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Vegetation, fuels, and fire-behavior responses to linear fuel-break treatments in and around burned sagebrush steppe: are we breaking the grass-fire cycle?

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Abstract

Background Linear fuel breaks are being implemented to moderate fire behavior and improve wildfire containment in semiarid landscapes such as the sagebrush steppe of North America, where extensive losses in perennial vegetation and ecosystem functioning are resulting from invasion by exotic annual grasses (EAGs) that foster large and recurrent wildfires. However, fuel-break construction can also pose EAG invasion risks, which must be weighed against the intended fire-moderation benefits of the treatments. We investigated how shrub reductions (mowing, cutting), pre-emergent EAG-herbicides, and/or drill seedings of fire-resistant perennial bunchgrasses (PBGs) recently applied to create a large fuel-break system affected native and exotic plant abundances and their associated fuel loading and predicted fire behavior.

Results In heavily EAG-invaded areas, herbicides reduced EAG and total herbaceous cover without affecting PBGs for 2–3 years and reduced predicted fire behavior for 1 year (from the Fuel Characteristic Classification System). However, surviving post-herbicide EAG cover was still > 30%, which was sufficient fuel to exceed the conventional 1.2-m-flame length (FL) threshold for attempting wildfire suppression with hand tools. In less invaded shrubland, shrub reduction treatments largely reduced shrub cover and height by ~ half without increasing EAGs, but then redistributed the wood to ground level and increased total herbaceous cover. Herbicides and/or drill seeding after shrub reductions did not affect EAG cover, although drill seedings increased PBG cover and exotic forbs (e.g., Russian thistle). Fire behavior was predicted to be moderated in only one of the many yearly observations of the various shrub-reduction treatment combinations. Over all treatments and years, FLs were predicted to exceed 1.2 m in 13% of simulations under average (11 km h^{-1}) or high (47 km h^{-1}) wind speed conditions and exceed the 3.4-m threshold for uncontrollable fire in 11% of simulations under high-wind speeds only.

Conclusions Predicted fire-moderation benefits over the first 4 years of fuel break implementation were modest and variable, but, generally, increases in EAGs and their associated fire risks were not observed. Nonetheless, ancillary evidence from shrublands would suggest that treatment-induced shifts from shrub to herbaceous fuel dominance are expected to improve conditions for active fire suppression in ways not readily represented in available fire models.

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Keywords Cheatgrass, Exotic annual grasses, Fire behavior modeling, Fuel characteristic classification system, Herbicide, Imazapic, Mowing, Rangeland, Sagebrush, Seeding, Treatment effectiveness

Resumen

Antecedentes Las barreras de combustibles en línea se están implementado para moderar el comportamiento del fuego y mejorar la contención del fuego en paisajes semiáridos como la estepa de artemisia de Estados Unidos, donde las extensivas pérdidas en la vegetación perenne y en el funcionamiento del ecosistema está resultando en la invasión de pastos anuales exóticos (EAGs en inglés), que fomentan incendios de vegetación más grandes y recurrentes. Asimismo, la construcción de estas barreras de combustibles también supone riesgos de invasión de la EAGs, lo que debe ser sopesado con los beneficios de la moderación en el desplazamiento del fuego mediante esos tratamientos. Investigamos cómo una reducción en la cantidad de arbustos (corte, segado de pastos), uso de herbicidas para EAGs, o el sembrado en surcos de arbustos resistentes al fuego (PBGs), aplicados todos de manera reciente para crear un sistema de gran barrera de combustibles, afecta la abundancia de plantas nativas y exóticas, su carga de combustibles asociada y el comportamiento del fuego.

Resultados En áreas fuertemente invadidas por EAGs, los herbicidas redujeron la EAG y la cobertura total de hierbas, sin afectar PGBs, por 3–4 años, y redujeron el comportamiento del fuego predicho por un año (basado en el sistema de clasificación de combustibles característicos). De todas maneras la supervivencia post-herbicida de EAG representó > 30% de la cobertura, lo que significó suficiente combustible como para exceder los 1,2 m convencionales de longitud de llama (FL) considerado como límite para combatir un incendio con herramientas manuales convencionales. En arbustales menos invadidos, los tratamientos de reducción en gran medida redujeron la cobertura y altura por aproximadamente la mitad sin incrementarse la cantidad de EAGs, pero entonces luego redistribuyeron el componente leñoso a nivel del suelo e incrementaron la cobertura total de hierbas. Los herbicidas y/o el sembrado de arbustos en surcos luego de la reducción de los arbustos no afectó la cobertura de EAGs, aunque el sembrado por surcos incrementó la cobertura de PBG y las malezas exóticas (i.e. cardo ruso). El comportamiento del fuego fue predicho como moderado en solo uno de los muchos años de observaciones de las varias combinaciones de los tratamientos de reducción. En todos los años y tratamientos, fue predicho que la longitud de llama (FLs) excedía los 1,2 m en el 13% de las simulaciones con condiciones de vientos promedio (11 km/h) o fuertes (47 km/h) altos, y excediendo los 3,4 m definido como límite para fuegos incontrolables en el 11% de las simulaciones solo bajo condiciones de vientos muy fuertes.

Conclusiones Los beneficios predeterminados de la implementación de las barreras de combustible para los primeros 4 años fueron modestos y variables, aunque generalmente, el incremento en las EAGs y su riesgo de incendio asociado no fueron observados. A pesar de esto, la evidencia auxiliar para los arbustales sugiere que es esperable que los cambios inducidos por los tratamientos que conllevan el cambio del dominio de combustibles de arbustales a pastizales mejorará las condiciones para una supresión más activa que no es rápidamente representada por los modelos de combustibles actualmente disponibles.

Background

Invasions by fire-adapted exotic annual grasses are altering fuel compositions and thus wildfire to their selective advantage over native vegetation in many habitats, globally (Aslan and Dickson 2020; Tomat-Kelly and Flory 2023), including invasion of perennial shrub-steppe of western North America by the winter-annual cheatgrass (*Bromus tectorum* L., Brooks et al. 2004, Davies and Nafus 2012, Bukowski and Baker 2013). The resulting grass-fire cycle can be difficult to reverse, and it negatively impacts high-value resources such as livestock grazing and wildlife habitat (Brunson and Tanaka 2004, Germino et al. 2016). Currently, only about half of the nearly 1 M km^2 that was once sagebrush steppe remains, due mainly to fire-mediated conversion to annual grassland (Miller et al. 2011) which has more than doubled the likelihood of wildfire (Bradley et al. 2018).

Reducing rates of landscape conversion to annual grasslands and protection of intact sagebrush steppe habitat for sagebrush obligates, such as the greater sage grouse (*Centrocercus urophasianus*), is a priority of the U.S. Department of the Interior (DOI) and other landowners (Integrated Rangeland Fire Management Strategy Actionable Science Plan Team 2016). Key aspects of this effort include pre-fire fuels management and active wildfire suppression, because native species, such as big sagebrush, are intolerant to frequent fire, owing to rapid loss of their seedbank (Wijayratne and Pyke 2012) and slow rates of recovery (Welch 2005; Pyke et al. 2020). Federal agencies, like the DOI's Bureau of Land Management (BLM), have invested tens of millions of dollars annually in recent decades to rehabilitate or restore sagebrush steppe following wildfire (Bureau of Land Management (BLM) 2020a). Land use and land condition changes have caused alterations to the fire regime in many locations, globally, and revegetation actions can moderate fire risks and behavior depending on how recovery commences, as shown in Australia (Collins et al. 2015). In the western USA, post-fire rehabilitation investments, however, are compromised by reburning and reinvasion by exotic annuals, with 26% of 3400 restoration seedings in sagebrush landscapes reburning from 1990 to 2019 and affecting nearly 500,000 ha (Pilliod et al. 2021). Considering the time needed for successful rehabilitation in sagebrush steppe (Nelson et al 2013; Shinneman and McIlroy 2016), protection of intact or recovering sagebrush steppe is vital. Most of the area burned annually in sagebrush steppe occurs in large "megafire" patches (> 100,000 ha), and thus, containment of wildfires through an initial attack when they are still relatively small is a core strategy for reducing the overall area burned.

In one of the most ambitious and proactive efforts to address the need to minimize wildfire spread, the US federal government recently proposed the construction of a network of linear fuel breaks (17,703 km) in sagebrush steppe of California, Idaho, Nevada, Oregon, Utah, and Washington (Bureau of Land Management (BLM) 2020b). Vegetation treatments used to create fuel breaks reduce and redistribute fuels, and typically include herbicides, mowing or hand-cutting, and drill-seeding of more fire-tolerant species (Shinneman et al. 2018). In the sagebrush steppe, mowing or hand cutting is intended to reduce shrub heights and abundances, and thus flame lengths (FL) and flame residence time, whereas chemical treatments are designed to limit annual herbaceous growth, benefitting perennial vegetation and reducing the horizontal continuity of fuels affecting wildfire rates of spread (ROS, Maestas et al. 2016). Reducing FLs increases the prospect for wildfire suppression. Specifically, reducing FL to < 1.2 m allows firefighters to directly suppress wildfires with hand tools or manipulate downwind fuels, whereas bulldozers and other equipment can be used if FLs < 2.4 m (Andrews and Rothermel 1982). Scenarios where FLs exceed 2.4 m are prone to increase rapidly spreading head fires that are less containable and are a greater threat to firefighter safety, and FLs > 3.4-m render wildfire suppression dangerous and ineffective or impossible (Andrews and Rothermel 1982). Fuel breaks are often placed along established roads, which provide better access to points of initial wildfire attack and can help constrain wildfire spread (Moriarty et al. 2016, Wollstein et al. 2022).

Despite the importance and expansion of fuel breaks, there are relatively few studies on their effects (reviewed in Shinneman et al. 2018 and 2019). Fuel breaks may facilitate the immigration/emigration of non-native plants onto and adjacent to established fuel breaks, and the invasions often affect fire behavior (Davies et al. 2011; Grupenhoff and Molinari 2021). Most fuel breaks will require multiple treatments that must be separated in time, such as pre-emergent herbicides and seeding applied to the same sites, to avoid counterproductivity. Additional complicating factors are that fuel-break treatments often require repetition for effective implementation or maintenance under varying weather conditions and across environmental gradients, such as soils and topography (Pyke et al. 2014). Thus, an understanding of the time course of vegetation responses over the years and in response to the serial, phased application of co-treatments is important.

Fuel-break effects or effectiveness has often been determined using expert opinion or recorded observations of fire-suppression personnel, following unplanned wildfire (Moriarty et al. 2016), and evidence thus far has focused largely on forest and chaparral settings characterized by greater fuel amounts and connectivity relative to sagebrush steppe (Keeley 2006; Syphard et al. 2011; Oliveira et al. 2016). Planned attempts to evaluate fuel break effects on fire behavior using prescribed fire are typically unacceptable in sagebrush steppe because of the preponderance of negative fire effects. Therefore, predictions of fire behavior using quasi-empirical models provide one of the only means for understanding how fuel breaks might affect fire behavior, specifically FL and ROS and reaction intensity (RI; Rothermel 1972; Prichard et al. 2013).

