Rangeland Ecology & Management 68 (2015) 367–374

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: http://www.elsevier.com/locate/rama

Litter Reduction by Prescribed Burning Can Extend Downy Brome Control☆,☆☆

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ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 8 May 2015
Accepted 8 May 2015

Keywords:
Bromus tectorum
cheatgrass
Imazapic
remnant plant community
soil seed bank
Tebuthiuron

ABSTRACT

Downy brome (*Bromus tectorum* L.) is a highly successful invasive species primarily because it fills an open niche in native plant communities. It also produces large amounts of litter over time. We hypothesized that removing accumulated litter with a prescribed burn before applying herbicides would improve herbicide efficacy, extending the duration of control. In January 2012, two downy brome-infested sites were burned. In March 2012, postemergent applications of glyphosate, imazapic, and tebuthiuron were made in a split-plot design. Aboveground biomass was collected at 6, 18, and 27 months after treatment (MAT) to evaluate treatment effects. In nonburned areas, all herbicide treatments were similar to the control 27 MAT; however, burning combined with imazapic or tebuthiuron reduced downy brome biomass 27 MAT by 81% ± 4.6 SE and 84% ± 19.3 SE, respectively. Remnant species responded positively to burning and herbicide treatments. Native cool-season grass biomass increased after burning whereas native warm-season grass biomass increased following tebuthiuron treatments. The impact of litter on imazapic and tebuthiuron availability was also evaluated. Herbicide interception increased in a linear relationship with increasing litter. For every 50 $g \cdot m^{-2}$ increase in litter there was a 7% increase in the amount of herbicide intercepted, meaning that 75% of the applied herbicide was intercepted by 360 $g \cdot m^{-2}$ of litter. A simulated rainfall event of 5 mm, 7 days after application, removed a significant amount of herbicide. This indicates that in sites with surface litter, timely precipitation could be critical for herbicide efficacy; however, when burning was used to remove litter and was followed by herbicides with residual soil activity, downy brome control was extended. Due to downy brome's relatively short seed viability in the soil, extending herbicide efficacy to several years could help to reduce the soil seed bank.

Introduction

The invasive winter-annual grass, downy brome (*Bromus tectorum* L.), infests over 22 million ha in the western United States (Duncan et al., 2004). Rapid range expansion has been possible, in part, because there is no native winter-annual grass competitor, allowing downy brome to fill a unique, unoccupied niche (Knapp, 1996; Mack, 1981). This competitive advantage has had devastating ecological effects, degrading the composition, structure, and function of rangelands (Devine, 1993; Duncan et al., 2004). Effects include decreased native plant abundance, decreased forage quality, and altered nutrient cycling, as well as increased wildfire frequency and severity (D'Antonio and Vitousek, 1992; Knapp, 1996; Morrow and Stahlman, 1984; Young and Allen, 1997; Young et al., 1976).

Downy brome's ability to alter wildfire cycles is often cited as a reason it has been able to successfully outcompete native perennial grasses and forbs in many arid plant communities (Melgoza et al., 1990; Young and Allen, 1997; Young et al., 1976). Seed germination begins in the late summer, and individuals complete their life cycle by producing seed and senescing before many native species break winter dormancy (D'Antonio and Vitousek, 1992; Young et al., 1969). For the remainder of the growing season, standing senesced tissue serves as a fine fuel source. When wildfires are ignited in dense infestations, the extent and severity of these fires supersedes that of historic fires, thus negatively affecting the native plant community (Brooks, 2002; Link et al., 2006). Studies have shown that downy brome and other annual grasses recover to prefire levels within two seasons after fire, outcompeting desirable species (Melgoza et al., 1990; Whisenant, 1990; Young et al., 1976).

Conversely, fire has been used as a method to control winter annual grasses and stimulate the native plant community. Research shows that a fall- or winter-timed burn, conducted when most desirable species are dormant, can provide short-term downy brome control by killing seedlings before they produce seed (Brooks, 2002; DiTomaso et al., 2006). Decreased seedling survival has been attributed to decreased water availability and increased soil temperature fluctuations observed after

☆ Research was partially funded by Dow AgroSciences.
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http://dx.doi.org/10.1016/j.rama.2015.05.006
1550-7424/

surface litter is removed (Adair et al., 2008; Evans and Young, 1970). In addition, burning can stimulate native grasses by removing years of accumulated surface litter (DiTomaso et al., 2006; Knapp and Seastedt, 1986; Whisenant and Uresk, 1990). Due to downy brome's ability to recover quickly after fires, prescribed burning is not recommended unless it is part of an integrated management plan wherein subsequent techniques are employed (Daubenmire, 1968; Keeley and McGinnis, 2007).

Perhaps the most common and effective subsequent management technique is the use of herbicides. Glyphosate, imazapic, and tebuthiuron have all shown efficacy in controlling downy brome, but the length of control that they provide is variable (Beck et al., 1995; Blumenthal et al., 2006; Davison and Smith, 2007; Elseroad and Rudd, 2011; Mangold et al., 2013; Morris et al., 2009; Morrow et al., 1977; Whitson and Koch, 1998). Long-term control by glyphosate is unlikely due to a lack of residual soil activity, but it has been reported to reduce downy brome during the season of application (Beck et al., 1995; Morrow et al., 1977; Whitson and Koch, 1998). Due to foliar and residual soil activity, imazapic and tebuthiuron can control downy brome for at least two seasons. Imazapic has provided variable control, ranging from one to three seasons; to our knowledge, only one study has reported control of downy brome by tebuthiuron (Davison and Smith, 2007; Duncan et al., 2009; Elseroad and Rudd, 2011; Kyser et al., 2007; Morris et al., 2009).

