The effects of cheatgrass management with indaziflam on live fuel moisture content in rangeland plant communities along the Colorado Front Range – Year 2

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Executive Summary

Cheatgrass invasion poses a major threat to rangeland plant communities along Colorado's Front Range (Front Range). However, the effects of invasive annual grasses, and other invasive annuals, on fire regimes and wildfire risks to people, property, and ecosystem integrity are less clear in these grassland ecosystems compared to sagebrush shrublands where the fire promoting effects of cheatgrass have been studied for decades. In addition, managers in Colorado have embraced the newer herbicide indaziflam (Rejuvra®, Envu) as a tool to reduce the abundance of invasive annuals in natural areas and open spaces, in many cases nearly eliminating invasive annuals for many years after treatment. Given (1) the relatively recent successes managers have achieved using indaziflam to manage cheatgrass and (2) the existing knowledge gap related to the fire promoting effects of cheatgrass in rangelands along Colorado's Front Range, the objective of our study was to measure the effects of indaziflam treatment, and subsequent reductions in cheatgrass abundance, on the live fuel moisture content (LFMC) of rangeland plant communities along the Front Range over the course of a summer fire season (approximately June-September). A measure of the amount of water contained in live vegetation, LFMC is a key driver of wildfire risk, with large and rapidly spreading wildfires becoming more likely as fuel moisture declines. We predicted that indaziflam treatment would increase LFMC in treatment plots compared to untreated control plots for at least a portion of the summer 2025 season. Importantly, this report details the second year and final year of a study initiated in 2024. Interpretation of results reported herein is likely to be enhanced if the reader is familiar with results reported in 2024. In addition, we added evaluation of key forage quality metrics (crude protein, acid detergent fiber [ADF], and total digestible nutrients [TDN]) to the project in 2025, predicting that indaziflam treatment would improve forage quality.

To achieve our objectives, we conducted bi-weekly biomass sampling at four research sites in Boulder County. Each location featured a treatment plot where indaziflam had been applied to manage cheatgrass sometime in the last several years (2018-2023) and a nearby untreated control plot. We used Analysis of Variance (ANOVA) to evaluate differences in LFMC between treatment and control plots, using each site as a replicate for the analysis (n=4). We found that indaziflam treatment significantly increased LFMC in treatment plots for seven of the nine sample timings included in the study. We also re-analyzed 2024 data from only the Boulder County study sites to permit comparison of treatment effects between years. Re-analysis suggested that treatment effects on LFMC were more modest in 2024 compared to 2025, likely because of differences in the amount and timing of precipitation in 2024 and 2025. Contrary to 2024, data presented in this report also suggest that overall biomass production (standing crop) was not significantly increased in treatment plots in 2025. Forage quality analysis suggested that treatment increased the crude protein content of forage throughout the summer 2025 season, but effects on ADF and TDN were only significant later in the summer (mid-September).

Our results suggest that indaziflam treatment can reduce fire risks by increasing LFMC in treated areas compared to untreated plant communities with abundant invasive annuals, but the effects of treatment may vary depending on the amount and timing of precipitation each year, with more and more consistent precipitation enhancing treatment effects on LFMC. It is important to note, however, that the mitigating effects of increased LFMC are unlikely to blunt fire risk during extreme fire weather (hot, dry, windy conditions). When conditions are less than extreme, however, indaziflam treatment is likely to reduce wildfire risk. Our results also suggest that indaziflam treatment increases forage quality, but that these effects vary according to the specific metric being measured and the timing of sampling.

Introduction

Exotic annual cheatgrass (*Bromus tectorum* L.) has invaded vast expanses of semi-arid rangeland in western North America (Bradley et al. 2018; Kleinhesselink et al. 2023), and increased fire frequency after cheatgrass invasion poses a threat to ecosystem integrity, public safety, and important infrastructure in invaded ecosystems. Cheatgrass litter provides a continuous layer of fine fuel that increases the likelihood of wildfire in invaded plant communities compared to those with little or no cheatgrass (Balch et al. 2013; Davies and Nafus 2013). While research clearly indicates that increased fire is linked to cheatgrass invasion in the sagebrush biome (Balch et al. 2013; Bradley et al. 2018; Davies et al. 2023), the impacts of cheatgrass invasion on wildfire in rangelands along the Colorado Front Range (henceforth Front Range) are less clear (Seastedt 2023).

Until recently, managers had few tools capable of achieving long term cheatgrass control. The herbicide imazapic (Plateau®, BASF) 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 (YAT) is typical (Mangold et al. 2013; Courkamp et al. 2022). Encouragingly, the newer herbicide indaziflam (Rejuvra®, Envu) has provided long-term (3+ years) cheatgrass control in several trials and operational treatments in the western US (Sebastian et al. 2016; Sebastian et al. 2017; Clark 2020), and more research is necessary to better understand the potential wildfire mitigation benefits of effective cheatgrass management.

Live fuel moisture content (LFMC) is an important driver of rangeland wildfire behavior because water contained in vegetation acts as a heat sink that slows down or prevents ignition and reduces the likelihood of wildfire spread (Viegas et al. 1992; Plucinski et al. 2010; Parks et al. 2014). Thus, the potential for wildfire increases as the fuel moisture content of vegetation declines. Fuel moisture can decline in response to dry weather conditions and/or over the course of the growing season as vegetation senesces and dries out, but research has also shown that cheatgrass invasion reduces fuel moisture relative to non-invaded shrub-dominated plant communities in the Great Basin (Davies and Nafus 2013). This is likely due to the early senescence of cheatgrass compared to other plants; senesced cheatgrass provides a source of dry fuel that will readily burn when other native plants are greener and better able to resist ignition, due in part to their higher LFMC. Accordingly, Nafus and Davies (2013) estimated that cheatgrass invasion extended the fire season by more than a month in their study.

While the impacts of cheatgrass invasion on fire regimes in the sagebrush biome are well-documented (Balch et al. 2013; Bradley et al. 2018; Davies et al. 2023), plant communities along the Front Range differ from these ecosystems in important ways (e.g., precipitation timing; vegetative composition). For example, sagebrush-dominated shrublands typically feature more abundant bare ground for cheatgrass to exploit and fill in, whereas grass-dominated rangelands have less open space. Thus, fuel continuity may be altered to a lesser degree by cheatgrass invasion in grass-dominated rangelands along the Front Range compared to Great Basin shrublands, blunting the potential influence of effective cheatgrass management on wildfire mitigation in these ecosystems. However, the early phenology of cheatgrass is distinct from co-occurring native plants in both systems, suggesting that cheatgrass invasion may substantially alter fuel moisture in Front Range rangelands, with subsequent impacts on wildfire risk.

