FINAL REPORT

Title: Assessment of fuel break performance – fire risk, ecology, and economy

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Abbreviations

ANOVA – Analysis of Variance

AUM – Animal Unit Month

BLM – Bureau of Land Management

GBFSE - Great Basin Fire Science Exchange

LFB – Linear Fuel Break

NDWI - Normalized Difference Water Index

NDVI – Normalized Difference Vegetation Index

RFPA - Rangeland Fire Protection Associations

SageSTEP - Sagebrush Steppe Treatment Evaluation Project

SRM – Society for Range Management

Keywords

Fuel break, fuel treatment, sagebrush, wildfire, fuel moisture, annual grass, rural economics.

Acknowledgements

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Project Overview

Wildfires are increasing in both size and frequency in sagebrush (*Artemisia* spp.) shrublands in the Great Basin, USA, threatening valued property and native vegetation that contribute to regional economies, and provide habitat for wildlife including many sagebrush obligate species such as the greater sage-grouse (*Centrocercus urophasianus*). Federal, state, and private landowners in Great Basin rangelands commonly utilize fuel breaks to stop or slow the spread of wildfire across the landscape and to protect assets at risk, including homes, infrastructure, high-quality native habitat areas, and farmland. Different types of fuel breaks are utilized either singularly or as part of a system. However, little information is available about the effectiveness of fuel breaks in controlling fire, and what their impacts (either positive or negative) are to natural resources where the breaks are installed. This project evaluates the ecological and economic trade-offs created by fuel breaks commonly implemented in Great Basin rangelands (Figure 1). Our study design builds on strong collaboration with stakeholders, including BLM Twin Falls District and Field Offices, local ranches, Rangeland Fire Protection Associations (RFPA), the University of Idaho Rangeland Center, and the Great Basin Fire Science Exchange (GBFSE). Deliverables include scientific research and models presented at conferences, webinars, graduate student theses, and refereed scientific journal articles.

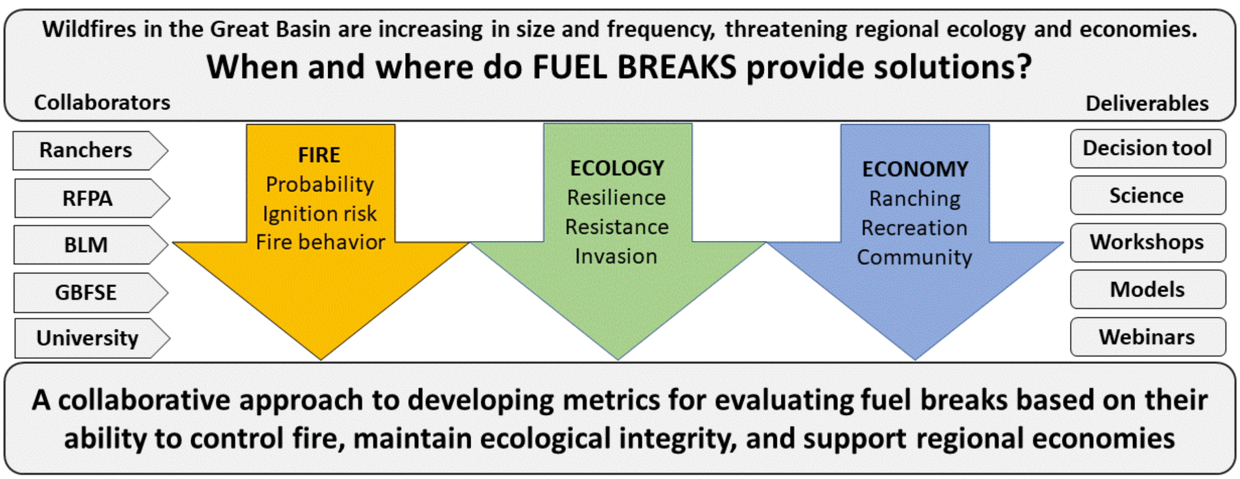

Figure 1. An integrated approach to developing end-user-based metrics for assessing fuel breaks in their ability to control fire, maintain resistance to invasion and resilience to fire, and support local economic interests.

Objectives

We propose to evaluate fire, ecological, and economic metrics and outcomes for fuel breaks in sagebrush steppe using existing fuel breaks on BLM-managed land in southern Idaho's Twin Falls District. Specifically, we propose to:

1. *Evaluate the effectiveness of fuel breaks at limiting fire size and fire behavior*. We will develop metrics describing the probability of a fuel break controlling fire and measures of fire

behavior based on fuels in and near the fuel breaks. We will evaluate the effectiveness of the fuelbreak system for reducing area burned and protecting natural habitat using landscape scale models.

2. *Assess the effects of fuel breaks on adjacent plant communities.* We will develop metrics for evaluating the plant community composition, and potential resistance to invasion and resilience to fire within and adjacent to existing fuel breaks.
3. *Evaluate the net economic benefits fuel breaks create for rural economies.* We apply results from objectives 1 and 2 to develop metrics for evaluating the economic benefits of fuel breaks to rural communities.

Background

Approximately 50% of the sagebrush steppe and semi-desert in the Great Basin have been lost to land-use change, development, invasive species, and altered fire regimes (Welch 2005). Wildfires are increasing in both frequency and size as a result of invasive annual flammable grasses such as cheatgrass (*Bromus tectorum*). Fire perimeter records from the Bureau of Land Management show that sites have burned up to six times since the mid 1950's, resulting in a fire every 10 years. Over the past two decades, fires in the Great Basin have also become increasingly larger; fires over 100,000 acres are now common, and many are much larger such as the Murphy Fire Complex (600,000 acres) 2007, Kinyon Road (>300,000 acres) 2012, and Soda Fire (280,000 acres) 2015. Frequent fire, particularly in Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*), has led to loss of sagebrush habitat and, in some cases, loss of the native perennial vegetation. Fire frequency (Bradley et al. 2018) and the number of large wildfires (Barbero et al. 2015) are predicted to increase in the western US as a result of future climate change coupled with continued annual grass invasion. These large, frequent, fast-moving fires are difficult to combat and have contributed to escalating costs for fire suppression and threaten local ranching communities. A national concern is also the loss of habitat for wildlife such as the greater sage-grouse (*Centrocercus urophasianus*), a sagebrush obligate species that has been considered for listing under the Endangered Species Act (USFWS https://www.fws.gov/greatersagegrouse/).

Nonindigenous annual grasses within sagebrush systems have shortened the fire return interval, particularly in the Wyoming big sagebrush ecosystem of the Great Basin (Strand et al. 2025). The shortened fire return interval negatively affects both plant and animal species. Current trends in fire suggest further losses of keystone species such as sage-grouse with over 40% loss in population in the next 30 years (Coates et al. 2016). Nonindigenous annual grasses directly impact sagebrush plant communities, decreasing native species numbers and diversity (Jones et al. 2018). Cheatgrass increases continuity and lengthens the fire season because it senesces and becomes available to burn early in the summer compared to native bunchgrasses that have natural interspaces of bare ground and stay green later into the summer (Pilliod et al. 2017). Since the year 1990 annual grass-dominated vegetation burned nearly four times more often than other sagebrush vegetation and those fires comprised 24% of land burned within the 50 largest fires from 2000 to 2012 (Balch et al. 2013). Maintaining healthy perennial grass abundance, cover, and diversity aid reduction in annual grasses (Davies and Svejcar 2008, Bowman-Prideaux 2019), so fuel breaks that foster perennial grasses while controlling annual grasses can reduce fire risk, and reducing annual grasses in sagebrush grasslands adjacent to fuel breaks further reduces fire risk.

Fire dynamics and ecological condition of Great Basin rangelands have implications for natural resource-dependent rural communities. Over 1 million people in the American West derive some income from grazing activities on rangelands (James et al. 2003). Ranchers in particular depend on both the quality and quantity of forage produced on rangelands for livestock production. Both fire cycles and invasive annual grasses have the capability to significantly impact production decisions and viability of a ranching operation. For ranchers who hold public lands grazing permits, allotments must be rested (not grazed) for at least two years post-burn, and during this time producers need to either find alternative forage sources to maintain the size of their herd or reduce their herd size. Increased biomass of invasive annual grasses change timing and quantity of available forage creating novel production challenges and potential negative economic consequences for livestock producers (Maher et al. 2013). While cheatgrass is nutritious for livestock, it is only palatable during the spring when it is green or winter after senescence, which provides a much shorter grazing season than most native plants (Schmelzer et al. 2014). In addition, the biomass produced by cheatgrass is highly variable and dependent on seasonal precipitation.

To combat these large and frequent fires, fuel breaks and fuel break systems are being implemented as a management strategy. Fuel breaks are intended to aid fire managers in suppression efforts because they slow down the fire, reduce the flame length, and under some weather and fuel conditions, even stop the fire (Moriarty et al. 2015). Fuel breaks are most commonly installed adjacent to existing roads to provide firefighters access to the fire and a safe location of staging fire suppression resources. A programmatic environmental impact statement (EIS) is currently evaluating a BLM proposal to create and maintain fuel breaks for an area nearly 224 million acres in the Great Basin including parts of California, Idaho, Nevada, Oregon, Utah, and Washington states. Fuel breaks are proposed along existing roads on BLM administered lands within sagebrush ecosystems with an effective treatment area of 38 million acres (DOI-BLM-ID-0000-2017-0001-EIS).

