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Downy Brome (*Bromus tectorum*) Control with Imazapic on Montana Grasslands

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Downy brome is a problematic invasive annual grass throughout western rangeland and has been increasing its abundance, spread, and impacts across Montana during the past several years. In an effort to develop effective management recommendations for control of downy brome on Montana rangeland, we compiled data from 24 trials across the state that investigated efficacy of imazapic (Plateau®, BASF Corporation, Research Triangle Park, NC) applied at various rates and timings and with methylated seed oil (MSO) or a nonionic surfactant (NIS). We ran a mixed-model ANOVA to test for main effects and interactions across application rate (70, 105, 141, 176, and 211 g ai ha^{-1}), application timing (preemergent [PRE], early postemergent [EPOST, one- to two-leaf growth stage], and postemergent [POST, three- to four-leaf growth stage]), and adjuvant (MSO, NIS). Application timing and rate interacted to affect downy brome control ($P = 0.0033$). PRE imazapic application resulted in the lowest downy brome control (5 to 19%), followed by POST application (25 to 77%) and EPOST application (70 to 95%). Downy brome control remained fairly consistent across rates within application timing. Adjuvant (MSO or NIS) did not affect downy brome control ($P = 0.2789$). Our data indicate that POST application at 105 to 141 g ai ha^{-1} provides the most-consistent, short-term control of downy brome. Furthermore, applying imazapic to downy brome seedlings shortly after emergence (one- to two-leaf growth stage) provided better control than applying it to older downy brome seedlings (three- to four-leaf growth stage).

Nomenclature: Imazapic; downy brome, *Bromus tectorum* L. BROTE.

Key words: Cheatgrass, Plateau, rangeland.

Downy brome (*Bromus tectorum* L.) is an invasive, annual grass and one of the most-problematic weeds on Montana crop, range, pasture, and Conservation Reserve Program (CRP) land. In particular, downy brome has increased substantially in Montana during the past several years and was listed as a ''regulated plant'' on the state noxious weed list in 2010. Downy brome covers nearly 23 million ha (57 million ac) in 17 western states (Rice 2005) and continues to invade new areas, despite extensive research and management efforts to curb its spread (Rice 2005). In other regions of the West, downy brome dominates large areas of rangeland, and in many cases, revegetation is required to rehabilitate those lands to functional, productive ecosystems (Davison and Smith 2007; Epanchin-Niell et al. 2009).

Chemical control is one of the most-widely used weed-management tools (Radosevich et al. 2007). Options for chemical control of downy brome on rangeland include glyphosate (e.g., Roundup Pro®, Monsanto Company, St. Louis, MO), imazapic (Plateau®, BASF Corporation, Research Triangle Park, NC), imazapic plus glyphosate (Journey®, BASF Corporation), rimsulfuron (Matrix®, E. I. DuPont de Nemours, Wilmington, DE), sulfometuron methyl + chlorsulfuron (Landmark®, DuPont), sulfosulfuron (Outrider®, Monsanto), and propoxycarbazone-sodium (Canter R+P®, Wilbur-Ellis Company, Fresno, CA) (Menalled et al. 2008). Of the herbicides available, imazapic is perhaps the most-commonly used for controlling downy brome on rangeland. It is relatively selective when used at low rates and may be used to control annual grasses and release remnant desirable grasses. Imazapic is readily absorbed through leaves, stems, and roots and will provide residual control of germinating weeds, depending on soil conditions (BASF Corporation 2008).