When one considers: (1) the destructiveness of recent wildfires; (2) recent advancements in cheatgrass management tools (e.g., indaziflam); (3) the potential effects of cheatgrass management on fuel moisture; and (4) the influence of fuel moisture on wildfire behavior, it is clear that more research is necessary to better understand the potential effects of cheatgrass management on fuel moisture content in Front Range rangelands. Accordingly, the objective of our study was to measure the effects of indaziflam treatment, and subsequent reductions in cheatgrass abundance, on the live fuel moisture content (LFMC) of rangeland plant communities along the Front Range over the course of a summer fire season (approximately June-September). We predicted that indaziflam treatment would increase LFMC in treatment plots compared to untreated control plots for at least a portion of the summer 2025 growing season. This report details the second and final year of a study initiated in 2024. For more extensive background information, see the 2024 project report (Courkamp and Watson 2024).

Since the project's methods remained largely the same, this report can be considered an addendum to the initial report, and fuel moisture results are best interpreted alongside results from 2024 (see *Discussion)*. However, the project was expanded in 2024 to include evaluation of key forage quality metrics (crude protein, acid detergent fiber [ADF], and total digestible nutrients [TDN]) in treatment and control plots. Recently published research from Boulder County indicates that important wildlife species like mule deer (*Odocoileus hemionus*) may preferentially utilize treated areas for foraging, particularly during winter months (Courkamp et al. 2025). While Courkamp et al. 2025 indicates that forage quantity (i.e., increased shrub leader growth) increased after indaziflam treatment, improved forage quality may also be contributing to increased mule deer utilization. This additional component of the study is a first-step towards evaluating the effects of cheatgrass management on forage quality. We hypothesized that cheatgrass management with indaziflam would increase forage quality in treatment plots compared to untreated control plots.

Methods

Study Sites

We selected four study sites for the project in Boulder County (Table 1; Figure 1). Treatment areas at all sites were treated with 102 g ai ha^{-1} of indaziflam (7 oz ac^{-1} Rejuvra®, Envu) in the last 7 years (2018-2023), but the details of treatment (timing, tank mix partner, application method) differ slightly between sites (Table 2). All sites were representative of Front Range grassland plant communities, and some of the more dominant native plant species across locations included western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), needle-and thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth), big bluestem (*Andropogon gerardii* Vitman), fringed sagebrush (*Artemisia frigida* Willd.), wild tarragon (*Artemisia dranunculus* L.), white sage (*Artemisia ludoviciana* Nutt.), and slimflower scurfpea (*Psoralidium tenuiflorum* [Pursh] Rydb.). While cheatgrass was a major component of the non-native plant community at all sites, non-native annual *Alyssum* spp. were also present and abundant at most sites. Other non-native/invasive species that were present at varying levels of abundance in study plots included common mullein (*Verbascum thapsus* L.), dalmation toadflax (*Linaria dalmatica* [L.] Mill.), and musk thistle (*Carduus nutans* L.). All study locations featured areas treated with indaziflam for cheatgrass control (treatment plots) and nearby similar untreated locations (control plots), and cheatgrass and non-native *Alyssum* spp. were largely absent from treated plots and relatively abundant (>15% canopy cover) in untreated control plots.

Table 1. Locations of the four study sites included in the project. All locations are UTM Zone 13N.

Study Site	UTM E	UTM N
Rabbit Mountain	483053	4453221
Hall Ranch Mine	474742	4450387
Highway 36A	476799	4446150
Highway 36B	478409	4448007

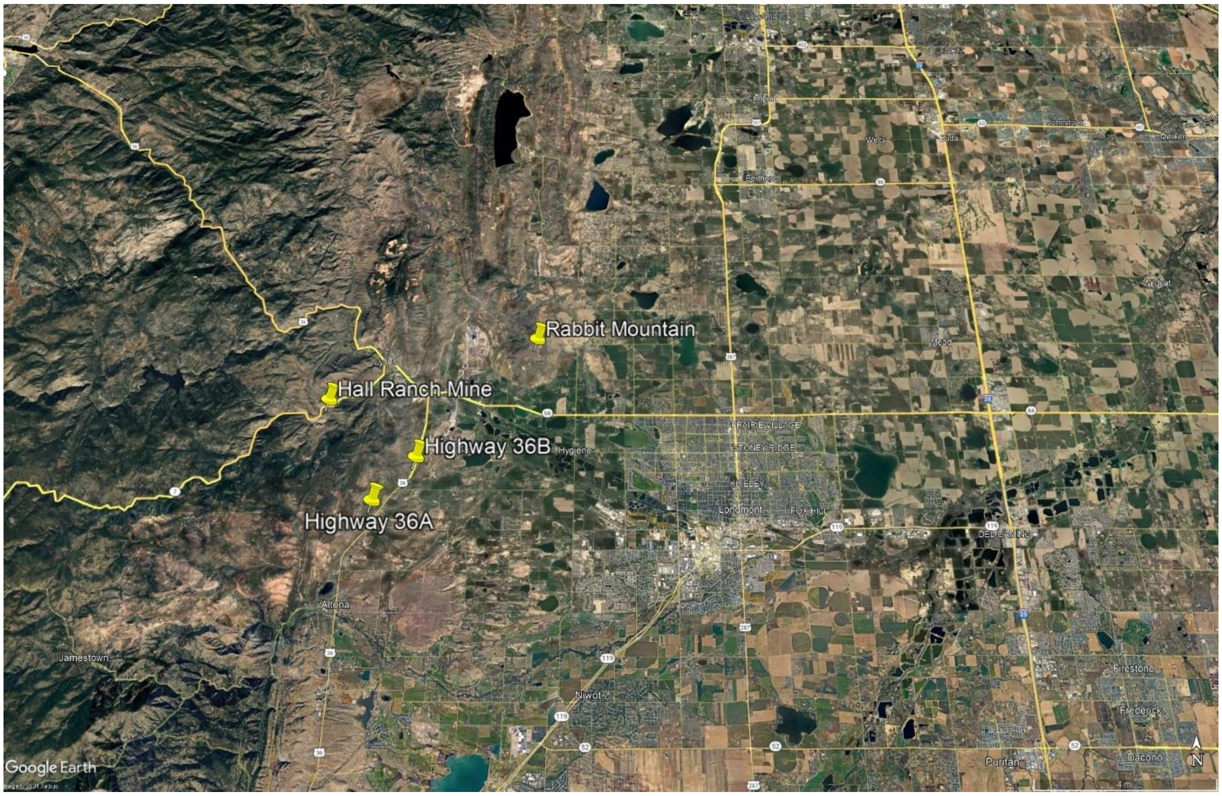

Figure 1. Map showing locations of the four Boulder County sites included in the study (Rabbit Mountain, Hall Ranch Mine, Hwy 36A, and Hwy 36B; Table 1).

Table 2. Treatment information for the six study sites included in the project.

