] Abbreviations: L, leaf number; T, tiller number.

[b] Demographic variables in the nontreated plots at maturity.

wheat mutant in the cultivar 'Fidel' was identified and isolated from a population derived through a seed mutagenesis procedure (Newhouse et al. 1992). The derived population has demonstrated resistance to several imidazolinone herbicides, including imazamox. Imazamox is currently registered for weed control in several crops and has demonstrated activity toward several grass and broadleaf weed species that are prevalent in small grain cropping systems (Ball et al. 1999; Pester et al. 2001).

The introduction of imidazolinone-resistant wheat may provide effective control for downy brome, but the optimum rate and application timing has yet to be determined. Therefore, the objective of this study was to evaluate the response of downy brome in winter wheat under different environmental conditions to imazamox applied at various rates and application timings.

MATERIALS AND METHODS

Field experiments were conducted at the Northwestern Agricultural Research Center near Kalispell, MT, during the 1997 to 1998 and 1999 to 2000 winter wheat growing seasons and at the Hyslop Research farm at Corvallis, OR, during the 1997 to 1998 and 1998 to 1999 winter wheat growing seasons. The soil type each year at Kalispell was a Kalispell fine sandy loam (coarse-loamy, mixed, Pachic Haploxerolls) with 2.2% organic matter and a pH of 6.9. The soil type each year at Corvallis was a Woodburn silt loam (fine-silty, mixed, mesic, Aquultic Argixerolls) with 2% organic matter and a pH of 5. Preplant and top-dress fertilizer applications were made at each site on the basis of soil test recommendations and yield potential.

The experimental design was a randomized complete block with three and four replications at Kalispell and Corvallis, respectively. Treatments consisted of two application timings (fall and spring) and seven rates of imazamox (0, 9, 18, 27, 36, 45, and 54 g ai/ha) arranged as a complete factorial. A hand-weeded control, outside of the factorial, was included for comparison. Plot sizes were 3 by 4.5 m at Kalispell and 2.4 by 8 m and 2.4 by 10 m at Corvallis during 1997 to 1998 and 1998 to 1999, respectively.

Herbicides were applied in 187 L/ha of total spray solution at 276 kPa with nonionic surfactant[4] at 0.25% (v/v) plus 28% urea ammonium nitrate at 2.3 L/ha. Herbicides were applied with a backpack sprayer equipped with XR11002 flat-fan nozzles[5] at Kalispell and with a unicycle sprayer equipped with XR8002 flat-fan nozzles[5] at Corvallis. Fall and spring applications were made when downy brome had approximately one to three leaves and two to four tillers, respectively. Winter wheat growth stage ranged from 1.5 to 4 leaves with fall applications and from four leaves to four tillers with spring applications (Table 1).

Broadleaf weeds were controlled in all plots with applications of selective herbicides. At Kalispell, bromoxynil (560 ai/ha) plus MCPA (560 ai/ha) was applied on April 2, 1998, and thifensulfuron (14 g ai/ha) plus tribenuron (7 g ai/ha) plus 2,4-D ester (140 g ai/ha) was applied on April 26, 2000. At Corvallis, bromoxynil (560 ai/ha) was applied on December 4, 1997, whereas no broadleaf herbicide application was required in 1998.

The imidazolinone-resistant wheat cultivar Fidel was planted to a depth of 4.5 cm using double-disk press

[4] Activator-90, a mixture of alkylpolyoxyethylene ether and free fatty acids, Loveland Industries Inc., P.O. Box 1289, Greeley, CO 80632-1289.

[5] Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189.

Table 2. Winter wheat injury response to imazamox rate and application timing 14 d after the spring treatments were applied.

Imazamox rate	Kalispell[a]		Corvallis			
			1997		1998	
	1997–1998	1999–2000	Fall	Spring	Fall	Spring
kg/ha	%					
0	0	0	0	0	0	0
9	0	0	0	0	2	0
18	0	0	0	0	0	0
27	7	0	5	0	2	2
36	3	0	10	0	5	0
45	2	0	17	0	9	0
54	9	0	33	0	11	0
LSD (0.05)	3.0		5.0			

[a] The main effect of application timing was nonsignificant; therefore, the data are averaged over fall and spring treatments.

drills with 15-cm row spacings at each location. Winter wheat was seeded at 85 kg/ha at Kalispell and at 136 kg/ha at Corvallis during mid-September and mid-October, respectively. Downy brome was broadcast over the study areas before establishing the plots each year. An additional planting of downy brome was seeded 1 wk after wheat planting at the Kalispell site during the 1999 to 2000 trial. Plots were evaluated for percent crop injury approximately 14 d after the spring herbicide treatments had been applied. Injury evaluations were on the basis of a scale of 0 to 100%, where 0% = no injury and 100% = complete death. Aboveground downy brome biomass was collected from two 0.14-m^2 quadrats at Kalispell and from a 1-m^2 quadrat at Corvallis in mid-June of each year. Plant samples were placed in a forced-air drier for 3 d at 38 C, after which the total biomass was determined. After maturity, plots were combine harvested to determine clean grain yield.