While fuel breaks themselves reduce available forage, they intend to mitigate the size and risk of unwanted wildfire. The decision to create fuel breaks creates a trade-off in forage production value. If the fuel break is successful in reducing damages from fire, the annual lost value of forage from the existence of the fuel break may be minor in comparison to the economic losses two-year grazing allotment closure and possible changes to the plant communities after the burn. However, if fuel breaks do not reduce the impacts of fire or negatively impact adjacent plant communities, the overall cost of fuel breaks may exceed their benefits. To evaluate these trade-offs, it is necessary to understand the effectiveness of fuel breaks in managing fire risk and size as well as how the fuel break impacts the plant communities, specifically forage production.

Several types of fuel breaks have been installed or are proposed to be installed in southern Idaho's sagebrush steppe. *Brown strips* are narrow fuel breaks (0-50 feet wide) where all vegetation is removed. The function of the brown strip fuel break is to limit fire starts along heavily used roads such as interstates or highways. *Mowed/grazed fuel breaks* can be wider (0-500 feet) and are intended to reduce vegetation height (< 12 inches) and compact the fuel bed to lower flame length and possibly fire rate of spread adjacent to all types of roads. *Green strips* (up to 500 feet wide) are meant to replace flammable contiguous vegetation with plant species that retain moisture later into the growing season and are short-statured to reduce flame length and fire rate of spread (Pellant 1994). Forage kochia (*Kochia prostrata*) or perennial grasses that stay green longer in the growing season (for example crested wheatgrass (*Agropyron cristatum*)) are seeded in green strips. *Herbicide treatments* targeting invasive flammable annual grasses next to roads are intended to reduce flammability and ignitability from lightning or humans because the native species stay green longer into the growing season. Herbicide treatments reduce the continuity of flammable fuel (annual grasses) and the likelihood of fire propagation.

The Fuel Treatment Effectiveness Database was used to assess the success of fuel breaks, suggesting that from 2006 to 2014 fire behavior changed 97% of the time and the treatment-controlled wildfire 95% of the time (Moriarty et al. 2015). Property protection has been effective and additional evaluation is needed to determine protection of conservation values. Experience within BLM suggests types of fuel breaks that should be effective. For example, green strips are useful for long-term management, brown strips can be used adjacent to roads and mowed vegetation can be effective with/without a green strip. Concerns for fuel breaks include invasive plant invasion into brown strips and concerns about a low mowing height that could weaken perennial grasses when those grasses are cut shorter than 4 inches (Shewmaker et al. 2007). It is therefore a high priority among a wide range of stakeholders to identify and evaluate metrics developed to assess fuel break performance in controlling wildfire and minimizing impacts on valued resources in sagebrush steppe ecosystems and rural economies.

Materials and Methods

Study area

The Bureau of Land Management Twin Falls District manages approximately 1.6 million hectares of rangelands in south-central Idaho. Soils are mostly silt-loams with smaller areas of sand-loams of alluvium, lacustrine, and loess parent materials (Soil Survey Staff and NRCS-USDA, 2023). The climate is an arid, temperate, continental climate with warm, dry summers (daytime highs between 25 and 35°C) and cool winters (daytime highs between -7 and 5°C) (PRISM Climate Group and Oregon State University, 2022). Long-term (1981 – 2010) average crop-year (October-September) precipitation ranged from 213 to 267 mm across the green strip linear fuel break (LFB) and from 250 to 257 mm across the targeted grazed LFB (PRISM Climate Group and Oregon State University, 2022). Vegetation field sampling occurred in 2021 and 2022 during which the annual crop-year precipitation was below average. Crop-year precipitation was 78%, 64%, and 98% of the long-term average in 2019-2020, 2020-2021, and 2021-2022 respectively for the green strips. Crop-year precipitation was 65%, 55%, and 83% of the long-term average in 2019-2020, 2020-2021, and 2021-2022, respectively, for the targeted grazed LFB. Large expanses (41%) of the district have burned since 1988 and 40% of the burned areas have experienced fire two or more times since 1988 (Figure 2).

We sampled 107 km of green strip LFB, about 75 km west of Twin Falls (Figure 3). Elevation ranged from 850 to 1335 m across the green strips and slopes were 0-5.5° with varying aspects. The installation of the green strips involved herbicides to remove and reduce existing vegetation before seeding. Starting in Spring 2016, the green strip LFB received several herbicide applications (imazapic, glyphosate, 2,4-D, and aminopyralid) before being seeded in Fall 2017 through Fall 2018 with select species (Table 1). After seeding, 61 km of the green strip LFB were temporarily fenced to exclude livestock and had not been grazed at the time of this study; these LFB, hereafter referred to as “not grazed”, represent green strips with a 4- or 5-year post-seeding rest period. The remaining 46 km of the green strips were rested from livestock grazing for one season after seeding these LFB, hereafter referred to as “allotment grazed”, represent green strips with a 1-year post-seeding rest period followed by 3-4 years of allotment cattle grazing. Portions of the green strips were treated again with the herbicide imazapic in Fall 2019 or Fall 2021.

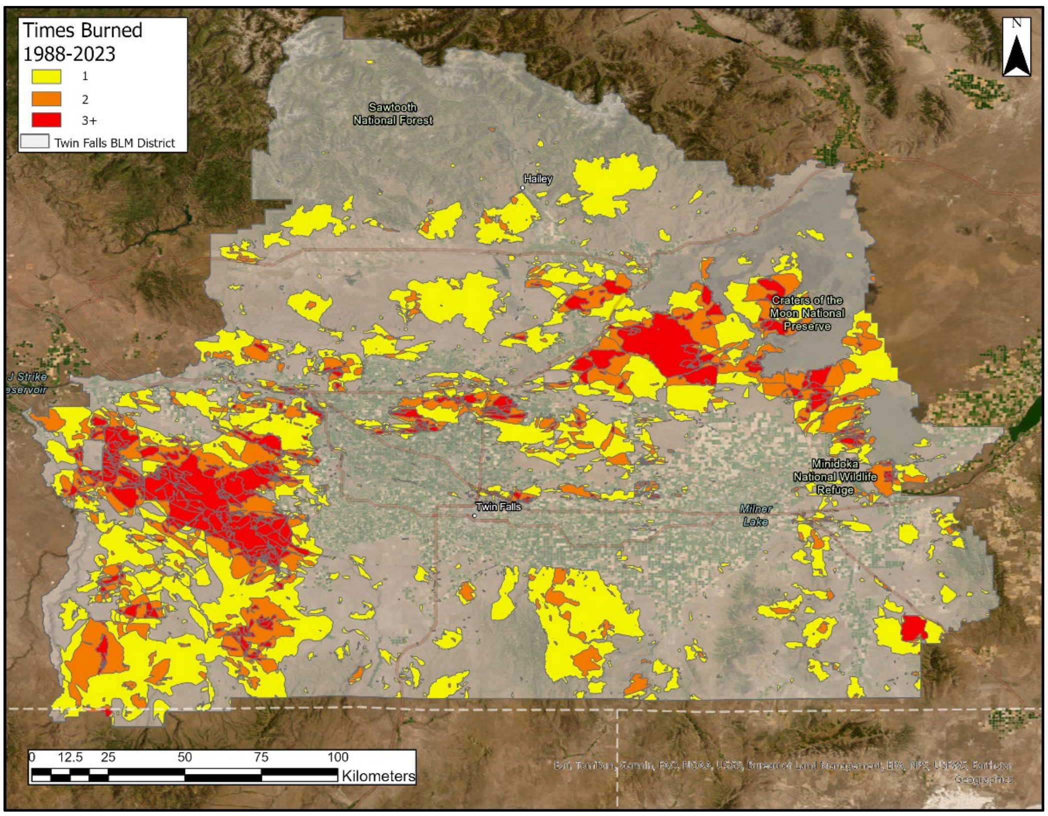

Figure 2. Fire frequency in the BLM Twin Falls BLM District from 1988-2023.

We also sampled 7 km of targeted grazed LFB, immediately south of the town of Shoshone (Figure 4). Elevation ranged from 1201 to 1289 m across the targeted grazed LFB and slopes were 0-5.5° with varying aspects. The establishment of the targeted grazed LFB involved herbicides, seeding, and grazing but with varying management objectives for each action. The area in which the targeted grazed LFB existed had burned in wildfires several times over the last 30 years. Most recently the 2017 Antelope wildfire burned approximately 66% of the total area currently occupied by the targeted grazed LFB (Figure 4). Following the 2017 Antelope wildfire, portions of the burned area were treated with herbicide (aminopyralid) in Fall 2017 and then seeded in Fall 2017 and Spring 2018 with select species (Table 1). The 2017 Shoestring wildfire burned an additional 1.3% of the area occupied by the targeted grazed LFB (Figure 4). Following the 2017 Shoestring wildfire, portions of the burned area were treated with herbicides (aminopyralid and 2,4-D) in Spring 2018 and seeded in Fall 2017 and Spring 2018 with select species (Table 1). The 2007 Red Bridge Road fire burned 71% of the area occupied by the targeted grazed LFB (Figure 4). Following the 2007 Red Bridge Road wildfire, portions of the burned area were treated with herbicides (clopyralid; 2,4-D; and chlorsulfuron) in Fall 2007 and then seeded in Spring 2008 with select species (Table 1). In Fall 2019, the targeted grazed LFB boundary was established with fence and cattle grazing began in Spring 2020 and continued throughout the study period.