Study Site	Treatment Date	Treatment Notes
Rabbit Mountain	1-December-2021	Aerial treatment (helicopter); 7 oz ac^{-1} Rejuvra (102 g ai ha^{-1} indaziflam) + 10 oz/ac glyphosate.
Hall Ranch Mine	3-April-2023	Ground treatment (fixed boom); 7 oz ac^{-1} Rejuvra (102 g ai ha^{-1} indaziflam).
Highway 36A	8-January-2018	Ground treatment (fixed boom); 7 oz ac^{-1} Rejuvra (102 g ai ha^{-1} indaziflam) + 12 oz/ac glyphosate.
Highway 36B	8-March-2021	Ground treatment (fixed boom); 7 oz ac^{-1} Rejuvra (102 g ai ha^{-1} indaziflam) + 10 oz/ac glyphosate.

Field Sampling

At each study site, six randomly located 3 x 3-m plots (permanent plots) were installed in the both the control and treatment plot. The corners of each permanent plot were marked with pin flags and large steel nails driven into the soil surface until approximately 2.5 cm remained above ground level. We collected vegetation canopy cover and fuel moisture data from these plots nine times over the course of the summer 2025 field season, initiating sampling during the week of 12-May and concluding sampling during the week of 1-September. Sampling took 1-2 days at all sites each time data were collected depending on the weather and competing field work priorities. Photographs were taken of overall treatment and control plots each time sampling occurred.

For cover data, we recorded ocular estimates of absolute percent canopy cover (cover) for grasses, forbs, shrubs, invasive annual grasses and non-native annual forbs (vegetation functional groups) in each permanent plot. We also recorded the cover of bare ground, litter, rock, and standing dead vegetation. For fuel moisture data, we clipped approximately 30 g of each vegetation functional group. We avoided collecting vegetation from inside permanent plots to prevent disturbing the vegetation and changing subsequent data collection, so vegetation samples for each functional group were collected in the immediate vicinity of each permanent plot. We attempted to roughly match the species composition of our biomass samples with the composition of the respective permanent plot, collecting individual samples for vegetation functional groups including: cool-season (C3) native perennial grasses, warm-season (C4) native perennial grasses, native perennial forbs, native perennial shrubs, invasive biennial/perennial forbs, invasive annual grasses, and invasive annual forbs. For shrubs, we collected both woody stem material and current-year's growth to approximate conditions of the shrub community in each plot. Invasive annual grasses included cheatgrass along with lesser amounts of Japanese brome (*Bromus japonicus* L.), while annual *Alyssum* spp. comprised the totality of invasive annual forb samples. Biomass samples were immediately placed in pre-weighed sealed plastic bags after collection and stored in a cooler until transport to Colorado State University campus (CSU) later that same day.

In addition, we collected biomass samples to estimate standing crop by completely clipping four 0.25-m^2 sampling quadrats in each treatment and control plot at each study site three times during the 2024 field season; once in early-July (early-season), once in late-July (mid-season) and once in mid-September (late-season). Frames were subjectively located to match the approximate composition of each permanent plot. All vegetation in each frame was clipped at ground level, excepting shrubs, for which all current year's growth (i.e., fresh shrub leaders) was removed from shrubs in each quadrat. After collection, samples were placed in paper bags and stored in a cooler until transport to CSU later that same day.

Lab Protocol

Biomass samples were weighed to the nearest 0.01 g in their sealed plastic bags immediately after transport to CSU, and wet weight was determined by subtracting the weight of the pre-weighed plastic bag containing each sample. Samples were then transferred to paper bags and placed in a drying oven for a minimum of seven days before being removed and weighed a second time (dry weight), again to the nearest 0.01 g. Live fuel moisture content (LFMC) for each functional group in each permanent plot at each sample timing was calculated as a percentage of dry matter using the formula:

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

Biomass samples for standing crop estimates were also placed in a drying oven for a minimum of seven days, after which they were weighed to the nearest 0.01 g to estimate production. These samples were then stored in a cold-room at CSU until they were shipped to Ward Labs (Ward Laboratories, Inc., Kearney, NE), for forage quality analysis in mid-October. Forage quality analysis measured three key forage metrics: crude protein content, acid detergent fiber (ADF), and total digestible nutrients (TDN). Crude protein and TDN are related to the nutrient content of forage (i.e., higher crude protein and TDN indicate increased forage quality), while ADF is a proxy for lignin, which is undigestible outside of a few very specialized herbivores, like termites (i.e., lower ADF indicates higher forage quality).

Data Summarization and Analysis

Data were summarized by multiplying the relative cover of each functional group by the corresponding LFMC and totaling up the resulting values to generate a weighted average LFMC for each plot and sample timing. Plots were considered subsamples for the purposes of analysis, thus values from each of the six treatment and control plots at each site were averaged to generate an overall LFMC for treatment and control plots at each site and sample timing (sites as replicates; n = 4). 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 the treatment by week interaction (fixed effects) with plot and site included as random effects to account for repeated measures and the paired design of our study, respectively. Visual inspection of quantile-quantile and fitted vs. residual plots was used verify that our data met the assumptions of ANOVA. Data from the 2025 did not initially meet the assumptions of

ANOVA due to a positive relationship between mean and variance, thus data were square-root transformed prior to analysis, but all data are shown in their original dimensions in the report. Fixed effects were considered significant when $P \leq 0.05$. When ANOVA indicated that treatment differences existed, we conducted post-hoc pairwise comparisons of LFMC in treatment and control plots at each sample timing using a Tukey adjustment, with differences considered significant when $P \leq 0.05$. To facilitate comparison and interpretation of data, we also re-analyzed data from 2024 using only data from the four Boulder County study sites in the analysis (2024 project included two additional sites in Jefferson County; Courkamp and Watson 2024). This analysis was conducted in the same manner as analysis of data from 2025, but the 2024 data did not require transformation.

We also conducted correlation analysis to evaluate relationships between vegetation functional groups and LFMC. Invasive annual grasses and invasive annual forbs were combined for the purposes of this analysis. Because vegetation data were not normally distributed, we investigated non-parametric correlations (Spearman's ρ) between LFMC and cool-season native perennial grass, warm-season native perennial grass, combined native perennial grass, native perennial forb, native perennial shrub, invasive biennial/perennial forb, and invasive annual cover. Relationships were considered significant when $P \leq 0.05$.

Student's t-tests were used to compare standing crop, crude protein, acid detergent fiber, and total digestible nutrients in treatment and control plots. Similar to LFMC, data were summarized by site ($n = 4$), and data from the early-, mid-, and late-season sample timings were analyzed independently. Differences were considered significant when $P \leq 0.05$.

