THESIS

EFFECTS OF CHEATGRASS MANAGEMENT ON WILDFIRE RISK AND REFINING CHEATGRASS TREATMENT PRACTICES IN COLORADO FRONT RANGE GRASSLANDS

Submitted by

John Watson

Department of Forest and Rangeland Stewardship

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Master's Committee:

Advisor: Mark W. Paschke
Co-Advisor: Jacob S. Courkamp

Franck E. Dayan

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ABSTRACT

EFFECTS OF CHEATGRASS MANAGEMENT ON WILDFIRE RISK AND REFINING CHEATGRASS TREATMENT PRACTICES IN COLORADO FRONT RANGE GRASSLANDS

Cheatgrass invasion is a critical threat to rangelands in the western United States. Cheatgrass invasion alters ecosystems by diminishing biodiversity and increasing fire risk by promoting fine fuel abundance and continuity. Live fuel moisture content (LFMC) is the water content in living vegetation and when reduced, increases the likelihood of wildfire ignition and potential rate of wildfire spread, making it a crucial predictor of wildfire risk. LFMC is often reduced in rangelands dominated by invasive annual grasses like cheatgrass (*Bromus tectorum* L.) because they senesce earlier in the season compared to native plants. Reductions in LFMC after annual grass invasion increase the likelihood of uncharacteristically frequent, large, and fast-growing wildfires that pose risks to human health, property, and native plant communities. While the impacts of cheatgrass invasion on fire regimes in sagebrush shrublands are well-understood, it is necessary to evaluate the impacts of cheatgrass management in different rangeland plant communities, including grasslands in semi-arid regions like Colorado's Front Range. The herbicide indaziflam (Rejuvra®, Envu) is widely used to manage cheatgrass in rangelands and several studies have verified its effectiveness for reducing cheatgrass abundance. We evaluated the effects of indaziflam treatment on LFMC at six grassland study sites in 2024 and four grassland study sites in 2025 located along the Colorado Front Range. Indaziflam

treatment increased LFMC in treated areas for portions of both summer growing seasons, indicating that treatments reduced wildfire risk for at least a portion of the year.

We also investigated how to effectively control cheatgrass without impacting co-occurring non-target species. Indaziflam is strictly pre-emergent and will not control seedlings established prior to treatment. To promote consistent treatment effectiveness and increase short-term cheatgrass control, land managers often add a post-emergent herbicide as a tank mix with indaziflam to control seedlings that have already germinated and established prior to application. While this is an effective strategy to control cheatgrass, post-emergent herbicides may impact co-occurring non-target plants. We evaluated the effects of two different post-emergent herbicides, rimsulfuron (Matrix®, Corteva) and imazapic (Plateau®, BASF), applied with indaziflam at different rates to determine which post-emergent tank mix provides the most satisfactory short-term cheatgrass control with the least impact to co-occurring non-target plants over the course of two years. The results indicated that all treatments completely controlled cheatgrass by year two of the study, and there were no differences in perennial grass or bare ground cover. We anecdotally observed impacts (stunting) on native perennial grasses resulting from treatments that included rimsulfuron, but these were not observed after the first year of the study and reduction in perennial grass cover were never statistically significant, indicating that non-target impacts were minor and transient when they occurred.

ACKNOWLEDGEMENTS

I could not have earned this degree without the immense support from the community I was fortunate to be a part of at Colorado State University in the Restoration Ecology lab. I would like to start off by thanking my advisor and mentor, Dr. Jacob Courkamp, who with his expertise in rangeland and weed science closely led me through the process of attaining my graduate degree and the completion of this research. I would also like to thank my co-advisor Dr. Mark Paschke, and Dr. Franck Dayan for serving on my committee. They provided valuable guidance and feedback, and their insights were great resources in assisting in the success of this research. This process was made much easier with the support of my fellow graduate students in the Restoration Ecology lab, Nate Nelson and Haley Monahan. Their advice and knowledge were extremely helpful, as well as their assistance with field work at times. The completion of this research would not have been possible without the incredible hard work from all the dedicated undergraduate lab technicians who reliably assisted in completing field work and assisted with lab work with great precision. Lastly, I would like to thank the agencies who provided the grants to fund this research: Boulder County Parks and Open Space, City of Boulder Open Space and Mountain Parks, City of Longmont Open Space and Trails, and Jefferson County Parks and Open Space.

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Introduction

Invasive annual grasses like cheatgrass (*Bromus tectorum*, L.) are a major concern for rangeland managers in the western United States. Cheatgrass is opportunistic, germinating in the fall, winter or early spring, exploiting soil moisture and nutrients before native plants begin growing (Melgoza et al. 1990; Knapp 1996; DiTomaso et al. 2000; Davies et al. 2021). Benefits associated with cheatgrass control include increases in native plant species richness and abundance (Clark 2020; Sebastian et al. 2025), increased pollinator resource availability (Arathi & Hardin 2021), and improved habitat for wildlife (Courkamp et al. 2025). Cheatgrass is known to increase fire frequency, and it is usually the first to invade post-fire (Shinneman & Baker 2009; Fusco et al. 2019), making it difficult for native plants to persist.

While the effects of cheatgrass invasion on fire regimes in sagebrush shrublands are well-understood (Balch et al. 2013; Bradley et al. 2018; Davies et al. 2023), it is necessary to evaluate the impacts of cheatgrass invasion and management in different rangeland plant communities, including grasslands in semi-arid regions like Colorado's Front Range, where homes and urban population centers exist in close proximity to grassland ecosystems. Recent analyses indicate that more houses are exposed to and destroyed by grassland and shrubland fires than by forest fires in the United States (Radeloff et al. 2023; Dutson et al. 2024). With increases in wildfire occurrence after exotic grass invasion reported elsewhere (Fusco et al. 2019), managers are growing more concerned about cheatgrass invasion on the Colorado Front Range, where cheatgrass may have contributed to recent destructive Front Range wildfires that spread rapidly out of control. The Marshall fire that occurred in 2021 in Boulder County, CO destroyed 1,109 homes, more than 30 commercial structures and total costs were over 35 million in tax dollars for community recovery (Boulder County 2026). Given that these uncharacteristically destructive fires are occurring more frequently, it is imperative to further evaluate the impacts of cheatgrass invasion and management on fire risk in grasslands along Colorado's Front Range.

Live fuel moisture content (LFMC) is expressed as the ratio of water content to plant dry weight and represents the amount of moisture that needs to evaporate from a fuel source before ignition can occur (Pivovaroff et al. 2019). Greater fuel moisture means reduced flammability and lower likelihood of ignition, hence LFMC has a major effect on ignition likelihood and potential rate of wildfire spread (Dimitrakopoulos & Papaioannou 2001; Anderson & Anderson 2010; Keeley et al. 2011). Compared to uninvaded plant communities, those invaded by cheatgrass typically have increased fuel amount and continuity and decreased moisture content (Davies & Nafus 2013). Fire behavior is heavily influenced by fuel moisture content, as the moisture contained within both live and dead fuels must evaporate before fuels can combust (Pyne et al. 1996). Reductions in LFMC after cheatgrass invasion are expected to increase the likelihood of uncharacteristically frequent, large, and fast-growing wildfires that pose risks to human health, property, wildlife habitat, and native plant communities (Radeloff et al. 2023; Molvar et al. 2024).

It costs much less to prevent/reduce cheatgrass invasion than to restore or rehabilitate invaded plant communities after uncharacteristically large and frequent wildfires, with the cost of not mitigating cheatgrass-fueled fires estimated at approximately $630 million to $1.2 billion in wildland-urban interface (WUI) firefighting annually (Perryman & Stringham 2012). Cheatgrass distribution is also closely linked to fire seasonality, with areas that support higher cheatgrass abundance being more likely to experience late-season fires (Bradley et al. 2018). Decreased fuel moisture content driven by cheatgrass invasion may be an underlying factor, as cheatgrass dries out earlier in the season compared to other perennial plants (Viegas et al. 1992; Chuvieco et al. 1999; Chuvieco et al. 2023; Ivison et al. 2024). It is important to note that once mean LFMC reaches a critical level, the threat of fire occurrence and spread increases, but this critical level is difficult to determine in different ecosystems (Chuvieco et al. 2009; Dennison & Moritz 2009; Dennison et al. 2008). However, research conducted in the California Chapparal identified thresholds of LFMC below which the likelihood of extreme fire is increased (79%; Dennison et al. 2008).

