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A Potential New Herbicide for Invasive Annual Grass Control on Rangeland

Derek J. Sebastian [a,*], James R. Sebastian [b], Scott J. Nissen [c], K. George Beck [c]

[a] Graduate Research Assistant, Bioagricultural Sciences and Pest Management Department, Colorado State University, Fort Collins, CO 80523, USA
[b] Research Associate, Bioagricultural Sciences and Pest Management Department, Colorado State University, Fort Collins, CO 80523, USA
[c] Professor and Extension Specialist, Bioagricultural Sciences and Pest Management Department, Colorado State University, Fort Collins, CO 80523, USA

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ABSTRACT

Downy brome (*Bromus tectorum* L.), a winter annual grass, is considered one of the most invasive non-native rangeland species in the United States. Although glyphosate, imazapic, and rimsulfuron are herbicides commonly recommended to control invasive, annual grasses, their performance is inconsistent and they can injure desirable perennial grasses. Indaziflam is a recently registered cellulose biosynthesis inhibiting herbicide, providing broad-spectrum control of annual grass and broadleaf weeds. Indaziflam is labeled for winter annual grass control in citrus, grape, and tree nut crops and could represent a new mode of action for selective winter annual grass control on rangeland. Three field experiments were conducted to compare indaziflam with imazapic, rimsulfuron, and glyphosate, three herbicides commonly used for downy brome control. Multiple herbicide application timings were evaluated. At all three sites, glyphosate and rimsulfuron provided less downy brome control than indaziflam 1 year after treatment (YAT). Percent downy brome control with imazapic decreased significantly 2 YAT (45−64%) and 3 YAT (10−32%). Across all sites and application timings, indaziflam provided the greatest downy brome control 2 YAT (89−100%) and 3 YAT (83−100%). Indaziflam did not significantly reduce species richness. This study demonstrates that indaziflam can provide extended downy brome control compared with currently used herbicides.

Introduction

Downy brome (*Bromus tectorum* L.) is a competitive winter annual grass that has rapidly spread throughout many regions of the United States. This species favors disturbed areas such as roadsides, overgrazed pastures, and abandoned crop fields (Mack, 1981; Meyer and Leger, 2010). The most recent estimates indicate downy brome infests > 22 million ha in the western United States, and the annual rate of spread is ~14% (Duncan and Clark, 2005). One consequence of downy brome invasion is increased fire frequency and intensity (D'Antonio and Vitousek, 1992; Keane et al., 2009). The cost of fighting downy brome−fueled fires was estimated to average $10 million per year in the Great Basin alone (Knapp, 1996). The fire return interval is four to six times shorter for downy brome−invaded sites (50−78 years) compared with native sites (~294 years) (Knapp, 1996; Balch et al., 2013).

Shorter fire return intervals further the replacement of native plants by downy brome. For example, increased wildfire frequency has contributed to significant reductions in plant communities dominated by sagebrush (Crawford et al., 2004; Baker, 2006; Keane et al., 2009), which provides essential habitat for sagebrush-dependent wildlife such as sage-grouse (*Centrocercus urophasianus* and *C. minimus*) (Crawford et al., 2004; Baker, 2006). Downy brome can decrease species diversity and productivity, increase soil erosion, and decrease abundance of soil biota (Belnap et al., 2005; DiTomaso et al., 2010). Furthermore, downy brome depletes soil moisture and nutrients before perennial grasses break dormancy in the spring (DiTomaso et al., 2010).

Herbicides are one of the most widely used tools for managing rangeland weeds (Mangold et al., 2013). Herbicides with residual soil activity are particularly important for controlling downy brome because the seedbank allows for rapid reinvasion (Morris et al., 2009). Imazapic has been one of the most commonly used herbicides on rangeland because of its residual soil activity and relative selectivity at low-use rates (Sebastian and Beck, 2004; Kyser et al., 2013; Mangold et al., 2013). Several other herbicides including glyphosate and rimsulfuron have been used for short-term downy brome control (Kyser et al., 2013). These herbicides do not provide consistent control of downy brome and can injure perennial grasses (Morris et al., 2009; Hirsch et al., 2012; Kyser et al., 2013; Mangold et al., 2013). Currently, there are no herbicides that consistently control winter annual grasses for multiple growing seasons without damaging co-occurring species.