Results

Invasive Annual Cover and Control

Invasive annuals were anecdotally controlled in treatment plots at all study sites (Figure 2). However, invasive annuals were beginning to re-establish in treatment plots at Highway 36A, where invasive annual cover ranged from 0-5 % early in the season, and 5-15 % later in the season. Despite this re-establishment, invasive annuals were still greatly reduced compared to control plots, where cheatgrass cover typically exceeded 25 %. The almost complete lack of invasive annuals in treatment plots at other study sites precluded traditional statistical comparisons, but photographic documentation of treatment effects is sufficient to establish that indaziflam treatment controlled invasive annuals in treatment plots. We show an example of photographic documentation of cheatgrass control at the Rabbit Mountain study site in Figure 2, and photographs of treatment and control plots at all study sites and sample timings are included as supplemental material.

Figure 2. Photograph showing the boundary between treatment plot (right) and control plot (left) at Rabbit Mountain on 24-June-2025. Note the reduction in cheatgrass (reddish brown) in the treated area (see Table 2 for treatment details).

Fuel Moisture Differences and Relationships with Vegetation Functional Groups

All fixed effects and interactions were significant in 2025 based on the results of ANOVA (treatment $P = 0.010$; week $P < 0.0001$; treatment x week $P < 0.0001$; Figure 3), suggesting that both treatment and sample timing influenced LFMC, and that the effects of treatment varied over the course of the season. Post-hoc pairwise comparisons of LFMC indicated that LFMC was significantly increased in treatment plots compared to control plots at seven of nine total sample timings, excluding the two earliest sample timings in the season (12-May and 26-May; Figure 3). The greatest differences in LFMC between treatment and control plots occurred on 23-June (52% in control plots vs. 108% in treatment plots), with comparable large differences also occurring for 9-June, 7-July, and 21-July (LFMC increased approx. 50% by treatment; Figure 3).

Re-analysis of 2024 data (only Boulder County study sites) suggested that the effects of treatment and week were significant ($P < 0.0001$), but their interaction was not ($P = 0.39$; Figure 4). This suggests that treatment effects on LFMC were less variable over the course of the 2024 season compared to the 2025 season. Post-hoc pairwise comparisons of LFMC indicated that LFMC was significantly increased in treatment plots compared to control plots at three of nine total sample timings, including 27-May, 24-June, and 19-August (Figure 4). Similar to 2025, the greatest difference in LFMC between treatment and control plots occurred on 24-June (69% in control plots vs. 128% in treatment plots), with a comparable difference also occurring for 27-May (162% in control plots vs. 220% in treatment plots; Figure 4).

Correlation analysis suggested that significant relationships existed between LFMC and the cover of several vegetation functional groups (Figure 5). The strongest positive relationships existed between LFMC and native perennial forbs ($P < 0.01$; $\varrho = 0.33$) and combined native perennial grasses ($P < 0.01$; $\varrho = 0.26$), while a strong negative relationship existed between LFMC and invasive annuals ($P < 0.01$; $\varrho = -0.37$; Figure 5). This suggests that plots with higher perennial grass and perennial forb cover, and low invasive annual cover, typically had higher LFMC. Positive correlations between LFMC and native cool- and warm-season perennial grasses were equally strong ($P < 0.01$; $\varrho = 0.12$), and invasive biennial/perennial forbs had the weakest relationship with LFMC ($P = 0.46$; $\varrho = 0.04$), suggesting that cool- and warm-season grasses make similar contributions to LFMC, while invasive biennial and perennial forbs have minimal effects on LFMC overall (Figure 5).

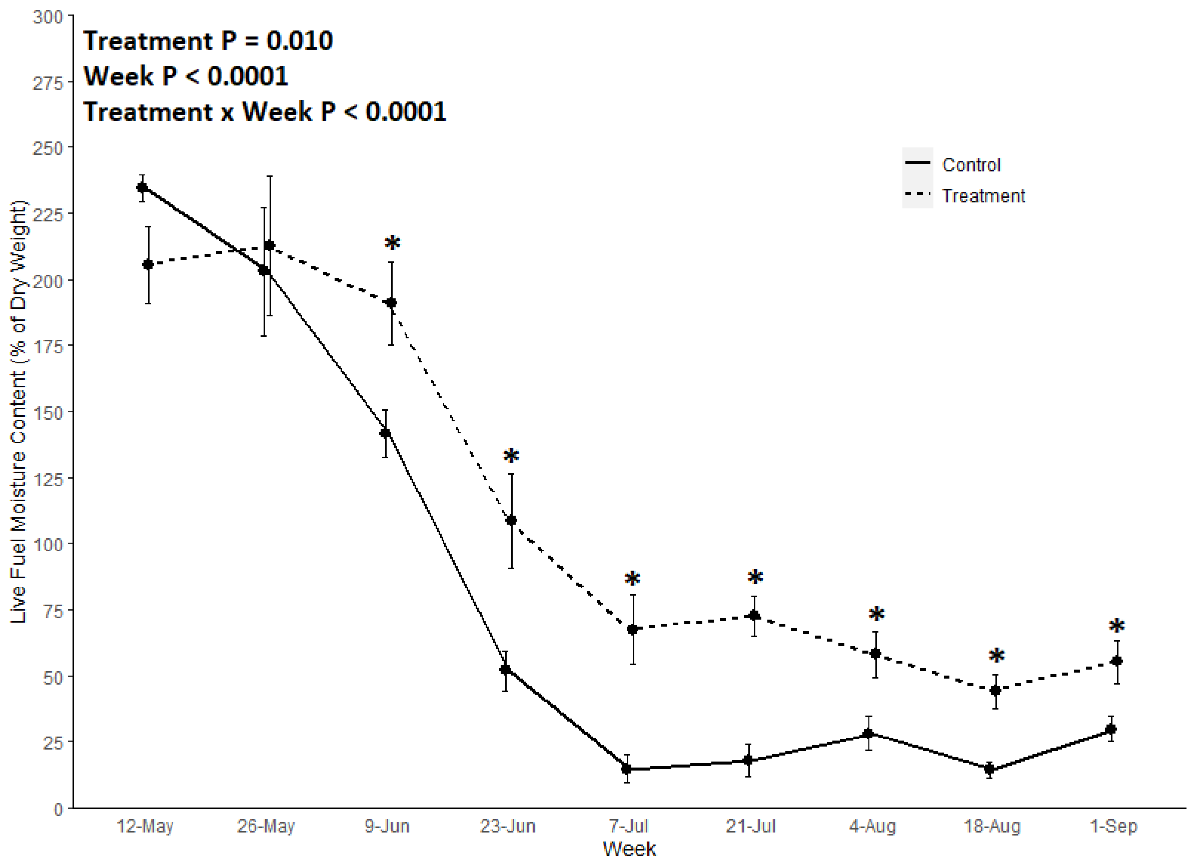

Figure 3. Bi-weekly mean live fuel moisture content (LFMC) in control plots (solid) and indaziflam treatment plots (dashed) at Boulder County grassland study sites in 2025. Error bars correspond to ± 1 standard error. Annotations show results of analysis of variance (ANOVA) with significant fixed effects shown in bold, 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=4).

