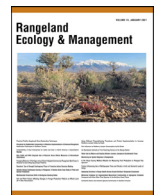




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Original Research

Effects of Using Indaziflam and Activated Carbon Seed Technology in Efforts to Increase Perennials in *Venttenata dubia*-Invaded Rangelands[☆]K.W. Davies^{a,*}, C.S. Boyd^a, O.W. Baughman^b, D.R. Clenett^c^a Authors are Rangeland Scientists, USDA - Agricultural Research Service, Burns, OR, USA^b Precision Restoration Scientist, The Nature Conservancy, Burns, OR 97720, USA^c Research Associate, US Department of Agriculture–Agricultural Research Service, Eastern Oregon Agricultural Research Center, Burns, OR 97720, USA

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ABSTRACT

Reestablishing perennial vegetation dominance in venttenata (*Venttenata dubia*)- and other annual grass-invaded rangelands is critical to restoring ecological function and increasing ecosystem goods and services. Recovery of perennial dominance in venttenata-invaded rangelands is challenging and constrained by a lack of established best management practices; however, preemergent herbicides can, at least temporarily, reduce venttenata. Indaziflam is a preemergent herbicide that has longer soil activity than other commonly used preemergent herbicides that needs evaluated to determine if it offers multiple-year control of venttenata and to determine its effects on residual perennial vegetation. Some venttenata-invaded rangelands may not have enough residual vegetation to occupy the site after venttenata control, but longer soil activity with indaziflam likely limits establishment of seeded species. However, incorporating seeds in activated carbon pellets, which can limit herbicide damage, may be a strategy for establishing perennial vegetations simultaneously with indaziflam application. We evaluated 1) applying indaziflam to control venttenata and 2) broadcast-seeding perennial grass seed incorporated in activated carbon pellets with a simultaneous indaziflam application at two sites for 3 yr post treatment. Indaziflam controlled venttenata for the 3 yr sampled. Perennial grasses increased with indaziflam at the site that had more residual perennial grasses before treatment. At the other site, perennial forbs increased with indaziflam. Indaziflam offers multiple-year control of venttenata; however, plant community response depends on composition before treatment. Seeding perennial grass seeds incorporated in activated carbon pellets while indaziflam controlled venttenata did not increase perennial grass abundance. Though this was likely associated with low establishment due to below-average precipitation post seeding and because broadcast seeding is often an ineffective seeding method, we cannot rule out nontarget herbicide damage. Further evaluations of activated carbon technologies used in conjunction with indaziflam are needed to determine if this can be an effective management strategy.

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Introduction

Exotic annual grass invasion and subsequent altered fire regimes have caused widespread ecological degradation around the world (Purdie and Slatyer 1976; Mack 1981; D'Antonio and Vitousek 1992; Brooks et al. 2004). These invasions greatly increase the risk of frequent, large wildfires (D'Antonio and Vitousek 1992;

Brooks et al. 2004; Balch et al. 2013; Pilliod et al. 2017; Smith et al. 2022); reduce biodiversity; and decrease ecosystem goods and services (Belnap and Phillips 2001; Crawford et al. 2004; Davies and Svejcar 2008; Davies 2011). Issues caused by these invasions are likely to escalate as annual grasses are expanding at unprecedented rates in many areas. In the Great Basin of the western United States, perennial plant communities are transitioning to exotic annual grasslands at a rate of ~200,000 ha annually (Smith et al. 2022). Expansion of annual grasses is caused, in part, by exotic annual grasses invading areas previously considered resistant to invasion (Smith et al. 2022). This is likely associated with climate change, but also the expansion of more recently introduced exotic annual grasses like venttenata (*Venttenata dubia* [Leers] Coss.)

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into areas where other annual grasses have not traditionally been an issue (Tortorelli et al. 2020; Smith et al. 2022).

Ventenata, also known as *wiregrass*, is a non-native annual grass that is rapidly invading rangelands, grasslands, grass-hay fields, and forest ecosystems in the western United States (Wallace et al. 2015; Avertt et al. 2016; Wallace and Prather 2016; Jones et al. 2020; Hart and Meador 2021; Ridder et al. 2021). Ventenata's success at invading this wide variety of plant communities is likely because it is highly competitive and can displace native perennial grasses and even other exotic annual grasses (Prather and Burke 2011; McKay et al. 2017; Jones et al. 2020). This subsequently leads to declines in biodiversity, degradation of wildlife habitat, and decreases in forage production (Fryer 2017; Jones et al. 2020). Similar to other exotic annual grasses, ventenata senesces earlier than native perennial grasses and increases fine fuel continuity, leading to increased potential for wildfires (Fryer 2017). Consequently, restoration of ventenata-invaded plant communities is often a management priority.