When designing a management plan, control is not the only objective. Ensuring management methods do not injure the remnant plant community will aid restoration success and prevent downy brome reinvasion (Blumenthal et al., 2006; Elseroad and Rudd, 2011). Herbicides can have negative impacts on desirable perennial grasses and forbs if rate and timing are not appropriate. For example, glyphosate can injure remnant plants; however, after a fall-timed application of 200 g $\cdot$ ha^{-1}, minimal injury occurred to western wheatgrass (*Pascopyrum smithii* [Rydb.] À. Löve) and blue grama (*Bouteloua gracilis* [Willd. Ex Kunth] Lag. Ex Griffiths) (Lym and Kirby, 1991). Previous studies have reported western wheatgrass and various needlegrass (*Nassella* spp.) injury after postemergent imazapic applications; however, native forb tolerance is high (Beran et al., 1999; Kyser et al., 2007; Shinn and Thill, 2004). Many native forbs are susceptible to tebuthiuron, but previous studies focusing on *Artemisia* L. spp. reduction reported the perennial grass community responded positively, and both blue grama and western wheatgrass were highly tolerant (Blumenthal et al., 2006; Whitson et al., 1988).

The overall goal of a sequential management plan is to restore ecosystem composition, structure, and function. Minimizing injury to the remnant plant community while providing adequate control can place the plant community on a trajectory toward recovery (Masters et al., 1996). Maximizing the duration of control is especially important when targeting downy brome as seed viability is short, and under favorable conditions nearly 100% of seed can germinate during one season (Burnside et al., 1996; Harper et al., 1965; Young et al., 1969). Strategies that take advantage of this weakness and decrease downy brome in the soil seed bank by providing control for three or more seasons should be pursued.

Recent publications have reported increased duration of downy brome and annual grass control when integrating prescribed burning and herbicides (Calo et al., 2012; Davies and Sheley, 2011; Kyser et al., 2007; Sheley et al., 2007). Following burning with herbicides can increase control duration; however, it is unclear exactly why this occurs. Studies have reported that removing surface litter mechanically or through burning decreases seedling survival (Adair et al., 2008; Evans and Young, 1970), but other studies have postulated that reducing surface litter increases herbicide efficacy by decreasing the amount of herbicide bound to litter (DiTomaso et al., 2006; Washburn et al., 1999). Despite much speculation, no quantitative studies have been conducted examining how surface litter interacts with herbicides used to control downy brome. We evaluated the effectiveness of integrating burning with glyphosate, imazapic, and tebuthiuron application for downy brome management and the recovery of the remnant plant community in foothills grasslands infested with downy brome. In addition, we conducted laboratory experiments to quantify herbicide interception by litter and the subsequent impact of rainfall on herbicide desorption.

Methods

Integrating Prescribed Burning with Herbicides

Site Description

The field study was conducted at two sites near Loveland, Colorado, from January 2012 to June 2014. Both the North and South study sites were located in an 889-ha Larimer County property, Devil's Backbone Open Space (lat 40°28′24″N, long 105°11′15″W) in foothills grasslands on the western edge of the short-grass steppe. Elevation was approximately 1 700 m, and both studies were on southwestern facing slopes. At the beginning of the experiment, downy brome dominated the sites. A remnant plant community composed primarily of western wheatgrass and blue grama still persisted. The Soil Survey of Larimer County Area, Colorado, described the potential plant community as a Loamy Foothill Range Site, dominated by western wheatgrass, blue grama, and green needlegrass (*Nassella viridula* [Trin.] Barkworth) (USDA-NRCS, 2014). The soil was classified as a Haplustoll, with cobbly to stony colluvium (USDA-NRCS, 2014). The depth to paralithic bedrock is estimated to be between 25 and 100 cm, and the soils are well drained with low water storage availability (USDA-NRCS, 2014). Four composite soil samples were collected from the top 20 cm of soil at each location and air dried for 24 h before sending subsamples to a private lab for analysis (Ward Laboratories, Inc., Kearney, NE). Soils analysis indicated that the North site had slightly higher organic matter (OM) compared with the South site, 3.5% $\pm$ 0.1 and 2.9% $\pm$ 0.3 (mean $\pm$ SE), respectively. The pH at both sites was 6.2 $\pm$ 0.1, and the cation-exchange capacity (CEC, meq $\cdot$ 100 g^{-1}) was 11.6 $\pm$ 0.4. The soils were classified as loam, with 46% $\pm$ 0.7 sand, 36% $\pm$ 0.8 silt, and 18% $\pm$ 0.4 clay.

Precipitation data were obtained from a weather station operated by Northern Colorado Water Conservancy District. Average yearly precipitation between 2001 and 2011 was 360 mm (NCWCD, 2014). In 2012, a severe drought reduced annual precipitation to 172 mm, half of the 11-yr average (NCWCD, 2014). Annual precipitation in 2013 was 428 mm due to a significant rainfall event resulting in 183 mm of rainfall in September (Fig. 1) (NCWCD, 2014).

