

Cheatgrass alters flammability of native perennial grasses in laboratory combustion experiments

Georgia R. Harrison

georgia.harrison@usda.gov

USDA-ARS Jornada Experimental Range: USDA-ARS Range Management Research

<https://orcid.org/0000-0003-0544-4471>

Lisa C Jones

University of Idaho College of Agricultural and Life Sciences

Lisa M Ellsworth

Oregon State University Department of Fisheries, Wildlife, and Conservation Science

Eva K. Strand

University of Idaho College of Natural Resources

Timothy S. Prather

University of Idaho College of Agricultural and Life Sciences

Research Article

Keywords: *Achnatherum nelsonii*, bluebunch wheatgrass, *Bromus tectorum*, cheatgrass, Columbia needlegrass, fire behavior, fuel moisture, invasive species, *Pseudoroegneria spicata*, rangeland, sagebrush steppe

Posted Date: April 16th, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-3642229/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Fire Ecology on November 26th, 2024. See the published version at <https://doi.org/10.1186/s42408-024-00338-z>.

Abstract

Background

The invasive annual grass cheatgrass (*Bromus tectorum*) increases fuel continuity, alters patterns of fire spread, and changes plant communities in sagebrush shrublands of the Great Basin (USA) and adjacent sagebrush steppe areas, but no studies have contrasted its flammability to native perennial grasses. Understanding cheatgrass flammability is crucial for predicting fire behavior, informing management decisions, and assessing fire potential of invaded areas. This study aimed to determine the flammability of cheatgrass compared to two native perennial grasses (Columbia needlegrass [*Achnatherum nelsonii*] and bluebunch wheatgrass [*Pseudoroegneria spicata*]) across a range of typical fire season fuel moistures.

Results

All three grass species had decreased flammability with increasing fuel moisture. Columbia needlegrass had on average 11% lower mass consumption than cheatgrass, and both perennial grasses had on average 13.5 s longer flaming durations and higher thermal doses (temperature over time) than cheatgrass. The addition of cheatgrass to the perennial grasses increased combined mass consumption, flaming duration, and thermal dose. For these three attributes, flammability increased with greater amounts of cheatgrass in the mixture, but flaming duration and thermal dose were not sensitive to cheatgrass fuel moisture. Maximum temperature and flame length of perennial grass combustion were similar with and without cheatgrass addition. Flammability of Columbia needlegrass when burned with cheatgrass was higher than expected based on the flammability of each respective species, suggesting that Columbia needlegrass may be susceptible to pre-heating from cheatgrass, causing increased mass consumption, flaming duration, and thermal dose. Conversely, flammability of bluebunch wheatgrass and cheatgrass together had both positive and negative interactive effects.

Conclusions

This study provides experimental evidence supporting previous qualitative observations of high cheatgrass flammability. Even at high fuel moisture, cheatgrass increased perennial grass flammability, suggesting that cheatgrass poses a significant fire threat to native grasses for an extended season than expected for the native grasses without cheatgrass. The study's findings inform invasive plant management and fire potential, and guide efforts to prevent or mitigate cheatgrass-induced wildfires.

Background

Annual grasses in the western US are spreading at an alarming rate (Germino et al. 2016), and land managers require science-based information on best practices to address this problem (Boyd and

Svejcar 2009, Sayre et al. 2012). One significant consequence of annual grass invasion is the shift in fire regime towards an increased invasive grass-wildfire feedback cycle, driven by increased fine fuel continuity, flammability of grasses, and faster postfire recovery of non-native species (D'Antonio and Vitousek 1992, Knapp 1996, Brooks et al. 2004, Balch et al. 2013). This phenomenon is pronounced in semiarid ecosystems with historically low fire occurrence (D'Antonio and Vitousek 1992, Brooks et al. 2004, Balch et al. 2013).

One way that science may inform management is by directly quantifying flammability of native and invasive plant species. Flammability encompasses four phenomena: (1) ignitability-the time elapsed until ignition once a material is exposed to a known ignition source, (2) sustainability-how well the fuel continues to burn, (3) combustibility-how rapidly or intensely a material burns, and (4) consumption-the quantity of material that is consumed (Anderson 1970). Fuel moisture is a major determinant of all four aspects of flammability (Rothermel 1972), and differs by plant functional group, changes throughout the season, and is sensitive to smaller scale changes, such as shaded microclimates or daily weather cycles (Rothermel 1972). Additionally, Cardoso et al. (2018) reported a shift in fire potential (ignitability) within tropical forest-savannahs of Lopé National Park, Gabon due to changes in understory species composition. Understanding species' flammability is necessary for understanding how they contribute to fuel loads and therefore potential fire behavior.

One way to assess species flammability is through field- or laboratory-based combustion experiments. Fuentes-Ramirez et al. (2016) measured the combustibility, sustainability, and consumption of the fire-intolerant creosote bush (*Larrea tridentata* [DC.] Coville), in combination with two invasive annual grasses (Arabian schismus [*Schismus arabicus* Nees] and compact brome [*Bromus madritensis* L.]) and two native plants (sub-shrub burrobush [*Ambrosia dumosa* (A. Gray) Payne] and annual forb Menzies' fiddleneck [*Amsinckia menziesii* (Lehm.) A. Nelson & J.F. Macbr.]). Each species was burned individually and in combination with creosote bush in laboratory combustion experiments. They found that invasive grasses spread fire quickly, burned briefly, and produced more intense fires, while native plants spread fire slowly. As a result, they classified invasive and native vegetation by their functional role in creosote bush flammability aspects - sustainability, combustibility, and consumption. Invasive grasses served as fire spreaders, and when ignited by "spreaders", native vegetation served as "igniters" of lower, dead branches of creosote bush. Spreader species had lower combustibility than igniters, but greater sustainability and consumption. The study concluded that these species have distinct flammability characteristics, and their arrangement on the landscape should be considered when assessing fire risk, especially in areas where fire-prone invaders are impacting native fire-intolerant species.

Flammability of two species burned together can be influenced not only by the flammability traits of the individual species but also by the interaction between the species. Blauw et al. (2015) investigated the impact of fuel moisture on species combustibility and consumption, both individually and when burned together. The study involved the combustion of two pleurocarpous moss species and two low-growing evergreen shrub species in various combinations. The combined combustibility and consumption varied depending on the species. Additionally, non-additive effects - deviations between observed and expected

combined flammability of two species - were more pronounced and varied at higher fuel moisture contents. These findings suggest that when projecting potential fire risk across multi-species landscapes, it may not be sufficient to consider the flammability of individual species alone, but that species interactions and how these interactions vary with fuel moisture must also be considered.

Within sagebrush shrublands, invasive winter annual grasses such as cheatgrass (*Bromus tectorum* L.), have altered fire through several mechanisms, including increasing fine fuel continuity (Whisenant 1990) and enabling fire spread (Link et al. 2006). Cheatgrass forms a highly flammable, continuous, fine fuel bed with a high fuel surface-to-volume ratio that readily ignites and rapidly carries wildfire even under wet early season conditions (Balch et al. 2013). Invasive grass-fueled wildfires often occur earlier in the season than was common historically, because cheatgrass cures, reducing stem and leaf moisture, before native plants senesce. More frequent fires can eliminate some sagebrush species, which are typically killed by fire, and require long fire return intervals to reach maturity and produce seed (Whisenant 1990).