Restoring perennial dominance in ventenata-invaded plant communities is challenging and constrained by limited knowledge of its ecology and management (Davies and Hamerlynck 2019; Ridder et al. 2022). This is in part the product of ventenata only becoming a substantial management concern in the past decade and a half (Wallace and Prather 2016). Recent studies suggest that preemergent herbicides can be effective at controlling ventenata (Sebastian et al. 2016; Wallace and Prather 2016; Davies and Hamerlynck 2019), particularly in areas where perennial grasses are still abundant (Koby et al. 2019; Hart and Meador 2021). Knowledge gaps remain because evaluations of preemergent herbicide effectiveness at controlling ventenata have been limited to a few plant communities and were generally in plant communities with substantial residual vegetation (e.g., Koby et al. 2019).

Control of ventenata with indaziflam is of particular interest to land managers because it has a longer soil residue time compared with other preemergent herbicides commonly used in rangelands (Brabham et al. 2014; Sebastian et al. 2017a). It is expected to control annual grasses for at least 2 to 3 yr, though control has been observed for almost 5 yr after application (e.g., Courkamp et al. 2022). Though indaziflam has been investigated as a control treatment for ventenata (Koby et al. 2019; Hart and Meador 2021), these studies evaluated effects for 1 yr post application (Hart and Meador 2021) or mixed indaziflam with other herbicides (Koby et al. 2019). The multiple-year effects of applying indaziflam for ventenata control remains unknown, particularly when it is applied as the sole herbicide treatment.

Indaziflam is often applied in areas where residual perennial vegetation is abundant because its longer soil residue time will likely prevent recruitment of perennial species from seed for several years. There is a desire to use it in exotic annual grass-invaded communities with less perennial vegetation because of longer annual grass control, but seeding of perennial species would need to be postponed for several years to prevent nontarget herbicide mortality. Thus, indaziflam is often not used in annual grass communities lacking abundant perennial vegetation because of concerns about having high bare ground and associated erosion risk for several years. Indaziflam use in heavily ventenata-invaded rangelands would be more acceptable if seeded species could be protected from nontarget herbicide damage, thus allowing them to establish at the same time ventenata is controlled. This would also give seeded species several years to become established and grow larger before potentially experiencing substantial competition from reinvading annual grasses. Activated carbon seed technologies (pellets and coatings) may be a method for allowing perennial vegetation to establish from seed at the same time indaziflam is controlling annual grasses (Clenet et al. 2019). Activated carbon has high surface area and can thereby adsorb and neutralize the ef-

fects of some herbicides (Coffey and Warren 1969). Activated carbon seed technologies have been used to protect seeded species from nontarget preemergent herbicide damage in the field and in grow room studies (Madsen et al. 2014; Davies et al. 2017; Davies 2018; Clenet et al. 2019, 2020; Brown et al. 2019). To date, activated carbon seed technologies used in conjunction with indaziflam have not been evaluated in the field, but have shown great promise in a grow room study (Clenet et al. 2019).

The purposes of this study were to 1) evaluate multiple year (3 yr) effects of using indaziflam to control ventenata and 2) investigate if an activated carbon seed technology will allow seeded perennial grasses to establish while indaziflam controls ventenata. We compared indaziflam treated and untreated ventenata-invaded rangelands at two sites to determine indaziflam effects. To accomplish the second purpose of our study, we broadcast seeded perennial grasses as bare seed and as seed incorporated into activated carbon pellets in ventenata-invaded rangelands followed immediately by an indaziflam application. This is in contrast to the recommended practice of waiting several years for indaziflam activity to subside before seeding. We hypothesized that 1) indaziflam application would reduce ventenata cover and density and increase perennial grass and forb cover and density, and 2) that seeding perennial grasses incorporated in activated carbon pellets compared with seeding perennial grasses as bare seed would reduce indaziflam nontarget damage, resulting in increased perennial grass cover and density.