Experimental Design and Measurements

The experiment was a split-plot design with burning as the main plot factor and herbicide treatments as the subplot factor. At each site, a prescribed burn was conducted in January 2012 when downy brome

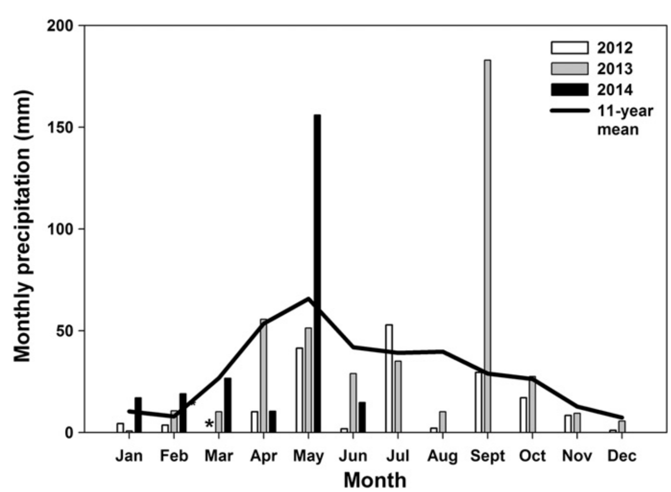

Fig. 1. Monthly precipitation for Loveland, Colorado, during the field experiment is depicted by shaded bars. These values are compared with the 11-year mean, depicted by the line (2001–2011). *In March 2012 there was 0 mm precipitation.

was at the seedling growth stage. In March 2012, six herbicide treatments were applied when downy brome was at the two- to three-leaf growth stage (early postemergent). The herbicides included in this study were imazapic (Plateau), tebuthiuron + aminopyralid (Spike 80 DF + Milestone), glyphosate (Rodeo), and nontreated control. This resulted in all possible combinations of main plot (burned and nonburned) and subplot factors (all herbicide treatments). Herbicide treatment combinations and rates can be found in Table 1. Aminopyralid was included in the tebuthiuron treatments as an experimental tank mix. Because of lack of downy brome control by aminopyralid in previous field studies and for the sake of brevity, this treatment will be referred to as tebuthiuron (Rinella et al., 2010). Imazapic treatments included 1.3% $v \cdot v^{-1}$ methylated seed oil, while glyphosate and tebuthiuron treatments included 0.25% $v \cdot v^{-1}$ nonionic surfactant. All treatments were applied to 3 × 9 m plots using a CO_2 pressurized backpack sprayer with a 3-m spray boom and six flat fan 11002VS nozzles (TeeJet Tech, Wheaton, IL). The backpack sprayer was pressurized to 206 kPa and calibrated to apply 187 $L \cdot ha^{-1}$.

To evaluate treatment effects, biomass was collected 6, 18, and 27 months after treatment (MAT). Biomass was collected 6 MAT by harvesting two randomly placed, 0.5-m^2 quadrats on the right side of each plot. All aboveground biomass was clipped and sorted into the following categories: downy brome, western wheatgrass, blue grama, sand dropseed (*Sporobolus cryptandrus* [Torr.] A. Gray), needle and thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth), green needlegrass, and native forbs. In addition, surface litter in each quadrat was collected. The same procedure was repeated 18 MAT, collecting biomass on the left side of each plot; 27 MAT, downy brome biomass was collected by placing the quadrats in the middle of each plot. All biomass samples were bagged and dried in a 60°C oven for 72 h before obtaining dry weights.

Herbicide Sorption to Litter

Litter Collection

Litter was collected adjacent to the North study area, outside of the prescribed burn area, in September 2012. Dead vegetation was raked from the soil surface and placed in large plastic containers. These containers were then stored at room temperature (16–24°C) and allowed to dry for several months before use. Litter composition could not be identified due to stem decomposition; however, litter was collected from the same plant community type in which the field experiment was conducted. Before use in experiments, the litter was sieved to remove soil, and only shoot segments between 20 and 200 mm in length were included.

Interception

In all laboratory experiments, 45 × 205 × 205 mm metal pans were used to capture herbicide and rainfall. To quantify herbicide interception by litter, 250 mL of methanol were poured into the metal pans and a 5-mm wire mesh screen was placed on top of the pan. Litter amounts of 120, 240, and 360 $g \cdot m^{-2}$ were spread evenly on top of the screen. To determine the total quantity of herbicide applied, a metal pan with an empty screen was included as a control. Imazapic and tebuthiuron were applied at the same rates used in the field study (Table 1) with an overhead track spray chamber (DeVries Manufacturing Corp, Hollandale, MN) equipped with a single flat fan 8002E nozzle and calibrated to apply 187 $L \cdot ha^{-1}$ at 172 kPa (TeeJet Tech). After herbicide application, a 10-mL aliquot was collected from the herbicide/methanol mixture from the bottom of each metal pan and stored at −20°C for analysis. There were four replicates per treatment, and the entire experiment was repeated.

Table 1
Herbicide treatments, rates, formulations and sources

Herbicide treatment	Rate ($g \cdot ha^{-1}$)	Trade name
Imazapic	105 ai	Plateau[1]
Imazapic + glyphosate	105 ai + 280 ae	Plateau[1] + Rodeo[2]
Tebuthiuron + aminopyralid	420 ai + 91 ae	Spike 80 DF[2] + Milestone[2]
Tebuthiuron + aminopyralid + glyphosate	420 ai + 91 ae + 280 ae	Spike 80 DF[2] + Milestone[2] + Rodeo[2]
Glyphosate	280 ae	Rodeo[2]
Control	NA	NA

[1] BASF Corp, Research Triangle Park, North Carolina.
[2] Dow Agro Sciences LLC, Indianapolis, Indiana.

Desorption

The largest amount of litter, 360 $g \cdot m^{-2}$, was spread evenly on top of a screen and placed over a metal pan containing 250 mL of methanol. Imazapic and tebuthiuron were applied using the same procedure previously described. After herbicide application, the treated litter and screen were removed from the pan and maintained at 10°C with 125 W fluorescent light exposure for 11 $h \cdot d^{-1}$. After a 7-d period, the treated litter (still on the screens) was placed over clean pans, and we simulated rainfall by applying water using the same overhead track spray chamber. Rainfall amounts of 5 and 15 mm were applied using an 8004E nozzle traveling at 1.2 $km \cdot h^{-1}$. After rainfall, the total water volume captured in the metal pan was measured and a 10-mL aliquot of the herbicide/water mixture was collected and stored at −20°C for analysis. Herbicide still sorbed to litter was desorbed by cutting litter into 3-cm segments, placing segments in a 950-mL glass jar containing 300 mL of methanol, and agitating with a table shaker for 8 h. After agitation, the litter and methanol were poured over a 90-mm filter placed in a Buchner funnel and drawn through the filter by a vacuum aspirator. The litter and filter were rinsed with an additional 200 mL of methanol, and total methanol volume was recorded to account for any evaporation. Herbicide/methanol samples were stored at −20°C until they were analyzed using high-performance liquid chromatography (HPLC).