Studies that have examined the impact of cheatgrass on fire activity in the Great Basin, USA, using remote sensing tools have demonstrated that cheatgrass has increased fire regionally, and that invaded areas are more likely to burn. Balch et al. (2013) examined the impact of cheatgrass on fire activity from 1980–2009 on a regional scale in the arid western US and found that areas with cheatgrass were more likely to burn, and fires started in cheatgrass were more likely to burn for multiple days and contribute to the largest fires of the year. Pastick et al. (2021) proposed a risk threshold of 10% invasive annual grass cover to heighten fire risk based on remotely sensed estimates of annual grass cover and fire occurrence. Even relatively small amounts of invasive annual grass on the landscape can increase wildfire risk (Balch et al. 2013, Pastick et al. 2021). However, this increased risk is widely attributed to increased fuel continuity, and little is known about the species-level flammability of cheatgrass. Link et al. (2019) experimentally ignited and quantified flammability of study plots in Grant County, Washington, USA that had been invaded by cheatgrass, but were revegetated with large bunchgrasses, but did not observe any differences in plot-level ignitability due to revegetation or cheatgrass abundance. No studies have quantified cheatgrass flammability, nor compared it to other native species present in the invaded ecosystem. The main goal of this study was to evaluate the flammability of cheatgrass and two native perennial bunchgrasses: Columbia needlegrass (*Achnatherum nelsonii* (Scribn.) Barkworth) and bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve). To address flammability, we posed three research questions:

1. How does the flammability of cheatgrass compare to that of Columbia needlegrass and bluebunch wheatgrass across a range of fuel moistures?
2. What effect does the addition of cheatgrass have on the overall flammability of Columbia needlegrass and bluebunch wheatgrass?
3. When cheatgrass and Columbia needlegrass or bluebunch wheatgrass are burned together, does the combined flammability result from a simple combination of the individual species' attributes, or are there additional interactions between the two species that alter the overall flammability?

From these questions, we developed three research predictions:

1. Cheatgrass will have higher flammability (ignitability, combustibility, consumption) than both Columbia needlegrass and bluebunch wheatgrass due to its high surface area to volume ratio and fine stems.
2. The addition of cheatgrass will increase the overall flammability (combustibility, sustainability) of Columbia needlegrass and bluebunch wheatgrass due to the higher fuel loads and lower moisture content of the annual grass compared to the perennials.
3. When cheatgrass and Columbia needlegrass or bluebunch wheatgrass are burned together, the combined flammability will not be a simple additive function of the individual species' attributes; rather, there will be greater (consumption, sustainability) due to cheatgrass preheating perennial grasses, resulting in an increased overall flammability.

Methods

Collection and processing of plant materials

Cheatgrass, bluebunch wheatgrass, and Columbia needlegrass were selected for combustion experiments due to their dominance in sagebrush steppe ecosystems. Plant materials were collected at Rinker Rock Creek Ranch (Blaine County, Idaho) during the last week of June 2021. Grasses were clipped within 1 cm of the soil surface to obtain only aboveground plant material. All materials were oven dried at 38°C for 72 hours and stored at room temperature until initiation of the combustion experiments in July and August of 2021.

Prior to combustion experiments, samples were rehydrated, following methods from Baluw et al. (2015). Oven-dried samples were weighed to a standard mass (20 g for individual species trials and either 2.5, 5, 10, or 15 g for combined species trials), and water was added by weight to achieve the desired percent relative fuel moisture. Samples were sealed in zip-top plastic bags for 48 hours before sample combustion. Prior to combustion, plants were weighed to obtain pre-burn wet mass and confirm moisture level. This rehydration method allowed us to achieve variation in fuel moisture, but these values should be considered relative to each other, and not necessarily representative of live fuel moisture as would be assessed in the field from freshly collected plants. Cheatgrass was rehydrated to 5, 10, 15, 25, 35, 45, and 55 percent moisture. Perennial grasses were rehydrated to 15, 25, 35, 45, and 55 percent moisture. Moisture ranges are based on fuel moisture content reported by Davies and Nafus (2013) from green-up until senescence and a separate, independent study with included fuel moisture sampling during the summer of 2021 (Johnston, unpublished data). A minimum of five replicates of each moisture level for each species were burned.

Each perennial grass species was also burned in combination with cheatgrass. Perennial grass mass was kept consistent (20 g). Two target perennial grass moisture levels were selected for combination experiments: a high (55%) and moderate (35%) moisture. Four levels of both cheatgrass mass (2.5, 5, 10,

and 15 g) and moisture (5, 15, 25, and 35%) were selected to reflect varying levels of cheatgrass invasion, from relatively low to high under different moisture regimes. Bluebunch wheatgrass combination trials were only burned with 2.5, 5, and 10 g of cheatgrass, but still at all four moisture levels. Four replicates of each annual and perennial grass combination at each fuel moisture were burned.

Combustion experiments

Combustion experiments were conducted inside a chamber at the University of Idaho's iFire laboratory (Moscow, Idaho). The chamber was constructed using a 10 cm diameter, 60 cm tall steel pipe, and elevated 2.5 cm above the ground to facilitate sample ignition (Fig. 1). For ventilation, approximately 15 holes, each with a diameter of 0.5 cm, were drilled into the walls of the chamber. Three Type K thermocouples (OMEGA Engineering) were inserted into the chamber at a height of 19, 33, and 48 cm from the base (Fig. 1).

For each combustion trial, samples were weighed to the nearest 0.01 g pre-burn to assess moisture achieved from rehydration. For trials with two species, perennial and annual grasses were weighed separately since they had been independently rehydrated to achieve different fuel moistures. Grasses were burned upright inside the combustion chamber to best mimic natural fuel structure. Perennial and annual grass species mixtures were mixed homogeneously and loaded 5 cm diameter PVC pipes, cut longitudinally (Fig. 2). Both halves of PVC were closed around the sample and released into the chamber, positioned vertically (Fig. 2).

One mL of isopropyl alcohol was placed on a watch glass centered under the combustion chamber (Fig. 2). The alcohol was ignited using a remote charge through a wire. Each burn was recorded on video. A height board with 10 cm increments was placed behind the combustion chamber, and maximum flame height for each trial was recorded by viewing the videos (Fig. 1). Most flame heights exceeded the height of the chamber. However, for flames that were shorter than the chamber, their height was estimated within a range based on the visibility through chamber vent holes in the recorded video. Temperature was recorded for each thermocouple throughout the experiment at 0.5 second intervals. All temperature data were trimmed at a 100°C temperature threshold. Post-burn plant material was weighed to the nearest 0.01 g. For combined perennial and annual grass trials, post-burn weight was of both species combined.