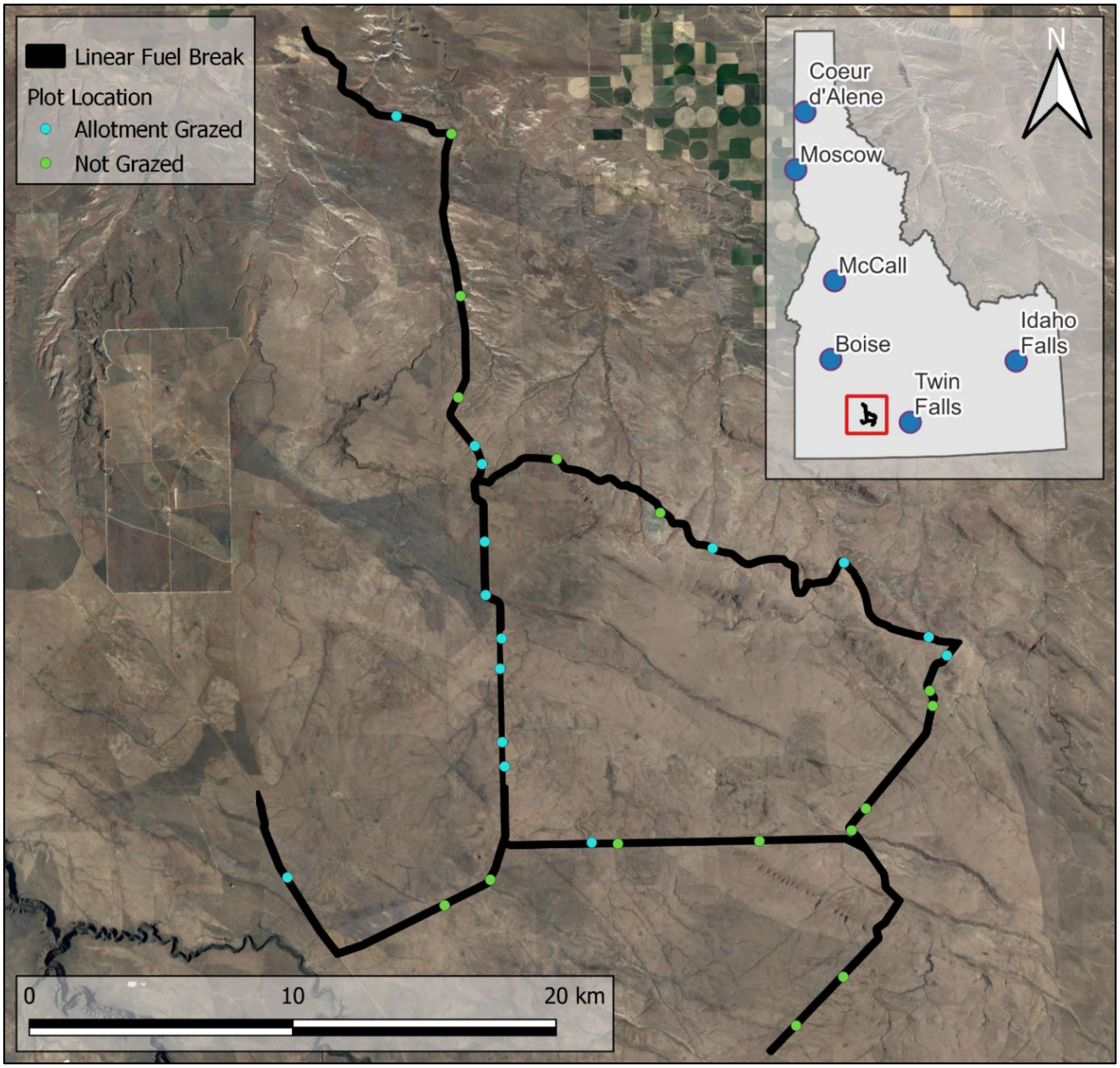

Figure 3. Green strip linear fuel breaks and plots in the Jarbidge Field Office, Twin Falls BLM District. Each plot location symbol represents two plots, one inside and one outside the linear fuel break.

Table 1. Summary of management activities of linear fuel breaks in the Twin Falls BLM District, as of Fall 2022, and plots sampled per linear fuel break. 'Type' is the grazing strategy implemented after the fuel break was seeded. 'Length' is the total road kilometers the fuel break follows, 'Width' is the extent of the linear fuel break off either side of the road, and 'Area' is the total hectares treated as linear fuel break. 'Imazapic' is the number of plots sampled that had been treated with imazapic after seeding and prior to sampling.

Type	Length Width Area	Seeded Species	Seeding Timeframe	Imazapic	Year Sampled – Number of Plots	Elevation Range (m)
Not Grazed	61 km 100 m 1220 ha	*Agropyron fragile* *Poa secunda* *Achillea millefolium* *Linum lewisii* *Sphaeralcea ambigua* *Kochia prostrata*	Fall 2017 – Fall 2018	2/15 plots[2]	2021 – 15 plots 2022 – 0 plots	850 – 1335
Allotment Grazed	46 km 100 m 920 ha	*Agropyron fragile* *Poa secunda* *Achillea millefolium* *Linum lewisii* *Sphaeralcea ambigua* *Kochia prostrata*	Fall 2017 – Fall 2018	8/15 plots[3]	2021 – 6 plots 2022 – 9 plots	915 – 1237
Targeted Grazed	7 km 0.5-1.6 km 2700 ha	*Agropyron fragile* *Elymus wawawaiensis* *Purshia tridentata* *Artemisia tridentata* *Poa secunda* *Thinopyrum ponticum* *Linum lewisii* *Penstemon palmeri* *Onobrychis viciifolia* *Achillea millefolium* *Kochia prostrata*[1]	Spring 2008 (2 plots) or Fall 2017/Spring 2018 (13 plots)	0/15 plots	2021 – 4 plots 2022 – 11 plots	1201 – 1289

[1]*Kochia prostrata* was seeded in the targeted grazed linear fuel break only in 2008.

[2]The 2 not grazed linear fuel break plots treated with imazapic were sampled ~20 months post-herbicide treatment.

[3]Of the 8 allotment grazed linear fuel break plots treated with imazapic, 7 plots were sampled ~8 months post-herbicide treatment and 1 plot was sampled ~32 months post-herbicide treatment.

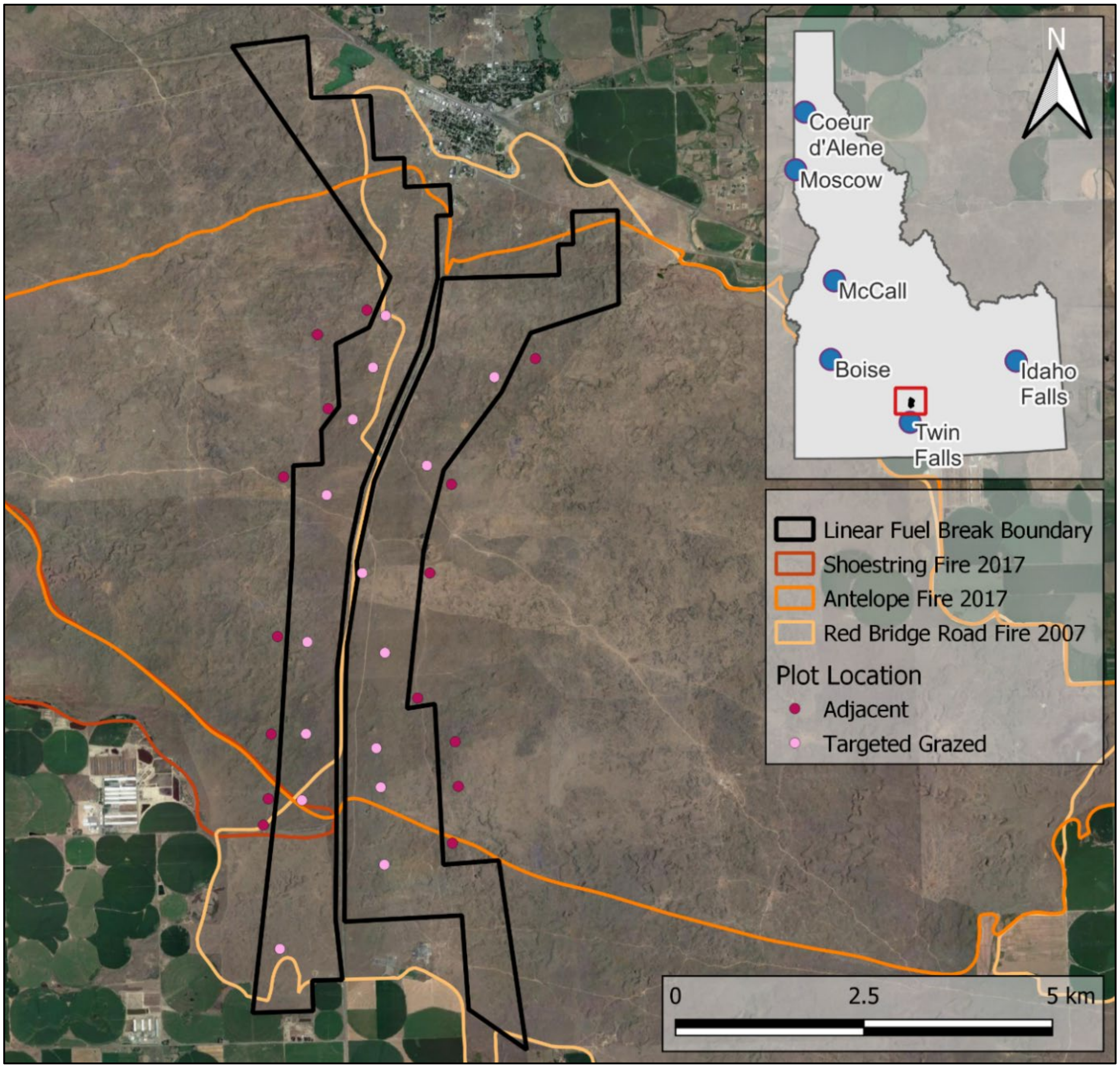

Figure 4. Targeted grazed linear fuel break and plots in the Shoshone Field Office, Twin Falls BLM District. Wildfire perimeters display where and when the most recent post-wildfire seedings occurred in this linear fuel break.