Our objective was to identify the near-term effects of herbicide, shrub reduction, and drill-seeding treatments on native and exotic plants and fuels, and the implication of these responses for predicted fire behavior, relative to management objectives and wildfire suppression thresholds. Management objectives of fuel breaks were to reduce fuels such that they produce fire behavior consistent with the standard fire behavior fuel model (FBFM) "GR1" which is characteristic of short, sparse dry-climate grass fuels (BLM 2017, Scott and Burgan 2005). GR1 is commonly used to represent fuels that are not an absolute barrier to fire spread but that exhibit the lowest ROS (≤ 9.8 m min^{-1}) and FL (≤ 0.8 m) among FBFMs with the potential for fire spread (BLM 2017, Scott and Burgan 2005). We also asked how the FL responses to treatments related to critical thresholds for fire suppression with hand tools (i.e., ≤ 1.2 m; Andrews and Rothermel 1982).

Fire-behavior predictions were made with the “Fuel Characteristic Classification System” (FCCS) that is based on Sandberg et al.’s (2007) reformulation of Rothermel’s (1972) surface fire spread equations to allow for multilayer input of field measurements including the amount, types, and arrangement of fuels (Ottmar et al. 2007; Prichard et al. 2013). The functionality of Rothermel-based models for a particular site is affected by user selection of the most appropriate fuel-bed input submodel for the site conditions. Other models rely on largely pre-set and stylized fuel bed characterizations (e.g., standard FBFMs; Burgan and Rothermel 1984). FCCS allows users to add an additional level of parameterization of FBFMs to better represent the vertical heterogeneity in fuels of a site, and FCCS also improved operability over the currently available physics-based fire prediction models that might otherwise allow for customization. Underlying assumptions of both Rothermel-based spread models and FCCS are that (1) fuel beds are continuous and uniform in lateral space, which is rarely true in sagebrush steppe and other semiarid habitats, and (2) atmospheric responses to fire do not feedback on fire behavior. Thus, the model predictions are of heuristic value, and the interpretation of results should consider these and other limitations.

Methods

Study area

The study area was located within and surrounding the 113,000-ha burn scar created by the 2015 Soda wildfire, which occurred along the border of southwestern Idaho and southeastern Oregon (Owyhee and Malheur counties, respectively, Fig 1; see also Price and Germino (2024a) for similar sites and methodology). Pre-fire vegetation consisted of sagebrush steppe with a mosaic of various community states that included mixed shrub-grass

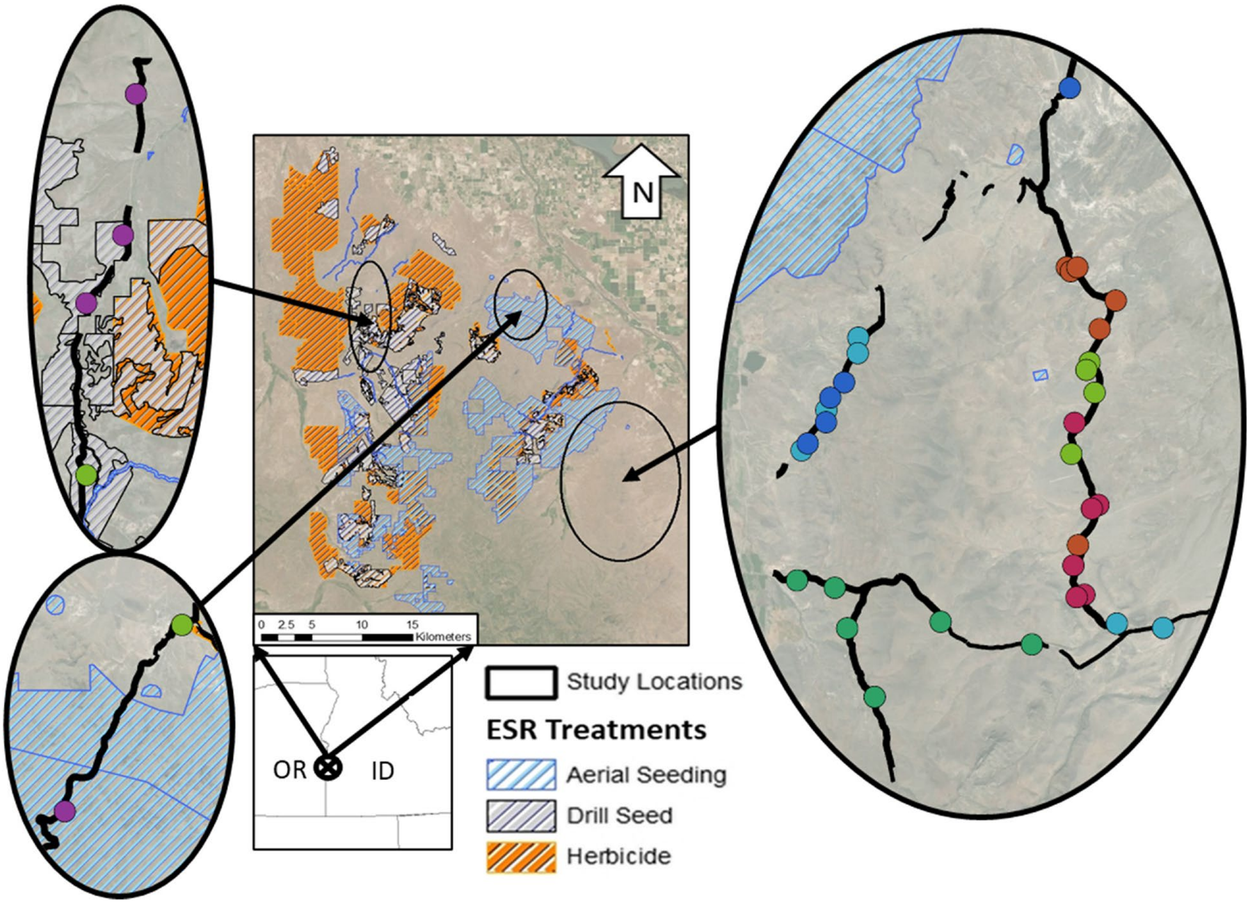

Fig. 1 Rehabilitation and stabilization treatments following the 2015 Soda fire, including aerial seeding of shrubs and perennial grasses (blue hatched), drill seeding of perennial grasses (grey hatched), and herbicide applications (orange hatched; center map) applied by the BLM Emergency Stabilization and Rehabilitation program (“ESR”; data courtesy of BLM). Elliptical pop-outs show where pairs of treated and untreated plots were located with varying treatment combinations (colored circles). Colored circles designate treatment combinations: purple = herbicide, light green = 2 × herbicide, light blue = hand cut, orange = hand cut + 2 × herbicide + 2 × drill seed, dark blue = mow, dark green = 2 × mow, red = 2 × mow + 2 × herbicide + 2 × drill seed (Table 1)

stands, perennial grass stands, and invaded annual grasslands. The burn area was topographically complex, covering large ranges in elevation (750–2055 m), mean–annual precipitation (230–550 mm year^{-1}), and mean-annual air temperature (6.8–10.8 °C; 30-year data, 800-m resolution; PRISM Climate Group, accessed July 2022). The entire area was grazed by livestock with primarily spring and summer use at stocking rates varying from ~ 2 to 4 ha per animal unit month. Grazing following the Soda wildfire was deferred across most of the landscape for two growing seasons post-fire, except in some heavily invaded areas where it was resumed after one growing season, and in a few areas deferred up to four seasons. Approximately 300 wild horses were present before the wildfire and were removed upon containment and returned 2 years later. Wildlife included mule deer (*Odocoileus hemionus*) and pronghorn antelope (*Antilocapra americana*), Greater sage-grouse (*Centrocercus urophasianus*), and a range of small mammals (e.g., lagomorphs, ground squirrels). For the greater area (extending ~ 5 km from the Soda wildfire boundary), ~ 98% of ignitions and ~ 71% of the area burned have historically occurred between July and September (from 1957–2021) with an average of 2.7 ignitions per year burning a mean ~ 1400 ha per wildfire (Welty and Jeffries 2021).

Following the Soda fire, the Bureau of Land Management (BLM) applied a suite of rehabilitation efforts that included repeated or multiphasic treatment combinations over most of the burned area, primarily seedings of perennials and applications of pre-emergent herbicides applied in sequential years (Fig. 1). To protect these rehabilitation investments and minimize the potential for future wildfires, the BLM began constructing a network of ~ 60-m-wide linear fuel breaks along primitive and improved roadways, within and surrounding the Soda burn scar in 2017 (Fig. 1; BLM 2017). Treatments applied throughout the network differed by plant community type: (1) annual-grass-dominated communities which lacked shrubs and (2) perennial-dominated communities which included large shrubs. Where annual grasses dominated, herbicides and drill seedings of non-native perennial species (primarily *Agropyron cristatum* (L.) Gaertn.) were prioritized. Where shrubs were dominant fuels, they were reduced using either tractor-pulled mowers or were manually "hand cut" with chainsaws to a height of ~ 20 cm, and some cut areas later received herbicides and some also received drill seedings. Additionally, to control exotic forbs, the use of the contact herbicide 2,4-D was used. Combinations of fuel reduction treatments were applied sequentially and sometimes repeatedly, resulting in seven unique treatment combinations which are hereafter referred to as "herbicide," "2 × herbicide + 2 × drill seed," "hand cut," "hand cut + 2 × herbicide + 2 × drill seed," "mow," "2 × mow," or "2 × mow + 2 × herbicide + 2 × drill seed," with "2 × " referring to repeated treatment applications (Table 1). Weather at the time of treatment implementation varied greatly in relation to 30-year climatic means: autumn weather in 2017 and 2020 were 30–50 mm more rain and was ~ 2 °C warmer than the mean climate, whereas autumn weather was closer to the long-term climate conditions in 2018 (− 10 mm, − 0.6 °C), 2019 (− 30 mm, + 0.7 °C), and 2021 (+ 1 mm, + 0.9 °C; PRISM Climate Group, Table 1).

Data collection and fire model parameterization

Our study approach entailed a tradeoff in experimental control and suppression of unwanted variability in return for realism in inferences reached, owing to the nature of the fuel-break treatments we evaluated, i.e., constructed for land management purposes. Data presented here are for 40 pairs of plots spanning ~ 60.7 km of linear fuel break treatments, with one plot of each pair located within the roadside fuel break, and the other paired plot located in untreated areas adjacent to the fuel break (Figs, 1, 2 and 3). Plots were selected using a stratified-random approach, specifically randomizing the dispersion of plots such that a minimum of five replicate plots occurred within each treatment combination. Plot centers were 30 m from the fuel-break treatment boundary (Fig. 3). Field sampling occurred after the natural summertime curing of fuels from 2018 through 2021, usually from September to October (November in 2018, to avoid interfering with treatment implementation).