Data analysis for individual and combined species trials

Data were summarized to assess four major phenomena of flammability. *Ignitability* was determined by assessing the probability of ignition, i.e., whether the sample ignited or not under standardized experimental conditions. This assessment was done visually during the trials and confirmed using video footage. Information from all trials was used to inform ignitability. For other attributes of flammability, temperature data from trials which ignited were used. *Sustainability* was assessed as flaming duration, which was the time in seconds that each thermocouple spent above 100°C. *Combustibility* was classified with three traits: maximum temperature, thermal dose, and maximum flame height. Maximum

temperature was calculated for each thermocouple. Thermal dose was the sum of each thermocouple's temperatures when they exceeded 100°C. Maximum flame height was estimated by reviewing the trial videos and approximating the highest point from the high board to the nearest 10 cm. *Consumption* was calculated as percent mass loss, using Eq. 1

$$[1] ML\% = \frac{(M_i - M_e)}{M_i} \times 100$$

To determine if data from all three thermocouples could be combined for analysis, an analysis of variance (ANOVA) test was implemented to test for differences in temperature across the three thermocouples. The lowest (19 cm) thermocouple was significantly different from the other thermocouples, and was removed from further analysis. Differences in ignitability, sustainability, combustibility, and consumption were first examined across the three species (categorical variable for species identity) using ANOVAs. A Tukey post-hoc test was used if ANOVA results yielded significance. Next, differences in ignitability, sustainability, combustibility, and consumption were tested across fuel moistures for all three species, with fuel moisture as a continuous predictor variable using linear regression analysis. We also examined and report significant interactions between fuel moisture (categorical) and species (categorical) for each attribute of flammability.

Differences between combined species sustainability, combustibility, and consumption when cheatgrass was added to perennial grasses compared to perennial grass alone was tested using multiple ANOVA tests. For these analyses, each perennial grass species and level of perennial grass fuel moisture (35 or 55%) was examined separately. We tested for differences by cheatgrass amount (continuous) and fuel moisture (categorical) using multiple ANOVA tests. To test for differences between the perennial grass alone (0 g of cheatgrass added) and perennial grasses with increasing amounts of cheatgrass, we used a Tukey post-hoc test. For all individual and combined species analyses, separate models were implemented for each combustion response variable.

Additive effects of combustion

To compare the sustainability, combustibility, and consumption of individual and combined fuel beds, effect size of non-additivity was calculated using Eq. 2

$$[2] \frac{(Observed - expected)}{Expected}$$

Observed values were obtained directly from trials involving two species, and the expected sustainability, combustibility, or consumption was calculated as a weighted average based on the results of individual species trials. Weights for each species were assigned based on their relative contribution to the total mass in the two-species trial.

Effect size was examined using a two-sided t-test and μ was set to zero to determine whether the mean effect size for each trial combination (perennial grass species x perennial grass fuel moisture x cheatgrass mass x cheatgrass fuel moisture) differed significantly from zero. A non-significant result

suggests additivity of sustainability, combustibility, or consumption, meaning that the observed flammability does not differ significantly from what is expected based on individual species fuel beds. A significant effect size indicates a nonadditive interaction between the two species. Positive and negative values of the effect size indicate different directions of non-additivity, and the value represents the strength of the nonadditive effect. A negative effect size means that the observed values are lower than expected, indicating that at least one species reduces flammability when combined. A positive effect size indicates that the two species together enhance the sustainability, combustibility, or consumption compared to their individual responses. Further, multiple linear regressions were used to examine whether non-additivity differed based on perennial grass species (categorical), perennial grass fuel moisture (categorical), cheatgrass mass (continuous), and cheatgrass fuel moisture (categorical). All statistical analysis was performed in R (version 4.0.3; R Core Team, 2023).

Results

Individual species flammability

All species maintained high ignitability across all fuel moistures (FM) tested (Fig. 3). Both perennial grass species had greater sustainability (flaming duration) than cheatgrass: Columbia needlegrass ($p = 0.008$) and bluebunch wheatgrass ($p = 0.052$) burned longer than cheatgrass by 15.2 and 11.8 s, respectively (Fig. 3; Supplemental Table 1). Both perennial grasses had a higher thermal dose than cheatgrass ($p < 0.001$; 14,382 and 8,645°C for Columbia needlegrass and bluebunch wheatgrass, respectively; Fig. 3; Supplemental Table 1). Columbia needlegrass had 11% lower consumption on average ($p = 0.003$) than cheatgrass (Fig. 3). All attributes of flammability decreased for all three species with increasing fuel moisture ($p < 0.001$; Supplemental Table 2). The interaction between species and fuel moisture was not significant ($p \geq 0.104$) for any flammability attribute.

Combined species flammability

Flaming duration, flame height, and mass consumption of combined perennial and cheatgrass fires were higher than when each perennial grass was burned alone (Fig. 4). The impact of cheatgrass on combined flaming duration, flame height, and mass consumption differed between the two perennial grass species (Fig. 4). Columbia needlegrass mass consumption and flaming duration with cheatgrass was greater than when Columbia needlegrass was burned alone (differences varied by cheatgrass mass, Fig. 4; Supplemental Table 3). Bluebunch wheatgrass with cheatgrass had greater flame heights than when bluebunch wheatgrass was burned alone (differences varied by cheatgrass mass, Fig. 4; Supplemental Table 4). There were no differences in maximum temperature nor thermal dose of perennial and cheatgrass combined trials compared to when each perennial grass was burned alone (Fig. 4).

Additive effects of combined flammability

We observed additive effects in sustainability, some metrics of combustibility, and consumption, indicating that the combined flammability was different than expected based on the flammability of each species alone. Columbia needlegrass and bluebunch wheatgrass differed in their additive effects (Fig. 5; Supplemental Table 5). Positive additive effects for Columbia needlegrass were observed for all attributes of flammability (consumption, flaming duration, maximum temperature, and thermal dose), meaning that the combined flammability was greater than expected from each species individual flammability (Fig. 5). These positive additive effects for Columbia needlegrass were typically observed across all levels of cheatgrass mass and fuel moistures. For bluebunch wheatgrass, we observed both negative and positive additive effects (Fig. 5). Negative additive effects (mass consumption and flaming duration) suggest that combined flammability was less than what would be expected from individual species flammability (Fig. 5). Positive additive effects were observed with bluebunch wheatgrass for flaming duration, maximum temperature, and thermal dose and generally, positive effects were only observed with the highest amounts of AG mass.

Discussion

Additions of cheatgrass increased overall flammability by increasing perennial grass sustainability, combustibility, and consumption. These findings provide experimental evidence supporting previous qualitative observations of high cheatgrass flammability (Link et al. 2006, Balch et al. 2013) and build on prior research of invasive grass flammability by Fuentes-Ramires et al. (2016). Our results broaden the scope of our understanding of invasive grass flammability by considering multiple mass ratios and fuel moistures of target species that represent fire season conditions in sagebrush shrublands.

Surprisingly, cheatgrass exhibited either similar or lower flammability at the individual species level than Columbia needlegrass and bluebunch wheatgrass. This contradicts our initial hypothesis, which anticipated that cheatgrass would have higher flammability than native grasses across tested fuel moistures due to its high surface area to volume ratio and fine stems. Specifically, Columbia needlegrass and bluebunch wheatgrass had similar sustainability and thermal dose, both of which were greater than cheatgrass. All three species had similar combustibility (maximum temperature and flame height) and were flammable, even at high fuel moistures.