To mitigate the negative impacts of cheatgrass on fire behavior, land managers must strategically integrate invasive species control to restore more resilient plant communities and break the grass-fire feedback loop (Fusco et al. 2019). Past research indicates that there is a strong relationship between temperature, precipitation, and fuel moisture (Flannigan et al. 2016). Thus, temperature increases in the future may lead to more fire activity due to drier fuels regardless of cheatgrass invasion, making mitigating the additional fire-promoting effects of cheatgrass invasion critical to effective management. Changes in relative humidity, winds, fuels (type, horizontal and vertical distribution etc.), ignitions and fire season length will also influence fire activity (Gillett et al. 2004; Flannigan et al. 2005; Parisien et al. 2011). Different plant functional groups also represent varying fuel types based on unique plant characteristics (Wragg et al. 2018; Radeloff et al. 2023). Therefore, it is necessary to measure differences in fuel moisture at a plant functional group level to explore these differences and how they play a role in influencing fire activity based on their morphological traits (Spasojevic et al. 2010; Pivovaroff et al. 2019; Meller et al. 2022).

Until recently, managers have lacked effective tools for managing cheatgrass. The herbicide imazapic (Plateau; BASF, Ludwigshafen, Germany) is often used to reduce cheatgrass abundance, but the long-term effects of imazapic treatment are variable, and reinvasion from the cheatgrass seed bank 2+ years after treatment is typical (Clark et al. 2020; Courkamp et al. 2022a; Nissen et al. 2025). The newer herbicide, indaziflam (Rejuvra®, Envu, Cary, NC) provides broad spectrum preemergent weed control (Envu 2025), and has been used as a highly effective tool to manage cheatgrass by depleting the cheatgrass seed bank (Clark et al. 2019; Courkamp 2022a; Davies et al. 2023). Indaziflam is a cellulose biosynthesis inhibitor (CBI) herbicide that provides a long period of residual soil activity, which is particularly important for depleting the cheatgrass seedbank and preventing rapid reinvasion (Morris et al. 2009; Sebastian et al. 2016; Davies et al. 2025a; Davies et al. 2025b). Indaziflam has reliably controlled annual grasses for as long as six years in several research trials (Courkamp et al. 2022b; Dombro et al. 2025a; Courkamp et al. 2025; Sebastian et al. 2025), and long-term control observed in other studies suggests that indaziflam treatment may nearly eliminate the cheatgrass seed bank (Sebastian et al. 2016; Courkamp et al. 2022a; Davies et al. 2025a; Dombro et al. 2025b). This makes indaziflam a uniquely effective tool for cheatgrass management, and it is likely that more managers will seek to manage cheatgrass in the future given the increased likelihood of success.

Fuel treatments (e.g., prescribed burns, herbicide application, livestock grazing) can effectively lower fire severity and can reduce wildfire risk in the WUI, where wildlands border homes and buildings (Dutson et al. 2025). With increased wildfire occurrence and severity in the expanding WUI (Liu et al. 2015; Radeloff et al. 2023), the advancement of cheatgrass management tools, and the potential effects of reducing cheatgrass abundance on LFMC, it is necessary to conduct further research to better understand potential effects of cheatgrass management with indaziflam on LFMC in semi-arid grasslands. We sought to build on previous research by measuring the effects of indaziflam treatment and subsequent reductions in cheatgrass abundance on LFMC. In this study, we collected bi-weekly vegetation biomass samples to measure plant LFMC across two summer growing seasons (approximately May-September 2024 & 2025) on the Colorado Front Range to understand how cheatgrass management influences LFMC, and, concurrently, wildfire risk. We also examined differences in LFMC among individual vegetation functional groups to better identify which groups most strongly influence LFMC throughout the growing season. By conducting this study, we sought to address how managing cheatgrass using indaziflam may reduce the risk of wildfire in semi-arid grassland plant communities during summer growing seasons. This study seeks to answer three primary questions:

1) Does indaziflam treatment increase wildfire risk in semi-arid grasslands?
2) How do the effects of indaziflam treatment on risk of wildfire in semi-arid grasslands change over the course of the growing season?
3) How do patterns in LFMC of different vegetation functional groups vary over the course of the growing season?

We predicted that indaziflam treatment would decrease wildfire risk in treatment plots compared to untreated control plots for at least a portion of the summer growing season, and that treatment effects on wildfire risk would be greatest later in the summer, after cheatgrass has dried out compared to native plants. We also predicted that cheatgrass would have the lowest LFMC compared to other vegetation functional groups for most of the summer growing season but were unsure how LFMC of other plant functional groups would compare to each other.

Methods

Study location

This study was conducted at six study sites, four in Boulder County, CO and two in Jefferson County, CO during the 2024 and 2025 growing seasons (May-September). The two Jefferson County sites were excluded from the study in 2025 due to logistical constraints. All study sites featured areas treated with indaziflam for cheatgrass control (treatment plots) and nearby similar untreated locations (control plots). Treatment areas at all sites were treated with 102 g ai ha^{-1} of indaziflam, but the details of treatment (timing, tank mix partner, and application method) differ slightly between sites (Table 1).

Table 1. Treatment information for the six Front Range grassland study sites included in the study.

Study Site	Treatment Date	Treatment Notes
Rabbit Mountain	1-December-2021	Aerial treatment (helicopter); 102 g ai ha^{-1} indaziflam + 351 g ai ha^{-1} glyphosate.
Hall Ranch Mine	3-April-2023	Ground treatment (fixed boom); 102 g ai ha^{-1} indaziflam.
Highway 36A	8-January-2018	Ground treatment (fixed boom); 102 g ai ha^{-1} indaziflam + 421 g ai ha^{-1} glyphosate.
Highway 36B	8-March-2021	Ground treatment (fixed boom); 102 g ai ha^{-1} indaziflam + 351 g ai ha^{-1} glyphosate.
Mathews-Winters Park	4-October-2022	Aerial treatment (helicopter); 102 g ai ha^{-1} indaziflam + 88 g ai ha^{-1} imazapic.
Mt. Galbraith Park	23-June-2021	Ground treatment (boomless); 102 g ai ha^{-1} indaziflam.

All study sites were located along the Colorado Front Range in the foothills region of the southern Rocky Mountains. The four sites ranged in elevation from 1676-1829 m. All untreated control areas were dominated by invasive annual grasses and forbs including cheatgrass, Japanese brome (*Bromus japonicus* L.) and non-native alyssum (*Alyssum* spp.). Other invasive plants present at our study sites included Dalmatian toadflax (*Linaria dalmatica* [L.] Mill.), common mullein (*Verbascum thapsus* L.), musk thistle (*Carduus nutans* L.) and field bindweed (*Convolvulus arvensis* L.). Treatment areas were dominated by native perennial grasses, forbs, and shrubs including western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), big bluestem (*Andropogon gerardii* Vitaman), needle-and thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth), hairy golden aster (*Heterotheca villosa* [Pursh] Shinners), lambs quarter (*Chenopodium album* L.), showy milkweed (*Asclepias speciosa* Torr.), slimflower scurfpea (*Psoralidium tenuiflorum* [Pursh] Rydb.), white sage (*Artemisia ludoviciana* Nutt.), rose (*rosa* spp.), mountain mahogany (*Cercocarpus montanus* Raf.), rubber rabbitbrush (*Ericameria nauseosa* [Pall. ex Pursh] G.L.), fringed sage (*Artemisia frigida* Willd.), and wild tarragon (*Artemisia dracunculus* L.).

Experimental design

At each study site (replicate), four 3 × 3-m subplots (subsamples) were installed at random locations in both the treatment and control plots. The corners of each subplot were marked with pin flags and large steel nails. We added two additional subplots in each control and treatment plot at each study site included in 2025 to better capture variation in the sampled plant communities. Bi-weekly vegetation canopy cover and fuel moisture data were collected from these plots nine times (sample timings) over the course of the summer 2024 and 2025 growing seasons. Sampling was not conducted during precipitation events to ensure accurate representation of LFMC. We also established repeat photo locations at each site. Locations were chosen such that photos represent and illustrate differences between each treatment and control area. Photographs were taken whenever LFMC sampling occurred to visually document conditions in each plot over the course of the growing season.