Imazapic was introduced for rangeland invasive plant management in 2001. Since then, it has been widely used for controlling downy brome in portions of the Great Basin

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Management Implications

Management of the invasive annual grass downy brome (*Bromus tectorum*) remains challenging on western rangeland. Chemical control has produced inconsistent results, especially with the herbicide imazapic (Plateau®, BASF Corporation, Research Triangle Park, NC). Downy brome has been increasing during the past several years on rangeland across Montana where effective management recommendations for chemical control are needed. We compiled data from 24 independent herbicide trials across Montana, from 2000 to 2010, which investigated the efficacy of imazapic applied at various rates and timings and with methylated seed oil (MSO) or a nonionic surfactant (NIS). We tested for general trends in downy brome control across application rate (70, 105, 141, 176, 211 g ai ha^{-1} [1, 1.5, 2, 2.5, and 3.1 oz ai ac^{-1}]), application timing (preemergent [PRE], early postemergent [EPOST, one- to two-leaf growth stage], and postemergent [POST, three- to four-leaf growth stage]), and adjuvant (MSO, NIS). Downy brome control was especially affected by application timing. PRE imazapic application resulted in the lowest downy brome control (5 to 19%), followed by POST application (25 to 77%) and EPOST application (70 to 95%). Downy brome control remained fairly consistent across rates within application timing. Adjuvant did not affect downy brome control. Our data indicated that an EPOST (downy brome at the one- to two-leaf growth stage) application at 105 to 141 g ai ha^{-1} provided the most-consistent control of downy brome. Most published literature on the efficacy of imazapic for controlling downy brome do not report growth stage at the time of application, but our data indicate that timing of imazapic application influences its efficacy. Therefore, land managers should be aware of the growth stage of downy brome when imazapic applications are made and interpret outcomes with this factor in mind.

and Intermountain West, demonstrating variable success (Davison and Smith 2007; Elseroad and Rudd 2011; Morris et al. 2009). A single application of imazapic at 105 g ai ha^{-1} (1.6 oz ai ac^{-1}) (Plateau® at 400 g ha^{-1}, = 5.7 oz ac^{-1}) provided 2 yr of downy brome control on rangeland in Nevada (Davison and Smith 2007). Elseroad and Rudd (2011) found that imazapic applied at 70 g ai ha^{-1} reduced downy brome frequency to 0% the first spring after treatment; the duration of downy brome suppression was site dependent, but it could last up to 4 yr. In contrast, Morris et al. (2009) found that imazapic efficacy varied across sites and rates at one and three growing seasons after a fall application. For example, when imazapic was applied at 70 g ai ha^{-1} at a Wyoming big sagebrush (*Artemisia tridentata* Nutt. spp. *wyomingensis* Beetle & Young) site, downy brome cover was reduced to approximately 10%, but when the same rate was applied to a salt desert shrub site, downy brome cover was only reduced to approximately 60% cover. Three growing seasons after imazapic application, downy brome cover returned to 100% and about 70% at the Wyoming big sagebrush and salt desert shrub sites, respectively.

Several herbicide efficacy trials that included imazapic for controlling downy brome were conducted in Montana during the past 10 yr, and the results were highly variable (unpublished data). Because results have been so variable, it has been difficult to provide consistent herbicide recommendations for land managers who wish to treat downy brome. The objective of this study was to compile data from efficacy trials for controlling downy brome with imazapic across multiple sites in Montana. We aimed to refine management recommendations over a wide range of environmental conditions by examining data for common trends across imazapic rates, timing of application, and choice of adjuvant. The nature of our data precluded us from attempting to explain the influence of abiotic and biotic environmental factors on imazapic efficacy.

Materials and Methods

We gathered existing data from 24 herbicide efficacy trials independently conducted in Montana that included imazapic among other treatments (Table 1). Trials were conducted from 2000 through 2010 at 17 sites at elevations ranging from 1,000 to 1,525 m (3,281 to 5,004 ft) above sea level and included rangeland, pasture, and Conservation Reserve Program (CRP) lands (Table 1). Most sites included a mix of perennial grasses and downy brome; four sites were characterized as downy brome monocultures. Common applications rates across sites included imazapic applied at 70, 105, 141, 176, and 211 g ai ha^{-1} (4, 6, 8, 10, and 12 oz Plateau ac^{-1}). Timing of application was based on downy brome growth stage and included late summer, before downy brome seedling emergence (preemergence [PRE]), or fall, when downy brome seedlings were at the one- to two-leaf growth stage (early postemergence [EPOST]) or the three- to four-leaf growth stage (postemergence [POST]). The PRE applications occurred in late August; EPOST applications occurred from early September to mid October, and POST applications occurred from mid September to late October, with the exception of one trial where the application occurred in mid December. Methylated seed oil (MSO) or nonionic surfactant (NIS) was used as adjuvants at variable rates within the range recommended on the label (0.25% to 1% v/v). Treatments were applied using backpack CO_2 boom sprayers delivering between 94 and 151 L ha^{-1} (10 and 16 gal ac^{-1}) (Table 1). Treatments were typically arranged in a randomized complete-block design with three to four replications at each site.