ANOVA was performed using SAS General Linear Model Procedures (SAS 1999). The data were analyzed as a split–split plot design with location as the main plot effect, year as the subplot effect, and imazamox timing and rates as the sub-subplot effect. Results were interpreted by significance ($P < 0.05$) of the highest order interaction.

Nonlinear regression was used to analyze the response of downy brome biomass and winter wheat grain yield to imazamox rate. Nonlinear regression was conducted using SAS–NLIN procedures, and the Gauss–Newton method was used to estimate parameters (SAS 1999). The effects of location, year, and application timing on parameter estimates were tested using *F*-test procedures.

Downy brome biomass, expressed as a percent of the nontreated, was regressed against imazamox rate using the following equation (Seefeldt et al. 1995):

$$Y = C + [(D - C)/\{1 + \exp[b(\log(x) - \log(I_{50}))]\}] \quad [1]$$

where Y is the predicted response of the downy brome variable as a function of imazamox rate, C and D represent the minimum and maximum asymptotes, respectively, b is the slope, and I_{50} is the dose causing a 50% reduction in downy brome dry weight. Winter wheat yield, expressed as a percent of the weed-free control, also was regressed against imazamox rate using the same equation but with a negative slope parameter value. The I_{50} value represents the dose causing a 50% reduction in winter wheat yield. For all response variables, the D and C parameters were bounded at 100 and 0, respectively.

RESULTS AND DISCUSSION

Crop Injury. Preliminary analysis indicated that the crop injury response to imazamox varied by locations, years, and years within location. Thus, the data are presented for each location by year (Table 2). Injury appeared as a reduction in plant height. Injury at Kalispell was similar between application timings, but there was a significant year by herbicide rate interaction (Table 2). Crop injury was not observed during the 1999 to 2000 season, but minor injury was detected during the 1997 to 1998 season and was most evident at the highest rate of imazamox. However, herbicide damage never exceeded 10%.

Crop injury was more apparent at Corvallis. But in contrast to Kalispell, crop injury at Corvallis varied by application timing, resulting in a year by timing by rate interaction (Table 2). Crop injury was greatest with fall applications. Injury was initially detected at the 27 g/ha rate and increased in severity as imazamox rate increased. The effect of application timing was consistent between years, but the magnitude of the response was greater during 1997 to 1998.

Wheat growth stage may have contributed to the ob-

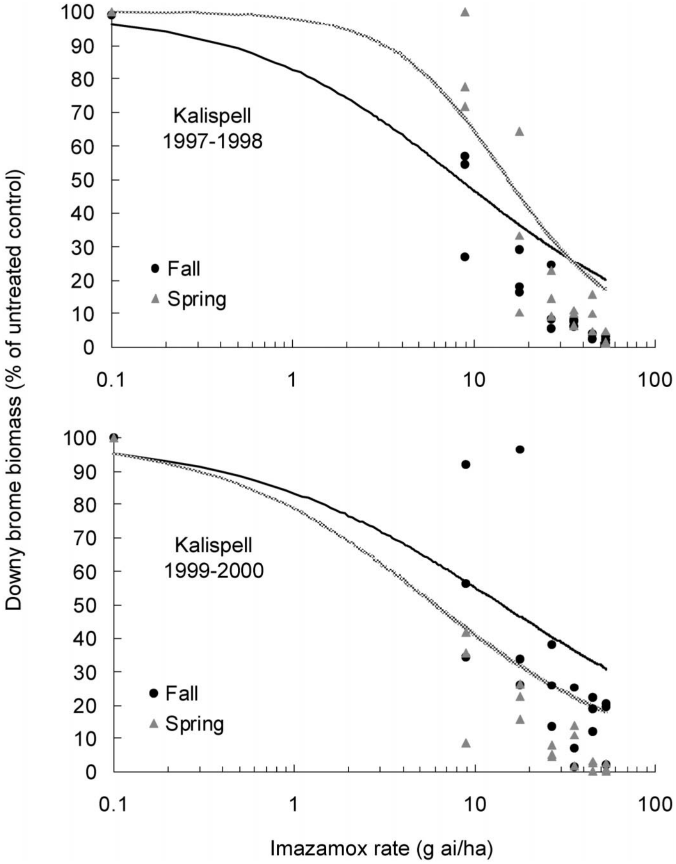

Figure 1. The response of downy brome biomass production at Kalispell, MT, as influenced by imazamox rate and application timing, expressed as a percent of the untreated control.