Vegetation functional group cover sampling

For cover data, we recorded ocular estimates of absolute percent canopy cover of vegetation functional groups for perennial grasses, shrubs, forbs (perennial and biennial forbs combined), invasive annual grasses and invasive annual forbs in each subplot. We also recorded the cover of bare ground, litter, rock, and standing dead vegetation.

LFMC sampling

For fuel moisture data, we clipped approximately 30 g of each vegetation functional group present in each subplot. We avoided collecting vegetation from inside subplots to prevent disturbing the vegetation and changing subsequent cover data collection, so biomass samples for each functional group were collected in the immediate vicinity of each plot. We matched the species composition of our biomass samples with the approximate composition of each respective subplot, and native and non-native species were combined for each functional group, excluding invasive annual grasses and invasive annual forbs, which were collected separately. For shrubs, we collected both woody stem material and current-year's growth to approximate fuel conditions. Biomass samples were immediately placed in pre-weighed sealed plastic bags after collection and stored in a cooler until transport to Colorado State University (CSU) campus later that same day for weighing (wet weight). After measuring the wet weight of each sample, we placed samples into a drying oven (55 C) for at least seven days before reweighing each sample to determine the dry weight. LFMC for each vegetation functional group in each plot at each sample timing was calculated as:

$$\text{LFMC} = ([\text{wet weight} - \text{dry weight}]/\text{dry weight}) \times 100.$$

Treatment evaluations and data analysis

Data were summarized by multiplying the relative cover of each vegetation functional group by the corresponding LFMC and totaling the resulting values to generate a weighted average LFMC for each subplot and sample timing. Values from treatment and control subplots at each site were averaged to generate an overall LFMC for treatment and control plots at each site (sites as replicates; n = 6 for year one and n = 4 for year two) and sample timing. These data were then used for repeated-measures Analysis of Variance (ANOVA) using the "LMER" package in R (R Core Team 2025). We used ANOVA to investigate the effects of treatment, week, and their interaction (fixed effects) with plot and site included as random effects to account for repeated measures and the paired design of the study, respectively. Visual inspection of quantile-quantile and fitted vs. residual plots were used to verify that our data met the assumptions of ANOVA, and effects were considered significant when $P \leq 0.05$. For year two of the study, LFMC data were square-root transformed before analysis to satisfy the assumptions of repeated-measures ANOVA. When ANOVA indicated that treatment differences existed, we conducted post-hoc pairwise comparisons of LFMC in treatment and control plots at each sample timing (Tukey's HSD), with differences considered significant when $P \leq 0.05$. All data presented herein are shown in their original dimensions.

To further investigate patterns in LFMC, we visually inspected data for each vegetation functional group by plotting mean LFMC for perennial grasses, forbs, shrubs, and combined invasive annual grasses and invasive annual forbs (henceforth invasive annuals) over the course of the growing season (treatment and control plots combined).

We also analyzed vegetation functional group cover. For these analyses, we used cover measurements from the 24-June sample timing for both years for consistency and to evaluate cover at approximate peak standing crop. We compared differences in mean cover in treatment and control plots using paired t-tests with differences considered significant when $P \leq 0.05$. We verified that data met t-test assumptions by inspecting quantile-quantile plots. Treatment resulted in very low invasive annual abundance in treatment plots, with invasive annuals being absent in many cases. This precluded statistical analysis using t-tests, so we calculated 95% confidence intervals for invasive annual cover in treatment and control plots, and considered samples significantly different when intervals did not overlap.

Results

In 2024, all fixed effects and interactions were significant in our ANOVA (treatment $P = 0.016$; week $P < 0.001$; treatment × week $P < 0.01$; Figure 1), suggesting that both treatment and sample timing (week) influenced LFMC. Post-hoc pairwise comparisons of LFMC indicated that LFMC was significantly increased in treatment plots compared to control plots at six of the nine total sample timings, excluding both the earliest and latest sample timings in the season (13-May and 2-September) as well as the 5-August sample timing (Figure 1). The greatest differences in LFMC between treatment and control plots occurred on 24-June (68% in control plots vs. 123% in treatment plots) and 19-August (44% in control plots vs. 88% in treatment plots; Figure 1).

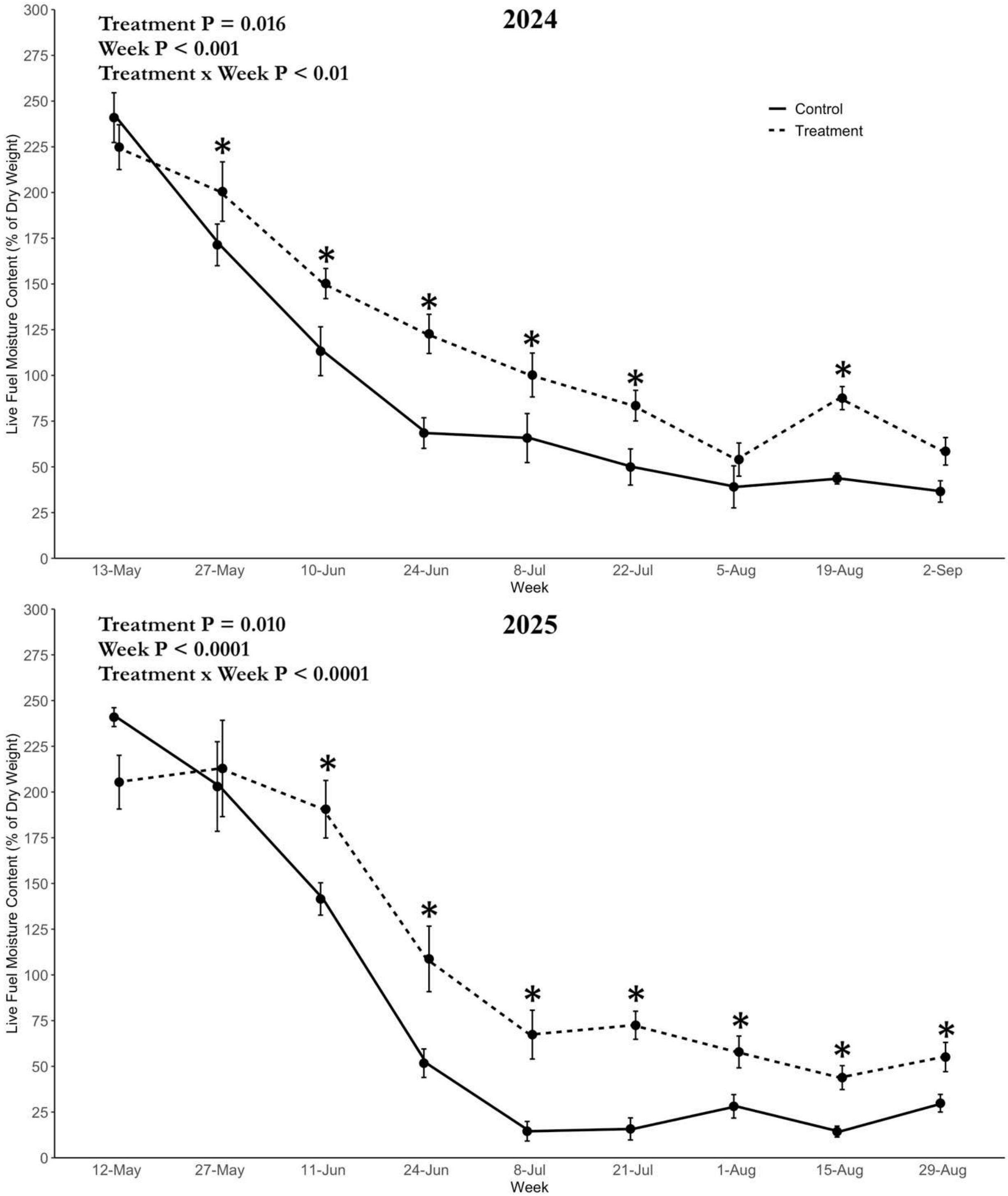

Figure 1. Bi-weekly mean (± SE) live fuel moisture content (LFMC) in control plots (solid) and indaziflam treatment plots (dashed) at grassland study sites in 2024 (top) and 2025 (bottom). Annotations show results of analysis of variance (ANOVA), while asterisks indicate significant differences between treatment and control plots within sample timing (week) based on the results of post-hoc pairwise comparisons using a Tukey adjustment ($P \leq 0.05$; n = 6 for 2024 and n = 4 for 2025).