Visual estimates of downy brome control (percentage) were recorded from 170 to 319 d after imazapic application, depending on the trial, which translated to a visual control rating during the first growing season following application in the previous fall. Control ratings were conducted when downy brome was mature but before seed dispersal. Percentage of canopy cover was determined by the point intercept method for 7 of the 24 trials. For those seven trials, downy brome control was calculated as

Table 1. Description of 25 herbicide-efficacy trials conducted in Montana to assess imazapic efficacy for control of downy brome. Details include trial locations, application dates, downy brome growth stage at time of imazapic application, amount of water applied with imazapic, elevation, site type, and soils and slope.

Location (nearest town)[a]	Application date	Downy brome growth stage[b]	Amount water applied	Elevation	Site type[c]	Soils; slope
			$L\ ha^{-1}$	m		%
Darby	August 23, 2001	PRE	126	1,194	R	Sandy loam; 5–8
Darby	October 15, 2001	POST	126	1,194	R	Sandy loam; 5–8
Darby	September 19, 2005	EPOST	126	1,194	R	Sandy loam; 5–8
Darby	September 19, 2005	EPOST	126	1,194	R	Sandy loam; 5–8
Frenchtown East	September 16, 2004	POST	151	1,186	R	Gravelly loam; 30–60
Frenchtown West	September 15, 2004	POST	151	1,227	R	Gravelly loam; 30–60
Hawthorne Springs (Frenchtown)	October 25, 2005	POST	135	1,220	R	Gravelly loam; 15–30
Huntley	August 29, 2008	PRE	94	920	P	Clay loam; 0–1
Jesson (Livingston)	October 17, 2009	EPOST	140	1,560	R	Sandy clay loam; 0–4
Jumbo (Missoula)	September 25, 2000	POST	126	1,075	R	Gravelly loam; 30–60
Jumbo (Missoula)	September 25, 2000	POST	126	1,075	R	Gravelly loam; 30–60
Jumbo (Missoula)	September 25, 2000	POST	126	1,075	R	Gravelly loam; 30–60
Jumbo (Missoula)	October 10, 2003	EPOST	129	1,075	R	Gravelly loam; 30–60
Logan	December 18, 2007	POST	94	1,297	P	Loamy sand; 15–20
Lower North Hills (Missoula)	October 27, 2004	POST	151	1,041	R	Gravelly loam; 15–30
McClay (Victor)	September 19, 2005	EPOST	126	1,000	R	Gravelly loam; 30–60
Middle North Hills (Missoula)	September 21, 2004	POST	151	1,106	R	Gravelly loam; 15–30
Mormon Ridge (Missoula)	September 25, 2000	EPOST	126	1,525	R	Sandy loam; 30–60
Mount Sentinel (Missoula)	September 17, 2004	EPOST	151	1,233	R	Gravelly loam; 30–60
Obrian (Missoula)	September 26, 2000	EPOST	126	1,220	R	Loam; 30
Toston	October 19, 2007	EPOST	126	1,209	CRP	Sandy loam; 5–15
Townsend	October 16, 2008	EPOST	126	1,173	CRP	Sandy loam; 5–15
Townsend	August 19, 2010; September 14, 2010; October 7, 2010	PRE EPOST POST	126	1,173	CRP	Sandy loam; 5–15
Winston	October 10, 2006	POST	126	1,340	R	Gravelly loam; 0–5

[a] Location of nearest town in parentheses if the location name is not a town.