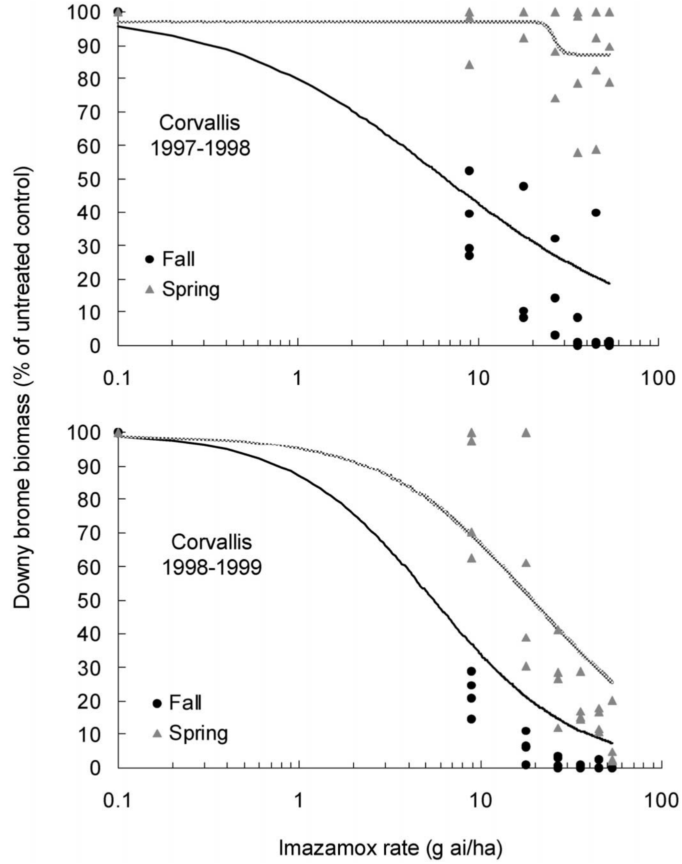

Figure 2. The response of downy brome biomass production at Corvallis, OR, as influenced by imazamox rate and application timing, expressed as a percent of the untreated control.

served injury because fall applications were made before tiller initiation. This relationship between wheat growth stage and herbicide injury also has been reported for sulfosulfuron in winter wheat (Kelley and Peeper 2003). In addition, Fidel is a winter wheat cultivar adapted to the growing conditions of France (Newhouse et al. 1992). The level of winter hardiness in Fidel is less than that of the currently recommended winter wheat cultivars grown in Montana and Oregon. In fact, this study was attempted at Kalispell during the 1998 to 1999 winter wheat growing season but was abandoned because of excessive stand loss resulting from winterkill. The lack of winter hardiness may have predisposed the crop to fall applications of imazamox.

Although it was beyond the scope of this research to quantify these interacting variables, the degree of crop injury observed in these experiments was similar to that reported previously by Ball et al. (1999). Nonetheless, the variable injury response among locations and years indicates that environment strongly interacts with the expression of herbicide resistance in this cultivar.

Downy Brome Biomass. Mature downy brome biomass and plant density in the nontreated plots are shown in Table 1. Downy brome biomass decreased as imazamox rate increased. However, the magnitude of the response varied by location, year, and application timing (Figures 1 and 2; Table 3). Generally, fall applications provided the greatest suppression of downy brome. The one exception to application timing occurred at Kalispell during 1999 to 2000. Although the *C* parameters were similar, Equation (1) predicted a lower I_{50} value for the spring applications vs. the fall applications (Figure 1; Table 3). This response may be attributed to the additional planting of downy brome seed during the fall of 1999. Although plant counts at application were not recorded, it is probable that seeds from the second planting either germinated in the fall after the imazamox applications had been made or possibly remained dormant and subsequently germinated in the spring. Others have documented erratic fall emergence patterns as well as spring germination events for downy brome (Anderson 1996; Thill et al. 1984). In either case, the fact that

Table 3. The parameter estimates of Equation (1) for downy brome biomass production as influenced by imazamox rate and application timing.[a]

	Parameter estimates					F-test comparison[b]				
	D	C	I_{50}	b	r^2		D	C	I_{50}	b
Kalispell 1997–1998										
Fall	100	0	8.4	1.70	0.96	Fall vs. spring	*	*	***	**
Spring	100	4.5	14.5	3.30	0.92					
Kalispell 1999–2000										
Fall	100	0	14.2	1.47	0.74	Fall vs. spring	*	*	**	*
Spring	100	2.2	5.7	1.70	0.95					
Corvallis 1997–1998										
Fall	100	2.2	6.2	1.70	0.88	Fall vs. spring	*	***	**	***
Spring	97	87	26.5	43.00	0.19					
Corvallis 1998–1999										
Fall	100	0.1	5.5	2.57	0.99	Fall vs. spring	*	*	***	**
Spring	99	1.4	19.2	2.5	0.85					

[a] Abbreviations: I_{50}, dose causing 50% reduction in downy brome dry weight.