In 2025, all fixed effects and interactions were significant in our ANOVA (treatment $P = 0.010$; week $P < 0.0001$; treatment × week $P < 0.0001$; Figure 1), suggesting that both treatment and sample timing influenced LFMC for two consecutive years. Post-hoc pairwise comparisons of LFMC indicated that LFMC was increased in treatment plots compared to control plots at seven of the nine total sample timings, excluding the two earliest sample timings in the season (12-May and 27-May; Figure 1). The greatest differences in LFMC between treatment and control plots also occurred on 24-June (52% in control plots vs. 109% in treatment plots) and 21-July (16% in control plots vs. 72% in treatment plots; Figure 1). There were also comparable large differences between treatment and control plots for 11-June and 8-July (LFMC increased approx. 50% by treatment; Figure 1). These results suggest that indaziflam treatment significantly increased overall LFMC across all Front Range grassland study sites for the majority of both the 2024 and 2025 summer growing seasons.

Visual inspection of line plots of LFMC by vegetation functional group (Figure 2) indicated that, in both years, forbs consistently exhibited the highest LFMC throughout the summer growing season. LFMC values were subsequently lower in shrubs, followed by perennial grasses, with invasive annuals exhibiting the lowest LFMC of all groups (Figure 2). All functional groups exhibited high LFMC early in the growing season that declined as the season progressed. In 2024, forbs averaged 187%, shrubs averaged 130%, perennial grasses averaged 96%, and invasive annuals averaged 53% LFMC across the sample timings included in the study. In 2025, forbs averaged 192%, shrubs averaged 124%, perennial grasses averaged 98%, and invasive annuals averaged 72% LFMC across the sample timings included in the study Invasive annuals only maintained high LFMC for the first few sample timings declining rapidly early in the growing season and remaining near 0% LFMC for the rest of the season in both years (Figure 2). The other groups maintained higher LFMC throughout the entirety of the growing season (Figure 2).

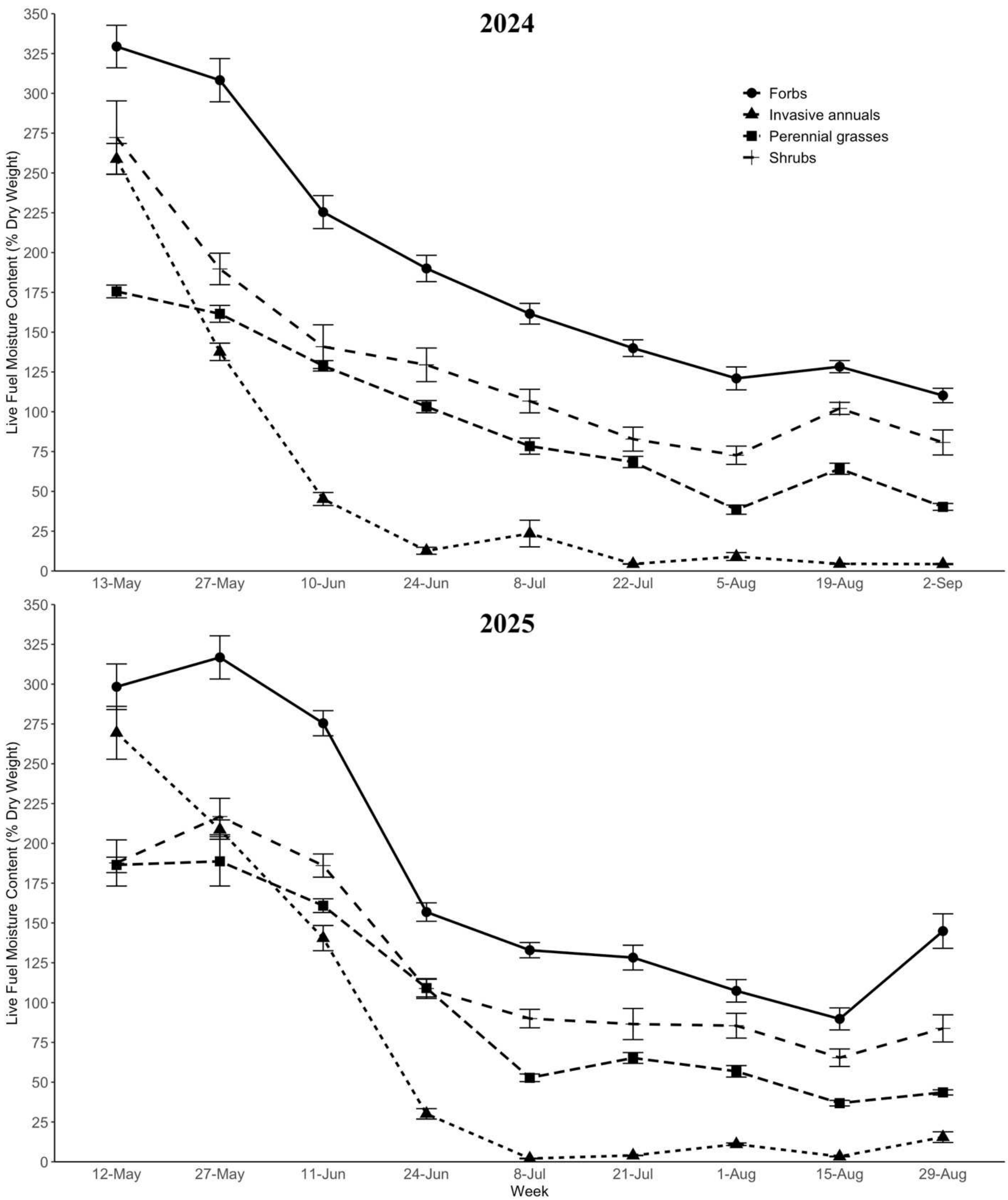

Figure 2. Bi-weekly mean (± SE) live fuel moisture content (LFMC) for vegetation functional groups at all Front Range grassland study sites in 2024 (top) and 2025 (bottom; n=6 in 2024 and n=4 in 2025).

In 2024, analysis of vegetation functional group cover at the 24-June sample timing showed significant differences in cover for perennial grasses and invasive annuals, but not forbs and shrubs (invasive annuals treatment CI = -2.96 - 6.71; control CI = 35.0 - 53.3; perennial grasses $P < 0.01$; shrubs $P = 0.16$; forbs $P = 0.56$; Figure 3).