[b] Timing abbreviations: PRE, preemergent; POST, postemergent, three- to four-leaf growth stage; EPOST=, early postemergent, one- to two-leaf growth stage.

[c] Site abbreviations: R, rangeland; P, pasture; CRP, Conservation Reserve Program land.

100 × (1 − [*percentage of downy brome canopy cover in treated plot/percentage of downy brome canopy cover in nontreated control*]).

Differences in downy brome control across trials were analyzed using a linear mixed-effects model to test main effects and interactions of application rate, application timing, and adjuvant. We were not able to analyze data for environmental factors like co-occurring vegetation or amount of litter present because the information collected for each location was not consistent across the 24 trials. To account for the bias of different locations and investigators, the model also included random effects of block within location within investigator (Pinheiro et al. 2011). Before the analysis, data were transformed using the $\arcsin\sqrt{\textit{percentage of control}}$ to meet assumptions of normality. Nontransformed means are presented for ease of interpretation.

Results and Discussion

Application timing and rate interacted to affect downy brome control ($P = 0.0033$). PRE application timing

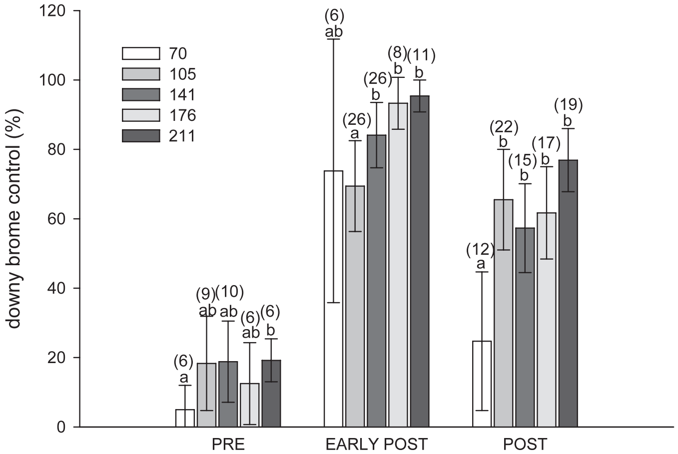

Figure 1. Downy brome control as affected by imazapic application timing and rate. Bars represent the mean percentage of control, and error bars represent 95% confidence intervals around the means. The numbers in parentheses above each mean indicate the number of observations (*n*) used to calculate each mean. Means with different letters are different from each other within an application timing ($\alpha = 0.05$). Application rates in grams of active ingredients per hectare are represented by the shades of gray fill, as indicated in the legend.

resulted in the lowest downy brome control, ranging from approximately 5 to 19% control (Figure 1), with minimal differences across rates, except that applying at 211 g ai ha^{-1} provided higher control than 70 g ai ha^{-1}. The EPOST application timing resulted in the highest and most-consistent downy brome control across treatments, ranging from approximately 70 to 95% control. Rates of 141, 176, and 211 g ai ha^{-1} showed higher downy brome control than did the 105 g ai ha^{-1} rate. The high variability in percentage of downy brome control when imazapic was applied as EPOST at 70 g ai ha^{-1} precluded us from detecting any differences with the other tested rates. POST application timing provided slightly lower control than did EPOST but higher control than PRE provided. In the POST treatments, downy brome control ranged from about 25 to 77%, and the 70 g ai ha^{-1} treatment provided the lowest downy brome control.