The addition of cheatgrass to both perennial grass species resulted in fires with greater consumption, flaming duration, and flame heights. We predicted that the addition of cheatgrass would increase the overall flammability of the perennial grasses due to the higher fuel loads and lower moisture content of cheatgrass compared to the perennials. This prediction held true for some attributes of flammability. When cheatgrass was added to each perennial grass species, the combined sustainability and consumption was higher than when perennials were burned alone. As little as 11% cheatgrass biomass (2.5 g of cheatgrass with 20 g of perennial grass) increased consumption. Combustibility (maximum temperature, thermal dose, and flame height) of both perennial grass species when burned with cheatgrass did not differ from cheatgrass burned alone. Further, we assumed that both perennial grass species would behave similarly and did not anticipate the differences between the two perennial grass

species. These findings underscore the significance of comprehending the intricate dynamics between cheatgrass and native vegetation when evaluating fire risk and devising science-based fire management strategies. It is not fair to assume that all perennial grass species will respond the same way to fire, so considering species composition could provide useful when assessing fire risk.

We also predicted that when burned together, combined flammability would not be a simple additive function of individual species' attributes; rather, there would be greater flammability due to cheatgrass preheating perennial grasses, resulting in an increased overall flammability. These results differed by flammability attribute, but there were markable differences in the two tested perennial grass species. Columbia needlegrass with cheatgrass created a more flammable (higher consumption, combustibility, and sustainability) mixture than would be expected based on each individual species flammability and their contribution by mass to the mixture. This contrasts with bluebunch wheatgrass, which had a lower consumption, sustainability, and maximum temperature than would be expected. Differences in observed versus expected flammability by perennial grass species suggests that these two perennial grass species may be differentially susceptible to pre-heating by cheatgrass. Even though the two perennial grasses had equivalent ignitability when burned alone, Columbia needlegrass may be more easily ignited by cheatgrass pre-heating compared to bluebunch wheatgrass. These different pre-heating traits may be due to plant structure as Columbia needlegrass leaves have a greater surface area to volume ratio than bluebunch wheatgrass leaves. Columbia needlegrass leaves are narrower and more needle-like, whereas bluebunch wheatgrass leaves are wider and longer. Differences in perennial grass combined flammability could be an important consideration for seeding post-fire, post-disturbance, or within fuel breaks (Shinneman et al. 2019).

Perennial grass fuel moisture did not affect flammability with the addition of cheatgrass across all levels of cheatgrass fuel moisture. Perennials at 55% or 35% fuel moisture behaved similarly, implying that the influence of cheatgrass on flammability persists from early to late portions of the fire season.

Second, the fuel moisture of cheatgrass when added to perennial grasses was also largely unimportant in explaining combined flammability. This observation suggests that the risk associated with cheatgrass invasion is primarily contingent on its presence and less so on the specific time and resulting fuel moisture within the growing season. We examined cheatgrass at 5–35% FM with perennial grasses, and our method of collecting grasses in the field, drying them, and then rehydrating them was consistent with other studies (Blauw et al. 2015), and provides repeatable measurements and experimental control. However, rehydration with additional water is not the same as intercellular water in live plants. Moreover, cheatgrass was mostly senesced and dry when collected. Differences between live intercellular water in plants versus our methods should be considered when interpreting our experimental results. Experimental fuel moistures should be considered relative to each other, and not necessarily a reproduction of live fuel moisture. Despite these limitations, our results shed light on the increased flammability of cheatgrass and its potential contributions to overall flammability on the landscape.

In this study, cheatgrass and perennial grasses were burned together in a homogenous mixture, with the plant material standing upright to simulate the structure of natural fuels. The main difference between the two fuel sub-layers was the natural height variation between perennials and annuals. However, the spatial distribution of fuels and the resulting fire spread between fuels was not examined. Cheatgrass and other invasive annual grasses create highly continuous fine fuel beds which facilitate fire spread between plants. Perennial grasses typically grow in tight bunches of live and dead plant material, while cheatgrass fills the plant interspaces (Pilliod et al. 2021). The flammability of each perennial grass species may vary depending on dead plant material within the bunch, which can be influenced by site climate, productivity, grazing and decomposition rate (Bansal et al. 2014). For instance, a perennial grass surrounded by dry dead plant material, including attached and detached litter, could be more susceptible to ignition by cheatgrass in the interspaces. This pre-heating effect from cheatgrass and dead perennial grass material may contribute to increased flammability, as observed with Columbia needlegrass in our study.

Flammability of cheatgrass was only examined in combination with two perennial grass species. To gain a more comprehensive understanding of cheatgrass flammability in sagebrush steppe, future research could explore the flammability of additional dominant species, including those commonly used within fuel breaks (Shinneman et al. 2019). Additionally, flammability experiments could consider the interaction of cheatgrass with other fuels, such as litter and lower shrub branches (Fuentes-Ramirez et al. 2016), since cheatgrass is often found in high density under shrub canopies. It is important to understand how annual and perennial grass species contribute to overall shrub flammability in sagebrush shrublands, as shrub components are a key driver of fire behavior in these ecosystems (Ellsworth et al. 2022).

Overall, our results support anecdotal observations and region-wide analysis concerning the profound impact of invasive annual grasses on fire regimes in Western rangelands. Across the western US, annual grasses are credited with altering fire regimes, causing increased fire occurrence and frequency and overall creating a more flammable landscape (Balch et al. 2013, Fusco et al. 2019). Trends in increased fire occurrence, size, and frequency hold true for many other invasive annual grasses other than cheatgrass, including *Taeniatherum caput-medusae*, *Schismus arabicus*, *S. barbatus*, *Imperata cylindrica*, *Neyraudia reynaudiana*, *Microstegium vimineum*, and *Miscanthus sinensis* (Fusco et al. 2019). Areas dominated by annual grasses which then burn are more likely to remain in an annual dominated state. In addition, fire can serve as a catalyst for shifting transitional communities toward an annual grass dominated state (Smith et al. 2023). Our study sheds light on some of the complex dynamics of flammability in sagebrush shrublands by exploring the interaction between native perennial grasses and cheatgrass.

Conclusions

While cheatgrass alone is not more flammable than the perennial grasses tested here, the addition of cheatgrass often resulted in increased flammability (sustainability, consumption, and thermal dose) of

the perennial grasses. However, cheatgrass more strongly increased the flammability of Columbia needlegrass compared to bluebunch wheatgrass, indicating species-specific responses to fire risk in the presence of cheatgrass. Grass species composition, not just the presence of cheatgrass, can influence overall flammability. As a result, post-fire restoration efforts could prioritize planting species which are less flammable in the presence of cheatgrass. Combined flammability of these perennial grasses did not differ across cheatgrass fuel moisture, suggesting an extended risk of fire that is greater than we anticipated.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

The authors offer the publishers permission to publish these research findings.

Availability of data and material

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

Funding

This project was partially supported by funding from Envu.

Authors' contributions

GH, TP, and ES conceived and designed the study with input from LJ and LE. GH led acquisition, analysis, and interpretation of the data with contributions from all authors. GH led the writing of the manuscript. All authors contributed to the revising of the manuscript and have approved the submitted version.

Acknowledgements

Thanks to Kayla Johnston, Sage Huggins, and Nichole Cussins for their assistance conducting laboratory combustion experiments. Cameron Weskamp and Tracey Johnson facilitated access to sampling locations at Rinker Rock Creek Ranch. Also, thanks to Matthew Germino for his review of an early version of this manuscript.