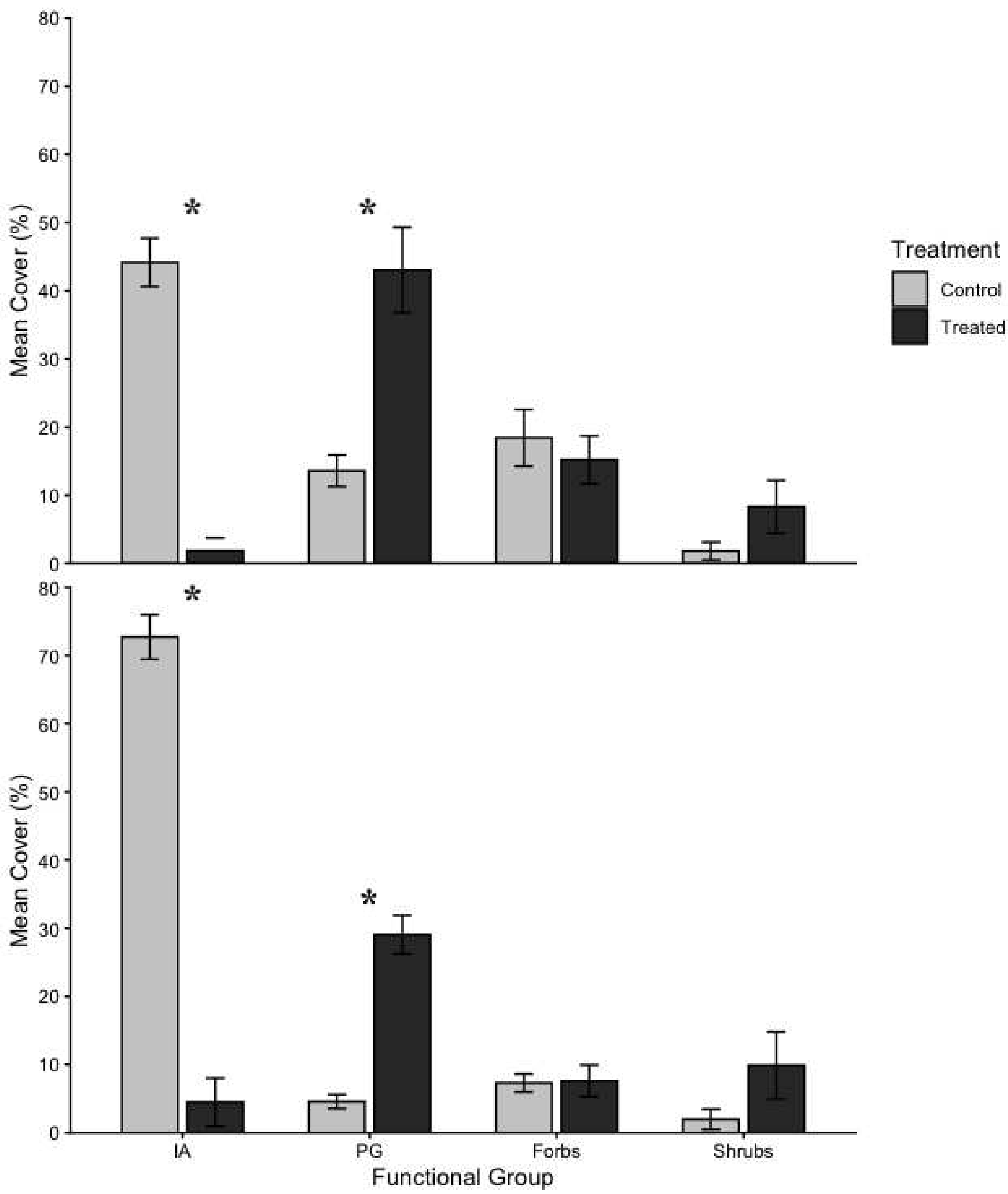

Figure 3. Mean (± SE) vegetation functional group (IA = invasive annuals; PG = perennial grasses; Forbs; Shrubs) cover in control plots (light grey) and treatment plots (black) at the 24-June sample timing across all Front Range grassland study sites in 2024 (top) and 2025 (bottom). Asterisks indicate significant differences based on the results of a t-test ($P \leq 0.05$), except in the case of invasive annuals, which were nearly absent from treatment plots, precluding statistical analysis using t-tests. For invasive annuals we calculated 95% confidence intervals and considered treatment and control samples different when confidence intervals did not overlap.

In 2025, analysis of vegetation functional group cover at the 24-June sample timing showed similar results to 2024 where there were significant differences in IA and grasses, but not forbs and shrubs (invasive annuals treatment CI = -6.8 - 15.8; control CI = 61.1 - 84.5; perennial grasses $P < 0.01$; shrubs $P = 0.20$; forbs $P = 0.90$; Figure 3). Perennial grass cover averaged 5% in control plots and 29% in treatment plots; invasive annuals averaged 73% in control plots and 5% in treatment plots; forbs averaged 6% in control plots and 8% in treatment plots; shrubs averaged 2% in control plots and 10% in treatment plots (Figure 3).

These results suggest invasive annuals were controlled in treatment plots during both years, but cheatgrass was encountered infrequently and at low abundance in some treatment plots. It was also common in control plots to have annual alyssum mixed in with cheatgrass, averaging 26% of the vegetation cover while 0% was observed in treatment plots in both years. Overall, in both years invasive annuals were greatly reduced in treatment plots compared to control plots, while perennial grass cover increased in treatment plots compared to untreated control plots.

Discussion

This study reinforces the results of previous studies indicating that indaziflam is an effective tool for long-term cheatgrass control, providing almost complete control of cheatgrass and other invasive annuals for up to six years after treatment (Davies et al. 2025a; Dombro et al. 2025a; Courkamp et al. 2025; Sebastian et al. 2025; Table 1; Figure 3). Beyond controlling invasive annuals, our results suggest that indaziflam facilitated the release of the perennial grasses in treatment plots (Figure 3).

Our observation of increased LFMC for the majority of two consecutive growing seasons, aligns with our predictions. Our results suggest that indaziflam treatment likely reduced the risk of wildfire ignition and the potential rate of wildfire spread at our sites by increasing LFMC for much of the summer, but not as much early in the season when cheatgrass was still green and growing (Figure 1). Much of the western United States is dominated by invasive annual grasses (Bradley et al. 2018; Smith et al. 2023; Boyd et al. 2024) making effective long-term annual grass control imperative to maintaining normal fire regimes and successful natural resource management. While it is difficult to quantify the reduction in fire risk associated with increases in LFMC comparable to those we observed in our project, our sites maintained LFMC levels above critical fire risk thresholds reported for similar rangeland ecosystems (79% in California chaparral; Dennison et al. 2008; Drucker 2024), below which fire risk increases substantially. Also aligning with our predictions, invasive annual LFMC was < 20% and lower than all other vegetation functional groups for most of both seasons included in our study (Figure 2). We observed cheatgrass as dead, dry fuel by mid- to late-June in control plots at our sites. These results suggest that cheatgrass approached the LFMC threshold for rapid ignition (Drucker 2024) early in the season, increasing fire risk. These findings support the suggestion that managing fuels using herbicides and other management interventions that reduce cheatgrass abundance (Kuhns & Daniels 2012; Dutson et al. 2024) may reduce wildfire risk.

Our results also highlight the threat of cheatgrass-fueled wildfires in Colorado Front Range grasslands (Prevéy & Seastedt 2015; Molvar et al. 2024). While the impacts of cheatgrass invasion on fire regimes in plant communities other than sagebrush shrublands (Plucinski et al. 2010; Simic et al. 2023; Chambers et al. 2024) have been somewhat overlooked, this study demonstrates how cheatgrass invasion reduces the LFMC of the perennial-dominated plant communities it invades and likely promotes wildfire in grasslands along the Colorado Front Range. This is especially pertinent given the rapid expansion of the WUI (Radeloff et al. 2023) and the increasing proximity of wildfire to homes and other important infrastructure (Dutson et al. 2024). Cheatgrass invasion and uncharacteristically frequent wildfire are a major threat to people, property, ecosystems, and ecosystem services (Oliveras et al. 2009; Plieninger et al. 2013; Cunningham et al. 2024). In addition, the implications of frequent cheatgrass-fueled wildfires do not become easier to navigate with climate change and increasing temperatures (Fried et al. 2004). As this study has shown, effective tools like indaziflam will be important for preventing uncharacteristic wildfires, before costly damage occurs and ecosystems are altered to a point that makes restoration more costly and difficult (Davies et al. 2021).

While conducting this study, we found that specific plant functional groups were likely driving LFMC increases in treatment plots. Perennial grass, shrub, and forb LFMC remained much higher than invasive annual LFMC for most of both seasons, with forbs having notably higher LFMC than all other functional groups (Figure 2). This shows that forbs may play a crucial role in increasing overall LFMC, and previous research has demonstrated that forbs can reduce both fire intensity and fire spread compared with other functional groups (Wragg et al. 2018). Forbs are known for their importance for increasing biodiversity, increasing pollinators, forage quality for wildlife and their overall aesthetic. This study demonstrated that forb species retained the highest percent LFMC throughout the entirety of the summer growing season (Figure 2) further illustrating the importance of increasing forb diversity in grassland plant communities. Managers more commonly use a mix of native grass seed in their seed mixes but with the implications of reducing wildfire ignition and rate of spread shown in this study, managers may want to consider adding more forb species to their seed mixes to potentially increase overall LFMC, and reduce the risk of wildfire that may result in the destruction of valuable property, and even more importantly human life. At our sites, perennial grasses also maintained relatively high LFMC throughout the growing season (Figure 2), and previous research indicates that perennial grasses maintain higher LFMC compared with invasive annual grasses, which fall below the ignition threshold before other grasses (Livingston et al. 2016). In our study, perennial grasses maintained LFMC above the threshold for rapid ignition for most of the growing season (Drucker 2024; Figure 2). This is a key finding because perennial grasses dominated the canopy cover of treatment plots (Figure 3). While it is notable that forb LFMC was greater than other functional groups, their cover was similar and lower than perennial grasses across treatment and control plots. This pattern may reflect increased competition between grasses (annual and perennial), and less competition between annual grasses and forbs, which had comparable abundance in treatment and control plots. This pattern suggests that when indaziflam effectively controls cheatgrass, it facilitates an increase in perennial grass abundance and subsequently increases plant community LFMC.