Indaziflam (Esplanade, Bayer CropScience, Research Triangle Park, NC), a recently registered cellulose biosynthesis inhibitor (CBI) herbicide, can provide broad-spectrum control of annual grass and broadleaf weeds (Jhala et al., 2013; Brabham et al., 2014). There are no reported cases of

* Correspondence: Derek Sebastian, Bioagricultural Sciences and Pest Management Dept, Colorado State University, Fort Collins, CO 80523, USA.
E-mail address: derek.sebastian@rams.colostate.edu (D.J. Sebastian).

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resistance to this mode of action in turf, ornamentals, citrus, grape, and tree nut crops (Brabham et al., 2014; Heap, 2014). Because indaziflam applied alone has little postemergence activity, it is commonly applied pre-emergence or as a tank mix with foliar-applied postemergence herbicides like glyphosate to provide residual weed control. Labeled application rates of indaziflam range between 51 and 102 g·ai·ha^{-1}, and it is fairly persistent in aerobic soils ($t_{1/2} > 150$ days) (Tompkins, 2010). Indaziflam is not currently labeled for use on sites grazed by domestic livestock; however, Bayer CropScience is conducting studies to establish a grazing tolerance (David Spak, Bayer CropScience). The Environmental Protection Agency establishes a grazing tolerance for herbicides used on any forage crop to determine the potential for the herbicide to appear in the milk or meat of domestic livestock should they consume treated forage (EPA, 2015). Herbicides without a grazing tolerance should not be used on grazed sites.

Indaziflam's residual activity on annual weeds in established turf (Brosnan et al., 2012; de Barreda et al., 2013) demonstrates the potential of indaziflam to control annual weeds such as downy brome on rangeland. The objective of this research was to compare indaziflam to glyphosate, imazapic, and rimsulfuron in terms of downy brome control and damage to co-occurring species.

Methods

Site Description

Field experiments were established in Colorado at three downy brome—infested sites in 2010. Sites 1 (lat 40°42′40″N, long 104°56′54″W, 1 585 m elevation) and 2 (lat 40°28′0.68″N, long 105°9′13″W, 1 676 m elevation) were 32 km apart. Site 3 (lat 39°28′42″N, long 107°53′0.45″W, 1 768 m elevation) was ~390 km from the other sites. Site 1 was located on an abandoned crop field with 90—100% canopy cover of actively growing downy brome (June 2010), a dense downy brome litter layer (2—6 cm), and no other species before herbicide application. Site 2 had a mixture of downy brome (60—80% canopy cover at peak standing crop), and other scattered desirable species (20—30% canopy cover) including western wheatgrass *(Pascopyrum smithii)*, blue grama *(Bouteloua gracilis)*, fringed sage *(Artemisia frigida)*, and scarlet globemallow *(Sphaeralcea coccinea)* before herbicide application (June 2010). Site 3 was a reclaimed oil pad drilled with western and streambank *(Elymus lanceolatus)* wheatgrass approximately 5 years before our study. Non-native crested wheatgrass *(Agropyron cristatum)* and native forbs were also present including scarlet globemallow, broom groundsel *(Senecio spartioides)*, and short's milkvetch *(Astragalus shortianus)*. Site 3 burned the year before herbicide treatment, resulting in the removal of all shrubs. Before herbicide application, downy brome and native plant canopy cover were approximately 70—90% and 10—20%, respectively (June 2010).

Four 10-cm-deep soil cores were taken in each replication, combined into one composite soil sample per site, and analyzed at the Colorado State University Soil Testing Laboratory. Soil series classification for Sites 1, 2, and 3 were Ascalon sandy loam (fine-loamy, mixed, superactive, mesic Aridic Argiustoll); unclassified sandy loam (sandy loam, haplustoll); and Ildefonso loam (loamy-skeletal, mixed, mesic Ustollic Calciorthid), respectively. Soil properties were 1.5% organic matter, pH 7.6, 62% sand, 16% silt, and 22% clay for Site 1; 2.50% organic matter, pH 6.30, 56% sand, 26% silt, and 18% clay for Site 2; and 1.5% organic matter, pH 7.9, 42% sand, 38% silt, and 20% clay for Site 3.