References

1. Anderson, H. E. 1970. Forest fuel ignitibility. *Fire Technology* 6: 312–319.
2. Balch, J. K., B. A. Bradley, C. M. D'Antonio, and J. Gómez-Dans. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Global Change Biology* 19: 173–183.
3. Bansal, S., R. L. Sheley, B. Blank, and E. A. Vasquez. 2014. Plant litter effects on soil nutrient availability and vegetation dynamics: changes that occur when annual grasses invade shrub-steppe communities. *Plant Ecology* 215: 367–378.
4. Blauw, L. G., N. Wensink, L. Bakker, R. S. P. van Logtestijn, R. Aerts, N. A. Soudzilovskaia, and J. H. C. Cornelissen. 2015. Fuel moisture content enhances nonadditive effects of plant mixtures on flammability and fire behavior. *Ecology and Evolution* 5: 3830–3841.
5. Boyd, C. S., and T. J. Svejcar. 2009. Managing Complex Problems in Rangeland Ecosystems. *Rangeland Ecology & Management* 62: 491–499.
6. Brooks, M. L., C. M. D'Antonio, D. M. Richardson, J. B. Grace, J. E. Keeley, J. M. DiTomaso, R. J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of Invasive Alien Plants on Fire Regimes. *BioScience* 54: 677.
7. Cardoso, A. W., I. Oliveras, K. A. Abernethy, K. J. Jeffery, D. Lehmann, J. Edzang Ndong, I. McGregor, C. M. Belcher, W. J. Bond, and Y. S. Malhi. 2018. Grass Species Flammability, Not Biomass, Drives Changes in Fire Behavior at Tropical Forest-Savanna Transitions. *Frontiers in Forests and Global Change* 1: 6.
8. D'Antonio, C. M., and P. M. Vitousek. 1992. Biological Invasions by Exotic Grasses, the Grass/Fire Cycle, and Global Change. *Annual Review of Ecology and Systematics* 23: 63–87.
9. Davies, K. W., and A. M. Nafus. 2013. Exotic annual grass invasion alters fuel amounts, continuity and moisture content. *International Journal of Wildland Fire* 22: 353.
10. Ellsworth, L. M., B. A. Newingham, S. E. Shaff, C. L. Williams, E. K. Strand, M. Reeves, D. A. Pyke, E. W. Schupp, and J. C. Chambers. 2022. Fuel reduction treatments reduce modeled fire intensity in the sagebrush steppe. *Ecosphere* 13.
11. Fill, J. M., B. M. Moule, J. M. Varner, and T. A. Mousseau. 2016. Flammability of the keystone savanna bunchgrass *Aristida stricta*. *Plant Ecology* 217: 331–343.
12. Fuentes-Ramirez, A., J. W. Veldman, C. Holzapfel, and K. A. Moloney. 2016. Spreaders, igniters, and burning shrubs: plant flammability explains novel fire dynamics in grass-invaded deserts. *Ecological Applications* 26: 2311–2322.
13. Fusco, E. J., J. T. Finn, J. K. Balch, R. C. Nagy, and B. A. Bradley. 2019. Invasive grasses increase fire occurrence and frequency across US ecoregions. *Proceedings of the National Academy of Sciences* 116:23594–23599.
14. Germino, M. J., J. C. Chambers, and C. S. Brown. eds. 2016. *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US: Causes, Consequences, and Management Implications*.

Cham: Springer International Publishing.

15. Knapp, P. A. 1996. Cheatgrass (*Bromus tectorum* L) dominance in the Great Basin Desert. *Global Environmental Change* 6: 37–52.
16. Link, S. O., C. W. Keeler, R. W. Hill, and E. Hagen. 2006. *Bromus tectorum* cover mapping and fire risk. *International Journal of Wildland Fire* 15: 113.
17. Newberry, B. M., C. R. Power, R. C. R. Abreu, G. Durigan, D. R. Rossatto, and W. A. Hoffmann. 2020. Flammability thresholds or flammability gradients? Determinants of fire across savanna–forest transitions. *New Phytologist* 228: 910–921.
18. Pastick, N. J., B. K. Wylie, M. B. Rigge, D. Dahal, S. P. Boyte, M. O. Jones, B. W. Allred, S. Parajuli, and Z. Wu. 2021. Rapid Monitoring of the Abundance and Spread of Exotic Annual Grasses in the Western United States Using Remote Sensing and Machine Learning. *AGU Advances* 2.
19. Pilliod, D. S., M. A. Jeffries, J. L. Welty, and R. S. Arkle. 2021. Protecting restoration investments from the cheatgrass-fire cycle in sagebrush steppe. *Conservation Science and Practice* 3.
20. Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. Page 48. General Technical Report, US Department of Agriculture, Forest Service, Intermountain Forest and Range Experimental Station, Ogden, UT.
21. Sayre, N. F., W. deBuys, B. T. Bestelmeyer, and K. M. Havstad. 2012. The Range Problem After a Century of Rangeland Science: New Research Themes for Altered Landscapes. *Rangeland Ecology & Management* 65: 545–552.
22. Shinneman, D. J., M. J. Germino, D. S. Pilliod, C. L. Aldridge, N. M. Vaillant, and P. S. Coates. 2019. The ecological uncertainty of wildfire fuel breaks: examples from the sagebrush steppe. *Frontiers in Ecology and the Environment* 17: 279–288.
23. Simpson, K. J., B. S. Ripley, P.-A. Christin, C. M. Belcher, C. E. R. Lehmann, G. H. Thomas, and C. P. Osborne. 2016. Determinants of flammability in savanna grass species. *Journal of Ecology* 104: 138–148.
24. Smith, J. T., B. W. Allred, C. S. Boyd, K. W. Davies, A. R. Kleinhesselink, S. L. Morford, and D. E. Naugle. 2023. Fire needs annual grasses more than annual grasses need fire. *Biological Conservation* 286: 110299.
25. Whisenant, S. G. 1990. Changing fire frequencies on Idaho's Snake River Plains: ecological and management implications. General Technical Report, US Department of Agriculture, Forest Service, Intermountain Research Center, Logan, UT.
26. Zanzarini, V., A. N. Andersen, and A. Fidelis. 2022. Flammability in tropical savannas: Variation among growth forms and seasons in Cerrado. *Biotropica* 54: 979–987.