HPLC Analysis

Interception

The herbicide interception samples were prepared by evaporating 2 mL of the herbicide/methanol sample to dryness, reconstituting in 1 mL of 10% acetonitrile and 0.5% phosphoric acid in HPLC grade water (mobile phase 1), and vortexing for 10 s. Final sample preparation is described as follows.

Desorption

The herbicide/water samples collected from the rainfall portion of the experiment were prepared by transferring 0.5 mL to a 0.45-μm nylon filter inserted into a 2-mL centrifuge tube. Tubes were centrifuged at 18 800 × g for 5 min (Sorvel Legend Micro 21, Thermo Fisher Scientific, Waltham, MA). The filtrate was transferred to a 1.5-mL HPLC vial and analyzed by HPLC (Hitachi L-7100, Schaumburg, IL).

To prepare herbicide/methanol samples from the litter extraction, we filtered 10 mL of the methanol extract through a 0.45-μm Teflon filter inserted into a 50-mL centrifuge tube and centrifuged at 25 000 × g for 20 m (Sorvall Legend XT Centrifuge, Thermo Fisher Scientific). After centrifuging, samples were evaporated to dryness in a Rapid Vap set to 45°C (Labconco, Kansas City, MO). Samples were reconstituted in 1 mL of mobile phase 1 and vortexed for 10 s. Final sample preparation followed the method previously described.

HPLC Analysis

The herbicide concentration in each prepared sample was determined by HPLC coupled with UV detection (Hitachi L-7100). Herbicides were separated on a Zorbax RX C8 4.6 mm × 250 mm column (Agilent Technologies, Santa Clara, CA) by transitioning the mobile phase from 10% acetonitrile to 60% acetonitrile over a 20-min period. The injection volume was 50 μL, and the UV detector was set at 250 nm. Imazapic and tebuthiuron were detected at retention times of 8.98 min and

10.92 min, respectively. Herbicide concentration was determined by comparison to a standard curve ranging between 0.05 and 10 $\mu g \cdot mL^{-1}$.

Statistical Analysis

Integrating Prescribed Burning with Herbicides

To determine differences between treatments, repeated measures analysis of variance (ANOVA) using the PROC MIXED method in SAS 9.3 was used (SAS Institute, 2010). To meet the normality and homoscedasticity assumptions of ANOVA, we transformed dry biomass data for each species using either a log ($x' = \log [x + 1]$) or square root transformation ($[x' = x + 0.5]^{0.5}$). Downy brome was analyzed separately from other species. All other species were combined into appropriate functional groups (native cool-season perennial grasses, native warm-season perennial grasses, and native forbs). Factors included in the model were site, burning, herbicide treatment, month after treatment, and all possible interactions. The random factor was site by burning within block, and month after treatment was defined as the repeated measure. Interactions and main effects with P values ≤ 0.05 were considered significant. Significant interactions were further analyzed by Fisher's Protected LSD tests. Means and SE presented in figures are the original, nontransformed data.

Herbicide Sorption to Litter

Interception data were analyzed using linear regression in PROC REG, and ANOVA was used to analyze sorption data in PROC GLM (SAS Institute, 2010). When analyzing interception data, herbicide and litter amount were factors. Herbicide and rainfall amount were factors when analyzing sorption data. To ensure laboratory methods resulted in high herbicide recovery rates, a mass balance was conducted and any experiment with greater than 10% herbicide loss was disregarded. After failing to reject the null hypothesis of a Levene's test that experimental variances are equal, replicated experiments were combined.

Results

Integrating Prescribed Burning with Herbicides

Downy Brome Response

Three-way interactions of location, burning, and year ($P < 0.0001$); location, herbicide treatment, and year ($P = 0.0341$); and burning, herbicide treatment, and year ($P = 0.0160$) were significant. The burning, herbicide treatment, and year interaction specifically refers to our study objectives and thus is the focus of this section. Due to the burning, herbicide treatment, and year interaction, downy brome biomass for each herbicide treatment is displayed according to the three harvest dates: 6, 18, and 27 MAT (Fig. 2). Unless specifically stated, mean comparisons refer to the nonburned control in the same harvest date.

Compared with control plots, all herbicide treatments significantly decreased downy brome biomass 6 MAT, regardless of the main plot factor (burned vs. nonburned) (Fig. 2). The tebuthiuron-alone treatment was the only herbicide treatment for which downy brome biomass in the burned plots was lower than the nonburned plots. With this one exception, there was no significant advantage, in terms of herbicide efficacy 6 MAT, from removing surface litter with a prescribed burn. All other herbicide treatments decreased downy brome biomass by at least 92% ± 1.0.