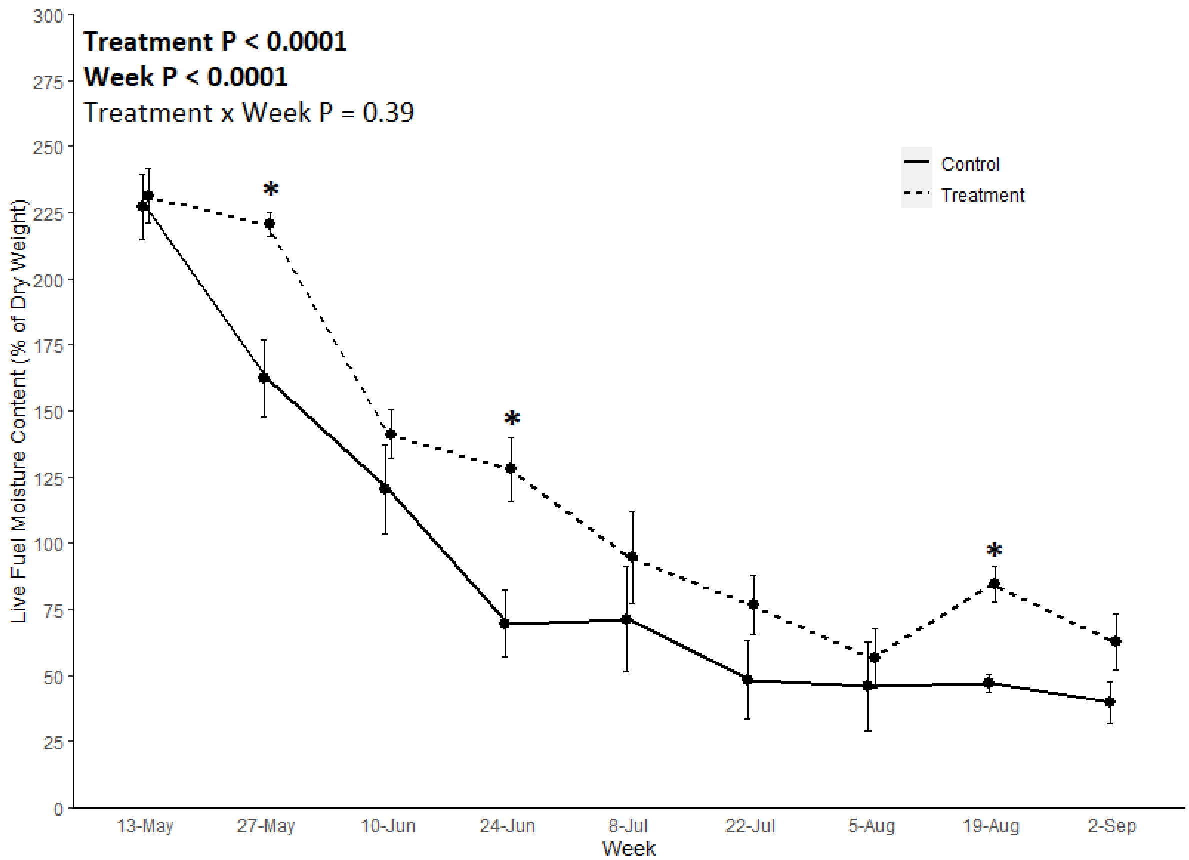

Figure 4. Bi-weekly mean live fuel moisture content (LFMC) in control plots (solid) and indaziflam treatment plots (dashed) at Boulder County grassland study sites in 2024. Error bars correspond to ± 1 standard error. Annotations show results of analysis of variance (ANOVA) with significant fixed effects shown in bold, 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≤0.05; n=4).

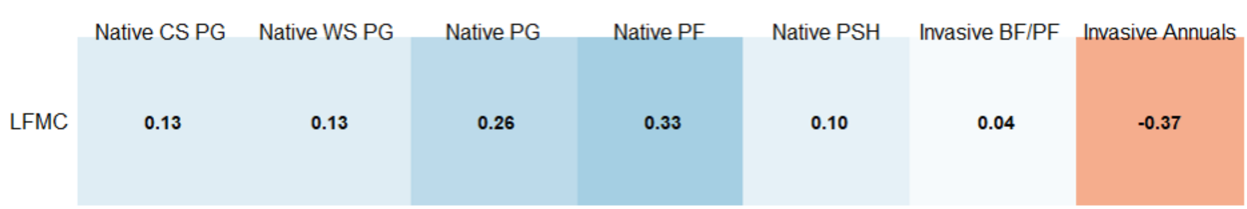

Figure 5. Non-parametric correlation coefficients (Spearman's ϱ) between live fuel moisture content (LFMC) and vegetation functional group cover for data collected at Boulder County grassland study sites in 2025. Abbreviations are as follows: CS = cool-season, WS = warm-season; PG = perennial grass, PF = perennial forb, PSH = perennial shrub, BF/PF = biennial/perennial forb. Positive values (blue) indicate a positive relationship and negative values (red) indicate a negative relationship between LFMC and cover of each functional group. All correlations were statistically significant (P≤0.05) except for relationship between LFMC and invasive BF/PF.

Standing Crop Comparisons

Standing crop was not significantly increased in treatment plots at any sample timing during the 2025 season (early-season P = 0.09; mid-season P = 0.15; late-season P = 0.39; Figure 6). Overall, standing crop was lower for the late-season sample timing compared to the early- and mid-season timings in both treatment and control plots (Figure 6), suggesting that vegetation may have been utilized by herbivores between sample timings (late-July to late-September).