Objective 1 and 2 – Effectiveness of fuel breaks and their plant community composition

Field Methods: Vegetation Cover, Fuel Loading, and Height

Thirty pairs of plots were surveyed across the selected green strips and the adjacent landscape. Each plot was 30 x 30 m and consisted of four parallel 30 m transects, surveyed following a modified SageSTEP protocol. Data were collected at each plot to estimate vegetation cover by species and fuel loading (coarse woody debris, shrub, and herbaceous) for parameterization of the fire behavior model. Twenty-one pairs of plots were surveyed in May – July of 2021 and nine pairs of plots were surveyed in May – June of 2022. Vegetation cover by species was estimated using the line-point intercept method on three 30 m transects per plot. Canopy cover was measured every 0.5 m along the transect for a total of 60 points per transect. These data were summarized by plot into percent canopy cover by species. Fuel loading of downed woody material was estimated using Brown's planar intersect method on three 30m transects per plot. For each transect, 1-hr and 10-hr fuels were counted along the first 2m of the transect, and 100-hr fuels were counted along the first 4m of the transect. Woody fuel loading was calculated by time-lag class. Fuel loading of shrubs was estimated using 5 circular subplots (3 m radius) evenly spaced along one 30 m transect. For each shrub rooted within the subplot we recorded species, height, length, and width. These measurements were used in allometric equations to estimate shrub fuel load. Fuel loading and height of herbaceous plants were estimated using a quadrat-based harvest transect method with eight 50 x 50 cm quadrats evenly spaced on one 30 m transect per plot. Heights of the tallest live perennial grass, live annual grass, and live forb within each quadrat were measured. All standing live and dead vegetation was clipped and sorted by live and dead functional groups (live perennial grasses, dead perennial grasses, live annual grasses, dead annual grasses, live forbs, and dead forbs). The samples were then dried and weighed to the nearest 0.01 g.

Statistical Analysis of LFB Treatments

We determined correlation with LFB treatment, sampling year, imazapic treatment, and elevation with each response variable using generalized linear models (GLM) or generalized least squares models (GLS) in a paired analysis. A GLM or GLS was created to evaluate variability with LFB treatment (generalized as LFB or adjacent landscape), sampling year, imazapic treatment, and elevation for each response variable. Separate GLM and GLS models were created for each not grazed, allotment grazed, and targeted grazed LFB treatments to evaluate variability between each LFB treatment and their respective adjacent landscapes.

Due to heteroscedasticity in the residuals when other weed cover was modeled using generalized linear models, other weed cover was analyzed using GLS statistical models with the constant plus power of the variance covariate function (not grazed and allotment grazed models), in which the variance was proportional to the constant plus the power of the variance covariate "elevation" within each stratum of the covariate "year". For other weed cover analysis of the targeted grazed LFB, other weed cover was analyzed using a GLS model with the identity constant variance function, in which the variance was allowed to be different for each stratum of the covariate "year". Fixed variables in each model were fuel break treatment, sampling year, imazapic treatment, and elevation; unless that variable was not a factor for the fuel break type, such as "year" for the not grazed LFB, then it was not included as a variable. Insignificant variables were dropped in turn from the model to find the most parsimonious model. A significant correlation was determined if the p-value was <0.05. These analyses were completed in R (R Core Team, 2022).

Fire Behavior Modeling

Species cover, fuel loading, and height were used to parameterize a dynamic custom fuel bed for each plot in the Fuel Characteristics Classification System (FCCS). The slope input was parameterized to the slope of each plot (mean = 3%). Wind speed was set to 15 km/hour, a typical windspeed for the area. Fire rate of spread and flame length were modeled in FCCS under four fuel moisture scenarios: uncured, one-third cured, two-thirds cured, and fully cured. See Johnston (2024) for details on modeling parameters.

Live Fuel Moisture Scenarios from Soil Adjusted Vegetation Index
Remote sensing was used to compare seasonal vegetation greenness between green strip fuel breaks and adjacent landscapes and to inform fuel moisture scenarios for fire behavior modeling. We calculated the soil adjusted vegetation index (SAVI) from Sentinel-2 imagery for the green strips and areas 100 m outside them from March through October (2020–2022). SAVI values were averaged by Julian date across years and smoothed using loess regression to assess differences in green-up, senescence, and curing. Both areas showed similar seasonal patterns, with peak greenness in late April to early May followed by senescence through summer and full curing by late August. However, green strips consistently maintained higher SAVI values during June through early August, indicating delayed senescence (Figure 5). At equivalent SAVI values, green strips lagged the adjacent landscape by approximately 40 days. Based on these differences, green strips were assigned a fuel moisture scenario one class greener than the surrounding landscape for fire behavior modeling.

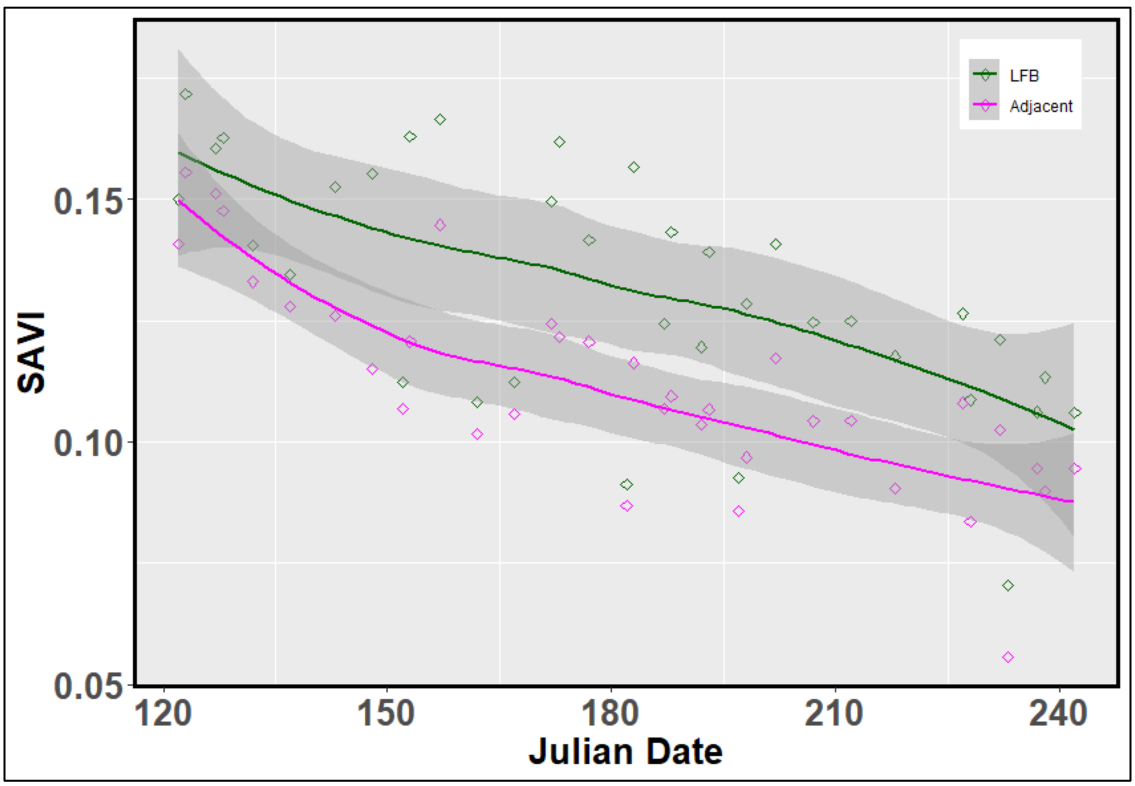

Figure 5. Soil adjusted vegetation index (averaged by Julian date for 2020-2022) for the linear fuel breaks and adjacent landscape from May 1st to August 31st (Johnston 2024). Diamond symbols are the mean values for the Julian date with smoothed loess regression lines and 95% confidence envelopes overlaid.

Fire Behavior Analysis through the Fire Season
We compared simulated fire behavior between the green strip and adjacent landscape for May, June, July, early August, and late August to determine if the green strip was a safer and more effective location for wildfire suppression activities at various times throughout the wildfire season. Thresholds for safety were defined by which suppression resources could safely engage a wildfire at a given flame length (Andrews and Rothermel, 1982). Thresholds for effectiveness

were defined by which suppression resources could construct a fireline fast enough to contain a wildfire with a given rate of spread (National Wildfire Coordinating Group, 2014). The green strip was determined to be a safer and/or more effective location for wildfire suppression activities if the average simulated flame length and/or rate of spread were below a lower threshold compared to the adjacent landscape.

Estimating Hectares Saved from Wildfire using Historical Records
Historical wildfire perimeter records from 1988-2023 (NIFC, 2022a) were used to estimate the area saved from fire due to the LFBs. Wildfires that had >60% of their area within the Twin Falls District and had >60% of their area in shrub or grass dominated systems were included. Shrub or grass dominated areas were defined as having <20% tree cover in the year preceding a given wildfire using the Rangeland Analysis Platform (RAP) cover dataset (Allred et al. 2021). The dataset was further subset to wildfires that interacted with a green strip (green strip fires) and wildfires that interacted with the same roads prior to green strip installation (road fires). From 1988-2023 there were 69 green strip fires and 98 road fires. RAP vegetation cover data were accessed and analyzed in Google Earth Engine (Gorelick et al. 2017). The wildfire selection process was completed in ArcGIS Pro (ESRI 2023). Data for these 167 wildfires were analyzed to determine if wildfires that interacted with green strips were different in size compared to wildfires that burned in those same areas prior to the green strip installation.