By the second harvest (18 MAT), there was a difference in downy brome biomass between the burned and nonburned controls, indicating that burning alone could decrease downy brome biomass, at least in the short term (Fig. 2). At this harvest date, glyphosate treatments were similar to the control when comparing within burned and nonburned main plots. Imazapic and tebuthiuron have residual soil activity, so these treatments were still highly effective when compared with the nonburned control. Downy brome biomass was lowest in burned areas compared with nonburned areas for the control and all herbicide treatments except for tebuthiuron, 18 MAT. In burned plots, imazapic and tebuthiuron

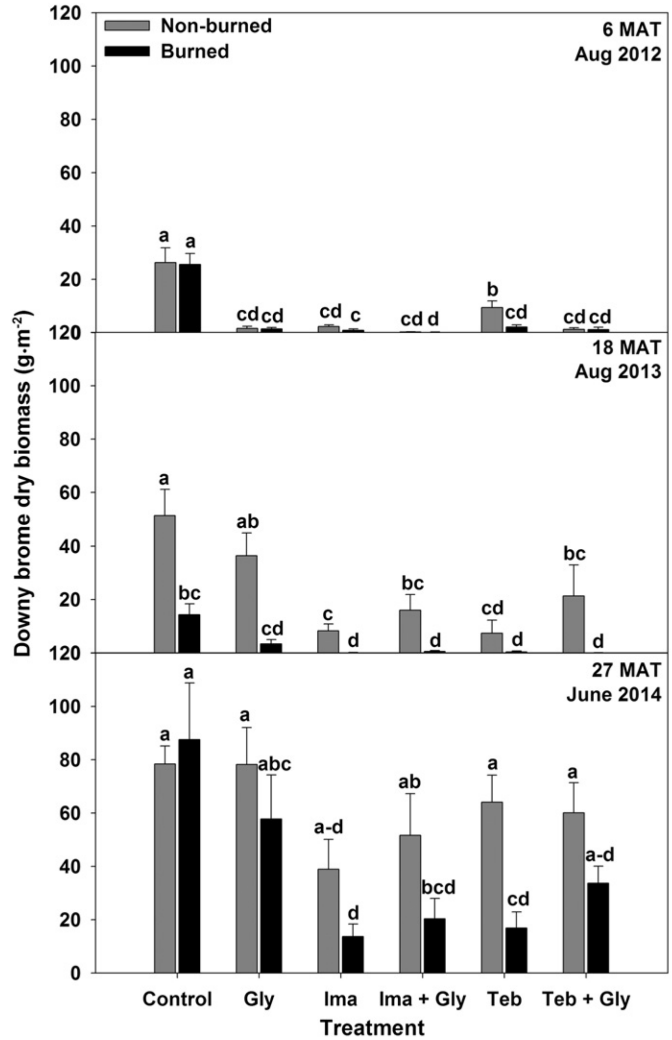

Fig. 2. Downy brome biomass collected 6, 18, and 27 months after herbicide treatments were applied. Different letters indicate differences among herbicide treatments within a burning treatment and within the data collection time point ($P < 0.05$). Herbicide treatment abbreviations and rates are as follows: Gly (glyphosate 208 $g \cdot ae \cdot ha^{-1}$), Ima (imazapic 105 $g \cdot ai \cdot ha^{-1}$), Ima + Gly (imazapic 105 $g \cdot ai \cdot ha^{-1}$ + glyphosate 208 $g \cdot ae \cdot ha^{-1}$), Teb (tebuthiuron 420 $g \cdot ai \cdot ha^{-1}$), and Teb + Gly (tebuthiuron 420 $g \cdot ai \cdot ha^{-1}$ + glyphosate 208 $g \cdot ae \cdot ha^{-1}$). (Mean [$n = 8$]).

reduced downy brome biomass by 96–99% ± 4.1; however, the same herbicide treatments were less effective in nonburned plots, reducing downy brome biomass by only 59–85% ± 11.5, 18 MAT.

The widespread effect of burning that we observed 18 MAT was no longer evident 27 MAT. Downy brome biomass was similar in the controls and the glyphosate-only plots for burned and nonburned treatments, 27 MAT (Fig. 2). In the nonburned areas, all herbicide treatments had the same downy brome biomass as the controls, indicating that in this study, herbicides alone could be expected to provide only two seasons of acceptable downy brome control. In the burned main plots, all herbicide treatments except for glyphosate and tebuthiuron + glyphosate were still providing a reduction in downy brome biomass. Imazapic and tebuthiuron treatments decreased downy brome biomass by 81% ± 4.6 and 84% ± 19.3, respectively, in the burned main plots, 27 MAT. At the end of the three-season evaluation period, imazapic and tebuthiuron combined with burning resulted in the greatest reduction in downy brome biomass.

Perennial Grass Response

The plant community at this location is dominated by native cool- and warm-season perennial grasses. The cool-season grasses were western wheatgrass, green needlegrass, and needle and thread, with western wheatgrass accounting for more than 98% of the total desirable cool season grass biomass. There were two native warm season bunch grasses, blue grama and sand dropseed. Blue grama was the dominant species in this functional group, representing 81% of the total warm-season grass biomass.

These two functional groups responded differently to the prescribed burn conducted in January 2012. Averaged across other factors, burning did not influence warm-season grass biomass ($P = 0.8743$). Site by year ($P = 0.0088$) and burning by herbicide treatment ($P = 0.0250$; Fig. 3) interactions affected cool-season grass biomass, but no other interactions were significant. Cool-season grass biomass was lowest in the control subplot of the nonburned main plot, and there was no difference among herbicide treatments in the burned main plot.

In contrast, herbicide treatments appeared to cause a shift in warm-season grass biomass at each site, as indicated by a significant herbicide treatment by site interaction ($P = 0.0009$). Warm-season grass biomass was slightly greater at the South site compared with the North. At the South site, tebuthiuron was the only herbicide treatment with greater warm-season grass biomass than the control (89 g · m^{-2} ± 13.1 vs. 65 g · m^{-2} ± 11.9, $P = 0.0208$). At the North site, there was more warm-season grass biomass in the glyphosate (45.3 g · m^{-2} ± 6.4, $P = 0.0108$), imazapic + glyphosate (54 g · m^{-2} ± 7.5, $P = 0.0009$), tebuthiuron (58.1 g · m^{-2} ± 7.6, $P = 0.0001$), and tebuthiuron + glyphosate (47 g · m^{-2} ± 7.2, $P = 0.0088$) treatments compared with the control (27 g · m^{-2} ± 5.3). There were no other significant interactions, including herbicide by burning ($P = 0.1496$), indicating that there was no warm-season grass biomass reduction when integrating these two strategies.