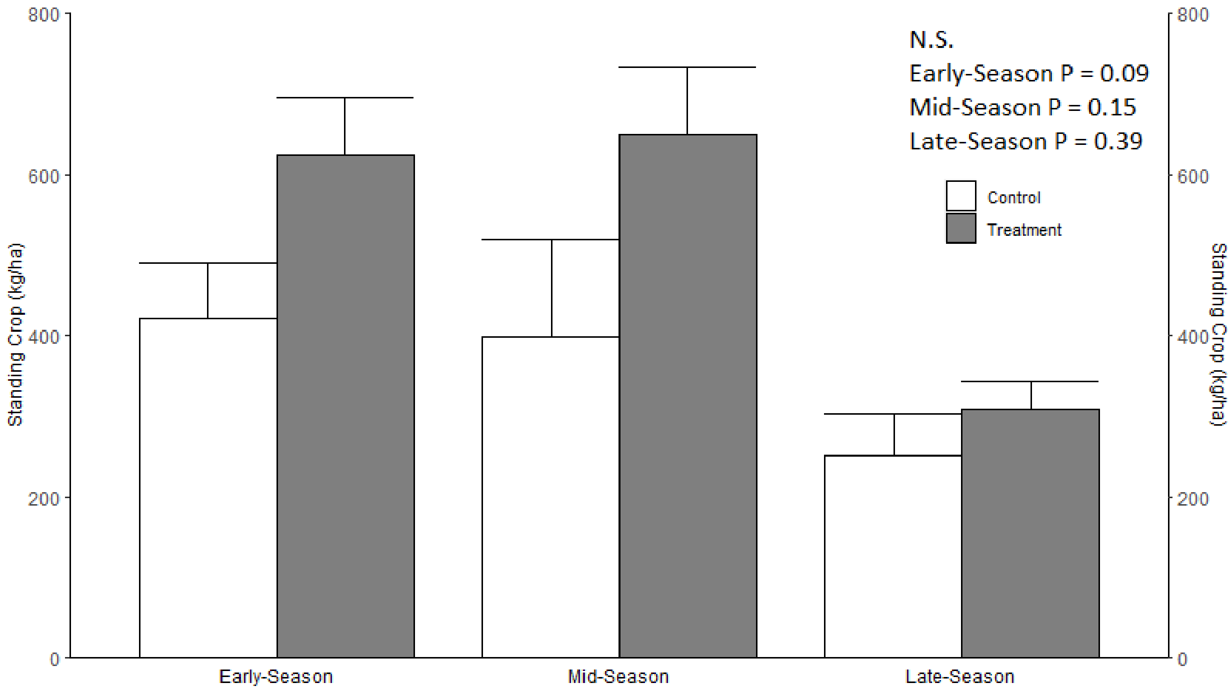

Figure 6. Mean total standing crop in control plots (white) and indaziflam treatment plots (grey) at Boulder County grassland study sites in 2025 for the early-season (early-July), mid-season (late-July), and late-season (mid-September) sample timings. Error bars correspond to ± 1 standard error. Differences between control and treatment plots were not significant at any sample timing based on the results of within-timing t-tests ($P \leq 0.05$; n=4).

Forage Quality

Forage quality analysis suggested that crude protein was significantly increased by treatment at all sample timings in 2025, but effects on ADF and TDN were only significant at the late-season sample timing (Figure 7), when ADF was reduced by treatment and TDN was increased by treatment. Thes results suggest that treatment increases the protein content for forage throughout the summer season, while effects on other forage quality metrics are more pronounced later in the season.

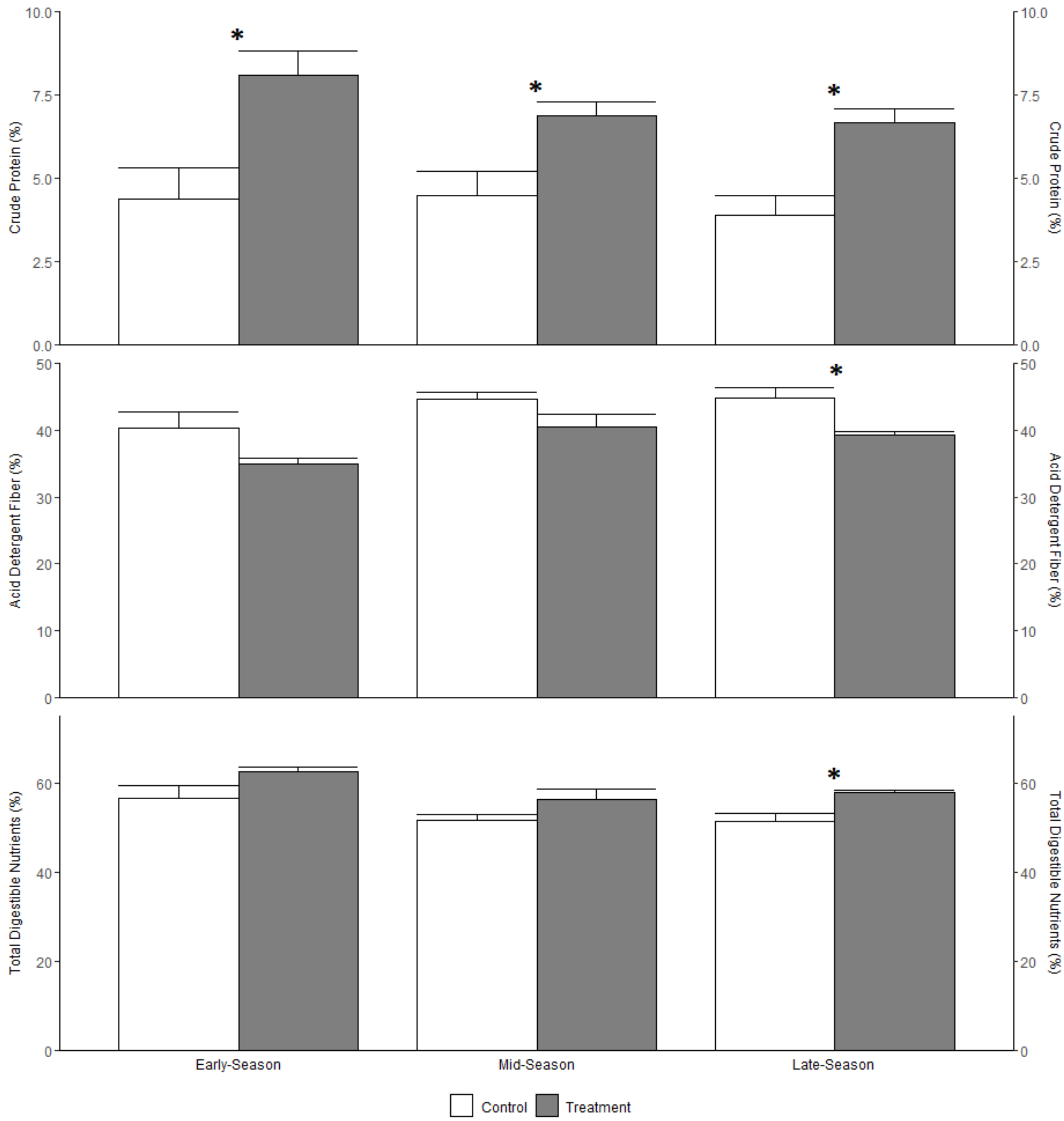

Figure 7. Mean crude protein (top), acid detergent fiber (ADF; middle), and total digestible nutrients **(**TDN; bottom**)** in control plots (white) and indaziflam treatment plots (grey) at Boulder County grassland study sites in 2025 for the early-season (early-July), mid-season (late-July), and late-season (mid-September) sample timings. Error bars correspond to ± 1 standard error. Asterisks indicate significant within-timing (early-, mid-, late-season) differences based on the results of a t-test (P≤0.05; n=4).