Generalized least squares (GLS) analysis with the identity variance function was used to determine if there was a statistical difference between size of green strip fires and road fires. Explanatory variables in the model were green strip interaction (yes or no) and fire year. A significant difference was determined if the p-value for green strip interaction was ≤0.05. Hectares saved due to green strips was estimated as the average difference between the green strip and road fires multiplied by the number of green strip fires. Statistical analysis was completed in R version 4.2.1 (R Core Team, 2022).

The area saved from wildfire by the LFB as also estimated by simulating burned area using the Fire Area Simulator (FARSITE) (Finney, 1998). The wildfire dataset described above was subset to those green strip wildfires where with existing ignition point data (NIFC, 2022b), the observed size was larger than 1 hectare, and ignition occurred between May and September. This subset selection resulted in 20 green strip fires from 2015-2023. Hectares saved was estimated as the simulated burned area minus the observed burned area. See Johnston (2024) for parametrization of the FARSITE model.

Objective 3 - Economic benefits fuel breaks create for rural economies

Overview of regional economy
The economic analysis focused on a system of LFBs managed by the Jarbidge Field Office in the Twin Falls BLM District. We collected data on LDB implementation and maintenance cost, wildfire suppression expenditures, post-fire restoration costs, and livestock forage replacement. These data were used to develop hypothetical fire scenarios to estimate the net economic benefits of the LFBs in the study area. The Twin Falls BLM District serves a predominantly rural economy where public lands play a critical role in sustaining local livelihoods. The study area straddles Owyhee County and Twin Falls County in southern Idaho. Owyhee County is sparsely

populated, with a population of 12,000 and a median household income of $59,773 (U.S. Census Bureau 2024). Beef production is the major economic sector, with a livestock inventory of 150,000 head of cattle supported by BLM-managed rangelands (USDA 2022). In Twin Falls County the population is 96,000 and the median household income is $65,300 (U.S. Census Bureau 2024). Beef production here ranks as the third largest agricultural sector, accounting for 11% of the regional economic output (Westerhold et al. 2021). The cattle inventory was over 250,000 in 2022 (USDA 2022).

Implementation and maintenance costs of LFB segments

The BLM has implemented green strip LFBs in Idaho since the mid-1980s to aid in suppression of undesired wildfire (USDI-BLM 1985; Pellant 1994). Green strip LFBs are commonly 100-150-m strips on each side of a road and the existing vegetation within the LFB is commonly replaced with more fire-resistant vegetation that can compete with invasive weeds (Pellant 1994). For this analysis, we used a 100-m on each side of the road in calculations per recommendations from the personnel at the BLM office (E. Kriwox and T. Erikson personal communication October 2023).

The Twin Falls BLM District provided data and context for the implementation and maintenance costs of the Jarbidge LFB segments. Fuel Break cost data were categorized into either implementation of a new LFB segment or maintenance of an existing LFB segment. Implementation of the Jarbidge LFB began in 2016 and was completed in 2018, and maintenance activities occurred in 2019, 2021, and 2024. Implementation costs included: 1) aerial herbicide application, 2) mowing, and 3) seeding of desired species (aerial and drill seeding; see Johnston et al. 2025 for more detail). Following the establishment of the LFB segments, maintenance was conducted as deemed necessary to regulate fuel loads and maintain desired vegetation. Maintenance activities included mowing and herbicide treatments conducted by and paid for by the BLM. Over the time period 2016 to 2024, the total implementation costs were $4,106,496 and the total maintenance costs were $170,421 for implementing 40,933 ha of LFB segments and conducting maintenance treatments on 2,160 ha.

Fire suppression and rehabilitation cost estimates

We estimated potential cost savings from reduction in fire size by focusing on 1) fire suppression costs, 2) rehabilitation costs, and 3) grazing revenue loss. We did not include costs of lost wildlife habitat, lost recreational opportunities, property damage/loss, or costs related to health effects from smoke because they accrue to different stakeholder groups and are complex to quantify.

Fire perimeter data for the time period 2013-2023 were obtained from the Interagency Fire Perimeter History dataset (NIFC 2025a). Suppression costs were obtained from the Incident Management Situation Report (NIFC 2025b; Nguyen et al. 2023). These data were supplemented with fire perimeter and suppression cost data from the BLM Districts. The final dataset included 771 fire that burned 2013-2023. For each fire we computed the mean suppression cost, the median suppression cost and the median suppression cost per hectare (Table 2). To estimate post-fire rehabilitation costs, we consulted local BLM district reports (personal communication E. Kriwox and T. Erikson).

Table 2. Summary of wildfire suppression costs for fires in different size classes in the Twin Falls BLM District and in Great Basin BLM Districts.

Fire size (ha)	No. of fires	Mean fire suppression cost	Median fire suppression cost	Median suppression cost·ha-1
Twin Falls BLM District fires 2013–2023				
< 500	66	$167 742	$51 500	$227.14
500–5 000	51	$285 745	$150 000	$110.27
5 000–20 000	11	$1 116 364	$275 000	$36.42
20 000–50 000	3	$17 200 000	$15 800 000	$433.11
> 50 000	0	–	–	–
Great Basin (ID, NV, UT) BLM Districts fires 2013–2023				
< 500	357	$149 231	$75 000	$327.04
500–5 000	320	$480 500	$200 000	$154.39
5 000–20 000	70	$1 213 371	$627 500	$82.02
20 000–50 000	15	$2 650 667	$2 600 000	$72.10
> 50 000	9	$4 244 444	$4 000 000	$35.94

Abbreviations: hectares (ha), number (no), cost per hectare (cost.ha-1), Bureau of Land Management (BLM), Idaho (ID), Nevada (NV), Utah (UT).

Grazing allotment closure cost

After a wildfire, damage costs include the foregone revenue from burned forage and postburn grazing closures on BLM grazing allotments. Grazing allotments are commonly closed for two years post-fire, sometimes longer, depending on post-fire recovery and rehabilitation status (personal communication E. Kriwox and T. Erikson). We calculated the revenue loss for closed grazing allotments by multiplying the federal grazing rate ($1.35 per Animal Unit Month [AUM]) by the lost AUMs reported. We also included the cost for finding replacement forage, by either leasing private pasture or purchasing grass hay. See Johnston et al. (2025) for more detail related to these calculations.

Pothole fire case study

To provide insight in the cost effectiveness of LFBs, we developed a case study around the 2019 Pothole Fire (Figure 6). The Pothole Fire burned 28,208 ha, affecting 12 BLM grazing allotments with 11,650 AUMs burned across 14,880 ha of BLM managed land. The Pothole fire interacted with several Jarbidge LFB segments, affecting the fire's overall size and costs (Table 3).

Table 3. Costs incurred by the 2019 Pothole Fire.

	Wildfire suppression	Rehabilitation (ESR)	Grazing fee revenue loss (2 yr)	Total
Total cost	$600 000	$1 699 509	$30 850	$2 330 359
Cost·ha^{-1}	$21.27	$114.21	$2.07	$137.55

Abbreviations: hectare (ha) emergency stabilization and rehabilitation (ESR), year (yr).

We used the Fire Area Simulator (FARSITE) to simulate the spread of the Pothole fire without the LFBs and estimated potential costs of the Pothole Fire had it not encountered the LFBs (Johnston 2024). Model inputs included fire behavior fuel models, fuel moisture content from the National Fuel Moisture Database, topography, weather, and ignition point data. Spatial data for the simulations were obtained from LANDFIRE version 2.3.0 (LANDFIRE 2022), NIFC, and the Rangeland Analysis Platform. See Johnston (2024) for more detail about the analysis and assumptions.

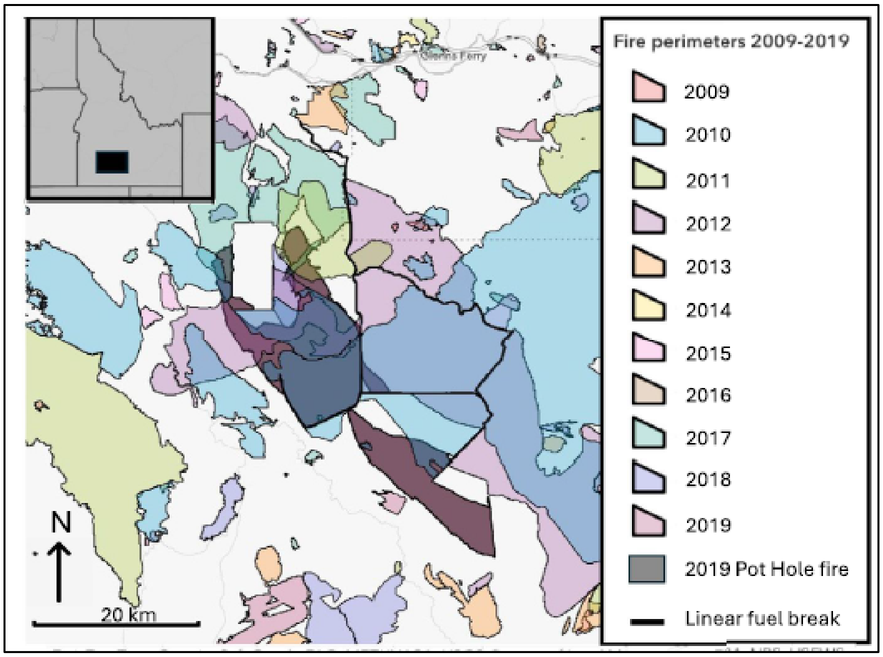

Figure 6. Historical fire perimeters around the 2019 Pothole Fire. Different fires are represented by different colors. The linear fuel breaks are marked with black lines.