Although imazapic is labeled for both foliar (POST) and soil (PRE) applications, current recommendations advise a soil application for controlling downy brome and Japanese brome (*Bromus japonicus* Thunb. ex Murr.) (Anonymous 2008; Morris et al. 2009; Sheley et al. 2007). Such recommendations are not in agreement with our results, suggesting that Montana land managers may be experiencing inconsistent results with imazapic because of application timing issues. Our data indicate that PRE applications of imazapic result in lower control of downy brome compared with POST applications. In fact, downy brome control in PRE applications across our trials was so low ($< 20\%$) that it would not be recommended even as an alternative to POST application. Furthermore, applying imazapic to downy brome seedlings shortly after emergence (one- to two-leaf growth stage) provided better control than applying it to older downy brome seedlings (three- to four-leaf growth stage). We cannot definitively explain why POST applications were more efficacious than PRE applications, but it could be associated with abiotic factors, such as temperature and precipitation. For instance, weather is typically cooler and wetter in Montana in September to October (EPOST and POST application timing) than mid to late August (PRE application timing), thus enhancing herbicide efficacy. Biotic factors likely played a role as well. As an herbicide with both foliar and root activity, imazapic may have been more effective because of multiple points of contact with downy brome tissue. Herbicides are typically more effective when applied to younger plant tissue (Ross and Lembi 1985) as demonstrated in winter-wheat (*Triticum aestivum* L.) systems where chemical control of downy brome is typically better with fall applications vs. spring applications, regardless of plant size (Geier et al. 1998; Stougaard et al. 2004).

Unfortunately, most published literature on the efficacy of imazapic for controlling downy brome report season and even date of application but not downy brome growth stage at the time of application (Baker et al. 2009; Elseroad and Rudd 2011; Davison and Smith 2007; Morris et al. 2009). In reviewing the literature, we found one study that addressed downy brome growth stage at the time of imazapic application. In this greenhouse study, imazapic was applied at 132 g ai ha^{-1} to downy brome seeds, to plants with two to four leaves, and to plants with 5 to 10 leaves (Owen et al. 2011). Downy brome mortality was 90 and 100% after imazapic treatment, regardless of timing of application; however, results from the greenhouse study contradicted results from a companion field study where growth stage was not reported (Owen et al. 2011). Because our data indicate that timing of imazapic application influences its efficacy, we believe researchers and land managers should be aware of the growth stage of downy brome when imazapic applications are made and interpret results with that factor in mind.

Application rate appeared less influential than timing did for determining downy brome control. In general, downy brome control remained consistent across all rates. The most noteworthy exception to that was in the POST treatment, where 70 g ai ha^{-1} resulted in lower control than did the other rates. Our results are consistent with label recommendations of 105 to 211 g ai ha^{-1} (Anonymous 2008) and those from other studies (Baker et al. 2009; Davison and Smith 2007; Elseroad and Rudd 2011; Owen et al. 2011). Downy brome control may increase with increasing imazapic application rate (Morris et al. 2009), but high rates can also increase the risk of injury to nontarget species (Kyser et al. 2007). Our data suggest that an imazapic rate as low as 105 g ai ha^{-1} can provide at least short-term (i.e., one growing season) control of downy brome. Although we were not able to assess injury to nontarget species, lower imazapic rates may provide effective downy brome control while minimizing nontarget effects. If downy brome can be effectively controlled with low rates of imazapic, desired nontarget species may increase because of less competition, thereby increasing the longevity of control (Davies and Sheley 2011).

Choice of adjuvant (MSO or NIS) did not affect downy brome control ($P = 0.2789$). Markle and Lym (2001) found that MSO outperformed other adjuvants when applied with imazapic for control of leafy spurge (*Euphorbia esula* L.). However, Grichar and Sestak (2000) did not find a benefit of using any type of adjuvant in conjunction with imazapic applications for controlling yellow nutsedge (*Cyperus esculentus* L.) or purple nutsedge (*Cyperus rotundus* L.). The Plateau label recommends MSO for POST applications instead of NIS (Anonymous 2008), but our data indicate downy brome control was not influenced by adjuvant.

Our results support the development of integrated weed-management strategies for downy brome. Conventional weed control has historically focused on chemical or mechanical disturbance or both, but such disturbance can enhance conditions that weeds are well adapted to exploit (Smith et al. 2006). Optimum timing of herbicide applications and integrating them with other management tools, such as prescribed fire (Calo et al. 2012), grazing (Diamond et al. 2012), revegetation (Whitson and Koch 1998), or biological control (Meyer et al. 2007) may maximize their effect on downy brome and help restore desired plant communities.

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