Interestingly, we observed trends in increased LFMC correlating with precipitation. In 2024, almost no precipitation occurred during the two weeks preceding the 5-August sample timing (Figure 5), and this was reflected in the comparable LFMC observed in treatment and control plots at this time (Figure 1). This dry period was followed by relatively wet weeks in early August and increasing LFMC in treatment plots at the next sample timing (19-August), when we observed a significant mean difference in LFMC. This suggests that vegetation in the treatment plots responded to precipitation while vegetation in control plots did not (Figure 1). The growth of perennial vegetation in treatment plots is also clearly represented in photographs from the Rabbit Mountain study site (Figure 4). It is encouraging that, while invasive annuals dry out after completing their short life cycle in the early summer, native plants will utilize moisture from late summer rain events and green up later in the season, increasing LFMC. It is important to consider precipitation as a driver of LFMC because precipitation can vary from year to year (Higgins et al. 2007; Easterling et al. 2017). Therefore, the effects of indaziflam treatment on LFMC may vary from year to year as they did slightly between 2024 and 2025 in this study. Overall, indaziflam treatment and cheatgrass control increased LFMC for most of the summer in both years, but our results also suggest that more consistent precipitation may lead to greater increases in LFMC as a result of treatment.

Figure 4. Left photo is of boundary between control (left) and treatment (right) plots at the Rabbit Mountain study site on 5-August-2024 and the right photo is the same photo point on 19-August-2024. Note the green-up in treatment plot due to late-summer precipitation.

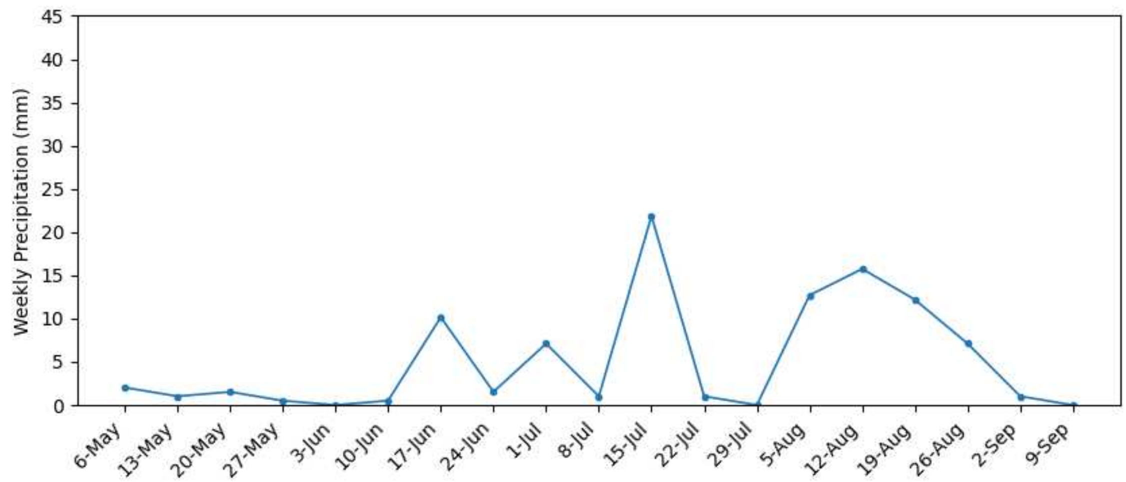

Figure 5**.** Weekly precipitation in Lyons, Colorado during summer 2024 (Station CO-BO-146; CoCoRaHS 2025). Total precipitation for the 2024 growing season (May-September) was 121.16 in comparison to a 30-year average of 239.78 in (PRISM 2025). Note the late summer rain event that caused a spike in LFMC during the 19-August sample timing (Figure 1).

This study demonstrates that indaziflam treatment can reduce wildfire risk, but managers should consider ways to integrate other tools and refine indaziflam treatment practices. Another useful tool that has become more available and efficient is remote sensing (Danson et al. 2004; Buchholtz et al. 2023; Wang & Xingwen 2023), which can be used to quickly identify areas of reduced vegetation moisture using the normalized difference vegetation index (NDVI), among other indices, to rapidly identify critically dry areas and reduced LFMC across time and space. This approach could be used to identify areas of high wildfire risk and, when paired with knowledge of cheatgrass abundance, candidate sites for indaziflam treatment. In addition, while this study is relevant to the Colorado Front Range and similar semi-arid grasslands, it is important to understand the effects of indaziflam treatment in other systems with varying precipitation patterns, and remote sensing tools may also be a useful tool for accomplishing this objective. Future research should also evaluate indaziflam treatment effects on LFMC outside of the growing season (May-September) to better understand wildfire risk and mitigation strategies in grasslands during drier winter years. In late 2025 and early 2026, the Colorado Front Range experienced small grassland fires due to uncharacteristically dry and windy conditions (Roedel 2026).

Fire regimes have shifted from their historical characteristics due to changing abiotic and biotic environmental factors, primarily stemming from improper wildfire management techniques and increased disturbance from human use. Historically, grassland fires that occur on the Colorado Front Range are characterized as frequent and low severity, therefore, fire is an important part of the ecosystem processes that exist there. Cheatgrass invasion causes fires to occur even more frequently than what the native plant community has adapted to. When managing for wildfires, especially in areas that are seeing rapid urbanization like the Colorado Front Range, it is important to remember we do not need to restore these systems back to the exact historical fire regime but use it as a guide for management. Wildfires need to be more manageable in these areas that are critical for protection and threaten human lives. By controlling the cheatgrass and preventing reinvasion you are shifting the ecosystem back towards its historical fire regime, allowing managers to better predict and maintain control when fires may occur.

Conclusion

This study further reinforces the findings of past research demonstrating the effectiveness of the herbicide indaziflam for reducing cheatgrass abundance, while also providing additional insight into how cheatgrass management influences wildfire risk. By reducing the dominance of invasive annual grasses, indaziflam treatment mitigates fuel conditions that contribute to uncharacteristic wildfires and promotes conditions that support higher and more stable LFMC throughout the growing season. These findings highlight the important link between invasive annual grass management and fuel characteristics that directly influence fire behavior in grasslands. It is important for managers to consider the detrimental costs of uncharacteristic wildfires fueled by invasive annual grasses, and the potentially costly loss of infrastructure and need for rangeland restoration, when this can be avoided by proactive cheatgrass management in grasslands like the ones that surround cities and homes all along the Colorado Front Range. Further, this work emphasizes the need for continued investigation of wildfire risks in grassland ecosystems, particularly in the context of invasive species management. Improved understanding of LFMC responses will aid land managers attempting to accurately assess wildfire risk, while also informing decisions related to wildlife habitat, livestock grazing, and native plant restoration. Effective cheatgrass control can help shift grassland communities toward more resilient native perennial systems, in conjunction with effective wildfire risk mitigation.

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Chapter 2: Evaluating indaziflam tank mix partner impacts on co-occurring non-target plant species

Introduction

Invasive annual grasses like cheatgrass (*Bromus tectorum* L.) are a major issue for land managers and pose major threats to native ecosystems across the western United States (Knapp 1996; Monaco et al. 2017; Davies et al. 2021). Cheatgrass life-history traits include variable germination timing, high seed production, rapid growth, and soil moisture and nutrient content exploitation, making it one of the most critical threats to native rangelands (Young et al. 1987; Arredondo et al. 1998; Germino et al. 2015; Davies et al. 2021). Further, research indicates that cheatgrass control may increase native plant species richness and abundance (Clark 2020; Sebastian et al. 2025) and pollinator resource availability (Arathi & Hardin 2021), along with improving wildlife habitat (Courkamp et al. 2025). Cheatgrass invasion also increases fine fuel continuity and abundance, increasing wildfire frequency, occurrence, and rate of spread; these impacts promote a grass-fire feedback loop that reduces the likelihood of native plant community persistence (Fusco et al. 2019). The negative ecological impacts of cheatgrass justify further research and development of improved management strategies.