Discussion

Our results indicate that indaziflam treatment increased LFMC at our study sites during the summer 2025 season, with significant increases in LFMC observed for seven of the nine total bi-weekly sample timings (Figure 3). This supports our prediction that indaziflam treatment would increase LFMC for at least a portion of the season and suggests that effective management of invasive annual plants can reduce the risk of catastrophic wildfires. This finding is more interesting when interpreted alongside the re-analyzed 2024 data (Figure 4), when more modest effects were observed. As a reminder, the 2024 project included two study sites in Jefferson County, and when these sites were included in the analysis we observed strong effects on LFMC, with significant increases in LFMC in treatment plots for six of the nine total sample timings (Courkamp and Watson 2024). However, when only Boulder County research sites are included in the analysis, the effects of treatment weaken somewhat, with significant increases in LFMC in treatment plots only observed for three of the nine total sample timings (Figure 4). Given that the study sites included in the 2025 project are the same as the Boulder County sites in 2024, this suggests that the effects of cheatgrass management with indaziflam on LFMC vary from year-to-year.

Interannual variability in the effects of cheatgrass treatment on LFMC is likely related to differences in precipitation in the different years. Conditions were very dry in 2024, with Boulder County study sites receiving approximately 50% of the precipitation expected between 6-May and 9-September based on the 30-year average, with most of that precipitation occurring later in the season in July and August (PRISM 2025; CoCoRaHS 2025; Figure 8). However, LFMC responded to late-summer rains, with increases in LFMC observed in treatment plots after precipitation in early-August 2024 (Figure 4; Figure 8; Courkamp and Watson 2024). This suggests that invasive annuals were unable to utilize moisture later in the season, while perennial plants, which were more abundant in treatment plots, were able to green-up and increase LFMC. Compared to the 2024 season, precipitation was increased overall and more consistent throughout the summer in 2025, with Boulder County study sites receiving approximately 70% of what is expected based on the 30-year average during the summer season and larger rain events occurring earlier in the summer (Figure 9). Given that we observed increases in LFMC in treatment plots after late-summer rains in 2024, increased precipitation and more consistent precipitation throughout the season likely contributed to the more pronounced and consistent treatment effects we observed in 2025. Overall, study results from both years indicate that cheatgrass management with indaziflam had a positive effect on LFMC, but that these effects varied each year depending on the amount and timing of precipitation, with greater treatment effects on LFMC observed during and after precipitation. Thus, cheatgrass treatment likely reduces the risk of uncharacteristically frequent and large wildfires, but these effects can be diminished somewhat by dry conditions.

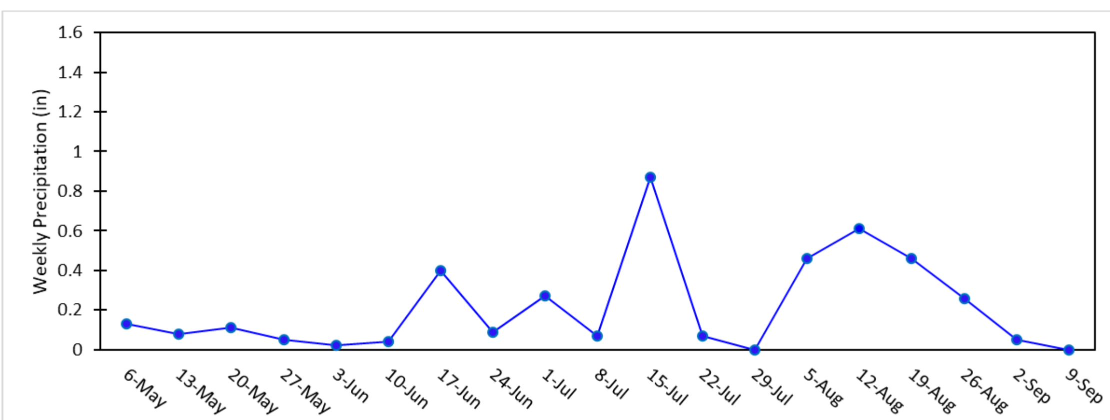

Figure 8. Weekly precipitation in Lyons during summer 2024 (Station CO-BO-146; CoCoRaHS 2025). Total precipitation for the 2024 growing season (May-September) was 4.77 in compared to a 30-year average of 9.44 in (PRISM 2025).

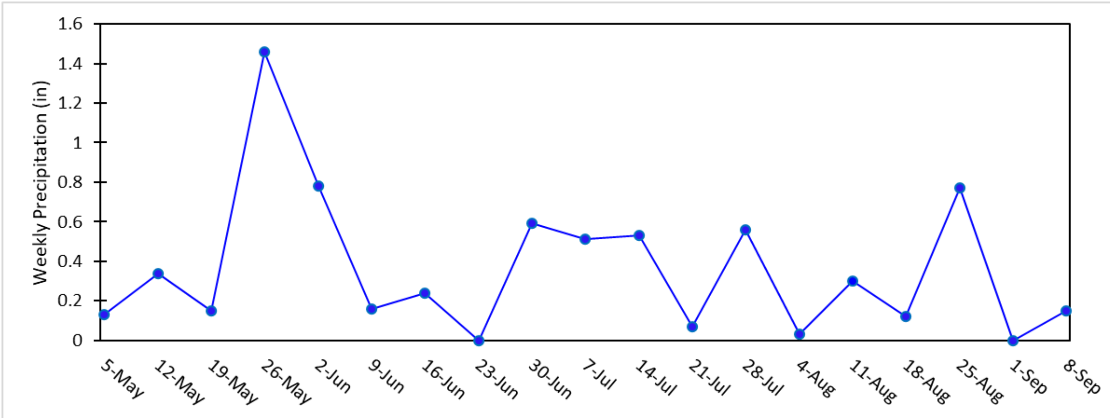

Figure 9. Weekly precipitation in Lyons during summer 2025 (Station CO-BO-146; CoCoRaHS 2025). Total precipitation for the 2024 growing season (May-September) was 6.89 in compared to a 30-year average of 9.44 in (PRISM 2025).