Results and Discussion

Objective 1 and 2 – Effectiveness of fuel breaks and their plant community composition

Comparison of grazed and ungrazed linear fuel breaks to the adjacent landscape

Linear Fuel Breaks v. Adjacent Landscape

Overall, LFB were significantly different from the adjacent landscape in invasive annual grass cover (Table 4). LFB treatment was correlated with lower invasive annual grass cover, but was not significantly different from the adjacent landscape in any other variable. Gap abundance, mean gap size, herbaceous fuel load, percent live herbaceous load, and maximum herbaceous height differences did not vary with any of the other explanatory variables. Invasive annual grass cover and other weed cover also varied with imazapic treatment (Table 4); imazapic treatment was correlated with lower invasive annual grass cover. However, imazapic treatment was also correlated with an increase in other weed cover. No other response variables were correlated with imazapic treatment. Sampling year 2022 (the average precipitation year) was correlated with increased invasive annual grass cover by 15 percentage points and an increased gap abundance by 0.38 gaps per meter on average. For every 100m increase in elevation, the difference in invasive annual grass cover between the LFB and the adjacent landscape decreased by 7 percentage points (Table 4).

Table 4. Model coefficients, standard error and p-values for the LFBs vs adjacent landscape analysis.

Response Variable	Intercept	Imazapic Treatment	Sampling Year 2022	Elevation
Invasive Annual Grass Cover (%)	-83.03 (± 27.67) p = 0.0046	-31.07 (± 7.17) p <0.0001	15.07 (± 6.02) p = 0.0164	6.94 (± 2.40) p = 0.0062
Other Weed Cover (%)	--- p = 0.9730	6.82 (± 2.99) p = 0.0273	--- p = 0.4515	--- p = 0.8820
Gap Cover (%)	--- p = 0.7300	--- p = 0.3890	--- p = 0.0816	--- p = 0.8320
Mean Gap Size (cm)	--- p = 0.1750	--- p = 0.2790	--- p = 0.6730	--- 0.8570
Gap Abundance (#/m)	--- p = 0.3049	--- p = 0.9685	0.3813 (± 0.1336) p = 0.0066	--- p = 0.8361
Herbaceous Fuel Load (kg/ha)	--- p = 0.0796	--- p = 0.5162	--- p = 0.0614	--- p = 0.8950
Live Herbaceous Fuel Load (%)	--- p = 0.0723	--- p = 0.6123	--- p = 0.8110	--- p = 0.6110
Maximum Herbaceous Height (cm)	--- p = 0.0685	--- p = 0.7027	--- p = 0.2611	--- p = 0.1004

Not Grazed Linear Fuel Breaks v. Adjacent Landscape

After controlling for other factors, the not grazed LFB did not significantly differ from the adjacent landscape for any response variable except invasive annual grass cover (p-value = 0.04) (Table 5). Invasive annual grass cover was 65 percentage points on average lower due to the LFB treatment. Dominant weed species in the not grazed LFB and adjacent area were Russian thistle (69% of weed cover), rush skeletonweed (9% of weed cover), kochia (7% of weed cover), burr buttercup (6% of weed cover), and tall tumble mustard (6% of weed cover).

Table 5. Model coefficients, standard errors, and p-values for the not grazed LFBs vs. adjacent landscape analyses.

Response Variable	Intercept	Imazapic Treatment	Elevation
Invasive Annual Grass Cover (%)	-65.31 (± 28.98) p = 0.0437	-30.17 (± 11.09) p = 0.0186	6.03 (± 2.58) p = 0.0374
Other Weed Cover (%)	--- p = 0.5195	3.55 (± 1.47) p = 0.0319	--- p = 0.9845
Gap Cover (%)	--- p = 0.2780	--- p = 0.7770	--- p = 0.3240
Mean Gap Size (cm)	--- p = 0.7430	--- p = 0.3580	--- p = 0.6500
Gap Abundance (#/m)	--- p = 0.2060	--- p = 0.8620	--- p = 0.3150
Herbaceous Fuel Load (kg/ha)	--- p = 0.2690	--- p = 0.2780	--- p = 0.2170
Live Herbaceous Fuel Load (%)	--- p = 0.3650	--- p = 0.3730	--- p = 0.5180
Maximum Herbaceous Height (cm)	--- p = 0.1500	--- p = 0.2490	--- p = 0.3470

Allotment Grazed Linear Fuel Break v. Adjacent Landscape

After controlling for other factors, the allotment grazed LFB significantly differed from the adjacent landscape in invasive annual grass cover (p-value = 0.04), gap abundance (p-value = 0.01), and maximum herbaceous fuel height (p-value = 0.02) (Table 6). Invasive annual grass cover was 19 percentage points lower on average due to the LFB treatment. LFB treatment was correlated with increased gap abundance of 3.4 gaps per meter on average. Maximum herbaceous fuel height was 105 cm shorter on average due to the LFB treatment. Dominant weed species in the allotment grazed LFB and adjacent landscape were Russian thistle (20% of other weed cover) and tall tumble mustard (70% of other weed cover).

Table 6. Model coefficients, standard errors, and p-values for the allotment grazed linear fuel break vs. adjacent landscape analyses.

Response Variable	Intercept	Imazapic Treatment	Sampling Year 2022	Elevation
Invasive Annual Grass Cover (%)	-18.77 (± 7.94) p = 0.0358	-56.24 (± 20.63) p = 0.0184	49.88 (± 21.01) p = 0.0351	--- p = 0.1568
Other Weed Cover (%)	--- p = 0.4441	--- p = 0.1068	--- p = 0.8783	--- p = 0.3817
Gap Cover (%)	--- p = 0.1060	--- p = 0.7900	--- p = 0.9140	--- p = 0.1630
Mean Gap Size (cm)	--- p = 0.0900	--- p = 0.6580	--- p = 0.4840	--- p = 0.5600
Gap Abundance (#/m)	3.38 (± 0.72) p = 0.0005	--- p = 0.3403	0.36 (± 0.13) p = 0.0168	-0.31 (± 0.07) p = 0.0005
Herbaceous Fuel Load (kg/ha)	--- p = 0.3360	--- p = 0.4830	--- p = 0.7620	--- p = 0.3430
Live Herbaceous Fuel Load (%)	--- p = 0.1160	--- p = 0.8960	--- p = 0.2560	--- p = 0.1520
Maximum Herbaceous Ht (cm)	-105.49 (± 39.01) p = 0.0180	--- p = 0.8091	--- p = 0.2274	9.05 (± 3.55) p = 0.0243

Targeted Grazed Linear Fuel Break v. Adjacent Landscape
After controlling for other factors, the targeted grazed LFB did not significantly differ from the adjacent landscape for any response variable (Table 7). Dominant weed species in the targeted grazed LFB and adjacent landscape were bulbous bluegrass (59% of weed cover) and tall tumble mustard (29% of weed cover).

Table 7. Model coefficients, standard errors, and p-values for the targeted grazed linear fuel break vs. adjacent landscape analyses.

Response Variable	Intercept	Sampling Year 2022	Elevation
Invasive Annual Grass Cover (%)	--- p = 0.3250	27.26 (± 11.45) p = 0.0332	--- p = 0.2672
Other Weed Cover (%)	--- p = 0.0812	--- p = 0.6845	--- p = 0.0826
Gap Cover (%)	--- p = 0.2170	--- p = 0.7240	--- p = 0.2260
Mean Gap Size (cm)	--- p = 0.0882	6.36 (± 2.40) p = 0.0199	--- p = 0.2499
Gap Abundance (#/m)	--- p = 0.4390	--- p = 0.7570	--- p = 0.4560
Herbaceous Fuel Load (kg/ha)	--- p = 0.4950	--- p = 0.1920	--- p = 0.7400
Live Herbaceous Fuel Load (%)	--- p = 0.3080	--- p = 0.2320	--- p = 0.3060
Maximum Herbaceous Height (cm)	--- p = 0.1870	--- p = 0.1030	--- p = 0.7610

Our analysis suggests that allotment-grazed LFBs were the most effective at creating a less flammable fuel bed, showing reduced invasive annual grass cover along with increased gaps and herbaceous fuel height that did not increase overall flammability. Importantly, this treatment was not associated with any changes that increased fire risk. It is not surprising that a grazed treatment outperformed a not grazed treatment considering the LFB were planted with species that are desirable forage for livestock. Others have found similar fuel bed changes with grazing-based fuel treatments (Davies et al., 2010; Launchbaugh et al., 2008; Orr et al., 2023; Thomas and Davies, 2023). Not-grazed LFBs also reduced invasive annual grasses but showed few other fuel improvements, suggesting that seeding alone may provide a useful foundation where grazing is not feasible, especially if paired with maintenance actions such as mowing or prescribed fire (Ellsworth and Kauffman, 2017; Starns et al., 2019). Targeted grazing did not improve fuel bed variables, likely because grazing intensity was low compared to studies where targeted grazing has been effective (Boyd et al., 2023; Davies et al., 2015; Diamond et al., 2009; Stephenson et al., 2023).