All of the FCCS's input options specific to sagebrush steppe were collected from each plot visit and used to parameterize model runs for each plot-sampling year combination. Fuel and Fire Tools version 2.0.2022 (which houses FCCS; https://depts.washington.edu/fft/) was used for this project. Fuel layers in FCCS that were applicable to our study were the "shrub," "herb," "wood," and "litter-lichen-moss" fuel layers. FCCS's "canopy" and "ground fuel" layers are more applicable to forested sites and were therefore not used in this study. FCCS's "shrub" layer requires inputs of percent of total shrub cover, percent of shrubs that were actively growing ("percent alive"), fractional cover by species, shrub height, needle drape (optional), and shrub fuel loading (which FCCS will estimate based on shrub species, cover, and height inputs). FCCS's "herb" layer includes inputs for standing herbaceous fuels and has the same fuel parameters as the shrub layer, except for needle drape. FCCS's "wood" layer contains several sub-layers for various arrangements and levels of decomposition of detached woody fuels, and our analysis used only the "sound wood" layer. Inputs required for "sound wood" layer include percent

Table 1 Timing and type of fuel treatments evaluated, and associated weather. "–" indicates no treatment at that time. Weather at the time of implementation is the average temperature and total precipitation relative to mean climate from the previous 30 years binned by season (fall = September through November; winter = December through February; spring = March through May; summer = June through August; PRISM 4 k). Weather for 2021 is based on annual values

Year	**Timing**	**Weather at time of treatment implementation**		**Fuels Treatments**						
		Variable	Relative difference from 30-year mean							
2017	Fall/Winter	Precipitation	wet: +50 mm	Herbicide (imzapic)	Herbicide (imzapic)	-	Herbicide (imzapic)	-	Mow	Mow + Herbicide (imazapic)
		Temperature	warm: +2°C							
2018	Fall/Winter	Precipitation	dry: -10 mm	-	-	Hand Cut	Hand Cut	Mow	-	-
		Temperature	normal: -0.6°C							
2019	Fall/Winter	Precipitation	dry: -30 mm	-	Drill Seed	-	Drill Seed	-	Mow	Mow + Drill Seed
		Temperature	normal: +0.7°C							
2020	Spring/Summer	Precipitation	wet: +50 mm	-	Herbicide (2,4-D)	-	Herbicide (2,4-D)	-	-	Herbicide (2,4-D)
		Temperature	normal: +0.2°C							
	Fall/Winter	Precipitation	wet: +30 mm	-	Drill Seed	-	Drill Seed	-	-	Drill Seed
		Temperature	warm:+2.2°C							
2021	No Treatments	Precipitation	normal: +1 mm	-	-	-	-	-	-	-
		Temperature	normal: +0.9°C	-	-	-	-	-	-	-
TOTAL				Herbicide	2x Herbicide + 2x Drill Seed	Hand Cut	Hand Cut + 2x Herbicide + 2x Drill Seed	Mow	2x Mow	2x Mow + 2x Herbicide + 2x Drill Seed

Fig. 2 Photo of a fuel-break treatment boundary with the mowing fuel-break treatment to the left and untreated control to the right. Photography by Matt Germino, U.S. Geological Survey, 2018

of total cover, depth, and fuel loading timelag class for fuel moisture gain or loss (i.e., 1-, 10- or 100-h timelag class, Brown 1974). FCCS's "litter-lichen-moss" layer is used to input detached herbaceous fuels and requires inputs of percent of total cover, relative cover by type ("grass" option was used), depth, arrangement ("normal" was used), and fuel loading.

We obtained the necessary information from the field required to create custom fuel beds for each plot x year combination in FCCS. Vegetation cover by species was quantified using digital grid-point intercept of species cover observed in four overhead photos of 2 × 3-m areas per plot, with the camera positioned perpendicular to the ground at 2-m height and photo edges excluded from sampling to avoid size distortion (SamplePoint, as described in Applestein et al. 2018; Fig. 3). Height and diameter of the first five mature shrubs (shrubs that had recently flowered or been cut) encountered starting at plot center, facing toward the treatment boundary, and moving clockwise within a 13-m radius were recorded, in addition to the fraction of each shrub that was alive versus dead (i.e., percent alive; Fig. 3). Mature shrubs were targeted for measurement as they were the focus of the fuel treatments. Height and diameter of five perennial bunchgrasses and the height of exotic annual grasses, as well as percent alive, were also recorded within the 13-m radius plot (Fig. 3). Biomass and depth of the litter layer (distance from the top of detached plant litter layer to soil surface) were sampled within two 1 × 1-m biomass quadrats per plot, with new sampling locations selected randomly each year to avoid clipping effects on subsequent biomass production (Fig. 3). All biomass was removed from each quadrat; then separated by fuel type,

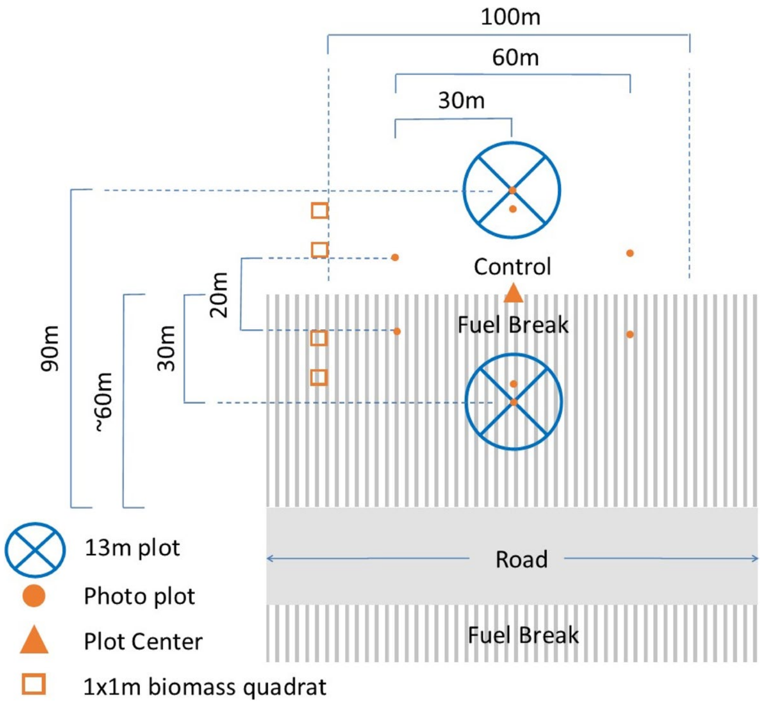

Fig. 3 Spatial layout of sampling in each pair of treated and untreated plots. Reproduced from Price and Germino (2024a)

specifically into wood size classes that correspond to nominal 1-, 10-, or 100-h timelag classes for fuel moisture gain or loss based on fuel diameter (large, 1000-h fuels were not present), herbaceous litter, or standing herbaceous fuels; dried for 48 h at 65 °C, and then weighed to 0.01-g resolution. Detached woody and herbaceous litter depths were sampled at five points across each 1-m quadrat to 0.5-cm resolution. Standing shrub biomass was not removed and was instead estimated from allometric equations within FCCS.

Model predictions were based on slopes of 0%, as all sites are positioned along 2-track or improved roadways. Fire behavior was estimated for two wind-speed scenarios, specifically 11 km h^{-1} (7 mph) and 46 km h^{-1} (28 mph) which represented mean and 97th percentile gust wind speeds for the months of July–September (fire season, starting in 1981 and ending 1996) from three weather stations located in the Reynolds Creek Watershed with close proximity to our monitoring points (hourly data, Hanson 2021). Mean wind speed was determined by averaging the mean hourly wind speed values for all 3 months over the 15 years and three stations, and the maximum wind speed was taken as the 97% percentile value from the same data assemblage. All fuel beds used the "full-cured scenario" fuel moisture scenario in FCCS (environmental scenario D2L1; 1 h = 6%, 10 h = 7%, 100 h = 8%, live herbaceous = 30%, live shrub = 60% moisture content), which represents late summer, when fuels are very dry, and risk of high-intensity fires is greatest. FCCS's "percent alive" parameter transfers a portion of the live fuel moisture to dead fuel moisture, similar to Behave + 's dynamic fuel model setting (Burgan and Rothermel 1984; www.firelab.org/project/behaveplus). For example, if the "herb" layer is parameterized as 75% alive in the fuel moisture scenario "D2L1" in FCCS, then 75% of the load has a fuel moisture content of 30%, and 25% of the load has a fuel moisture content of 6%. FCCS does not have inputs for fuel surface area-to-volume ratio, fuel moisture of extinction, or fuel-bed depth, and so each is instead inferred within FCCS from the species and fuel information entered by the user into each fuel layer. For example, vegetation height parameters across fuel layers are used by FCCS to calculate fuel bed depth, and species-specific information is used to determine fuel surface area-to-volume ratio and fuel moisture of extinction separately for each fuel layer within FCCS. This is a vast improvement over other available fire models of similar design in which the user enters only a single fuel surface area-to-volume ratio that then describes the entirety of the fuel bed. In reality, a fuel bed is comprised of a range of fuel moistures and fuel surface area-to-volume ratios, which interact with one another such that the finer and drier fuel elements aid in the ignition of coarser and wetter fuel elements.

Analysis

All analyses were performed in R Version 4.0.3 (R Core Team 2022) and R Studio Version 1.0.143 (RStudio Team 2020). Raw data failed to meet the assumptions of normality and generalized linear mixed-effect models failed to converge with the inclusion of random effects accounting for both the pairing of plots and repeated measurements. These problems were overcome by instead using the treated-minus-control difference in vegetation or fire behavior for each pair of plots as the response variable, which better met the assumptions of normality (evaluated via QQ plots and skewness; Bulmer 1979, Knief and Forstmeier 2021) and reduced the structure of the random effect to controlling for only repeat measures (since the pairing of plots was now accounted for within all response variables). In several cases, however, an additional exponential transformation was required to meet model assumptions (specifically, fire behavior responses). Separate linear mixed effect models (lme4; Douglas 2015) were then used for each response variable as explained by the interaction between treatment type and year of observation (i.e., response ~ treatment type X year observed + (1|pointID)). Statistical significance was then based on whether the 95% confidence interval for each response variable estimate crossed zero, utilizing the "emmeans" package in R (Lenth 2021). All data are available from Price and Germino (2024b).

Results

Plant-community responses

From the first to 5th sampling year, bare-ground cover increased by 145% whereas EAG and Sandberg bluegrass cover decreased by 23 and 13%, respectively, over all plots (Figs. 4 and 5). Sandberg bluegrass—which is notable among native perennials for having traits that are similar to cheatgrass and other EAGs such as relatively short life span, low-stature, shallow-rooting, and early season phenology—was generally abundant (up to > 40% cover, Fig. 4).

A single application of the herbicide imazapic in 2017 onto areas that were heavily invaded by annual grasses ("herbicide" or "double herbicide + double drill seed") led to delayed and temporary reductions in exotic-annual grass (EAG) cover, specifically reducing EAG cover by 27–43% in 2019 and 2020 relative to untreated controls (Fig. 4). Similar reductions in EAG cover followed the application of the herbicide 2,4-D combined with drill seeding of perennials in 2020 (Fig. 4). Shrub reductions generally did not affect EAG cover, with only a few transient short-term exceptions of increases or decreases after treatments (Fig. 4).

Perennial bunch grass (PBG) cover was low across all years and treatment combinations (0–12%), and no significant differences between fuel break and controls existed for any years other than 2021, when PBG was increased following repeated drill seedings where exotic annual grass abundances were low (i.e., the 3-part treatment combinations, Fig. 4). PBG cover also significantly increased from ~ 1% in 2020 to a modest 6% of ground area in 2021 for the "2 × mow" treatment combination without any drill seedings (relative to ~ 3% PBG cover in the control; Fig. 4).

Sandberg bluegrass cover was unaffected by treatments with a few exceptions, including increases following mowing in the "2 × mow" treatment and variable responses to herbicide for the combined herbicide and drill seeding treatment (Fig. 4). Exotic forb cover, which was predominately Russian thistle (*Salsola tragus* L.) with some prickly lettuce (*Lactuca serriola* L.), was also unaffected by treatments except in 2021, where they increased substantially, by ~ 40% to 700%, for all treatments other than "herbicide" and "2 × mow," in addition to a small increase in 2019 in the combined mowing, herbicide, and drill seedings (Fig. 4).