Figures

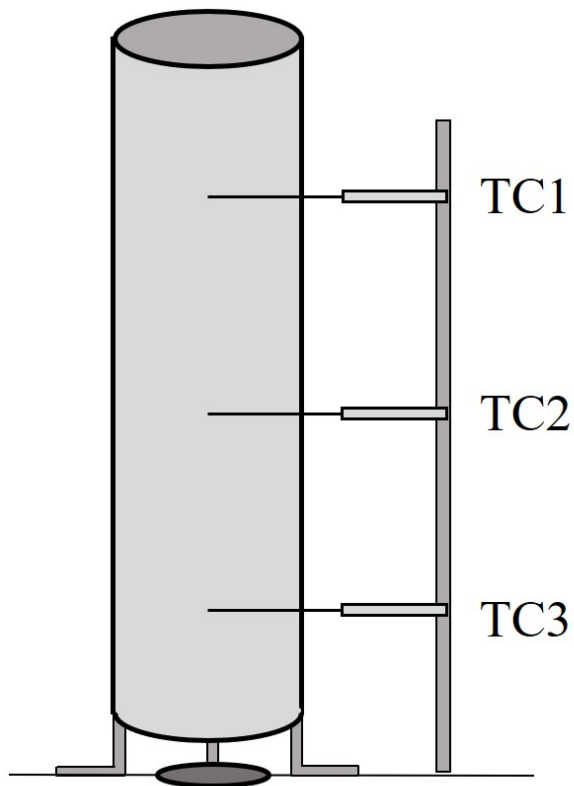
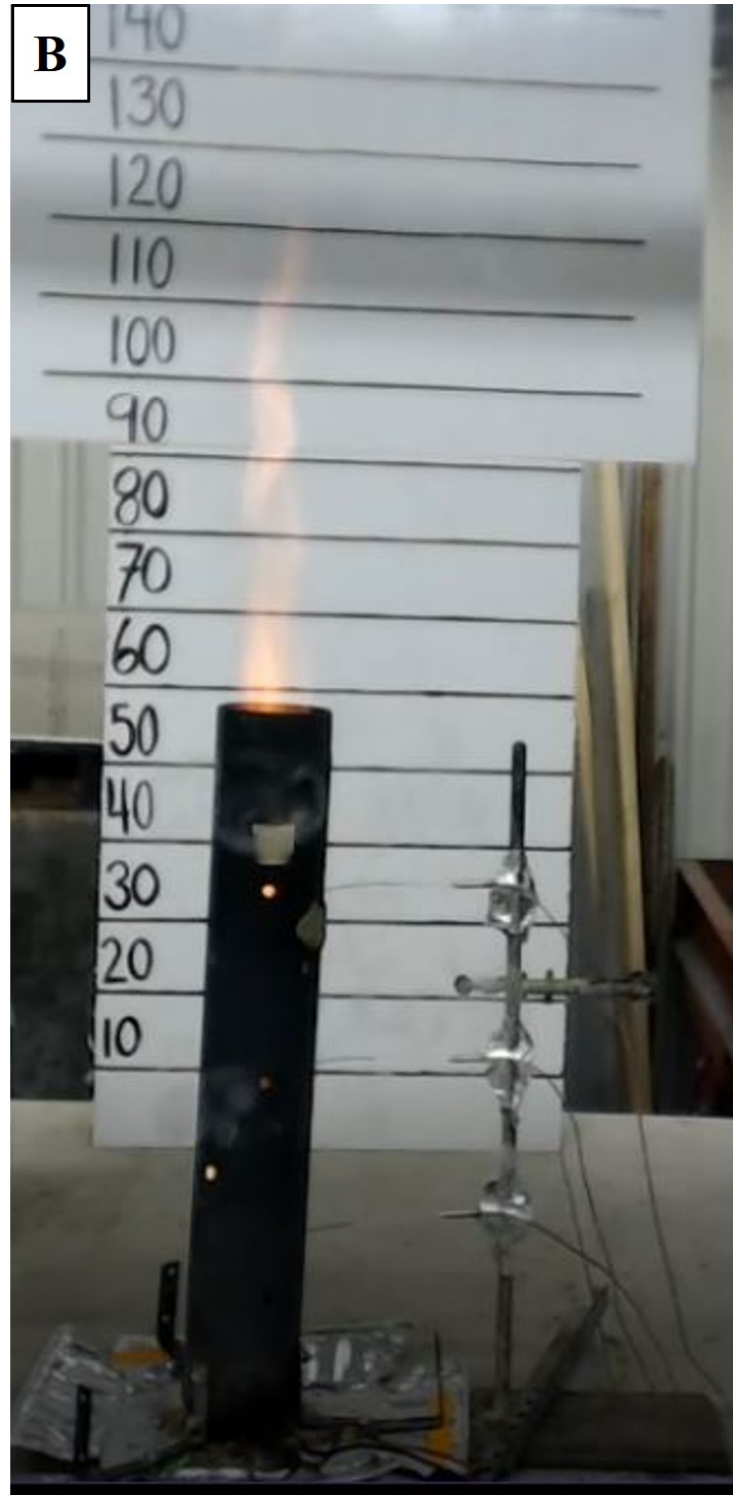
A**B**

Figure 1

Diagram (A) and photo (B) of combustion chamber with three thermocouples (TC). The main chamber is a 10 cm diameter pipe raised 2.5 cm off the ground. Thermocouples extend into the center of the chamber at 19, 33, and 48 cm from the base.

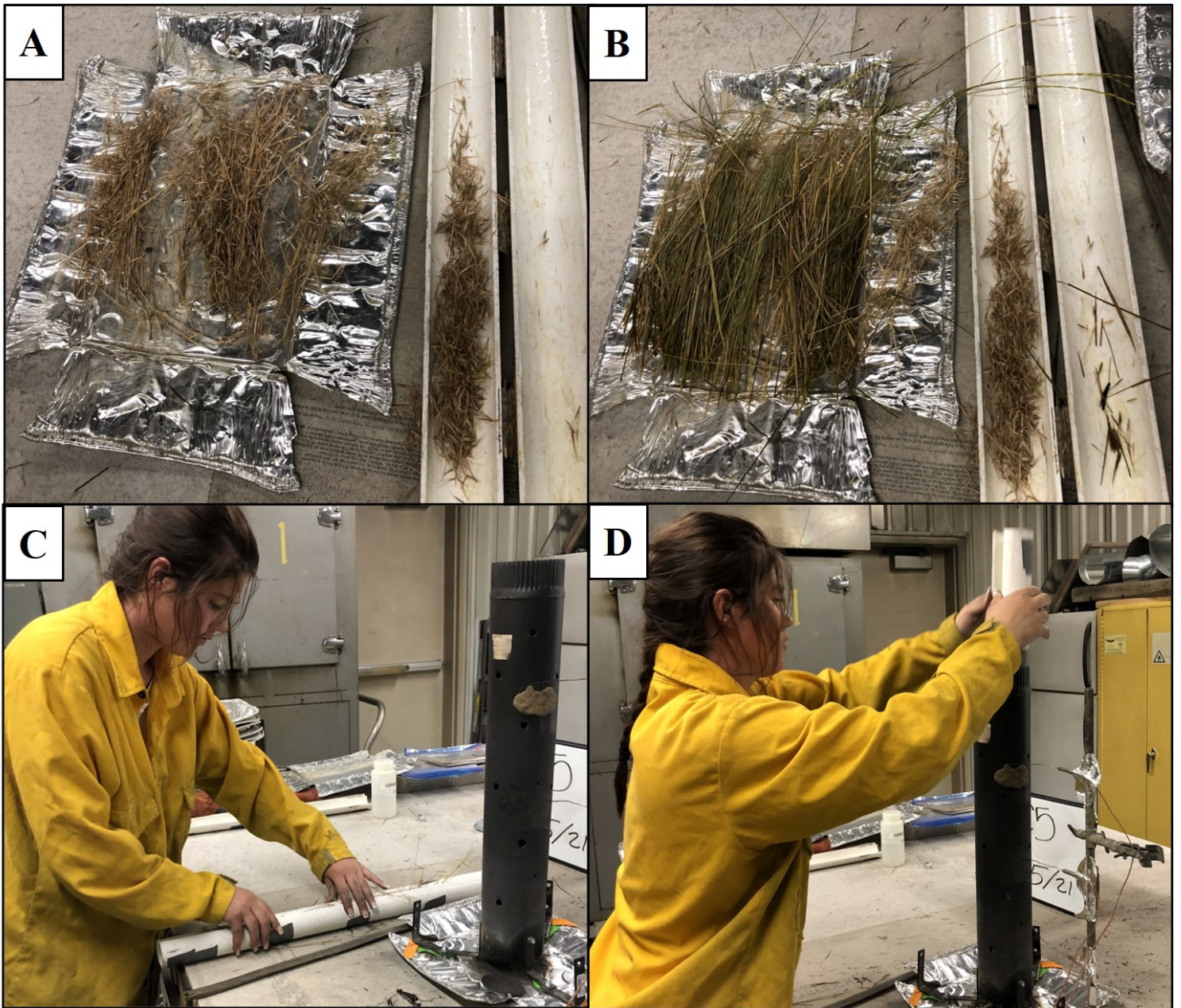


Figure 2

Loading plant material into the combustion chamber. Panels A and B show combining annual (A) and perennial (B) grasses. Panels C and D show vertical sample loading into the combustion chamber.