Native Forb Response

Native forbs were highly variable, so no individual species data were collected; however, the dominant species were tarragon (*Artemisia dracunculus* L.), prairie sagewort (*Artemisia frigida* Willd.), scarlet globemallow (*Sphaeralcea coccinea* [Nutt.] Rydb.), and Cuman ragweed (*Ambrosia psilostachya* DC.). Forb biomass was affected by both burning and herbicide treatment, as indicated by the interaction of these two factors ($P = 0.0031$; Fig. 4). No other interactions were significant. All herbicide treatments containing imazapic increased forb biomass when burned, and tebuthiuron reduced forb biomass in burned and unburned treatments, with the lowest forb biomass occurring in the burned main plots in treatments containing tebuthiuron. In addition, forb biomass varied by year ($P = 0.0014$). Biomass was greatest during the second evaluation period, where rainfall was above the 11-year average (Fig. 1).

Litter

Monitoring the quantity of litter during the course of this research was important to understanding the impact of the prescribed burn on litter and determining the quantity of litter that was present for herbicide interception. We did not determine the amount of litter immediately following the prescribed burn, but 6 months after the herbicide applications, the amount of litter in the burned study area was 30 g · m^{-2} ± 5, whereas in the nonburned study area, litter amount was 10-fold greater (300 g · m^{-2} ± 14). Over the next 12 months (18 MAT), the difference between litter amount in the burned and nonburned study area was much smaller. The amount of litter in the burned main plot had increased to 47 g · m^{-2} ± 3, whereas in the nonburned main plot litter had decreased to 194 g · m^{-2} ± 8. This decrease in litter was most likely due to differences in precipitation. In 2012, precipitation was half of the 11-year average, decreasing total biomass production (Fig. 1). The drop in litter biomass observed in 2013 is most likely due to a lack of vegetative productivity during 2012.

Herbicide Sorption to Litter

Interception

Herbicide interception was similar for imazapic and tebuthiuron ($P = 0.7373$). There was a positive linear correlation between litter amount and herbicide interception for both herbicides ($R^2 = 0.8805$, $Y = 0.13x + 27.38$, $P < 0.0001$). At the lowest litter amount, 120 g · m^{-2}, 42.5% ± 1.6 of the herbicide was intercepted by the litter, whereas at the highest litter amount, 360 g · m^{-2}, 74.6% ± 1.8 of the herbicide was intercepted. The highest litter amount was close to the amount of litter collected in the field in the nonburned main plot in 2012. Theoretically, our results indicate that only 25% of herbicide is immediately available after herbicide application due to interception, and as surface litter increases by 50 g · m^{-2}, herbicide interception increases by 7%.

Desorption

Our results indicate that a significant amount of the herbicide intercepted by litter can be removed with a single rainfall event, even 7 days after the initial application. More imazapic desorbed from the litter than tebuthiuron following each rainfall event ($P = 0.0001$),

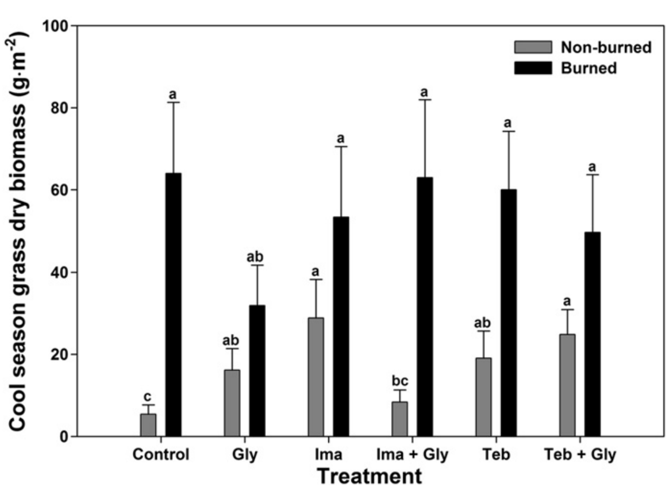

Fig. 3. Native perennial cool-season grass biomass averaged over the 6 and 18 months after herbicide treatment data collection time points. Different letters indicate differences among means ($P < 0.05$). Herbicide treatment abbreviations and rates are as follows: Gly (glyphosate 208 g · ae · ha^{-1}), Ima (imazapic 105 g · ai · ha^{-1}), Ima + Gly (imazapic 105 g · ai · ha^{-1} + glyphosate 208 g · ae · ha^{-1}), Teb (tebuthiuron 420 g · ai · ha^{-1}), Teb + Gly (tebuthiuron 420 g · ai · ha^{-1} + glyphosate 208 g · ae · ha^{-1}). (Mean [$n = 8$]).