Experimental Design

Herbicides were applied from August to September 2010 before downy brome emergence (PRE) and November to December 2010 when downy brome had 1—3 leaves (EPOST). In addition, at Sites 1 and 2, applications were made March 2011 at the 2 leaf to 1 tiller stage (LPOST). Treatments were applied to 3 × 9 m plots arranged in a randomized complete block design with four replications. All treatments were applied with a CO_2-pressurized backpack sprayer using 11002LP flat fan nozzles calibrated to deliver at 187 L·ha^{-1} at 207 kPa. At Sites 1 and 2, herbicide treatments applied at all three timings were rimsulfuron (Matrix, Bayer CropScience, 53 g·ai·ha^{-1}), imazapic (Plateau, BASF, 105 g·ai·ha^{-1}), indaziflam (Esplanade, Bayer Crop Science, 58 g·ai·ha^{-1}), glyphosate (Roundup Weathermax, Monsanto, 630 g·ae·ha^{-1}), imazapic 105 g·ai·ha^{-1} + glyphosate 210 g·ae·ha^{-1}, indaziflam 58 g·ai·ha^{-1} + glyphosate 630 g·ae·ha^{-1}, indaziflam 58 g·ai·ha^{-1} + rimsulfuron 53 g·ai·ha^{-1}, and nontreated. Site 3 treatments were imazapic applied PRE, indaziflam applied PRE, imazapic + glyphosate applied EPOST, rimsulfuron applied EPOST, and nontreated. All treatments included 1% v·v^{-1} methylated seed oil.

Treatment Evaluation and Analysis

Percent control was visually estimated from June 2011 to 2013. Control was determined by comparing visual estimates of downy brome canopy cover in the treated compared with nontreated plots (downy brome canopy cover estimates before herbicide application were previously described).

For Sites 1 and 2, all percent control data were arcsine square root transformed. After failing to reject the null hypothesis of equal variance, the same residual variance was assumed for Sites 1 and 2 ($P = 0.374$). Repeated measures analysis of variance was performed using the PROC MIXED method in SAS 9.3, testing for treatment effects at $\alpha = 0.05$ (SAS Institute, 2010). Factors included in the repeated measures model statement were site, treatment, year, and interactions, with year as the repeated measure. Using AIC model selection, a Tukey-Kramer adjustment was performed and the heterogeneous variance first-order autoregressive structure (ARH[1]) was chosen. Further analysis of the year by treatment interaction was performed in PROC GLIMMIX using the LINES statement. This statement provided comparisons between all pairs of least squares means across years ($P < 0.05$, Fig. 1). For Site 3, the same analysis was performed, but site was dropped from the model and the Tukey-Kramer adjustment was removed.

A separate evaluation in 2013 at Site 3 was conducted to determine native species' tolerance to herbicide treatments. Omitting downy brome, numbers of plants per plot were determined for each of the five desirable grass and forb species. Species richness was then calculated by determining the number of species present in each plot. Perennial grass injury was visually estimated for crested, western, and streambank wheatgrass (June 2013). Western and streambank wheatgrass injury data were pooled. PROC GLIMMIX was used to determine differences between least squares richness and frequency means. The richness data were assumed to follow a Poisson distribution.

Results

Indaziflam and imazapic applied PRE provided similar downy brome control 1 YAT, while indaziflam outperformed imazapic 2 and 3 YAT. Indaziflam PRE provided superior downy brome control compared with rimsulfuron PRE (Fig. 1). Indaziflam and imazapic at the EPOST and LPOST application timings provided similar downy brome control 1 YAT. Conversely, indaziflam provided greater downy brome control than imazapic and the other herbicides, 2 and 3 YAT (see Fig. 1).