Total herbaceous cover was reduced in 2018 and 2019 by 3% to 21% following the 2017 imazapic spraying in plots heavily invaded by annual grasses (Fig. 4). Total herbaceous cover inside shrub reduction treatments appeared unaffected by hand cutting, however, mowing treatments led to significant increases of 17% to 78% in most years following fuel break construction (the exceptions being 2019 for the "mow" and "2 × mow + 2 × herbicide + 2 × drill seed" treatments; Fig. 4).

Bare soil exposure was unaffected by treatments except for transient decreases following shrub reductions ("hand cut" and "2 × mow") and increases following the combination of herbicides and drill seeding (Fig. 5). There were few treatment effects on herbaceous litter cover, with only short-term increases in heavily invaded areas. Mean herbaceous litter cover across all years was 15% of the ground area and was unaffected by shrub-reduction treatments (Fig. 5).

Shrub cover and height were approximately halved by shrub-reduction treatments, except for the "hand cut" treatment where considerable regrowth occurred following treatment (Fig. 6; Appendix). Significant reductions in cover and height of shrubs led to a mean 2.5-fold increase in wood litter, ultimately accounting for ~ 15% of the ground cover (Fig. 5). The only situations where wood litter did not increase were the treatment combinations where shrub covers were not reduced ("hand cut"; Fig. 6).

Fuel loading and fire behavior

Total fuel loading was generally unaffected by treatments except for a ~ 54% reduction caused by the "2 × mow + 2 × herbicide + 2 × drill seed" treatment evident

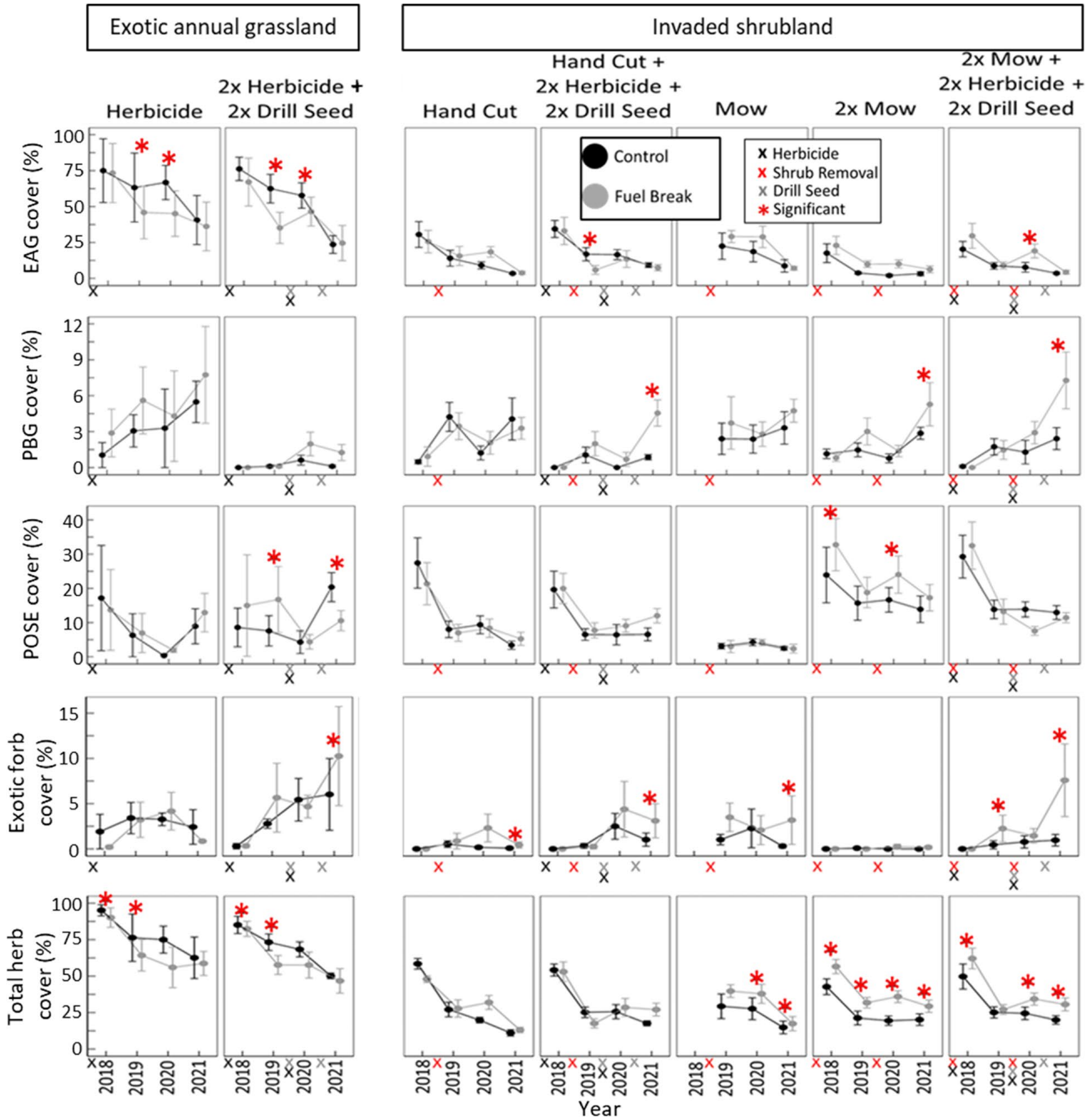

Fig. 4 Observed mean cover (± standard error) response of exotic annual grasses (EAG), perennial bunchgrasses (PBG), Sandberg bluegrass (POSE), exotic forbs and total standing herbaceous (total herb) fuels to fuel-break treatments compared to paired control plots. Colored "x" references the timing of fuel treatments relative to data collections (see also Table 1) and asterisks reference statistical significance (95% confidence interval). *X*-axis ticks are the year of measurement (fall), but symbols for control and fuel break at each time point are staggered on the *X*-axis value to minimize overlap (i.e., measurements were simultaneous)

in 2021 (Fig. 7). Mean total loading for the "hand cut" treatment in 2021 was ~ 7600 kg ha^{-1} compared to ~ 2800 kg/ha in the control; however, significant differences were not found, likely owing to large variability for that treatment (95% CI: minimum ~ 4300 kg ha^{-1}, maximum 11,000 kg ha^{-1}; Fig. 7). Of the fuel loads measured, only 5% of control plots and 3% of treatment plots were representative of FBFM GR1 (i.e., ≤ 896 kg ha^{-1} total fuel load; Scott and Burgan 2005).

Total reaction intensity (RI) did not differ between treated and untreated areas, but a transient compensatory RI increase in the individual contribution of standing

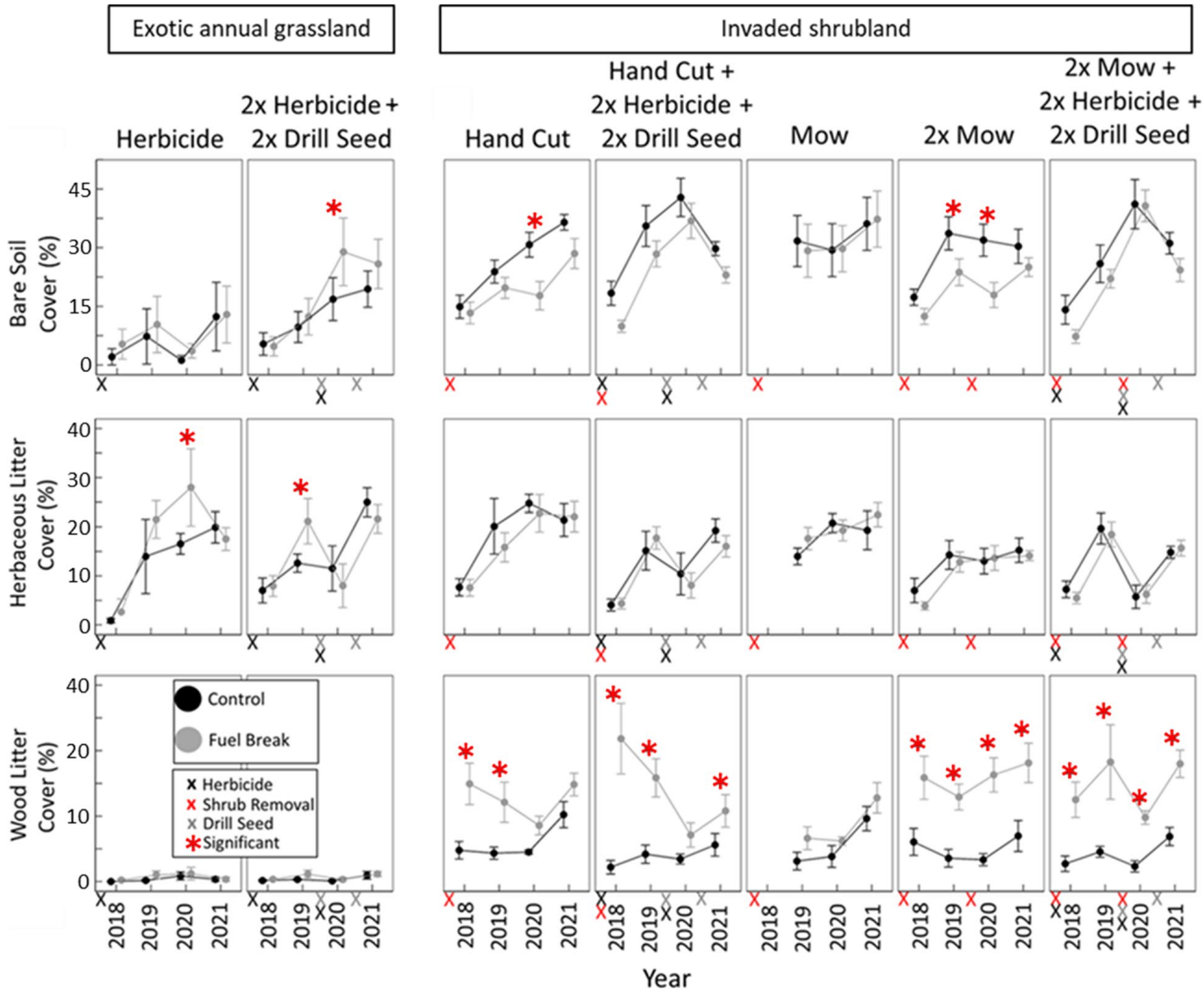

Fig. 5 Observed mean cover (± standard error) response of bare ground and litter cover to fuel-break treatments compared to paired control plots. Colored "x" references the timing of fuel treatments relative to data collections (see also Table 1) and asterisks reference statistical significance (95% confidence interval)

herbaceous fuels was apparent where shrub-reduction treatments had been implemented (Fig. 8). Herb and wood-litter fuels contributed only a small amount to RI in untreated control plots that had shrubs (Fig. 8).

Predicted rates of spread (ROS) were comparable between fuel-break treatments and controls, except for a temporary ~ 80% reduction in 2019 for the "herbicide" treatments in exotic annual grassland at both low and high wind speeds (11 and 47 km h^{-1}, Fig. 9, left panels). Mean predicted ROS in these exotic annual grasslands generally exceeded the 9.2 m min^{-1} ROS nominally expected of FBFM GR1 under both average and high-wind speeds, with ROS up to 240 m min^{-1} in treated and untreated areas alike (Fig. 9). For areas treated with shrub reductions, mean ROS was lower than that expected of FBFM GR1 under average-wind speeds, however, at high-wind speeds, predicted ROS exceeded the ROS expected of GR1 (9.2 m min^{-1}) for ~ 13% of fuel break and 47% of untreated mean modeled fire behavior values (Fig. 9).