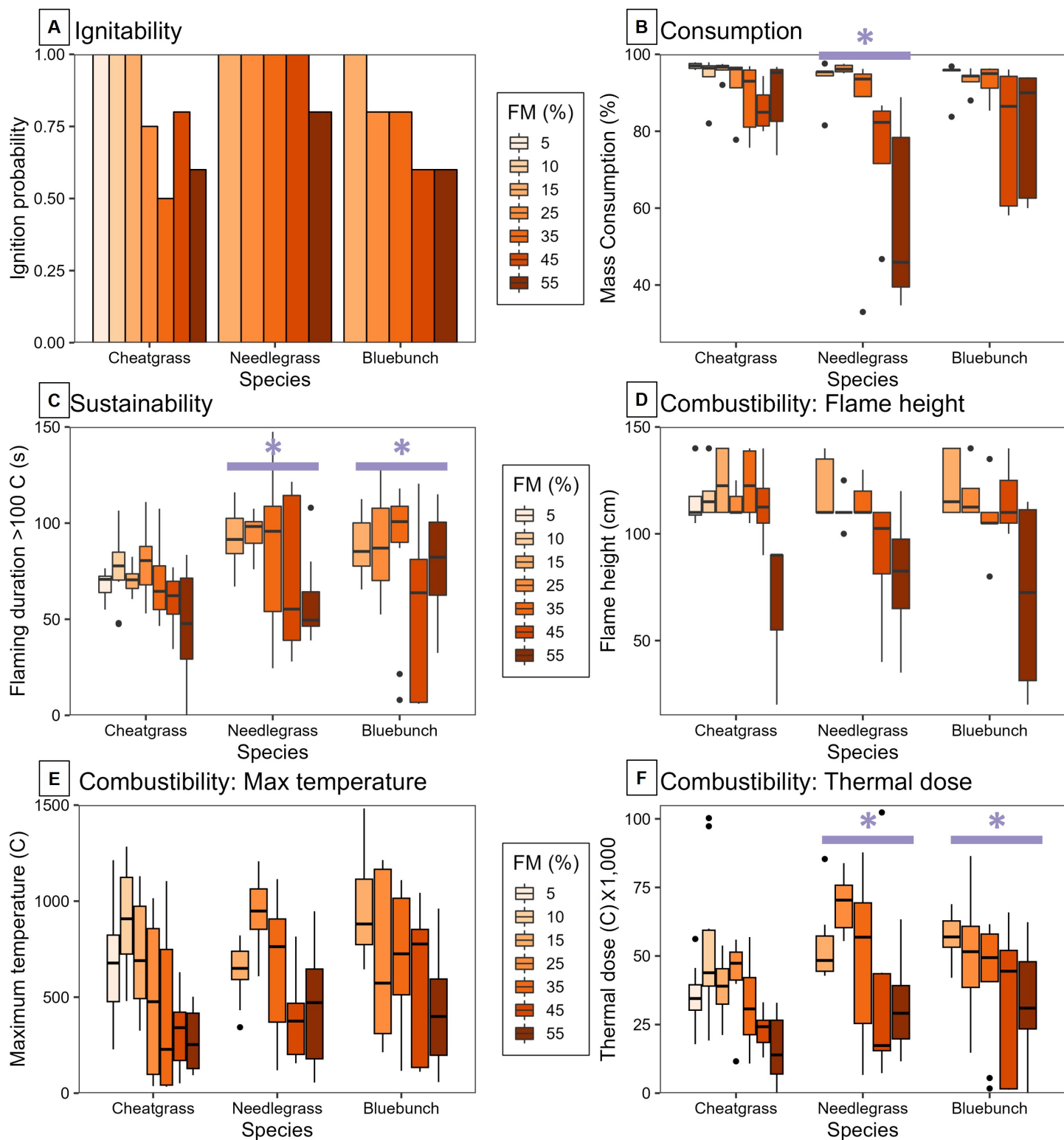


Figure 3

Flammability of individual species with increasing fuel moisture (FM). Differences between each species' flammability were examined using multiple, one-way ANOVA tests, significance across species is represented with purple asterisk and bars (Supplemental Table 1). Perennial grass species had higher thermal dose and flaming duration than cheatgrass. Differences in flammability attributes by fuel moisture were examined using multiple linear models. For all attributes, flammability decreased with

increasing fuel moisture ($p < 0.001$; Supplemental Table 2). The interaction between species and fuel moisture was not significant.