[b] * Not significant at the 0.05 probability level; ** Significant at 0.01 probability level; *** Significant at 0.001 probability level.

spring-applied imazamox was more efficacious at this one environment indicates that reduced rates of fall-applied imazamox may not have sufficient soil residual activity to control late-germinating downy brome cohorts. Although late-emerging cohorts do not compete with winter wheat to the same extent as early-emerging seedlings (Anderson 1996; Wicks 1966), such plants are still capable of producing seed, which perpetuates the weed problem (Thill et al. 1984).

Nonetheless, downy brome control in the remaining three environments was greatest with fall applications. In all three instances, the I_{50} parameter estimates were significantly lower for the fall applications (Table 3). This response to application timing was especially evident at Corvallis during 1997 to 1998, where the spring applications failed to provide adequate control of downy brome even at the highest rate applied (Figure 2). Equation (1) predicted that the C parameters differed significantly. Fall applications reduced downy brome biomass to 2% of the nontreated check, as compared with 87% for the spring applications. Likewise, the b parameter estimates also differed significantly between the two application timings ($b = 1.7$ and $b = 43$ for the fall and spring applications, respectively). There was no apparent explanation for the lack of control with the spring application.

With the exception of Corvallis during 1997 to 1998, the C parameter estimates were not significantly different between the two application timings in the other environments. This response demonstrates that downy brome biomass reduction would be similar between fall and spring applications when the highest rate of imazamox is used. Nonetheless, fall applications had lower I_{50} values in three of four environments, demonstrating that fall applications were more effective in suppressing downy brome at low to moderate rates of imazamox. This response to application timing is consistent with other research pertaining to the control of downy brome in winter wheat (Blackshaw and Hamman 1998; Geier et al. 1998).

Winter Wheat Yield. The yield response to downy brome interference was marginal in all environments. At Kalispell, wheat yields in the nontreated and hand-weeded plots averaged 4,170 and 4,330 kg/ha in 1997 to 1998 and 6,010 and 7,360 kg/ha in 1999 to 2000, respectively. At Corvallis, wheat yields in the nontreated and hand-weeded plots averaged 3,240 and 3,524 kg/ha in 1997 to 1998 and 7,010 and 7,420 kg/ha in 1998 to 1999, respectively.

Although downy brome competition had a negligible effect on yield, ANOVA indicated that winter wheat yield was affected by imazamox rate but not by application timing. This response was consistent among environments, allowing the data to be combined over locations and years (data not presented). Although wheat yield response to imazamox rate was significant, the magnitude of the effect was minor ($r^2 = 0.06$). The D and C parameter values were 100 and 91, respectively, indicating that wheat yield declined by less than 10% in the absence of imazamox. Furthermore, the I_{50} value was 57.9, indicating that high rates of imazamox were needed before wheat yield was affected. Although imazamox generally provided excellent suppression of downy brome, the minimal yield reduction associated with the nontreated control demonstrates that the competitiveness of downy brome was negligible in these environments.

Downy brome interference can reduce winter wheat grain yield from 20 to 92% depending on weed densities, emergence patterns, and environmental conditions (Rydrych and Muzik 1968; Thill et al. 1984). Both the Kalispell and Corvallis locations are considered high-rainfall areas, receiving 500 and 1,000 mm of annual precipitation, respectively. Because the negative effect of downy brome interference on crop yield is primarily attributed to competition for soil moisture (Harris 1967; Harris and Wilson 1970; Morrow and Stahlman 1984), it is not surprising then that yield losses were marginal in these environments.

Nonetheless, the competitive effect of downy brome for available water necessitates that downy brome be eliminated soon after emergence to minimize yield reductions under most dryland production systems. Downy brome competes effectively for soil moisture because of its shallow, fibrous root system that enables downy brome to extract most or all of the available soil moisture from the upper layers of the soil profile (Morrow and Stahlman 1984). Furthermore, the root system of downy brome can continue to grow and extract water throughout the winter, making downy brome extremely competitive in dryland environments (Harris 1967; Harris and Wilson 1970).

In this study, fall applications of imazamox generally provided the most consistent suppression of downy brome. However, excellent downy brome control was generally obtained with spring imazamox applications when applied at the highest rates. Thus, the development of imidazolinone-resistant winter wheat provides an opportunity to effectively control downy brome over an extended period of time with minimal crop injury potential.

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