Methods and Materials

Study area

We conducted this study at two ventenata-dominated sites in eastern Oregon, one south of Fox, Oregon and another north of Long Creek, Oregon. The Fox Site is 1 352 m above sea level on a 2° west-aspect slope. The Long Creek Site is 1 270 m above sea level on a 6° north-aspect slope. Soils at both study sites are a heavy clay gravelly loam. Long-term average annual precipitation (1991–2020) at the Fox and Long Creek Sites were 488 mm and 445 mm, respectively (PRISM 2022). Crop yr precipitation (Oct.–Sept.) at the Fox Site was 122% of the long-term average the yr before treatments (2018–2019) and 85%, 69%, and 102% in 2019–2020, 2020–2021, and 2021–2022, respectively (PRISM 2022). Crop yr precipitation (Oct.–Sept.) at the Long Creek Site was 126% of the long-term average the yr before treatments (2018–2019) and 86%, 69%, and 109% in 2019–2020, 2020–2021, and 2021–2022, respectively (PRISM 2022). The potential natural vegetation for these study sites were native bunchgrass communities dominated by Idaho fescue (*Festuca idahoensis* Elmer), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] A. Löve), and *Poa* species. Before treatment, the Fox Site averaged 13% perennial grass and 25% annual grass cover. The Long Creek Site averaged < 1% perennial grass and 30% annual grass cover. Domestic livestock were excluded from sites for the duration of the study with a four-strand barbed wire fence. Wildlife species were not excluded from study sites.

Experimental design and measurements

A completely randomized block design at two sites was used to evaluate indaziflam effects and the effects of perennial grass seeds incorporated in activated carbon pellets in conjunction with indaziflam application in ventenata-dominated rangelands. Treatments were 1) untreated control, 2) bare seed and indaziflam, 3) seed incorporated in activated carbon pellets and indaziflam, and 4) no seed and indaziflam. Treatments were applied to 5 × 10 m plots and replicated four times at each site. Treatments that included seeding were broadcast seeded by hand on September

10–11, 2019. Seeding treatments were seeded with Sherman bluegrass (*Poa ampla* Merr.), intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D.R. Dewey), desert wheatgrass (*Agropyron desertorum* [Fisch. Ex Link] Schult.), and Siberian wheatgrass (*Agropyron fragile* [Roth] P. Candargy) at a rate of 5.6 kg pure live seed·ha⁻¹ for each species for a total of 22.4 kg pure live seed·ha⁻¹. Activated carbon pellets were composed of 43% calcium bentonite, 33% activated carbon, 6% worm castings, 14% compost, and 4% seed by dry weight. Dry materials were mixed and then water was added until a doughy consistency that could be passed through a pasta extruder (Model TR110, Rosito Bisani, Los Angeles, CA) was achieved. The activated carbon dough mixture was extruded through an 8-mm diameter circular die for all species except Sherman big bluegrass, a much smaller seeded species, which was pushed through a 5-mm diameter circular die. Smaller activated carbon pellets may be more effective for smaller seeded species (Baughman et al. 2021). All extruded pellets were cut to ~12 mm in length. Indaziflam was applied after seeding on September 15, 2019. Indaziflam was applied at a rate of 66.7 g ai·ha⁻¹ with 128 L water·ha⁻¹ using a diaphragm backpack sprayer (Solo Inc., Newport News, VA). During herbicide application, temperatures ranged between 21°C and 24°C, average wind speed varied from 2 km·h⁻¹ to 14 km·h⁻¹, and relative humidity ranged from 24% to 38%.

Vegetation cover and density were measured in June 2020, 2021, and 2022. Herbaceous cover by species was visually estimated in six 0.2 m⁻² quadrats located at 3-, 6- and 9-m locations on two, 10-m transects in each treatment replicate. The 10-m transects were placed at the 1- and 3-m location on the short edge of the treatment replicate and ran parallel to the long edge of the treatment replicate. Bare ground and litter cover were also estimated in the 0.2 m⁻² quadrats. Visual estimates of cover were aided by markings that divided the quadrats into 5%, 10%, 25%, and 50% segments. Perennial herbaceous density was measured by species by counting all individuals rooted in the 0.2 m⁻² quadrats. Rhizomatous species were considered individual plants if separated by ≥ 15 cm. Annual herbaceous density was measured by counting all individuals rooted in a permanently marked 10% segment of the 0.2 m⁻² quadrats. Woody vegetation was not present at either study site.