At Site 3, Indaziflam PRE, rimsulfuron EPOST, and imazapic + glyphosate EPOST provided similar downy brome control 1 YAT. According to point estimates, imazapic PRE resulted in only 32% downy brome control 3 YAT (Fig. 2), while indaziflam PRE provided 100% downy brome control 3 YAT. Indaziflam provided a significant improvement over currently recommended treatments (see Fig. 2).

At Site 3, where herbicide impacts on nontarget species were evaluated, there were no significant differences in species richness between the herbicide treatments and the nontreated (Fig. 3). Imazapic PRE caused no visual injury to any of the perennial wheatgrass species,

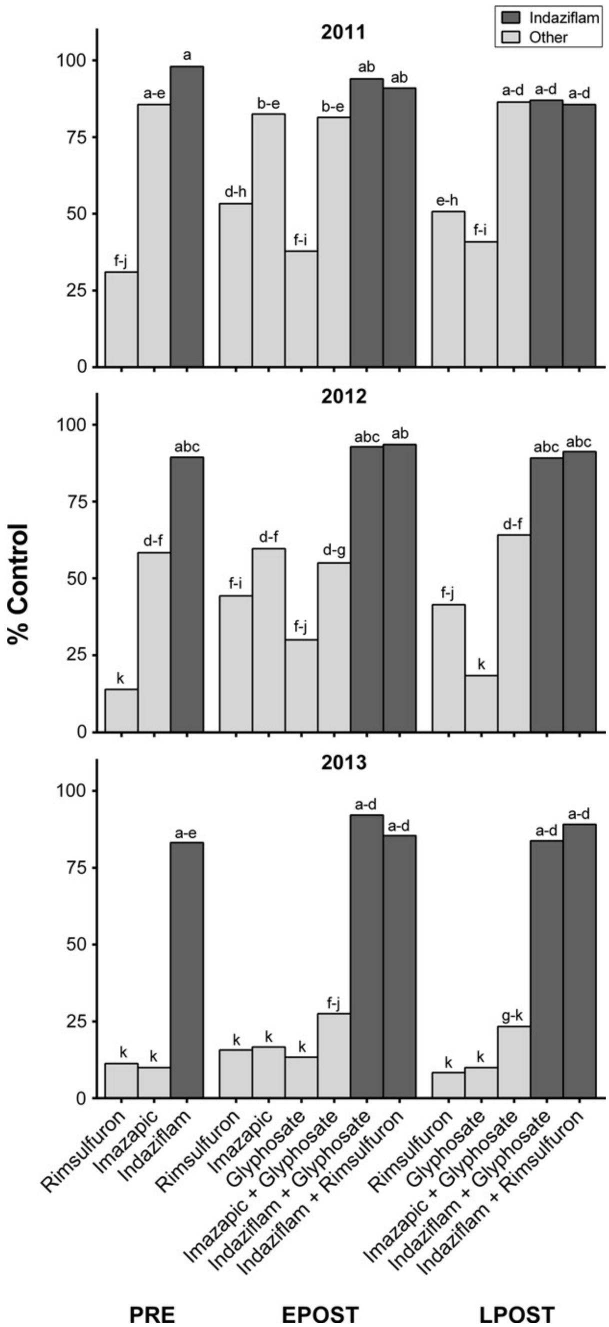

Figure 1. Sites 1 and 2 percent downy brome control compared with the nontreated 1, 2, and 3 YAT. Data from sites were combined for analysis of variance. Application timings included pre-emergence, applied August 2010 (PRE), early postemergence at the one- to two-leaf stage, applied December 2010 (EPOST), and late postemergence at the two-leaf to one-tiller stage, applied March 2011 (LPOST). Letters indicate differences among herbicide treatments across all three timings and years, using least squares means ($P < 0.05$). Herbicide treatment rates are as follows: rimsulfuron (53 g·ai·ha^{-1}), imazapic (105 g·ai·ha^{-1}), indaziflam (58 g·ai·ha^{-1}), glyphosate (630 g·ae·ha^{-1}), imazapic (105 g·ai·ha^{-1}) + glyphosate (210 g·ae·ha^{-1}), indaziflam (58 g·ai·ha^{-1}) + glyphosate (630 g·ae·ha^{-1}), indaziflam (58 g·ai·ha^{-1}) + rimsulfuron (53 g·ai·ha^{-1}), nontreated.

while indaziflam PRE, rimsulfuron EPOST, and imazapic + glyphosate EPOST resulted in perennial grass injury of 5% ± 0.3%, 28% ± 2%, and 28% ± 2%, respectively (see Fig. 3).