Herbicide treatment with imazapic successfully reduced invasive annual grasses but promoted other problematic weeds, such as Russian thistle and tall tumble mustard, indicating that herbicide use should be paired with additional weed control strategies. Russian thistle and tall tumble mustard proliferation and spread can be inhibited by regular mowing that damages the plants and eliminates their ability to release mature seed (Maron and Jefferies, 2001; Matchett et al., n.d.; Simmons et al., 2007; Smith et al., 2018). Russian thistle can also be controlled with a variety of pre-emergent herbicides, including atrazine, bromacil, chlorsulfuron, hexazinone, imazapyr, napropamide, simazine, and sulfometuron, but not all are labeled for rangeland use and Russian thistle has developed resistance to some herbicides (Lyon et al., 2021; Saari et al., 1992; Young and Whitesides, 1987). Management practices that promote or add mycorrhizal fungi in the soil may also be effective at reducing success of weed species (Doerr et al. 1984; Goodwin 1992).

Climate variability also influenced fuel characteristics, with wetter years potentially increasing fire risk by allowing fuels to accumulate, underscoring the need for follow-up management and multi-year monitoring. Overall, allotment grazing emerged as the most successful strategy for reducing fuel bed flammability, though integrated management approaches are necessary to address weeds, climate-driven fuel changes, and long-term effectiveness.

Comparison of linear fuel breaks to adjacent areas through the fire season

Results demonstrate significant differences in modeled flame length and fire rate of spread across seasons (Figure 7 and 8). Modeled flame length in the green strips was below the threshold of safety for hand crew and engine crew wildfire engagement throughout the entire "average" fire season, under all fuel moisture scenarios (Figure 7). Modeled flame length in the adjacent areas surpassed the threshold for hand crew and engine crew safety by July in our "average" fire season, with wildfire behavior only safe for bulldozer operators and aircraft (Figure 7). Modeled rate of spread was lower on average in the green strips compared to the adjacent areas regardless of the fuel moisture scenario (Figure 8). Modeled rate of spread in the green strips was conducive to effective suppression efforts made by hand crews and engine crews for the duration of an "average" fire season (Figure 8). By July, modeled rate of spread in the adjacent areas required bulldozers for effective suppression efforts to occur (Figure 8).

Green strip wildfire size was significantly smaller than road wildfire size (p-value <0.001) by an average of 824 hectares (a 13.8% reduction in average size; Figure 9). Estimated hectares saved by green strips based on historical records totaled 56,856 hectares from 1988-2023, which is just over 1,624 hectares/year on average.

Total observed burned hectares was 58,634. Total simulated burned hectares was 479,071. Estimated total hectares saved was 420,437. Estimated hectares saved ranged from 21-138,874 for each individual wildfire (Table 8). Average hectares saved per green strip wildfire was 21,022.

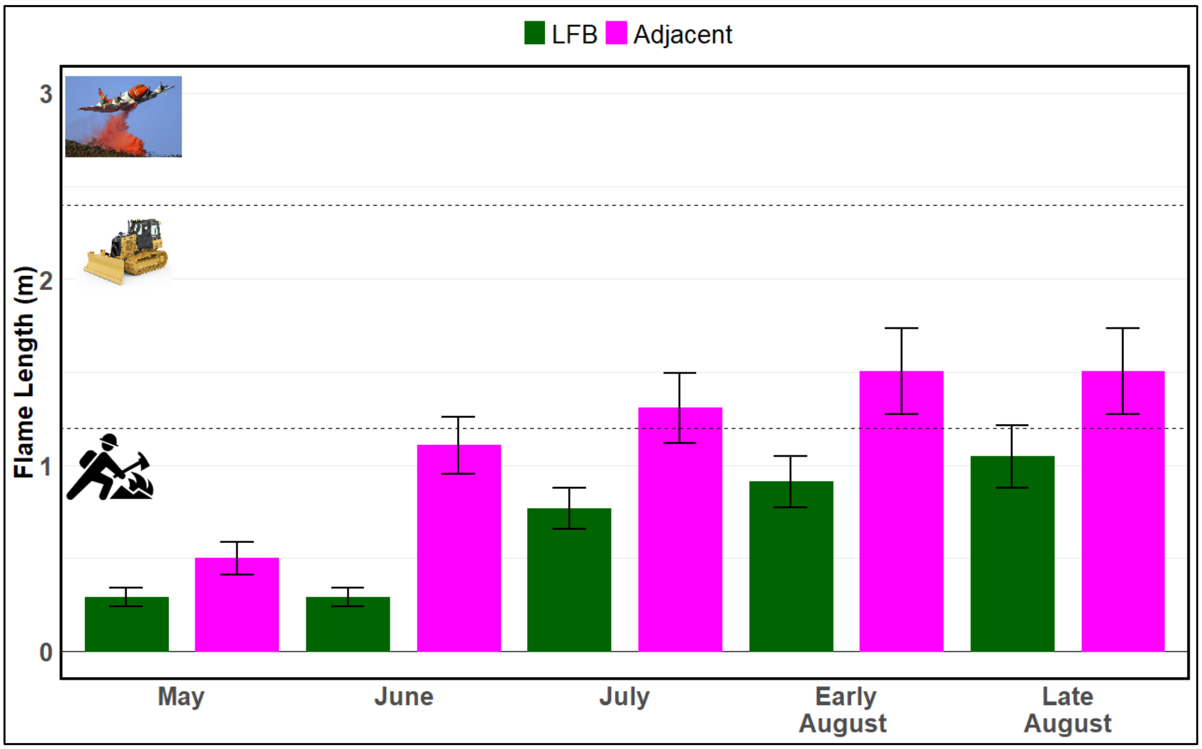

Figure 7. Average (±S.E.) simulated flame length for the green strips (LFB) and adjacent landscape through a growing season. Slope was set to the slope of each plot, mean = 3%. Wind speed for all simulation runs was 15 km/hour. Horizontal lines denote thresholds for safety defined by which suppression resources could safely engage a wildfire with that flame length. When flame length is above 2.4 m then air resources are typically needed for ground crews to safely engage the wildfire. When flame length is below 2.4 m but above 1.2 m, then dozer operators can safely engage the wildfire. When flame length is below 1.2 m, then all resources can safely engage the wildfire.

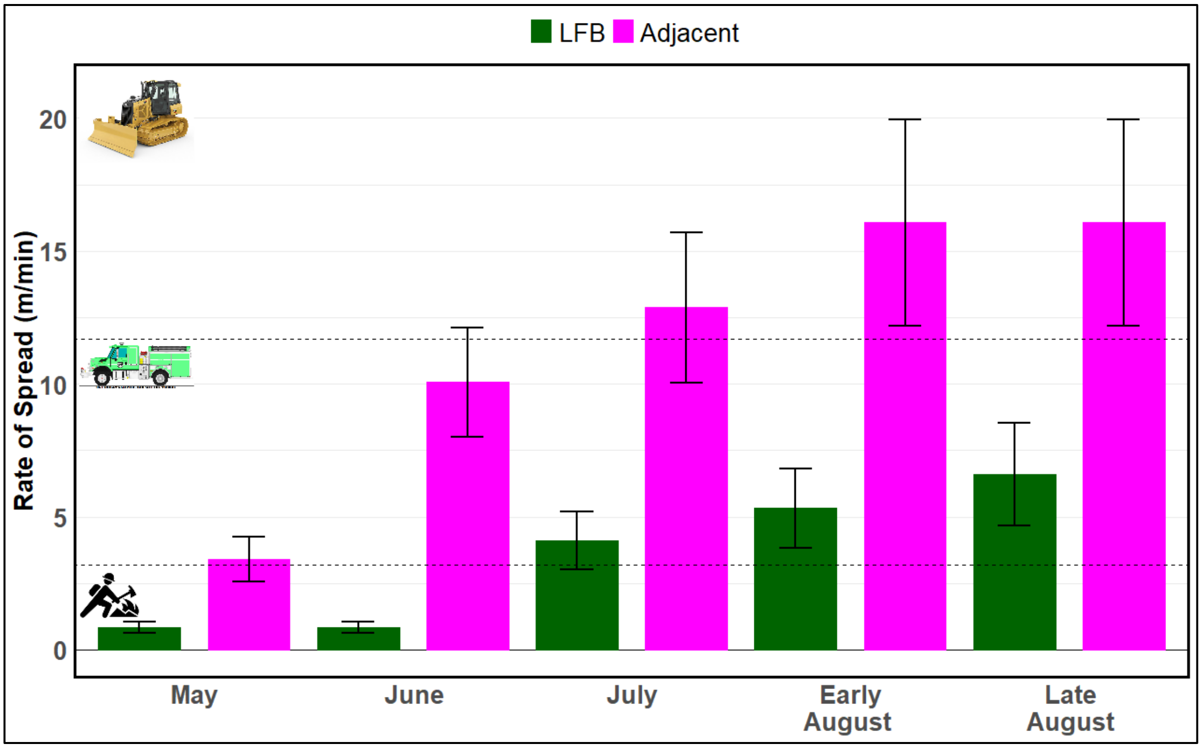

Figure 8. Average (± S.E.) simulated rate of spread for the green strips (LFB) and adjacent landscape through a growing season. Slope was set to the slope of each plot, mean = 3%. Wind speed for all simulation runs was 15 km/hour. Horizontal lines denote thresholds for suppression effectiveness defined by which suppression resources could effectively suppress a wildfire with that rate of spread. When rate of spread is above 11.7 m/min then dozers are typically needed to effectively suppress the wildfire. When rate of spread is below 11.7 m/min but above 3.2 m/min, then engine crews employing mobile attack strategies are typically needed to effectively suppress the wildfire. When rate of spread is below 3.7 m/min, then hand crews can be effective at suppressing wildfire.