Statistical analysis

We used repeated measures analyses of variances using the mixed-model method in SAS (v. 9.4, SAS Institute, Cary, NC) to evaluate the effects of indaziflam and incorporating seeds in activated carbon pellets seeded simultaneously with indaziflam application. Year was the repeated variable, and random variables were block and block-by-treatment interactions in analyses. The effects of indaziflam were evaluated by comparing the no-seed and indaziflam treatment with the untreated control. The effects of incorporating seeds into activated carbon pellets were investigated by comparing bare seed and indaziflam, no seed and indaziflam, and seeds incorporated in activated carbon pellets and indaziflam treatments. Covariance structure was determined using the Akaike's Information Criterion and was compound symmetry for all analyses. Variables that did not meet analysis of variance assumptions were square root transformed to better meet assumptions. For analyses, herbaceous vegetation was divided into the following groups: perennial grasses (excluding Sandberg bluegrass [*Poa secunda* J. Presl]), Sandberg bluegrass, exotic annual grasses, perennial forbs, and annual forbs. Sandberg bluegrass was analyzed individually from the other perennial grasses because it responds differently to management and disturbances, is smaller in stature, and develops earlier (McLean and Tisdale 1972; Jensen et al. 1992; Davies et al. 2021). Perennial grasses resulting from the seeded treatments were

too infrequent to analyze separate from the perennial grass group. Thus, all perennial grasses were grouped together for analyses. The exotic annual grasses group was predominantly *ventenata*. Non-transformed data are presented in figures and text. Means were separated using the LS function in SAS. Means were considered different at $P \leq 0.05$ and were reported with standard errors.

Results

Indaziflam application

The effect of indaziflam on perennial grass density varied by year and site (Fig. 1A; $P=0.027$). In the first yr after indaziflam application, perennial grass density was greater in the untreated control compared with the indaziflam treatment at the Fox Site. The next 2 yr, perennial grass density was greater with indaziflam at the Fox Site. Perennial grass density was low at the Long Creek Site and generally similar between treatments in all 3 sampling years. Sandberg bluegrass density response to indaziflam varied by site (see Fig. 1B; $P=0.020$). Sandberg bluegrass density was greater at the Fox Site and generally less at the Long Creek Site with indaziflam. Exotic annual grass density was reduced with indaziflam, but the level of control varied among years (see Fig. 1C; $P=0.016$). Indaziflam reduced exotic annual grass density the most in the second yr after application. Perennial forb density was greater at the Long Creek Site and increased with indaziflam compared with the Fox Site, where perennial forb density was lower and decreased with indaziflam (see Fig. 1D; $P=0.010$). Indaziflam reduced annual forb density at both sites for the 3 post-treatment sampling years ($P=0.008$). Annual forb density averaged 6.3 ± 2.1 and 28.4 ± 5.6 individuals·m⁻² in the indaziflam and untreated control, respectively.

Indaziflam effect on perennial grass cover was influenced by site and yr (Fig. 2A; $P=0.036$). At the Fox Site, perennial grass cover was similar between indaziflam and control treatments the first growing season post treatment but 1.6- to 2.4-fold greater with indaziflam in the second and third yr post treatment. Perennial grass cover was low at the Long Creek Site and generally did not vary with indaziflam application. The response of Sandberg bluegrass cover to indaziflam varied by site (see Fig. 2B; $P=0.004$). Sandberg bluegrass cover was 1.6- to 3.3-fold greater with indaziflam at the Fox Site by the second and third yr post treatment, but indaziflam did not appear to have an effect on Sandberg bluegrass cover at the Long Creek Site. Exotic annual grass and perennial forb cover response to indaziflam varied by site (see Fig. 2C and 2D; $P=0.031$ and < 0.001 , respectively). Exotic annual grass cover was greatly reduced with indaziflam application; however, the untreated control plots in the Long Creek compared with the Fox Site had approximately twofold greater annual grass cover. Indaziflam application increased perennial forbs by 1.9- to 2.9-fold at the Long Creek Site. In contrast, indaziflam appears to have not affected perennial forb cover at the Fox Site. Indaziflam effects on annual forbs was influenced by site and yr ($P=0.049$), but annual forb cover was always $< 1\%$ regardless of indaziflam treatment, site, or yr. This suggests that any effects were biologically insignificant. Bare ground's response to indaziflam varied by site (see Fig. 2E; $P < 0.001$), but indaziflam increased bare ground at both sites. The Long Creek compared with Fox Site had greater bare ground with and without indaziflam application. Litter decreased with indaziflam (see Fig. 2F; $P=0.002$) and was greater at the Fox than Long Creek Site ($P < 0.001$).