Discussion

Indaziflam is the first CBI herbicide that could potentially be used for winter annual grass control on rangeland. Indaziflam inhibits root elongation in seedling grasses and broadleaf species, providing broad-spectrum weed control. In this study, there were only minimal negative impacts on the native perennial plant community (Fig. S1; available online at [http://dx.doi.org/10.1016/j.rama.2015.11.001]). Imazapic and rimsulfuron inhibit the enzyme acetolactate synthase (ALS), an herbicide mode of action prone to resistance evolution. A downy brome biotype identified in Madras, Oregon in 1997 has confirmed resistance to ALS inhibiting herbicides, thus illustrating the importance of finding new modes of action for winter annual grass control (Park and Mallory-Smith, 2005; Heap, 2014).

Indaziflam may provide rangeland managers with another option for managing downy brome and may prove even more effective if integrated with other control methods. In addition, indaziflam provided 80−99% control of feral rye (*Secale cereale* L.) 3 YAT (Sebastian et al., 2014). This suggests indaziflam has the potential to control other invasive winter annual grasses such as medusahead (*Taeniatherum caput-medusae* [L.] Nevski), ventenata (*Ventenata dubia* (Leers) Coss), Japanese brome (*Bromus japonicus* Thunb.), and jointed goatgrass (*Aegilops cylindrical* L.).

There is a fundamental need for new downy brome management strategies that provide consistent control without negatively impacting native plants (see Fig. S1). The long-term residual downy brome control provided by a single indaziflam application could provide the opportunity to significantly reduce downy brome in the soil seed bank and reduce the amount of fine fuel produced by new downy brome crops. By increasing the fire return interval and reducing downy brome in the soil seed bank, remnant native plant communities would have a much better chance to dominate invaded sites.

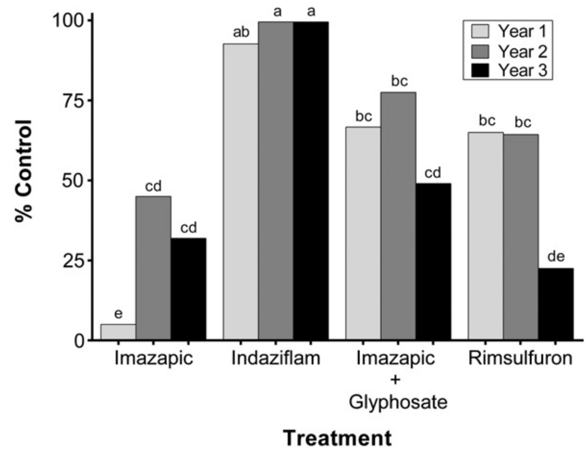

Figure 2. Site 3 percent downy brome control compared with the nontreated 1, 2, and 3 YAT. Application timings included PRE, applied September 2010, and EPOST at the one- to three-leaf stage, applied November 2010. LPOST was not studied at Site 3. Letters indicate differences among herbicide treatments across all years, using least squares means ($P < 0.05$). Herbicide treatment rates are as follows: imazapic (PRE, 105 g·ai·ha^{-1}), indaziflam (PRE, 58 g·ai·ha^{-1}), imazapic (EPOST, 105 g·ai·ha^{-1}) + glyphosate (210 g·ae·ha^{-1}), rimsulfuron (EPOST, 70 g·ai·ha^{-1}), nontreated.