Imazapic (Plateau®, BASF) is a post-emergent herbicide that is widely used to manage cheatgrass but typically fails to control cheatgrass effectively past 2 years after treatment (YAT; Mangold et al. 2013; Clark et al. 2019; Courkamp et al. 2022a). Rimsulfuron (Matrix®, Corteva) has also previously been used as a post-emergent herbicide to control invasive annual grasses, but it only provides short-term control (Kyser et al. 2013; Wallace & Prather 2016). More recently, the herbicide indaziflam (Rejuvra®, Envu) has been used as a highly effective tool to manage cheatgrass. It has broad spectrum preemergence activity with long soil residual activity, which is important for cheatgrass seedbank management (Sebastian et al. 2016; Sebastian et al. 2017; Clark 2020; Courkamp et. al. 2022a). Indaziflam targets the top layer of the soil, selectively controlling annual grasses with relatively shallow roots, while established native perennials with deeper roots avoid herbicide uptake (Clark 2020). Several studies have verified its effectiveness for reducing cheatgrass abundance without causing damage to native perennials (Sebastian et al. 2016; Sebastian et al. 2017; Courkamp et al. 2022a; Courkamp et al. 2022b; Sebastian et al. 2025) and its ability to provide long-lasting control of cheatgrass, reducing its density and cover for up to six YAT (Courkamp et al. 2025; Dombro et al. 2025; Sebastian et al. 2025; Watson et al. in preparation). However, control in the first year after treatment application can be variable when using indaziflam on its own (e.g., Courkamp et al. 2022b), likely due to indaziflam's lack of post-emergent activity.

Adding post-emergent herbicides as tank mixes with indaziflam may help managers achieve more effective and consistent short-term control of cheatgrass, and more reliably and immediately mitigate its harmful ecological impacts. Previous studies have observed excellent control when adding post-emergent tank mixes to indaziflam, while also observing positive native grass and forb cover responses (Clark et al. 2019; Clark 2020; Seedorf et al. 2022), but more research is necessary to evaluate a broader array of treatments and timings at a wider variety of sites. When mixing pre-emergence herbicides with post-emergence herbicides, managers are simultaneously controlling the annual grass seed bank as well as seedlings that have already emerged. Adding a post-emergence tank mix may be especially critical for cheatgrass management due to its ability to emerge and grow at different times of year based on the timing of resource availability (Young et al. 1987), which makes it difficult for managers to consistently time treatments to maximize herbicide effectiveness. Applying indaziflam with a post-emergence tank mix partner in the fall may produce short- and long-term cheatgrass control with minimal impacts to native plants that are dormant when herbicide is applied, but the potential for non-target impacts to native plants with different herbicides and application rates has not been fully explored.

The study site was invaded by both cheatgrass and Japanese brome (*Bromus japonicus* L.), which were combined for the purposes of the study, given they are nearly identical and they are referred to as "invasive annual grass" (IAG). Identifying effective post-emergent tank-mix partners is essential for promoting consistent cheatgrass treatment outcomes while limiting unintended impacts to co-occurring non-target species. Accordingly, this study addresses the following research question:

1) What post-emergence tank mix treatment provides the most satisfactory short-term IAG control while minimizing negative impacts to co-occurring non-target species cover?

We predicted that all treatments including post-emergent herbicides would provide short-term IAG control, and that impacts to co-occurring perennials, if they occur, will be transient and dissipate by the second year after treatment.

Methods

Study site

The study was conducted at Hall Ranch Open Space in Boulder County, CO west of Lyons, CO (40°12'57.5"N 105°19'11.6"W). The study site was located at an elevation of approximately 1,890 m. The herbicide application was conducted on 2-October-2023. The weather conditions were 18-21 C, with a slight breeze (<2.2m s^{-1}). Perennial plants were dormant and previous year's growth of IAG was 20-40% canopy cover; IAG seedlings were 2.5-5.1 cm (1-2 leaves). The local plant community can be described as semi-arid rolling grasslands infested with IAG. Native grass and forb species present at the site included western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve), prairie sandreed (*Calamovilfa longifolia* [Hook.] Scribn.), blue grama (*Bouteloua gracilis* [Willd. Ex Kunth] Lag. Ex Griffiths), needle-and-thread (*Heterostipa comata* [Trin. & Rupr.] Barkworth), heath aster (*Symphyotrichum ericoides* [L.] G.L. Nesom), slender cinquefoil (*Potentilla gracilis* Douglas ex Hook.), hairy false goldenaster (*Heterotheca villosa* [Pursh) Shinners], and white sage (*Artemisia ludoviciana* Nutt.). Minor shrubs were also present at the site including fringed sage (*Artemisia frigida* Willd.), and rubber rabbitbrush (*Ericameria nauseosa* [Pall. Ex Pursh] G.L. Nesom & Baird).

Experimental design and measurements

Herbicide treatments were applied using a CO_2-pressurized custom-built back-pack sprayer with 11002LP flat-fan nozzles (TeeJet® Spraying Systems, P.O. Box 7900, Wheaton, Il 60187) delivering 187 L ha^{-1} at 207 kPa. Including an untreated control, eight indaziflam treatments were applied with two different post-emergent tank mix partners at varying rates to 3 × 9-m plots in a randomized complete block design with four replications (n = 4). Herbicide treatments evaluated in the study (Table 1) included one indaziflam application rate (73 g a.i. ha^{-1}) mixed with two imazapic rates (88 g a.i. ha^{-1} and 52 g a.i. ha^{-1}), and three rimsulfuron rates (210 g a.i. ha^{-1}, 140 g a.i. ha^{-1} and 70 g a.i. ha^{-1}). All treatments included a 0.25% v/v non-ionic surfactant.

Table 1. Herbicides treatments evaluated in the study.

Herbicide Treatments	Application Rates
Rej. 5	Indazilfam 73 g a.i. ha^{-1}
Rej. 5 + Plateau 3	Indaziflam 73 g a.i. ha^{-1} + Imazapic 52 g a.i. ha^{-1}
Rej. 5 + Plateau 5	Indaziflam 73 g a.i. ha^{-1} + Imazapic 88 g a.i. ha^{-1}
Rej. 5 + Matrix 2	Indaziflam 73 g a.i. ha^{-1} + Rimsulfuron140 g a.i. ha^{-1}
Rej. 5 + Matrix 3	Indaziflam 73 g a.i. ha^{-1} + Rimsulfuron 210 g a.i. ha^{-1}
Rej. 5 + Matrix 1 + Plateau 3	Indaziflam 73 g a.i. ha^{-1} + Rimsulfuron 70 g a.i. ha^{-1} + Imazapic 52 g a.i. ha^{-1}
Rej. 5 + Matrix 2 + Plateau 3	Indaziflam 73 g a.i. ha^{-1} + Rimsulfuron 140 g a.i. ha^{-1} + Imazapic 52 g a.i. ha^{-1}

Vegetation functional group cover sampling and analysis

To quantify herbicide treatment effects, ocular estimation of percent vegetation functional group cover (nearest 1%) was conducted in each study plot. We categorized the different vegetation functional groups as IAG, perennial grasses, forbs (perennial and biennial combined), and shrubs. Bare ground cover was also measured. We did not include forbs and shrubs in our analysis because their abundance was limited and inconsistent in our study plots. Measurements occurred annually on May 20th in 2024 and 2025, approximately 8 and 20 months after application, respectively (henceforth 1 and 2 YAT, respectively).

Field data were used for repeated-measures Analysis of Variance (ANOVA) using the "LMER" package in R (R Core Team 2025) with treatment as a fixed effect, and block included as a random effect. For all comparisons, data were analyzed independently in each year due to interannual variation, visual inspection of quantile-quantile and fitted vs. residual plots were used to verify that data met the assumptions of ANOVA, and means were considered significant when $P \leq 0.05$. Nearly all treatments eliminated IAG from our study plots (mean = 0), precluding statistical analysis using ANOVA. To evaluate treatment effects on IAG, we calculated 95% confidence intervals for all treatments resulting in non-zero means for IAG cover and considered these significantly different from treatments with a mean of zero when their confidence intervals did not overlap with zero.

Results

Treatments did not significantly reduce IAG canopy cover 1 YAT, but all treatments did significantly reduce IAG canopy cover by 2 YAT (Figure 1). It is important to note that the lack of treatment effects 1 YAT was likely due to the low abundance of IAG in the control plots, and that IAG were absent from all treated study plots at this time. There were no differences in perennial grass or bare ground cover in both years (Figure 1).