Seeds incorporated in activated carbon pellets

Seeding perennial grasses in activated carbon pellets when indaziflam was applied to control *ventenata* did not influence peren-

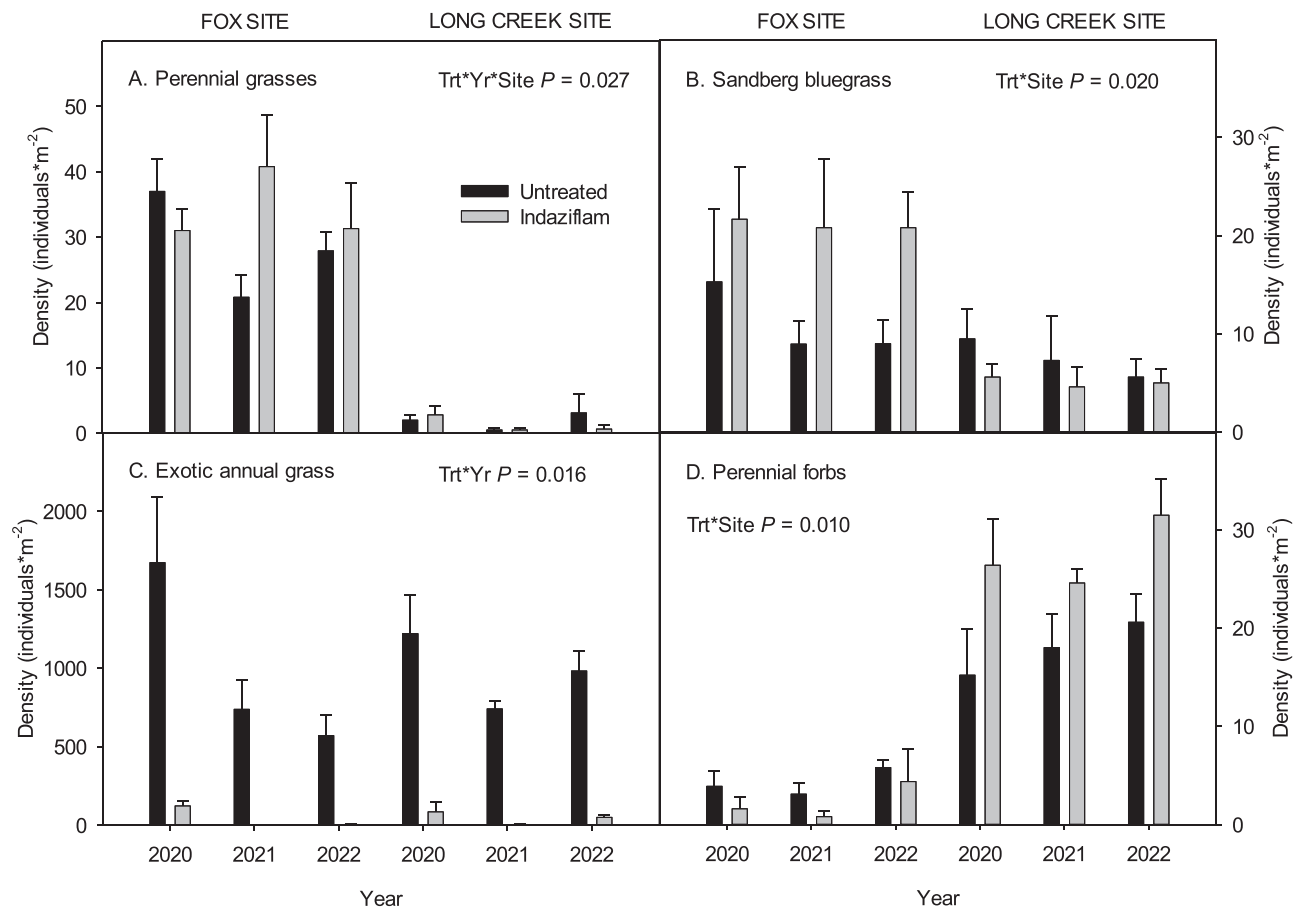


Figure 1. Density of vegetation groups in untreated control and indaziflam treatments at two sites in eastern Oregon for three post-treatment growing seasons. Trt = treatment ($n = 2$), Yr = year ($n = 3$), and Site = study site ($n = 2$).