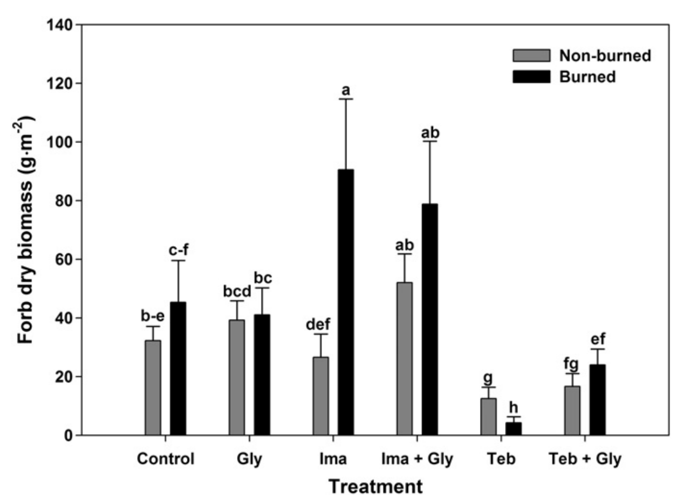

Fig. 4. Native forb biomass averaged over the 6 and 18 months after herbicide treatment data collection time points. Different letters indicate differences among means ($P < 0.05$). Herbicide treatment abbreviations and rates are as follows: Gly (glyphosate 208 g · ae · ha^{-1}), Ima (imazapic 105 g · ai · ha^{-1}), Ima + Gly (imazapic 105 g · ai · ha^{-1} + glyphosate 208 g · ae · ha^{-1}), Teb (tebuthiuron 420 g · ai · ha^{-1}), Teb + Gly (tebuthiuron 420 g · ai · ha^{-1} + glyphosate 208 g · ae · ha^{-1}). (Mean [$n = 8$]).

and more herbicide was removed with the larger rainfall amount ($P = 0.002$). The interaction between herbicide and rainfall amount was not significant ($P = 0.7814$). On average, rainfall removed 69.5% ± 2.6 and 59.5% ± 2.6 of the intercepted imazapic and tebuthiuron, respectively. The herbicide was not tightly bound to the litter, and 57.5% ± 2.6 of the intercepted herbicide could be removed with as little as 5 mm of rainfall. However, when the rainfall amount was tripled (15 mm), only 14.1% ± 2.6 more herbicide was desorbed. The methanol extractions we conducted to establish a mass balance for herbicide recovery suggested that somewhere between 15% and 25% of the herbicide is difficult to remove from litter and will be essentially nonavailable.

Discussion

Integrating Prescribed Burning with Herbicides

We found that burning alone decreased downy brome biomass for two seasons (Fig. 2), although the effect of burning was not apparent until the second season due to a severe drought that occurred during the first growing season (Fig. 1). Other studies have found that annual grasses have decreased after burning, especially in years with little precipitation (Whisenant, 1990; Whisenant and Uresk, 1990). Sheley et al. (2007) noted a decrease in winter annual grass biomass when comparing burned and nonburned plots, but due to the difficulty of replicating prescribed burns, no statistical analysis was conducted. There appear to be both short-term and long-term impacts associated with burning to decrease litter accumulation in downy brome-infested sites. In the short term, removing litter with a prescribed burn appears to favor the native plant community and makes it more difficult for downy brome to germinate and establish (Adair et al., 2008; Evans and Young, 1970). On the other hand, numerous studies have determined that downy brome-infested sites have increased fire frequency, which negatively impacts the native community and tends to increase the downy brome density (D'Antonio and Vitousek, 1992; DiTomaso et al., 2006; Melgoza et al., 1990). So a prescribed burn represents the first phase of an integrated program using the sequential application of different techniques for downy brome control.

In this study, our sequential techniques were a prescribed burn followed by herbicides. Imazapic and tebuthiuron have both foliar and residual soil activity, causing decreased downy brome biomass for two seasons whether these herbicides were applied alone or used in combination with burning. The importance of soil activity is exemplified by our results using glyphosate alone. Glyphosate is highly effective in controlling downy brome when applied to the foliage, but it has no soil activity (Beck et al., 1995; Morrow et al., 1977; Senseman, 2007; Whitson and Koch, 1998). Therefore, downy brome control with glyphosate was only detectable during the first season (Fig. 2), and by 18 MAT downy brome biomass in plots treated with glyphosate alone was similar to the control.

We hypothesized that by using these sequential treatments we could extend downy brome control beyond using herbicides alone. Our results suggest herbicides with residual soil activity provided no more than two seasons of control when they were not part of an integrated management plan, and this duration of control is similar to previous reports (Kyser et al., 2013; Morris et al., 2009).

Overall, downy brome biomass was lowest in plots where burning was integrated with imazapic and tebuthiuron treatments at the final harvest date (27 MAT), supporting our general hypothesis. Several other studies have reported longer downy brome control when integrating burning and herbicides (Calo et al., 2012; Kyser et al., 2007). In addition, increased herbicide efficacy following prescribed burning has been observed in several studies where medusahead (*Taeniatherum caput-medusae*[L.] Nevski) was the target species (Davies and Sheley, 2011; Kyser et al., 2007; Sheley et al., 2007).

Burning and herbicide treatments had only minor effects on the remnant plant community. Cool-season grass biomass increased in response to burning, whereas warm-season grass biomass increased after tebuthiuron treatment (Fig. 3). Although no treatments decreased perennial grass biomass in our study, other studies have reported injury to perennial grasses following imazapic applications, especially as rate increased (Monaco et al., 2005; Shinn and Thill, 2004). In our study, native forb biomass increased when imazapic was applied after a burn but decreased in the tebuthiuron treatments, especially when combined with burning (Fig. 4). Our results contradict a study evaluating forb response after imazapic application in sagebrush-dominated sites, where a decrease in forb cover was reported (Davies and Sheley, 2011). Several other studies have reported that numerous forbs are tolerant to imazapic (Beran et al., 1999; Kyser et al., 2007, 2013).