Predicted flame lengths (FL) were comparable between fuel-break treatments and controls, except for temporary ~ 68% reductions in 2019 for the "herbicide," "2 × herbicide + 2 × drill seed," and "hand cut + 2 × herbicide + 2 × drill seed" treatment combinations at both low and high wind speeds (Fig. 10). FL exceeded the 0.8-m FL expected of the GR1 FBFM in 14% of fuel break and 33% of the untreated mean modeled fire behavior values at low wind speed (Fig. 10). Similar to what was observed for ROS, these exceedances tended to occur in plots where EAG cover was greater than 30% (Fig. 4). Under

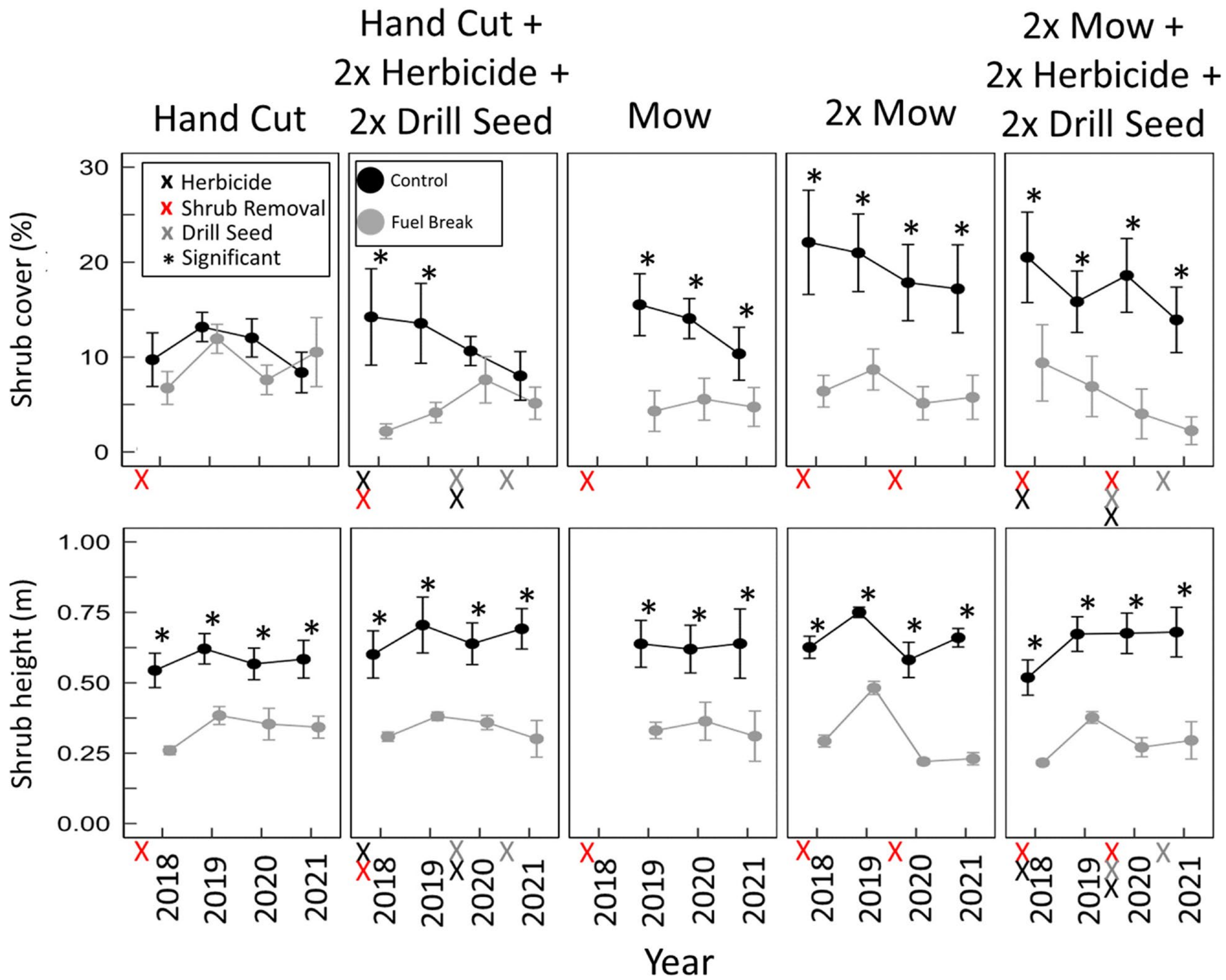

Fig. 6 Observed mean (± standard error) response of shrub cover, shrub height, and wood litter cover to fuel-break treatments compared to paired control plots. Colored "x" references the timing of fuel treatments relative to data collections (see also Table 1) and asterisks reference statistical significance (95% confidence interval). Herbicide and drill seed treatments are not shown here as they did not strongly impact shrub volume

high wind speeds, mean FLs in EAG-dominated areas were as large as 5.8 m, and all exceeded both the 1.2-m threshold for fire-suppression using hand tools and the 0.8-m FL expected of the GR1 FBFM (Fig. 10). In contrast, FL for plots with shrubs present at low wind speeds were all less than the 1.2-m fire threshold, and only two control and no treated mean modeled fire behavior values exceeded the FL expected of GR1 (Fig. 10). At high wind speeds, FL for plots with shrubs exceeded the 1.2-m threshold in 26% of untreated and 6% of treatment mean modeled fire behavior values and exceeded the FL expected of GR1 for 62% of untreated plots and 38% of treated plots (Fig. 10).

Overall, only 13% of all plot observations, under both wind speeds, exceeded the 1.2-m FL threshold for non-vehicle suppression and exceeded the threshold FL for any type of control (3.4-m) in 11% of high-wind observations (Fig. 11). The FL exceedances of the 3.4-m threshold were only observed where EAG cover was generally greater than 30% (Figs. 4 and 11).

Mechanisms of predicted fire behavior responses

To determine how woody litter or total herbaceous fuel abundances contributed to the net impacts of treatments on ROS and FL in FCCS, we observed the fire-behavior responses to step increases in litter or herbaceous fuels in the FCCS trial parameterized for shrub reduction. Modeling was performed using the standard fuel bed 56 in FCCS (sagebrush shrubland – exotic species), which does not normally include wood litter fuels, and so nominal values of them were added (5% wood litter cover at a depth of 0.25 cm with a total loading of ~ 1120 kg ha^{-1} which was distributed as 40% 1-h fuels, 50% 10-h fuels, and 10% 100-h fuels). The

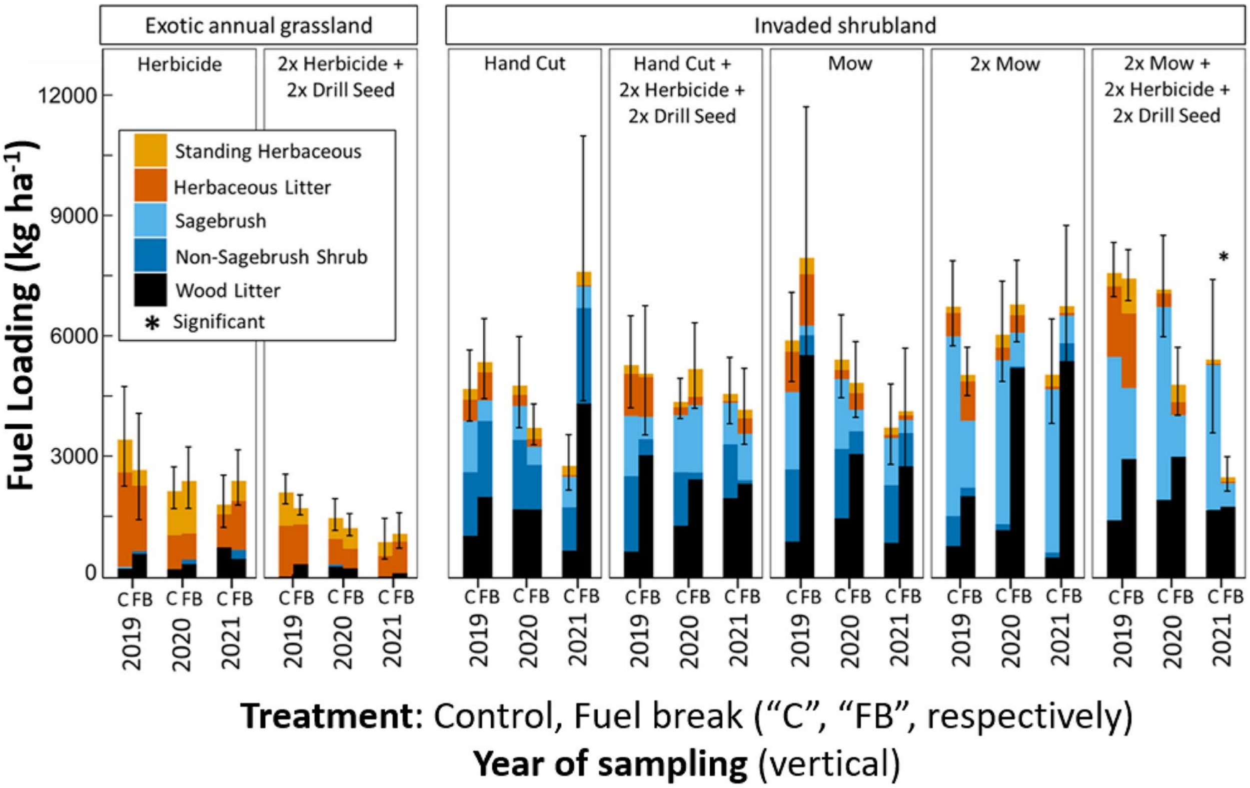

Fig. 7 Contribution of different fuel types to fuel loading (kg/ha) by treatment combination and year for paired fuel break (FB) and control (C) plots. Error bars (standard error based on raw values) and significant differences (95% confidence interval) reference total loading

default herbaceous cover was reduced from 46.5% to 20% and fuel loading was reduced from 1569 kg ha^{-1} to 448 kg ha^{-1} to better reflect the vegetation and fuels observed at our sites in the simulation. The shrub-reduction "treatment" in this modeling exercise reduced height and cover by half, leading to reduced ROS and FL (Fig. 12). Increasing wood litter cover from 5 to 6% produced a steep decrease in ROS and FL but increases in wood litter cover beyond 7% (to 14%) led to marked increases in ROS and FL (Fig. 12). Most importantly, the scenario with > 11% woody litter cover produced ROS and FL similar to the default fuel bed (56) without the shrub reduction. In a second set of model runs evaluating the effect of step changes in herbaceous cover (20–29%) and loading (450 to 650 kg ha^{-1}), addition of relatively small amounts of herbaceous cover and loading produced fire behavior which immediately surpassed that predicted by the default fuel bed (56) without the shrub reduction (Fig. 12). These model predictions indicated that small increases in woody litter or herbaceous fuels following shrub reduction are sufficient to cause equivalent fire behavior in shrub-reduction compared to untreated control plots.