nial grass and Sandberg bluegrass density ($P = 0.432$ and 0.818 , respectively). Densities of perennial grasses were similar among bare seed and indaziflam (17.4 ± 3.2 individuals·m⁻²), activated carbon pellets and indaziflam (21.6 ± 4.8 plants·m⁻²), and indaziflam only treatments (20.9 ± 4.2 plants·m⁻²). Similarly, exotic annual grass density was not influenced by seeding perennial grasses incorporated in activated carbon pellets ($P = 0.923$). Perennial forb and annual forb densities were also not affected by the activated carbon pellet treatment ($P = 0.976$ and 0.578 , respectively).

Perennial grass and Sandberg bluegrass cover were not influenced by incorporating perennial grass seeds into activated carbon pellets compared with bare seed and an unseeded control when indaziflam was applied to control ventenata ($P = 0.712$ and 0.754 , respectively). Perennial grass cover values were similar among bare seed and indaziflam ($12.2\% \pm 2.4\%$), activated carbon pellets and indaziflam ($11.6\% \pm 2.2\%$), and indaziflam only treatments ($12.3\% \pm 2.5\%$). Exotic annual grass cover was similar among treatments ($P = 0.897$). Perennial forb and annual forb cover did not vary among treatments ($P = 0.954$ and 0.715 , respectively). Bare ground and litter cover were similar among treatments ($P = 0.194$ and 0.632 , respectively).

Discussion

Our study highlighted that indaziflam effects in ventenata-invaded rangelands vary substantially by pretreatment plant community characteristics. Though indaziflam effectively controlled ventenata at both sites, the response of perennial plant groups to ventenata control was different between sites. This likely was the

result of differences in plant community composition before herbicide treatment and interactions between perennial plant groups after herbicide treatment. In contrast to what we expected, we found no evidence that perennial grass cover or density increased with seeding perennial grasses as seeds incorporated in activated carbon pellets compared to bare seed and an unseeded control at the same time indaziflam controlled ventenata. However, we speculate that our study failed to test the ability of activated carbon pellets to reduce indaziflam nontarget herbicide damage to seeded species because establishment was poor due to below-average precipitation and inadequate seed-to-soil contact from broadcast seeding.

Our results suggest that indaziflam controls ventenata for at least 3 yr post application. Similar to our results, indaziflam effectively controlled other invasive annuals for multiple years (Sebastian et al. 2016, 2017b; Courkamp et al. 2022). Though ventenata control with indaziflam was substantial in the first yr post application, control improved from yr 1 to yr 2 (see Fig. 1C). This may be because indaziflam has low mobility in the soil, with most of it retained in the soil at shallow depths (Jhala and Singh 2012; Guerra et al. 2016; González-Delgado and Shukla 2020). Indaziflam was still effectively controlling annual grasses in the third yr post application but may not be quite as effective as it was in the second yr post application. Though there appears to be a slight decrease in indaziflam activity by the third yr post application, indaziflam may substantially reduce ventenata in subsequent years. In support of this, indaziflam reduced an exotic annual grass, cheatgrass (*Bromus tectorum* L.), for almost 5 yr in Wyoming (Courkamp et al. 2022). Clearly, indaziflam controls ventenata and other exotic