We did confirm that many forbs are susceptible to tebuthiuron. This was expected because most tebuthiuron research has focused on forb control, especially *Artemisa* spp. (Blumenthal et al., 2006; Whitson et al., 1988). During the time span of this study, we found no evidence that integrating burning and herbicides decreased desirable native perennial grass biomass more than either method alone. Actually, none of the herbicide treatments we studied prevented the increase in cool-season native perennial grass biomass in response to fire. Similar studies have reported that perennial grasses responded favorably to burning followed by imazapic (Davies and Sheley, 2011; Sheley et al., 2007). As a result, land managers should consider their remnant plant community when designing an integrated management plan to minimize injury to the native plant community and increase the probability of successful long-term restoration (Blumenthal et al., 2006).

Herbicide Sorption to Litter

After herbicide desorption by simulated rainfall, 20% of imazapic and 27% of tebuthiuron were still sorbed to the litter, suggesting that in the absence of litter, more herbicide would reach the soil, extending downy brome control. Numerous studies have reported longer-term annual grass control after litter removal compared with paired sites where litter is still present (Calo et al., 2012; Davies and Sheley, 2011; Kyser et al., 2007; Monaco et al., 2005; Sheley et al., 2007). These studies only imply that herbicide sorption to litter may be decreasing duration of control because of the confounding effects of prescribed burning (Evans and Young, 1970). The results of our sorption experiments demonstrate that litter intercepted the vast majority of imazapic and tebuthiuron and that even after a sizeable precipitation event, a significant amount of herbicide remained sorbed to litter. The amount of litter that we used to measure herbicide interception was similar to what we measured at our field sites; however, it does not represent the maximum litter amount that has been measured in an annual grass infestation. There are reports of litter that has accumulated up to 885 $g \cdot m^{-2}$ (Ogle et al., 2003). Interception could approach 100% in these situations, and without a timely rainfall event, downy brome could germinate and establish with no herbicide effects. The variability in downy brome control provided by imazapic could be the result of herbicide interception combined with the lack of timely precipitation.

Timing and amount of precipitation have been cited as primary reasons restoration efforts succeed or fail (Hardegree et al., 2012). From 2012 to 2014, precipitation varied greatly, affecting downy brome and litter biomass (Figs. 1 and 2). Downy brome biomass was low in 2012, doubled in 2013, and more than tripled by 2014 (Fig. 2). In 2012, litter amount was high in the nonburned study area, but less than 66% of litter remained in 2013 due to lack of precipitation the previous season. Fluctuations in litter and downy brome biomass due to precipitation have been reported previously and serve to remind us why generalizing the effects of treatment is so difficult (Bansal et al., 2014; Morris et al., 2009; Uresk et al., 1979; Whisenant, 1990). In September 2013, the Front Range of Colorado experienced some extreme weather that NOAA (2013) classified as a 1 000-year rainfall event. Our field sites received more precipitation during the month of September than the total precipitation received for all of 2012 (Fig. 1). This above-normal precipitation resulted in a massive downy brome recruitment event and a significant increase in downy brome biomass in 2014. Herbicide treatments not combined with burning were no longer effective; however, herbicide treatments combined with burning were still providing a significant reduction in downy brome biomass.

Integrating burning with herbicides can provide longer and more consistent downy brome control; however, there is still much debate around which herbicide rates and timings are most efficacious (Kyser et al., 2007; Morris et al., 2009). Mangold et al. (2013) speculated that abiotic factors such as precipitation were responsible for much of the variability in the success of imazapic treatments. The results of our sorption and desorption experiments suggest a plausible explanation for why timely rainfall appears to be such a driving factor for success.

The goal of increasing the duration of control is based on the concept that, due to downy brome's short seed viability, providing multiple seasons of control could drive down the soil seed bank, increasing long-term management success (Burnside et al., 1996; Harper et al., 1965; Young et al., 1969). There may be unintended consequences associated with the combination of burning and herbicides. Removing litter would make more of the herbicide immediately available in the soil solution; therefore, it is possible that desirable remnant or seeded species could be injured. Other studies have reported injury to desirable species as herbicide rate increases (Kyser et al., 2007; Morris et al., 2009); however, in our study native forbs and native cool-season perennial grasses responded favorably to imazapic whereas native warm-season perennial grasses were unaffected (Figs. 3 and 4). Imazapic and tebuthiuron treatments increased cool-season perennial grass biomass and tebuthiuron increased warm-season perennial grass biomass but reduced forb biomass (Figs. 3 and 4). Nonetheless, caution should be taken when determining herbicide application rate, especially at low-litter sites. It is likely that land managers will need to determine herbicide and application rate on the basis of individual site characteristics and management objectives.

Management Implications

When designing a restoration plan, land managers should consider the historical plant community and potential successional trajectories, as well as their current plant community and subsequent land management objectives. In this study, glyphosate was only effective in the season after application, whereas imazapic and tebuthiuron controlled downy brome for two seasons in the nonburned study area and for at least three seasons in the burned study area, indicating burning extended the length of herbicide control by at least one season. Using prescribed burning and herbicides in combination as part of an integrated management plan can cause functional group dynamics to change. Imazapic may shift the plant community by increasing native forb biomass, whereas tebuthiuron may shift the plant community to grassland-favoring warm-season grasses with little forb diversity. Burning at a time when desirable species are dormant may improve conditions for native grasses and reduce or eliminate conditions that favor downy brome. Our laboratory studies indicated that herbicides are intercepted by surface litter, but a significant amount of herbicide can be desorbed by a single precipitation event. Ultimately, herbicide interception by litter combined with the lack of a timely precipitation event may reduce the success of herbicide treatments if not integrated into a sequential management plan.

Acknowledgments

The authors thank Larimer County Weed District, especially Bobby Goeman and Tim D'Amato, for use of their property and various other efforts and the Larimer County Sherriff's Office for assistance in conducting the prescribed burns. Additionally, we thank Jim Sebastian and Rachel Asquith for providing technical assistance.

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