Implications

One of the major limitations for downy brome management is the lack of consistent long-term control (Morris et al., 2009; Kelley et al., 2013; Mangold et al., 2013). In our study, indaziflam provided better downy brome control than currently recommended herbicides 2 and 3 YAT. Indaziflam caused only mild injury to perennial grasses and did not negatively impact species richness. Because downy brome seeds remain viable in the soil for ≤ 5 years, managing downy brome with glyphosate, imazapic, or rimsulfuron would require yearly herbicide applications (Wicks et al., 1971). In addition, the repeated use of

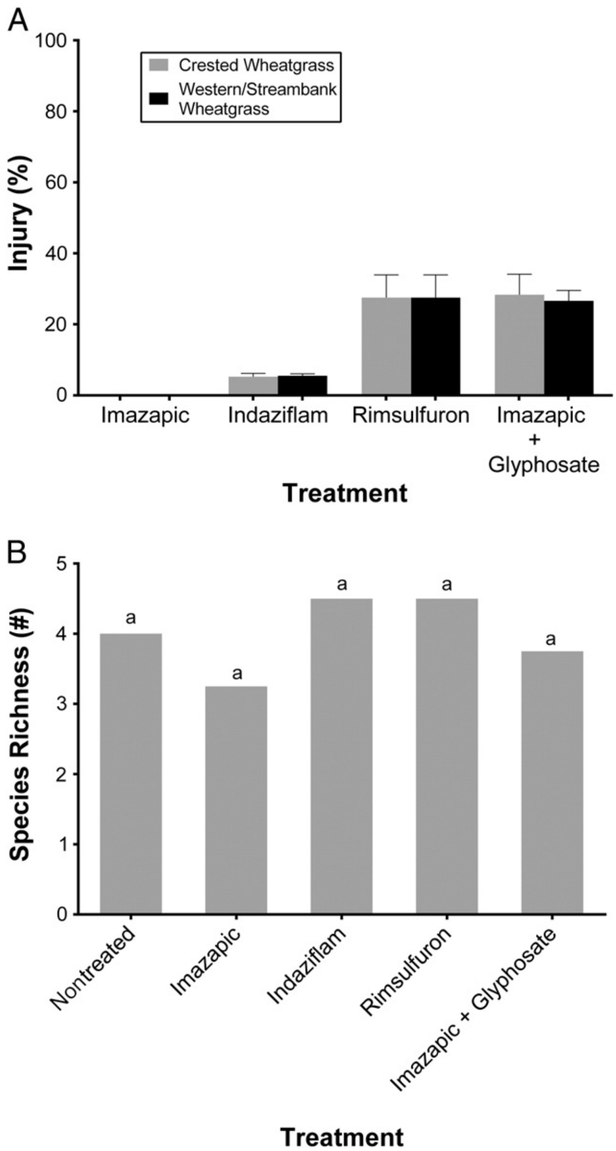

Figure 3. Site 3. **A**, Perennial grass injury from herbicide treatments compared with the nontreated. **B**, Species richness (#) for each treatment. Letters indicate differences among herbicide treatments using least squares means ($P < 0.05$). Herbicide treatment rates are as follows: imazapic (PRE, 105 $g \cdot ai \cdot ha^{-1}$), indaziflam (PRE, 58 $g \cdot ai \cdot ha^{-1}$), imazapic (EPOST, 105 $g \cdot ai \cdot ha^{-1}$) + glyphosate (210 $g \cdot ae \cdot ha^{-1}$), rimsulfuron (EPOST, 70 $g \cdot ai \cdot ha^{-1}$), nontreated.

ALS-inhibiting herbicides such as imazapic and rimsulfuron can lead to resistant downy brome populations. Therefore new herbicide modes of action are increasingly important for winter annual grass control on rangeland. Indaziflam has the potential to have positive long-term impacts on the structure and function of rangeland communities invaded by winter annual grasses. Unfortunately, indaziflam cannot be used on sites grazed by domestic livestock; however, Bayer CropScience is conducting studies to establish a grazing tolerance. Indaziflam is currently labeled for use on open spaces, natural areas, and other nongrazed sites.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rama.2015.11.001.

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