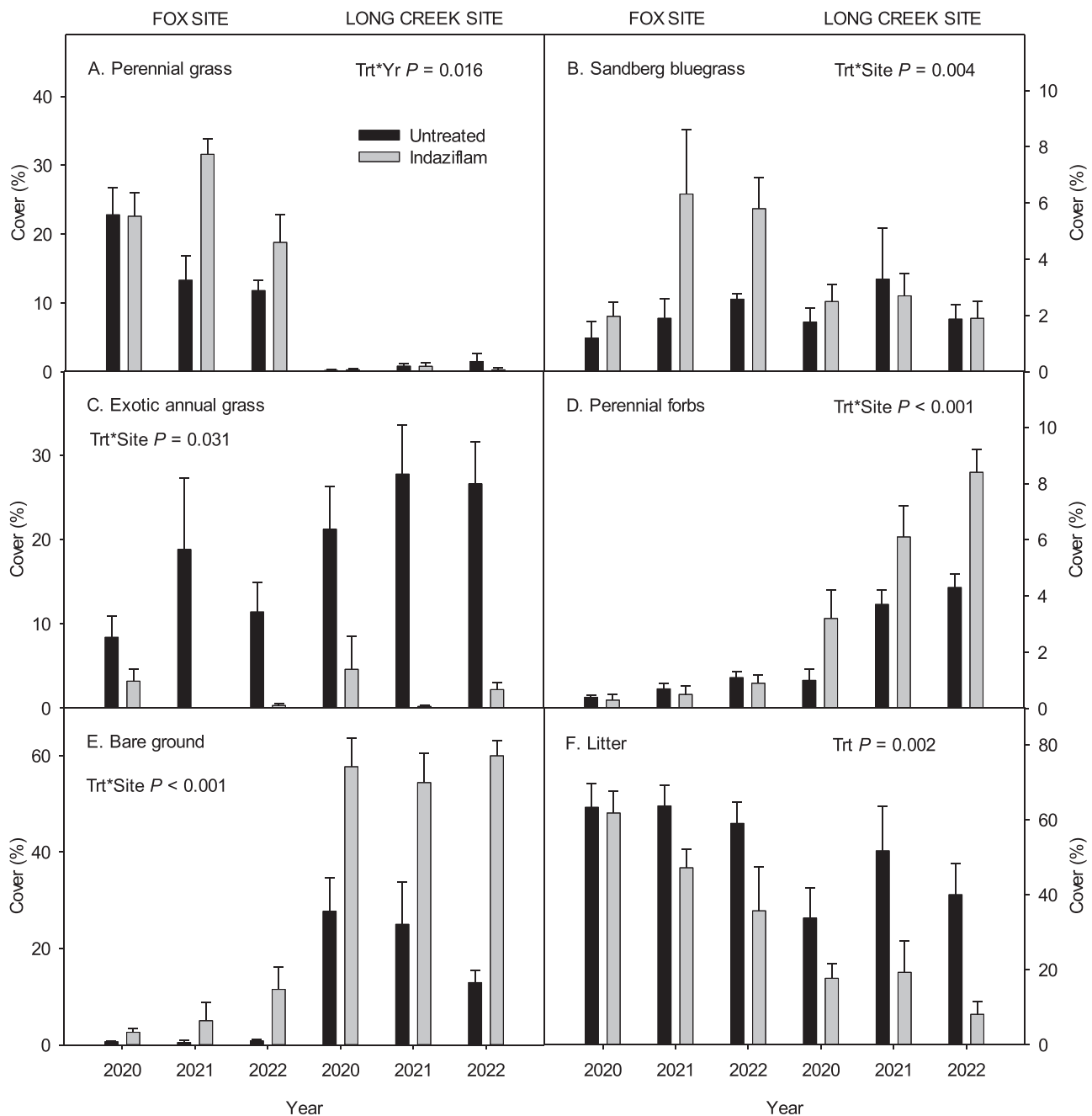


Figure 2. Cover of vegetation groups, bare ground, and litter in untreated control and indaziflam treatments at two sites in eastern Oregon for three post-treatment growing seasons. Trt = treatment ($n = 2$), Yr = year ($n = 3$), and Site = study site ($n = 2$).

annual grasses for multiple years, making it an effective management tool to reduce their effects in plant communities.

Indaziflam effects, via control of ventenata, on perennial vegetation groups varied by site, which varied considerably in composition, indicating the importance of knowing pretreatment community characteristics. Perennial grasses increased substantially with indaziflam control of ventenata, where they were more abundant before treatment (Fox Site), but they did not increase where they were less abundant pretreatment (Long Creek Site). In contrast, perennial forbs increased substantially with ventenata control at the Long Creek Site. Unexpectedly, perennial forb abundance decreased with indaziflam application at the Fox Site. We expect that the increase in perennial grasses, including Sandberg bluegrass, at the Fox Site with indaziflam control of ventenata likely

increased competition effects on perennial forbs, indicating that interactions between plant groups may also determine response to indaziflam control of invasive annual grasses. Perennial grasses are well known to be competitive with other plant groups and can limit the abundance of native forbs (Brown and Bugg 2001; Dickson and Busby 2009). Results of our study suggest that the selection of areas for ventenata control with indaziflam and development of management goals for ventenata-invaded rangelands need to consider current community composition. For forage management objectives and likelihood of limiting post-treatment reinvasion, perennial grasses need to be abundant enough to respond to the decrease in ventenata with indaziflam application.