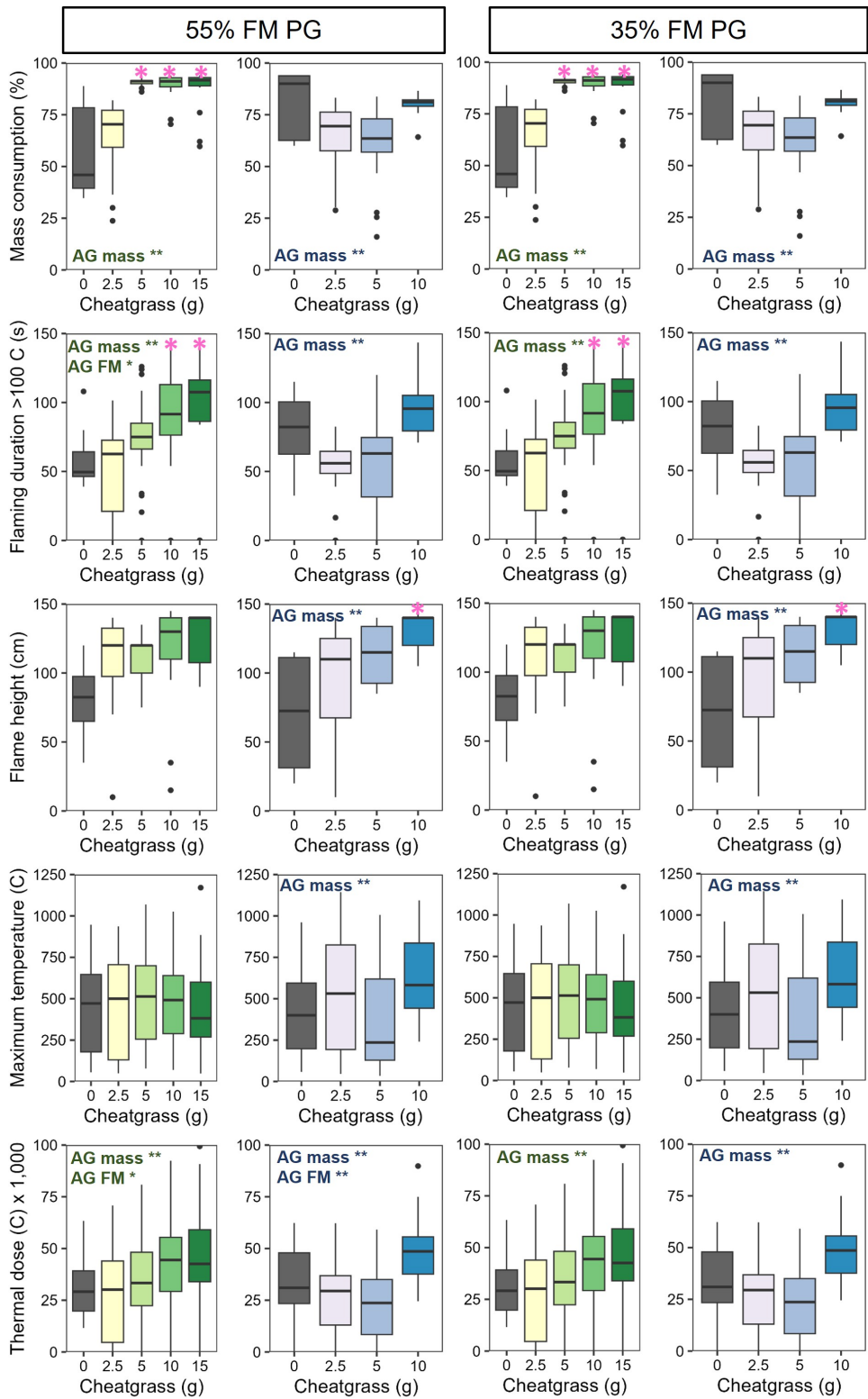


Figure 4

Flammability of perennial grasses at 55% (left) and 35% (right) fuel moisture (FM) burned alone (grey boxes) and with increasing amounts of cheatgrass added to the mix. Left column with green boxes is Columbia needlegrass; right column with blue boxes is bluebunch wheatgrass. Pink single asterisk

indicates statistical difference from perennials burned alone. For each perennial grass species at both 35 and 55% FM, tests for differences in each flammability attribute were examined by annual grass (AG) mass and FM using an ANOVA test. Cheatgrass fuel moisture (range 5-55%) was not significant, so data represent all cheatgrass fuel moistures. Significant terms are represented within each panel, with ** = $p < 0.01$; * = $p < 0.05$. See Supplemental Tables 3 and 4 for full model outputs.

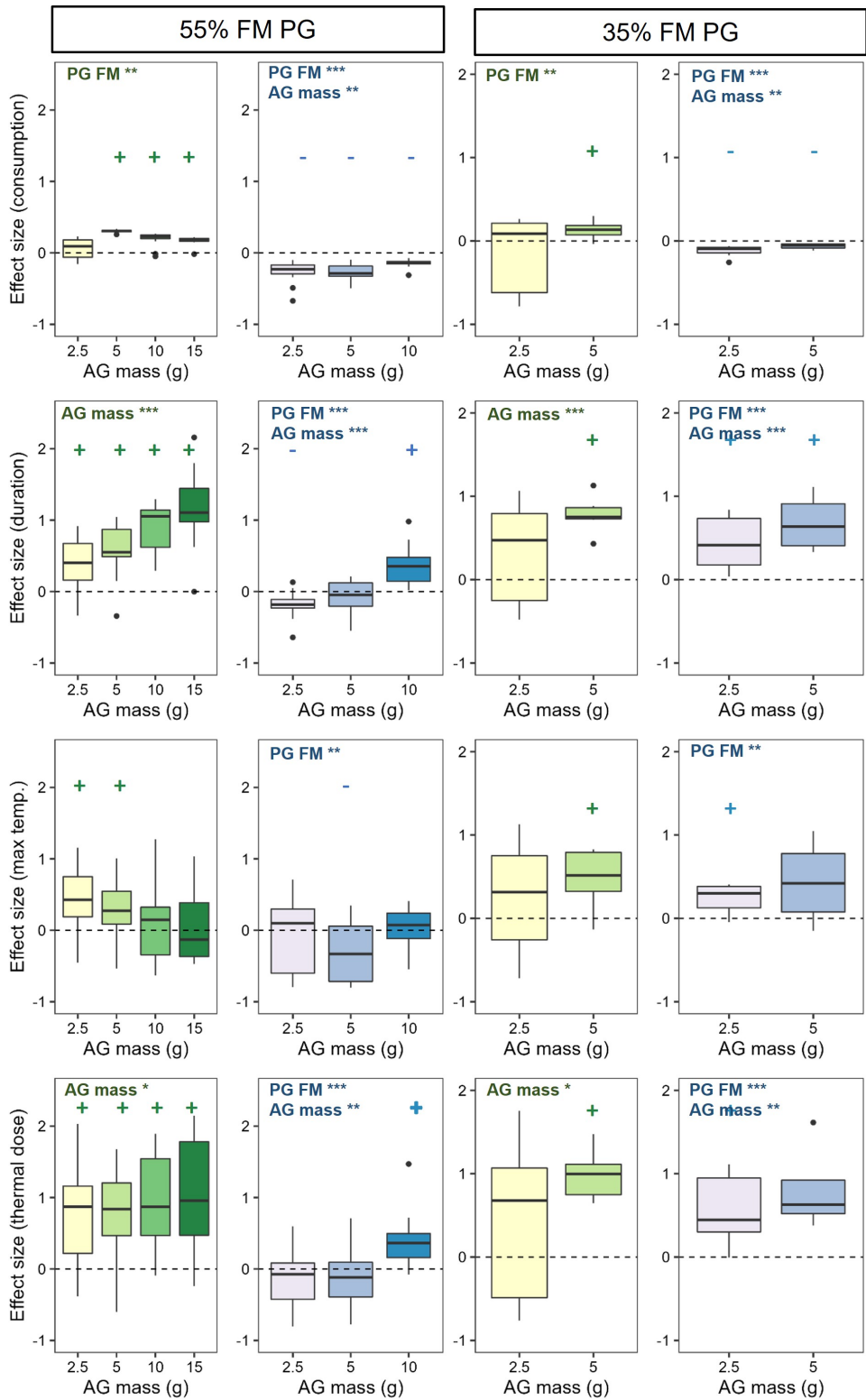


Figure 5

Effect size between observed and expected flammability of 55% (left) and 35% (right) fuel moisture Columbia needlegrass (green) and bluebunch wheatgrass (blue) with varying annual grass (AG) mass. Mean effect sizes that do not overlap with 0 indicate the presence of nonadditivity. + or – indicates statistically different from 0 and direction of difference. Differences in effect size for each perennial grass (PG) species by PG fuel moisture (FM) annual grass (AG) FM, and AG mass using multiple, linear models. Significant model terms are displayed in each panel, with *** = $p < 0.001$; ** = $p < 0.01$; and * = $p < 0.05$ (Supplemental Table 5).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplimentalHarrisonetal.CheatgrassCombustion.docx](#)