Correlation analysis also suggests that native perennial grasses and native perennial forbs have strong positive associations with LFMC, while invasive annuals have strong negative associations with LFMC (Figure 5). These results are not surprising and align with results from the 2024 season (Courkamp and Watson 2024). However, we observed stronger relationships overall between LFMC and native perennial grasses, native perennial forbs, and invasive annuals compared to 2024 (Courkamp and Watson 2024), which could also be related to increased precipitation in 2025 (i.e., more precipitation allowed for greater contributions of perennial vegetation, or lack thereof, to LFMC). We also included several additional vegetation functional groups in our analysis in 2025, including native cool-season perennial grasses, native warm-season perennial grasses, and invasive biennial/perennial forbs. We found similar relationships between cool- and warm-season grasses and LFMC, while invasive biennial/perennial forbs had only a very weak and insignificant relationship with LFMC (Figure 5). However, it is possible that distinguishing between native perennial forbs and invasive biennial/perennial forbs, which were combined in 2024, may have contributed to the stronger relationship between native perennial forbs and LFMC observed in 2025 (Figure 5; Courkamp and Watson 2024). Analyzing correlations between vegetation functional groups and LFMC at specific study sites may further elucidate site-level relationships because plant communities differ between sites, but that is beyond the scope of this project and report.

Estimates of standing crop suggest that, while standing crop was higher in treatment plots compared to control plots throughout the 2025 season, these differences were not statistically significant (Figure 6). This contrasts somewhat with results from 2024, when we observed significant increases in standing crop in treatment plots both early and late in the season (Courkamp and Watson 2024). We are unsure what might be driving this difference between 2024 and 2025, but it may be related to increased early-season precipitation in 2025 compared to 2024 (Figure 8; Figure 9), which likely increased the growth of invasive annuals and contributed to more even standing crop estimates between treatment and control plots. It is also interesting that standing crop was markedly lower in both treatment and control plots for the late-season timing compared to the early- and mid-season sample timings in 2025 (Figure 6). This pattern was also observed in 2024 and suggests substantial utilization of these vegetation resources by wild herbivores between the mid-season (late-July) and late-season (mid-September) sample timings. More research understanding the effects of herbivory on standing crop in areas treated with indaziflam may help managers better understand treatment outcomes. In addition, future studies may wish to further evaluate differences in the quality and quantity of forage for wildlife given that our study suggests utilization is occurring in treated areas and recent research suggests that key wildlife species (e.g., mule deer) may preferentially forage in treated areas (Courkamp et al. 2025).

Forage quality analysis indicated that treatment consistently increases crude protein content of available forage throughout the summer season, while effects on ADF and TDN are only significant later in the season (Figure 7). These results suggest that cheatgrass management likely has positive effects on forage quality, but effects vary depending on the time of sampling. It is likely that native perennial vegetation, which was much more abundant in treatment plots (data not shown), is contributing to improved forage quality, but more research is necessary to better understand the effects of treatment on forage quality of specific vegetation functional groups (e.g., shrubs, forbs, and grasses). Biomass data collected for this project could be used to further analyze these relationships, but that is beyond the scope of this project and report.

It is also important to note that we observed excellent invasive annual control in treatment plots at all sites except one, Highway 36A, where we observed sparse invasive annuals establishing in treatment plots in 2025. It is important to note that treatments at Highway 36B occurred in January 2018, more than seven years prior to the initiation of sampling in 2025 and more than three years before treatment occurred at the other Boulder County study sites (Table 2). Considering the time that has passed since treatment occurred, it is not surprising that invasive annuals are beginning to re-establish in treated areas at Highway 36A. Overall, it is remarkable that we observed effective control across most of the different treatment timings and application methods implemented at our study sites (Table 2). This speaks to the versatility of indaziflam as a tool for managing invasive annuals, and this versatility is likely related to the long period of residual activity that is unique to indaziflam among other herbicides typically used for invasive annual grass control (e.g., Plateau®). Our results further support the conclusion that indaziflam is an effective tool for annual weed control in rangelands and natural areas, a finding that has been replicated in many studies (Sebastian et al. 2016; Sebastian et al. 2017; Clark 2020; Courkamp et al. 2022).

Implications and Next Steps

Key findings from our study include:

(1) Indaziflam treatment exerted significant effects on LFMC in treatment plots, with treatment increasing LFMC for seven of the nine total sample timings included in the study in 2025 (Figure 3). The observed differences in LFMC suggest that relatively high levels of vegetation moisture content persist longer into the summer season after indaziflam treatment, reducing the likelihood of wildfire ignition and the potential rate of wildfire spread in treated areas.

(2) High LFMC was positively related to native perennial grass and native perennial forb cover, and negatively associated with invasive annual cover (Figure 5), suggesting that increased LFMC after treatment may result from increases in native perennial herbaceous plants in treated areas. Relationships between LFMC and native cool- and warm-season perennial grasses were very similar, and relationships between LFMC and invasive biennial/perennial forbs were weak and non-significant.

(3) Re-analysis of 2024 data for only the Boulder County study sites suggests that treatment effects on LFMC were more modest in 2024 compared to 2025 (Figure 3; Figure 4). This is likely related to increased precipitation and more consistent precipitation in 2025 compared to 2024 (Figure 8; Figure 9), and aligns with findings reported in 2024, which indicated that LFMC responded positively to late-summer precipitation in treatment plots but not control plots.

(4) Indaziflam treatment resulted in successful invasive annual control at all study sites except Highway 36A, where sparse invasive annuals were observed re-establishing in treatment plots. This is likely related to when treatments occurred at the different study sites since treatments at Highway 36A occurred well before treatments at other sites (2018; 3+ years earlier than other sites). Taking time since treatment into account, the consistency of indaziflam treatment effects across various timings and application methods (Table 2) speaks to its versatility as a tool for managing invasive annuals.

(5) Standing crop was lower overall in both treatment and control plots for the late-season sample timing compared to the early- and mid-season sample timing (Figure 6), suggesting that substantial utilization of vegetation by wild herbivores occurred between the mid- and late-season sample timings (late-July to mid-September).

(6) Forage quality was increased by treatment, but effects on specific forage quality metrics varied, with more consistent effects on crude protein throughout the season, and significant effects on ADF and TDN occurring only later in the summer (Figure 7).

In addition, our results and experiences with this project suggest several topics that warrant further investigation. These include, but are not limited to:

(1) Our study focused exclusively on live fuels, and better accounting for dead fuels and litter while sampling could provide more detailed information on the potential effects of treatment on wildfire behavior.

(2) Anecdotal observations suggest that indaziflam treatment results in large increases in perennial forb abundance. In particular, we observed much more abundant slim-flower scurfpea (*P. tenuiflorum*) and white sage (*A. ludoviciana*) in treated areas. Future research may seek to better understand the mechanisms behind these apparent increases in perennial forbs (i.e., differences in new plant recruitment vs. release of existing plants over time), and their implications for wildfire risk and wildlife habitat quality.

Finally, this report represents a first step towards analyzing and presenting the results of this project, but more analyses will be conducted in the future using additional data that is not presented in this report. For example, study plots were instrumented with temperature and humidity sensors that recorded data every 30 minutes for the duration of the summer 2024 and 2025 seasons. Additional analyses will, at a minimum, investigate vegetation functional group-specific patterns in LFMC. All additional results will be shared with project partners in the future.

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