Discussion

Our observations are among the few to inform on the ecological risks and management outcomes of "real" operational (and not experimental) linear fuel breaks in sagebrush steppe and similar semiarid habitats. Thus, the vegetation, fuels, and predicted fire behavior reported here were more variable than was observed in smaller-scale experiments that had greater control over natural sources of variability (e.g., sagebrush removal treatments in Prevéy et al. (2010a,b), mowing in Davies et al. (2011), and/or mowing and prescribed fire in Pyke et al. (2022) and Ellsworth et al. (2022)). Variability in treatment outcomes is a concern for fire and fuel managers because treatments are designed to create defensible space for wildland firefighters. Our study did not evaluate fire perimeter spread, i.e., the 3-dimensional interaction across space during fire spread, but the high spatial variability across the fuel

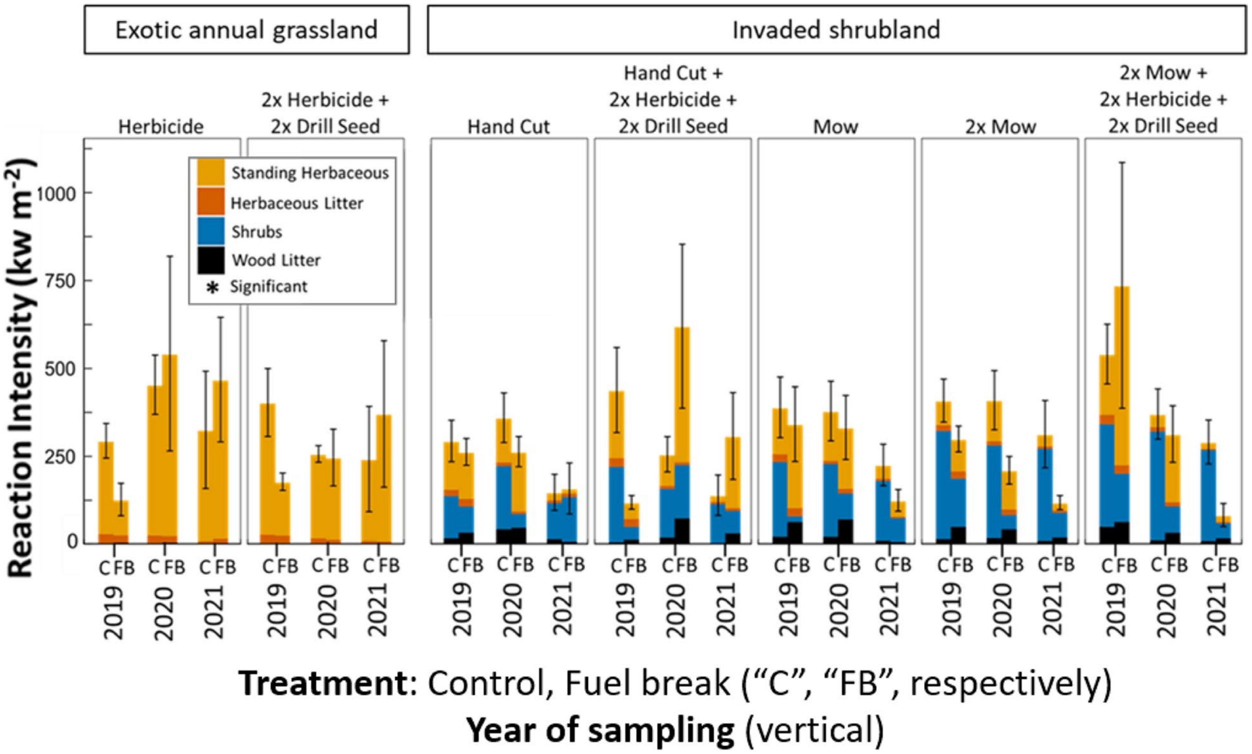

Fig. 8 Contribution of different fuel types to fire reaction intensity (kw m^{-2}) by treatment combination and year for paired fuel break (FB) and control (C) plots, predicted in FCCS parameterized at 11 km/h wind speed. Error bars (standard error based on raw values) and significant differences (95% confidence interval) reference total loading

breaks reported here suggests that fire behavior could be complex in terms of patterns of intensity and spread.

Treatments of herbaceous fuels

Fall imazapic applications created transient reductions in EAGs for up to 2 years, which is consistent with other studies (e.g., Applestein et al. 2018; Germino and Lazarus 2020; Lazarus and Germino 2021b; Ellsworth et al. 2022), although some plot-scale studies have reported up to 4 years of control (Lazarus and Germino 2022). Imazapic is a pre-emergent herbicide with limited post-emergent qualities that inhibit the biosynthesis of branched amino acids, thereby impeding plant growth and development. Repeated loss of new recruits suppresses populations of annuals, thus relieving perennial vegetation of competition from annual herbs following successful imazapic applications. Although the imazapic-induced reductions in our study were seemingly large in heavily EAG-invaded sites, they were generally insufficient to reduce fuel loads and corresponding fire behavior to levels that were less than or equal to that expected of FBFM GR1. The lack of stronger and more sustained reductions of EAGs where they were dominant prior to herbicide application is consistent with previous findings in which broadscale herbicide treatments (> 30,000 Ha) had markedly reduced efficacy when made on areas having > 40% EAG cover compared to much stronger effects when applied onto bare soil, e.g., immediately after fire (Fig. 4; Applestein et al. 2018; Germino and Lazarus 2020; Lazarus and Germino 2022). Imazapic must be applied and incorporated evenly onto soil surfaces, because small amounts of patchiness in broadcast herbicide spray coverage can allow "escapes". EAGs that evade herbicide treatments often become relatively large and fecund, thereby enabling reinvasion. Untreated patches are more likely where dense mats of EAG litter intercept herbicide spray and prevent its contact with soil. Lastly, the post-spray longevity of herbicide applications can be impacted by site characteristics, such as clay content (affecting absorption), microbial decay/degradation, and soil fertility (Lazarus and Germino 2022), and the edaphic variables are often patchy in sagebrush steppe environments (Germino et al. 2018), and thus contribute to variability in treatment outcomes.

Secondary or follow-on invasions by exotic forbs after treatment of exotic-annual grasses are not uncommon

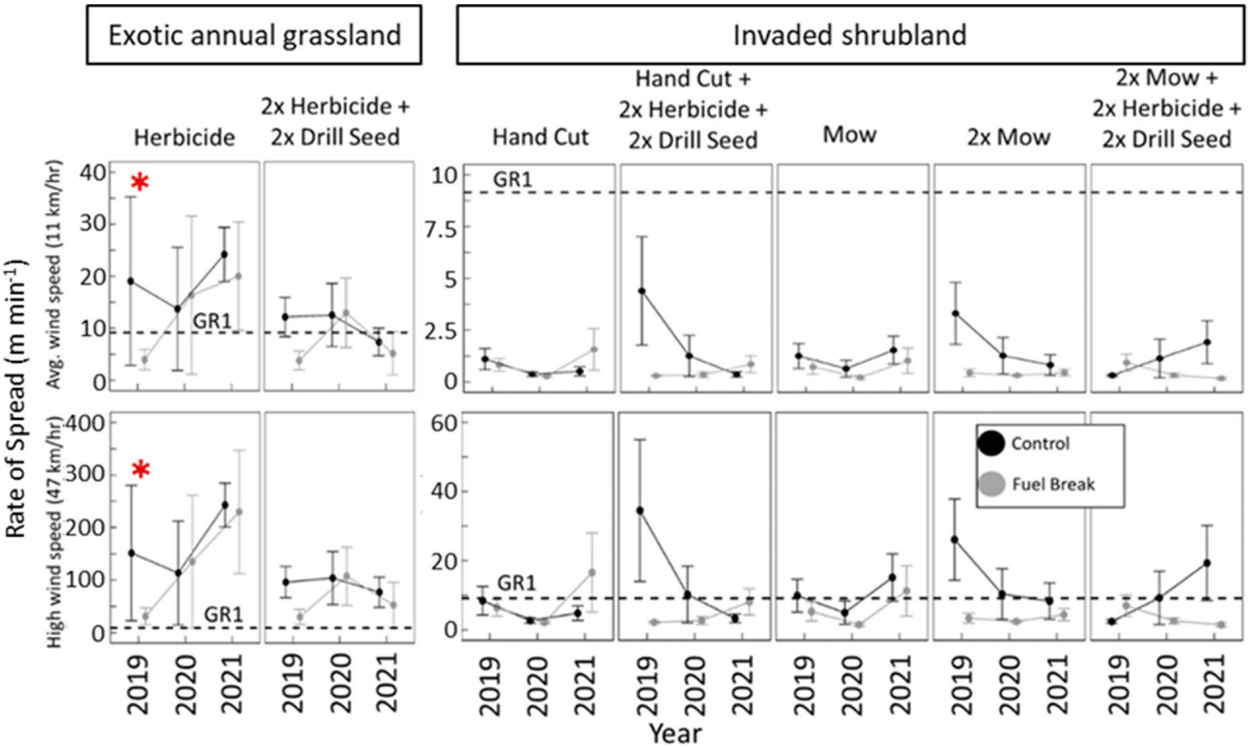

Fig. 9 FCCS predicted mean rate of spread (± standard error) for fuel-break treatments compared to paired control plots under average or high wind speeds for different treatment combinations. Red asterisks reference statistical significance (95% confidence interval). Horizontal, black-dashed line references the standard fire behavior fuel model GR1. The *y*-axes do not share common limits

in sagebrush steppe (Donaldson and Germino 2022) and were a substantial plant-community response to the fuel treatments we observed. The forb invaders are often fast-growing, exotic, tap-rooted, and relatively tall-statured forbs such as skeletonweed (*Chondrilla juncea* L.; e.g., Lazarus and Germino 2021a, Donaldson and Germino 2022) that can be significant fuel sources (Pilliod et al. 2017). In our study, Russian thistle was the primary exotic forb invader whose emergence following imazapic application was substantive and yet was likely underestimated by the seasonal timing of our sampling. In the spring of 2020, following our measurements in the fall of 2019 and prior to our measurements in the fall of 2020, Russian thistle invaded the fuel breaks, and local fuel managers quickly applied the broadleaf herbicide 2,4-D, causing the remaining Russian thistle seedling biomass to be recorded as “herbaceous litter” in our fall 2020 sampling. The Russian thistle invasion may have been stimulated by a combination of relatively wet conditions leading into the 2020 growing season following dry 2018–2019 conditions created deep-soil water recharge that selectively benefitted tap-rooted forbs (Prevéy et al. 2010a,b; Pilliod et al. 2017), combined with the non-target outcome of imazapic spraying (Lazarus and Germino 2021a,b; 2022). Moreover, only one of two drill seedings led to perennial grass recruitments, and the failed seeding coincided with the Russian thistle invasion and dry conditions of 2019 (Table 1).