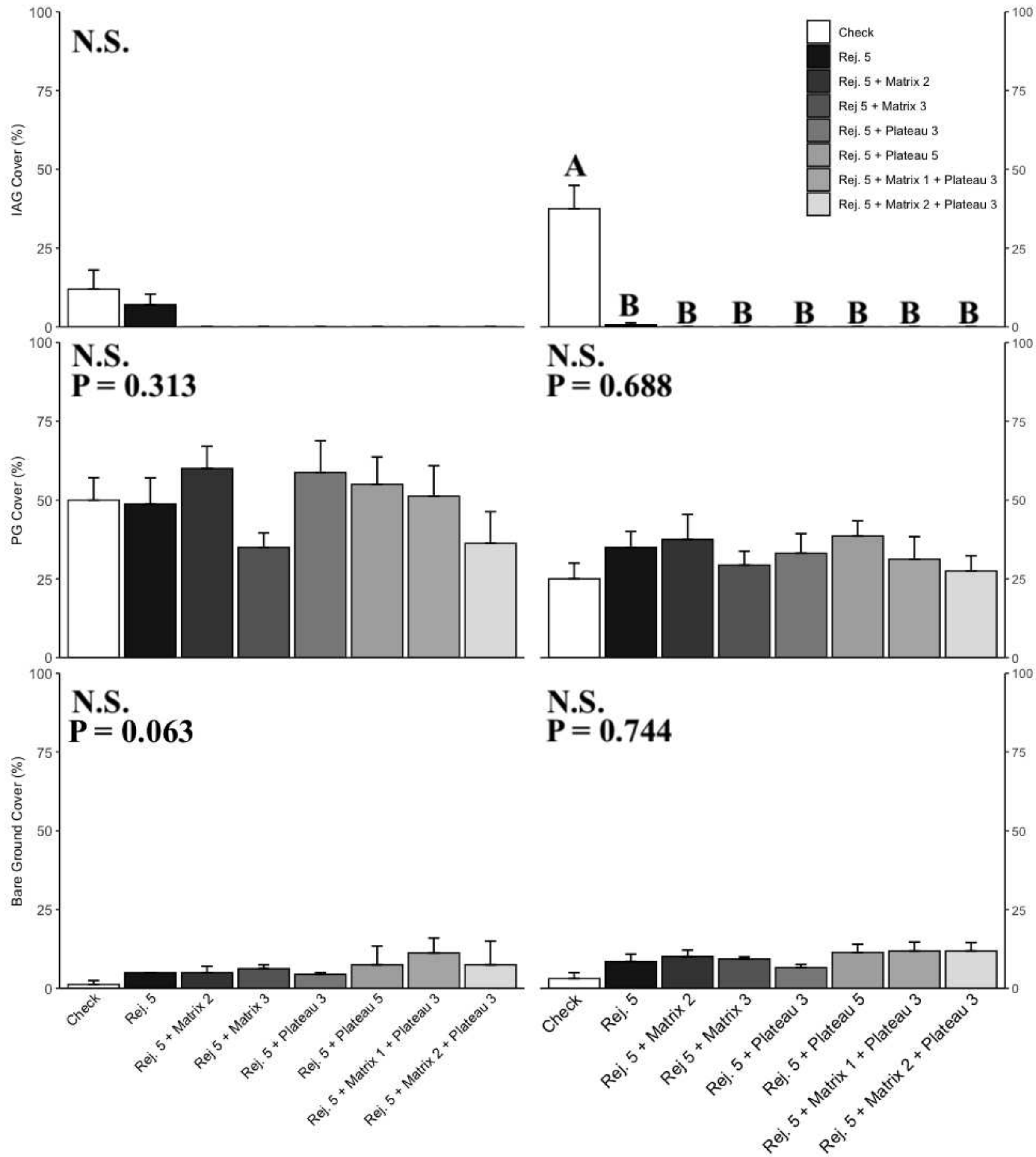

Figure 1. Mean (± SE) cover of invasive annual grasses (IAG; top), perennial grass (PG; middle), and bare ground (bottom) in treated and untreated (check) plots (n = 4) at 1 year after treatment (YAT; left panels) and 2 YAT (right panels). Annotations show results of analysis of variance (ANOVA; $P \leq 0.05$). Herbicide treatments were applied on 2-October-2023 using a CO_2-pressurized, custom-built backpack sprayer calibrated to deliver 187 L ha^{-1} at 207 kPa. See Table 1 for detailed treatment information.

Discussion and Conclusion

Herbicide treatments did not reduce IAG canopy cover at 1 YAT, likely due to the lack of IAG in control plots (Figure 1). By 2 YAT, all treatments provided satisfactory IAG control, and IAG canopy cover increased substantially in control plots (Figure 1). No differences were detected for perennial grass cover or bare ground in either year. However, field observations of stunting indicated that treatments containing higher rates of rimsulfuron (210 g a.i. ha^{-1}) and combinations of all three herbicides may have resulted in short-term impacts to perennial grasses. These short-term effects diminished by 2 YAT.

Figure 2. Photographs of representative untreated control plot (left) and plot treated with 73 g ai ha^{-1} indaziflam (Rejuvra®, Envu) and 210 g ai ha^{-1} rimsulfuron (Matrix®, Corteva) 1 year after treatment. Note the appearance of minor impacts to perennial grasses. No significant differences in perennial grass cover were detected in our analysis.

It is also interesting to note that bare ground cover did not increase significantly either 1 or 2 YAT (Figure 1). This may be due to the increased perennial grass cover resulting from release of the native perennials after IAG control, but we did not detect an increase in perennial grasses in our analyses. Overall, treatment effects on all response variables, including bare ground, appear to be minor and not statistically significant. Our results indicate that all treatments effectively controlled IAG 2 YAT with little to no effect on the above ground native plant community (Figure 1) further reinforcing results of previous research trials (Sebastian et al. 2017; Mangold 2024; Davies 2025; Nissen et al. 2025). While we did not detect any significant reductions in perennial grass cover, managers should be aware that treatments including rimsulfuron may result in minor and transient impacts to perennial grasses based on anecdotal observations of our study plots (Figure 2). These impacts were not observed for treatments including indaziflam and imazapic, suggesting that this treatment combination may be less likely to result in damage to established perennial grasses while providing IAG control comparable to all other treatments included in the study (Figure 1).

Herbicide selection and application rate are critical factors determining treatment success and minimizing non-target impacts (Davies & Sheley 2011; James et al. 2015). Herbicide applications can also be expensive (Sheley et al. 2010) so the results of this study may be useful for managers making treatment plans and seeking to avoid wasting resources on ineffective or damaging herbicide applications. Indaziflam can be applied with a post-emergent tank mix partner to achieve short-term IAG control without impacts on co-occurring non-target species, and our results suggest that indaziflam applied on its own may provide comparable control with almost no potential for non-target impacts when environmental conditions limit short-term IAG establishment as occurred 1 YAT in our study. However, environmental conditions are unpredictable and their effects on IAG are not fully understood (Young et al. 1987), so including a post-emergent herbicide as a tank mix when applying indaziflam is likely advisable in most cases. This is crucial information for land managers when determining how to control invasive annual grasses in native plant-dominated rangelands (D'Antonio & Vitousek 1992; Chambers et al. 2014) and mitigating non-target impacts is crucial to meeting weed management and restoration objectives. Future research should continue to investigate the potential for non-target impacts when using different post-emergent herbicide tank mixes across a wider variety of sites, years, and application timings, which are likely to influence treatment outcomes.

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APPENDIX

(a)

(a)

(c)

(d)

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(f)

(g)

(h)

Figure 1. 2024 photo-point photos from the Rabbit Mountain study site taken at sample timings (week) showing treatment boundaries with the untreated control plots on the left and treatment

plots on the right (photos are in chronological order from left to right; (a) 28-May; (b) 10-Jun; (c) 24-Jun; (d) 8-Jul; (e) 23-Jul; (f) 5-Aug; (g) 19-Aug; (h) 2-Sep).


(a)


(b)


(c)


(d)


(e)


(f)

(g) *(h)*

Figure 2. 2025 photo-point photos from the Rabbit Mountain study site taken at sample timings (week) showing treatment boundaries with the untreated control plots on the left and treatment plots on the right (photos are in chronological order from left to right; (a) 12-May; (b) 11-Jun; (c) 24-Jun; (d) 8-Jul; (e) 21-Jul; (f) 1-Aug; (g) 15-Aug; (h) 29-Aug).