In sites with inadequate perennial grass abundance to occupy the site after ventenata control, seeding is likely necessary. How-

ever, preemergent herbicide toxicity likely limits seeded species establishment while ventenata is controlled. Though we speculate that activated carbon seed technologies would allow seeded species to establish while indaziflam controls exotic annual grasses, our results did not provide evidence to support this. Specifically, we cannot conclude that incorporating seeds in activated carbon pellets allows successful establishment of perennial grasses while indaziflam controls annual grasses because perennial grass abundance and cover did not differ among activated carbon pellets, bare seed, and nonseeded treatments. We expect that this was caused by poor establishment of seeded species, not necessarily the effects of nontarget herbicide damage. We surmise that nontarget damage from indaziflam was not limiting establishment from seeds incorporated in activated carbon pellets because a grow room study demonstrated that activated carbon pellets protected a perennial grass and a shrub from indaziflam damage (Clenet et al. 2019). However, we cannot definitively conclude that nontarget indaziflam damage did not limit or at least partially limit seedling establishment in the activated carbon pellet treatment in this field experiment. This challenge of evaluating how to alleviate specific barriers (such as competition with invasive annuals, or nontarget damage to seeded species from preemergent herbicides) while in the presence of other major barriers (such as drought and unfavorable seedbed conditions) is a constant hurdle for both research and management in semiarid regions where multiple barriers to successful restoration often co-occur. Multisite and multiyear trials, though costly and time consuming, are necessary to address this hurdle.

The lack of establishment of seeded perennial grasses in the activated carbon pellet treatment was likely associated with the seeding method and postseeding weather. Establishment may have been greater if activated carbon pellets were seeded in drill rows instead of broadcast seeded. Broadcast seeding is often an ineffective seeding treatment to establish perennial grasses because of poor seed-to-soil contact, though exceptions occur (Svejcar et al. 2023). Furthermore, drill rows were used in prior field studies, reporting that activated carbon pellets were effective at preventing nontarget preemergent herbicide damage (Davies et al. 2017; Davies 2018; Clenet et al. 2020). Below-average precipitation in the year following seeding may have also been a factor contributing to the lack of establishment in the activated carbon pellet treatment. In a survey of the literature, successful establishment of seeded plants in rangelands was most common in above-average precipitation years (Hardegree et al. 2011). Further field evaluations of the ability of activated carbon seed technologies to limit indaziflam damage to seeded species are warranted, especially across a range of weather years and site conditions. We also suggest that activated carbon seed technologies be evaluated in the field by ensuring that seed-to-soil contact is greater than achieved with broadcast seeding.

Management Implications

Indaziflam affords multiple year control of exotic annual grasses including ventenata. The response of the other vegetation to ventenata control with indaziflam appears strongly related to pre-treatment plant community composition. If perennial grasses co-occupy the site with ventenata, indaziflam application appears to release them, which may result in substantial increases in their abundance. If perennial grass abundance is low, controlling ventenata may not necessarily result in increases in perennial grasses. However, other plant groups may increase, such as perennial forbs. These results imply that it would be valuable to treat ventenata-invaded rangelands earlier in the invasion, before substantial losses in perennial vegetation. Carefully selecting ventenata-invaded sites, based on community composition, for indaziflam application will

increase the probability of achieving management goals. Additional research is needed to identify specific community composition thresholds to target. Ventenata-invaded rangelands lacking enough perennial grasses to occupy the site after indaziflam application are still a management challenge. We cannot recommend seeding perennial grasses as seed incorporated in activated carbon pellets concurrent with indaziflam application at this time because we found no evidence to support using this strategy. We expect this was caused by low establishment due to below-average precipitation, as well as using broadcast seeding, which is often unsuccessful. Hence, we suggest further evaluations of activated carbon seed technologies with indaziflam application to determine if this could be an effective revegetation strategy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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