Response to shrub removal treatments

Shrubs can occupy a substantial fraction of community biomass and control of soil growth resources, and thus shrub removals were both expected and observed to “release” herbaceous growth, particularly fast-growing exotic invaders if they are present and perennial vegetation is not sufficiently abundant (Prevéy et al. 2010a,b). In a remote area with a low-percent cover of EAGs, Davies et al. (2011) observed mowing of sagebrush to induce many-fold increases in EAGs, albeit with small absolute abundances. In contrast, Prevéy et al. (2010a,b) observed that hand-cutting sagebrush led to large absolute increases in EAGs and exotic forbs in a wildland-urban interface where these exotics are generally more prevalent. Our remote study region was far more invaded than the Davies et al. (2011) study site, but less invaded than that of Prevéy et al. (2010a,b), and yet we observed EAG

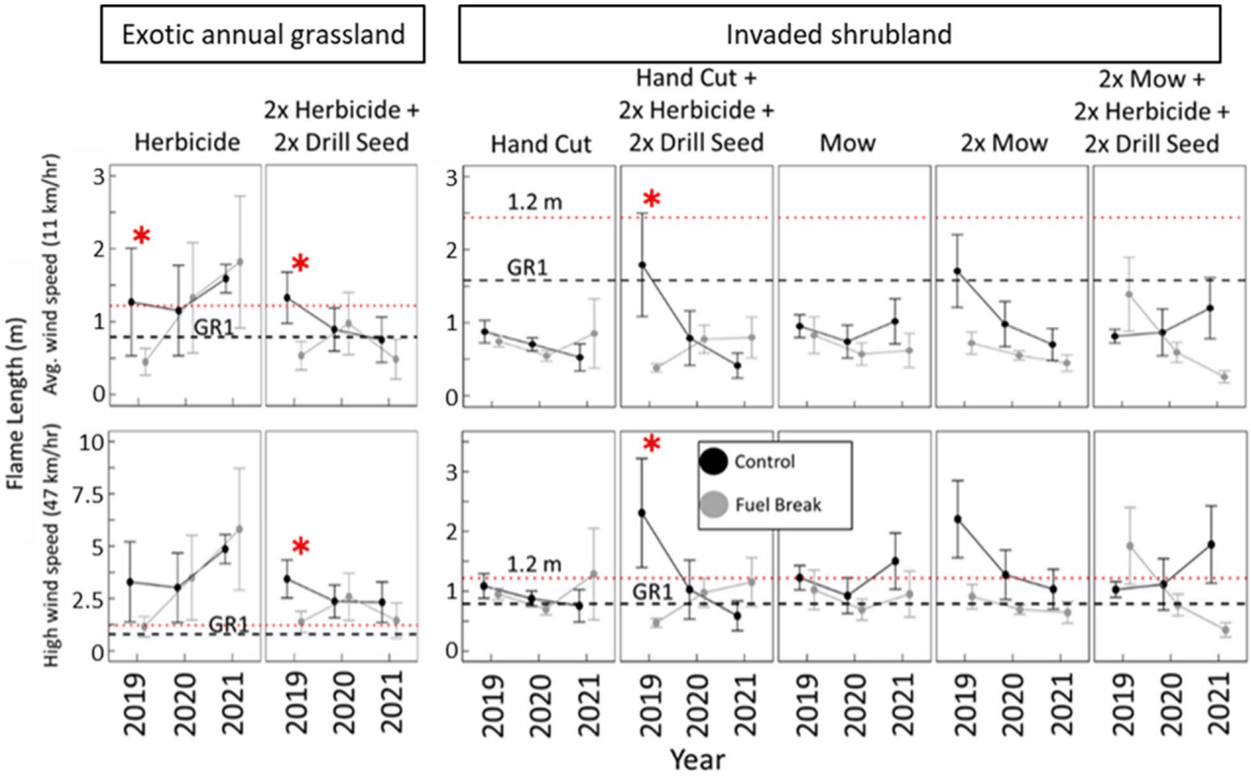

Fig. 10 FCCS reported means of flame length (± standard error) for fuel-break treatments compared to paired control plots. Red asterisks reference statistical significance (95% confidence interval). Horizontal lines reference the standard fire behavior fuel model GR1 (black dashed) and 1.2 m (red dotted). The *y*-axes do not share common limits

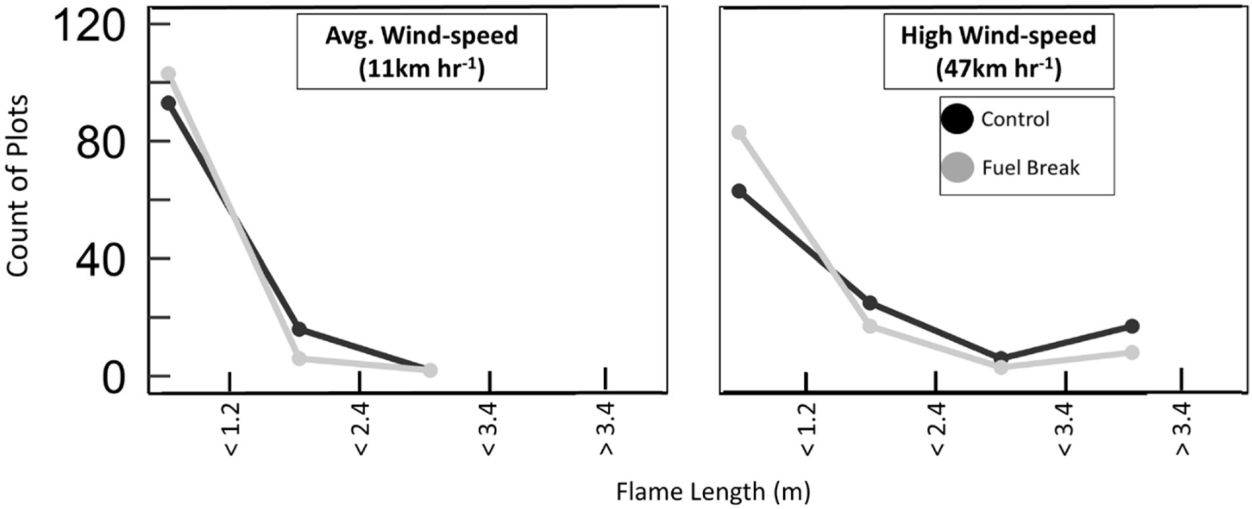

Fig. 11 Number of individual plot-year simulations of flame lengths that aligned with different categories of nominal wildfire suppression, with hand tools (flame length < 1.2 m), with heavy equipment (< 2.4 m), with aircraft (< 3.4 m), or flame lengths of fires that are uncontainable (> 3.4 m) (values correspond to 4, 8, and 11 ft, respectively). Values include data from 2019 to 2021

invasion onto the fuel breaks in only 1 of 27 mean comparisons (Fig. 4). Thus, the risks of EAG-invasion following shrub removal were minimal within the timeframe and landscape observed in this study. Notably, EAG invasion is generally expected to progressively increase in future years where EAG cover is > 20% (Germino et al.

2022a,b), and while EAG abundances were initially close to this threshold in shrub communities observed, they decreased in subsequent years.

Although EAGs did not increase following mowing of shrubs (except for a single plot × sampling year combination; Fig. 4), compensatory increases in herbaceous cover were observed and shrub fuels were largely redistributed from coarse-live forms to finer-textured and dead wood litter (Fig. 13). Ellsworth et al. (2022) observed similar increases in herbaceous and wood litter fuels following shrub reductions, as in our study, however, they predicted fire behavior to be significantly reduced following shrub reductions, whereas we did not. Compensatory increases in fuels appeared to contribute greatly to similar fire behavior between shrub-removal and control plots in our study (Fig. 12). The large-plot treatment areas in Ellsworth et al. (2022) were at considerably higher elevations, mostly > 1450-m elevation compared to the < 1370-m elevations and greater EAG cover of our plots. The increased prevalence of herbaceous fuels, with low moisture content, in treated areas following shrub reduction treatments may have diminished the impacts of shrub reductions in our study, compared to the Ellsworth et al. (2022) study.

Fire behavior

Long-time fire management officers who oversaw the fuel break implementation expected greater reductions in fire behavior (RI, FL, ROS) in response to shrub reductions than were predicted by FCCS, even considering the compensatory increases in herbaceous fuels that occurred (L. Okeson, C. Cromwell; BLM Boise District Fire and Fuels Program; oral communication; November 2018). The shrub-cutting treatments produced transient or no reductions in predicted fire behavior (Figs. 8 and 9), which were already less than management thresholds in nearly all untreated conditions (Fig. 10). These outcomes differ from other studies in which treatments that reduced shrubs decreased FCCS-predicted RI, FL, and ROS for up to 17 years following treatment (Reis et al. 2019; Ellsworth et al. 2022; 10-year post-treatment). Similar findings have also been noted in Australia where treatment-induced shrub reductions in dry eucalyptus-heath ecotones decreased predicted fire behavior (specifically FL) for up to 4 years following treatment (Grant et al. (2021) using the Dry Eucalypt Forest Fire Model, Furlaud et al. (2023) using McArthur's MK5 fire behavior equations).

We asked whether different methods of parameterizing shrub fuels would have led to greater treatment effects on fire behavior predicted by FCCS. We considered other published methods for estimating shrub loading (Rittenhouse and Sneva 1977; Cleary et al. 2008; Ellsworth et al. 2022) because shrub loading was the only input parameter for FCCS that we did not directly measure in each field plot and thus had relied on FCCS to estimate it from our shrub cover measurements. However, these alternate methods for parameterizing shrub loading did not lead to the expected differences in predicted fire behavior (not shown here). Compensatory increases in standing herbaceous fuels combined with the redistribution of standing wood fuels to surface litter were likely responsible for the lack of predicted differences in fire behavior between treated and untreated plots (Fig. 12).

Fuel beds dominated by herbaceous fuels (specifically EAGs, Fig. 10) produced some of the most extreme modeled fire behavior in this study (Figs. 9 and 10), even though their non-modeled fuel attributes are more amenable to fire suppression (e.g., flame residence times; Morvan 2007). Similar extreme fire behavior was observed during the 2015 Soda wildfire in which herb-dominated fuel beds produced ROS and FL up to 150 m min^{-1} and 3 m, respectively (BLM 2017). Fine-textured herbaceous fuels produce fuel beds that are more easily ignited for a longer time fraction of each year and facilitate the passage of fire more readily in time and space (Pilliod et al. 2017; Smith et al. 2022). The dense and rapidly curing canopies that EAGs like cheatgrass produce magnify the contribution of herbaceous fuels to landscape-level fire spread relative to native perennials (thus extending the fire season; Brooks et al. 2004; Davies and Nafus 2013). Because combustible elements first act as a heat sink before they become ignited and serve as a heat source, coarse fuel elements like wood do not produce as extreme of fire behavior compared to readily ignitable fine textured herbaceous fuels. Though EAGs are not normally recognized as causing greater FLs, the greater ROS they create contribute positively to FCCS-predicted FL (Rothermel 1972) because FL is the product

(See figure on next page.)

Fig. 12 FCCS predicted flame length (top) and rate of spread (bottom) for three hypothetical scenarios, initialized using FCCS standard fuel bed 56 (sagebrush shrubland – exotic species), under two wind speeds (solid line/primary *y*-axis = average wind speed, dashed line/secondary *y*-axis = high wind speed). Hypothetical scenarios were (1) a shrub reduction (orange line), (2) a shrub reduction with a simultaneous increase in wood litter coverage (gray line), and (3) a shrub reduction with a simultaneous increase in standing herbaceous cover and loading (blue line). *X*-axes are color coded to match their corresponding scenarios. Herb fuel height in these scenarios was ~ 0.3 m

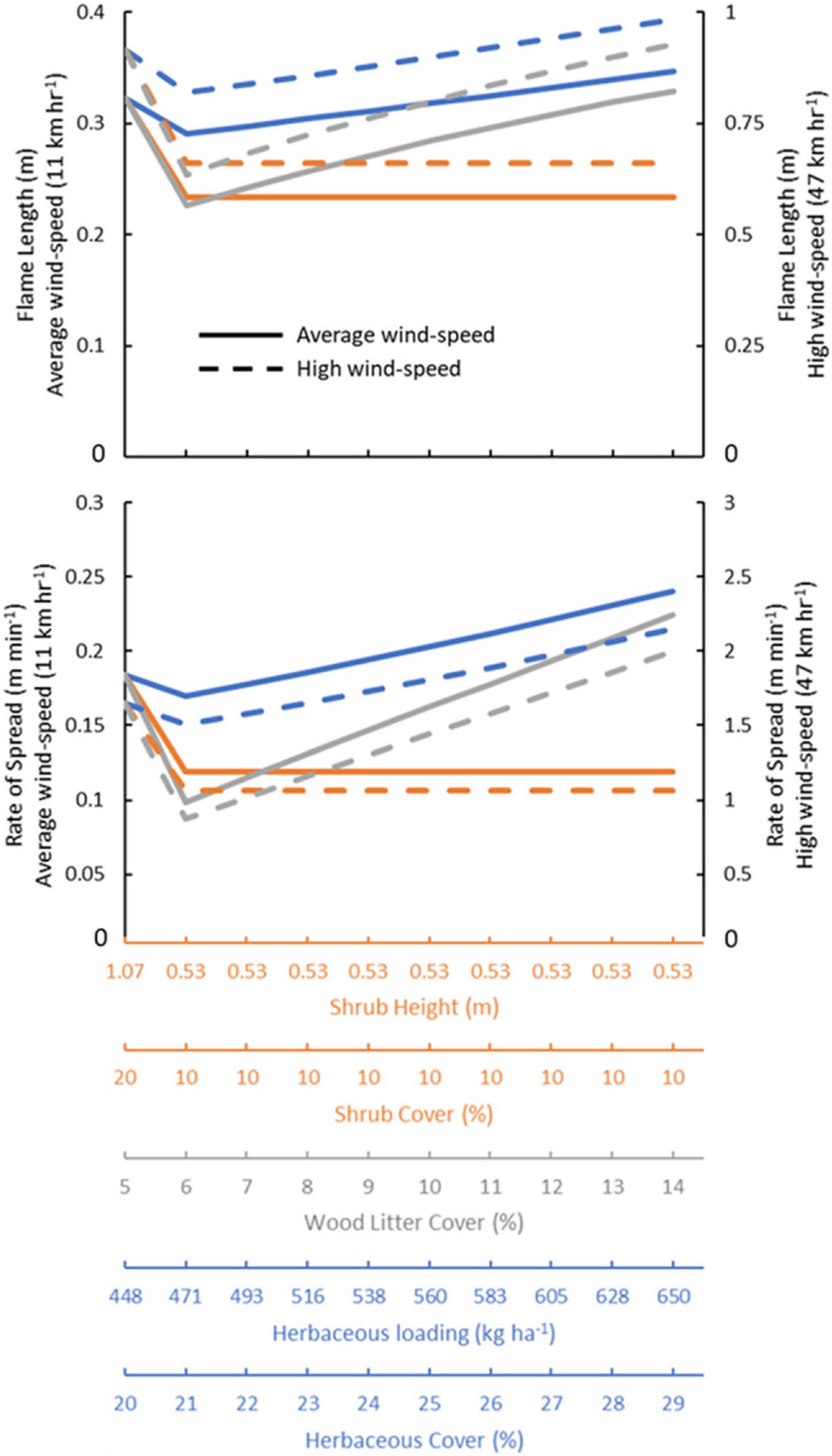

Fig. 12 (See legend on previous page.)

Fig. 13 Overhead photos looking down onto the surface 1 year after a mowing treatment (left) and 2 years after a treatment of cutting shrubs near the base by hand (right). Photographs by Samuel Jake Price, 2021

of reaction intensity × rate of spread × flame residence time in the model (Prichard et al. 2013).

Use and application of fire models in sagebrush steppe

FCCS, like any fire model, is foremostly valuable as a heuristic tool, and secondly, as an accurate predictor of fire behavior, owing to issues such as representation of shrub flammability at input fuel moistures. Also, FCCS, along with many other operable fire models, was initially designed for forested landscapes that differ strongly from the heterogeneity observed in mixed shrub-grasslands such as sagebrush steppe. In FCCS, key assumptions such as lateral homogeneity of fuels are poorly met by the heterogenous interspersion of perennial crowns and fuel discontinuities, i.e., bare soil interspaces, in the canopy structure of un-invaded sagebrush steppe. Moreover, there are few validations available for FCCS in sagebrush steppe settings, and obtaining validations for true wildfire conditions (during hot and dry conditions) is not trivial because wildfire is not planned and prescribed fires are increasingly rare. Custom inputs into FCCS, such as in this study, create parameterizations that have never been validated. Thus, the FCCS predictions of fire behavior presented here are proposed to represent relative differences in predicted fire behavior. Physical-based models that allow representation of the three-dimensional heterogeneity of structure, mass, and energy flow in fires (Linn et al. 2020) may someday overcome some of the limitations of FCCS, but they currently do not match the operability of FCCS or other Rothermel-based fire models for the large wildfire areas of concern in sagebrush steppe.

Conclusions

According to the FCCS model, the fuel treatments we evaluated had a modest effect on fire behavior, which may relate to model limitations or to natural variability (Price and Germino 2024a, b). Non-target impacts of fuel break construction on EAG invasion were negligible. Regardless of modeled fire behavior, our results suggest that reduction of shrubs and increases in herbaceous fuels observed in our study (relative to the control) reflect a directional change toward a desired fuels-management state. The intended effect of the fuel break implementation was to alter fuels such that conditions favored increased fire suppression efficacy and wildfire fighter safety. In reality, this meant converting shrub-dominated fuel beds to herbaceous-dominated ones. On one hand, herbaceous fuels, especially grasses, are well known to have increased the frequency and size of fires across broad scales (Balch et al. 2013; Dennison et al. 2014; Weber and Yadav 2020). On the other hand, the conversion from shrub to herb-dominated fuels benefits wildfire suppression because grass-dominated fuels (1) can be more thoroughly covered by flame retardants to reduce combustibility, (2) have lower flame residence times and thus are more readily extinguished, (3) have reduced spotting distances, conferring less ability of the fire front to cross barriers, and (4) are more amenable to creating backfires that then serve as refuge for wildfire fighters when situations become untenable (Maestas et al. 2016). None of these factors are directly captured or addressed by FCCS or other available fire behavior models, and thus an opportunity exists for new modeling approaches.

Appendix

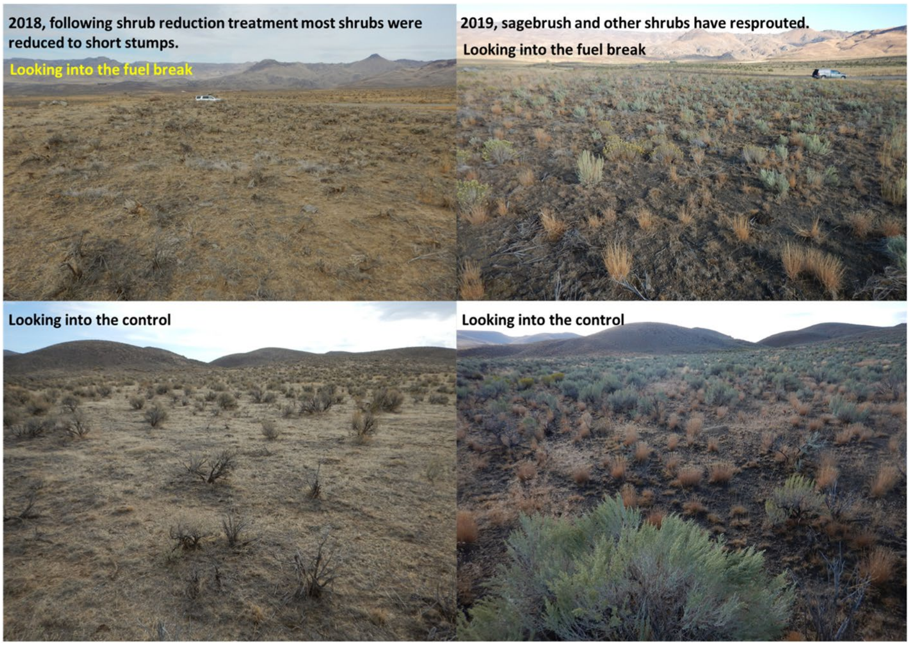

Fig. 14 Photo comparison with 2018 on the left and 2019 on the right. Top: sagebrush and other shrubs inside the fuel break resprouted the year following shrub reduction treatment. Bottom: after the warm and dry summer of 2018, many shrubs in the paired control seemingly died (left); however, new growth on many can be seen in 2019 (right). Photographs by Samuel Jake Price, 2021

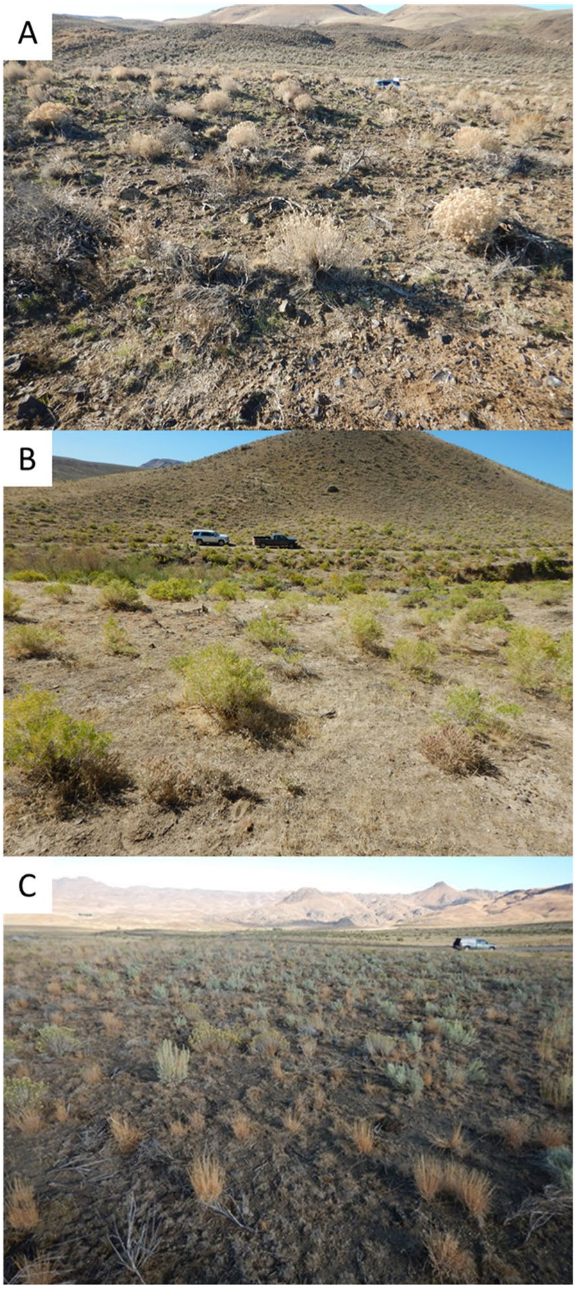

Fig. 15 Examples of shrub regrowth following hand-cutting treatments. Recruitment and regrowth of species such as **A** green rabbitbrush, **B** greasewood, and **C**, in some cases, sagebrush were observed in years following shrub-reduction treatments. Photographs by Samuel Jake Price, U.S. Geological Survey, 2021

Glossary

DOI	Department of the Interior
BLM	Bureau of Land Management
FL	Flame length
ROS	Rate of spread
RI	Reaction intensity
EAG	Exotic annual grass
PBG	Perennial bunchgrass
FBFM	Fire behavior fuel model
FCCS	Fuel Characteristic Classification System

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Authors' contributions

MJG conceived, supervised, and procured the funding of the project. SJP performed the analyses. SP provided key guidance on fire-behavior modeling. All authors wrote, edited, read, and approved the final manuscript.

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Availability of data and materials

Data are available from Price and Germino (2024b) at https://doi.org/10.5066/P18BXKBX.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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