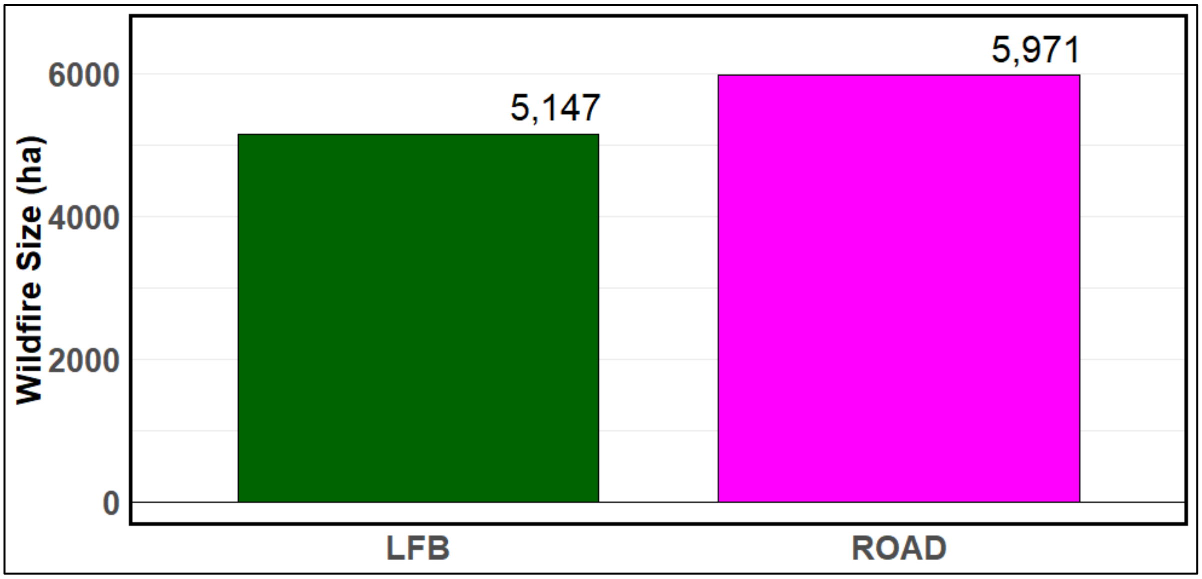

Figure 9. Mean wildfire size for wildfires between 1988-2023 that interacted with green strips (LFB, n = 69) and those that interacted with the same roads prior to green strip installation (Road, n = 98). Green strip wildfires were significantly smaller by 824 ha on average compared to road wildfires.

Table 8. Observed and FARSITE simulated burned area for the 20 selected green strip wildfires. "Hectares saved" was computed as (Simulated Hectares minus Observed Hectares).

Name	Year	Discovery Date	Contained Date	Observed Hectares	Simulated Hectares	Hectares Saved
20 Mile	2015	8/14/2015	8/15/2015	201.56	29,090.27	28,888.72
Saylor	2015	8/14/2015	8/15/2015	914.65	8,291.42	7,376.77
Whiskey	2017	9/1/2017	9/3/2017	762.16	16,232.48	15,470.32
Centennial	2017	6/28/2017	6/30/2017	7,554.45	146,428.10	138,873.66
Loveridge	2017	7/9/2017	7/11/2017	15,646.90	20,451.45	4,804.55
Pothole	2018	8/22/2018	8/23/2018	1,948.36	39,777.67	37,829.31
East Saylor	2018	7/16/2018	7/17/2018	90.84	21,676.81	21,585.97
Mule Creek	2018	7/21/2018	7/22/2018	26.07	819.90	793.83
Bear Trap	2018	8/4/2018	8/5/2018	26.77	3,035.38	3,008.61
Balanced Rock	2018	8/29/2018	8/30/2018	53.25	6,847.30	6,794.05
Pothole	2019	8/6/2019	8/8/2019	27,154.20	86,791.77	59,637.57
Milner 2	2019	7/27/2019	7/28/2019	114.01	871.90	757.89

Flint Mesa	2019	8/10/2019	8/12/2019	627.58	76,823.67	76,196.09
Castleford Butte	2021	7/3/2021	7/5/2021	2,190.29	6,236.32	4,046.03
Midpoint	2022	6/24/2022	6/24/2022	3.31	647.21	643.90
Milner	2022	7/26/2022	7/27/2022	6.64	828.54	821.90
Owsley	2022	7/31/2022	8/1/2022	1.43	1,091.10	1,089.67
Castleford Butte	2022	8/10/2022	8/11/2022	2.62	543.15	540.53
Crow's Nest	2023	5/2/2023	5/3/2023	35.45	11,291.96	11,256.51
Grindstone	2023	5/22/2023	5/22/2023	1,273.43	1,294.33	20.90
			TOTAL	58,633.98	479,070.70	420,436.76
			Average	2,931.70 (± 1,521.29)	23,953.54 (± 8,472.48)	21,021.84 (± 7,790.09)

Green strips in the Twin Falls BLM District were generally safer and more effective locations for wildfire suppression, and were associated with reduced fire behavior and smaller wildfire size throughout the fire season, even after fuels were fully cured. These results are consistent with the real-life accounts of fire managers across the Great Basin who have reported green strips decreasing fire behavior and supporting more efficient fire suppression (Bureau of Land Management, 2020; Harrison et al., 2002; Moriarty et al., 2015). These results also support published opinion pieces that green strips can be beneficial to wildland fire suppression efforts (Maestas et al., 2016; Wollstein et al., 2022). Notably, the green strips were estimated to be safer and more effective for wildfire suppression throughout the entire fire season, not just for a month or two, even once both the green strips and adjacent landscape were fully cured.

Modeling and historical analysis suggest green strips have saved substantial burned area over the past 35 years, though estimates are uncertain due to limitations of fire behavior models and assumptions used in simulations. No other study has attempted to estimate this specific metric for green strips (or linear fuel breaks more broadly), but these findings are consistent with what fire managers would expect based on their personal experiences using green strips in wildfire suppression (Bureau of Land Management, 2020; Moriarty et al., 2015). Effectiveness may decline under extreme fire weather conditions, and results may not apply uniformly across years or regions. Strategic placement based on historical ignitions, wind patterns, and landscape resilience appears critical, and while planned expansion of green strips is supported by these findings, additional studies across the Great Basin and further evaluation of ecological, economic, and social trade-offs are needed. Prioritizing green strips around areas optimal for sagebrush restoration and/or areas with high resistance to annual grass invasion and resilience to wildfire could be an approach aimed at using green strips to protect assets (Meinke et al., 2009; Pilliod et al., 2021). Where and under what conditions green strips have been successful in the past could also be informative for future green strip placement (Weise et al., 2023).

Objective 3 - Economic benefits fuel breaks create for rural economies

The suppression costs for the 2019 Pothole Fire (28,208 ha) was reported to be $600,000 i.e. $21.27 per ha. These costs are much lower than the estimated median per-hectare cost in our dataset for fires 20,000-50,000 ha, i.e. $72.10 per ha. According to those calculations, the cost of the Pothole fire would have been $1,072,818, suggesting significant savings that can likely be attributed to the LFBs.

Burned area simulations (Johnston 2024) suggested that in the absence of the LFBs, the 2019 Pothole Fire would have burned an area of 86,624 ha, just over three times the actual size of the fire. Table 9 summarizes the cost for the 2019 Pothole Fire and expenditures of wildfire suppression, rehabilitation, and grazing permit revenue loss incurred by the BLM for three simulated scenarios (3x, 2x, and 1.5x the size of the actual 2019 Pothole Fire). The cost savings for the Pothole fire case study were estimated to be $2,616,099 to $6,720,224, depending on model assumptions, savings that can likely be attributed to the implemented LFBs.

Table 9. Actual fire size and costs of the 2019 Pothole Fire and three simulated fire scenarios: 3x, 2x, and 1.5x larger than the actual size.

Fire scenario	Wildfire size (ha)	Suppression cost	ESR cost	Grazing fee revenue loss (2 yr)	Total cost	Cost difference (scenario – 2019 fire cost)
2019 Pothole fire	28 208	$600 000	$1 699 509	$30 850	$2 330 359	–
~3× larger (FARSITE)	86 624	$3 113 543	$6 960 109	$89 461	$9 050 468	**$6 720 224**
2× larger	56 416	$2 027 771	$4 532 942	$58 264	$6 210 631	**$3 880 387**
1.5× larger	43 312	$3 122 710	$3 480 055	$44 730	$4 946 253	**$2 616 009**

Abbreviations: hectares (ha), emergency stabilization and rehabilitation (ESR), year (yr).

We estimated the cost of providing alternative forage post-fire for a cattle herd size of 300 head, a ranch size representative of our study area. The loss of grazing lease revenue for the BLM would amount to $2,398. We estimated the cost of an alternative grazing lease on private land to $7,393 and the cost of replacement grass hay to a cost of $72,232 (Table 10). We also estimated the cost of forage loss and cost of replacement forage for the actual 2019 Pothole Fire and the hypothetical scenarios of a 3x, 2x, and a 1.5x larger fire, see Table 11.

Table 10. Cost and change to ranch income for providing alternative forage for a herd of 300 cattle (Johnston et al. 2025).

Replacement forage source	Cost of 1 776 AUMs	Ranch income before operating costs with forage source
Federal grazing lease	$2 398	$31 711
Private range grazing lease	$33 744	$7 393
Purchased grass hay	$112 385	–$72 232

Abbreviations: animal unit months (AUMs).

Table 11. Total cost of replacing all AUMS lost on BLM lands after the 2019 Pothole fire including the hypothetical scenarios of a 3x, 2x, and 1.5x larger fire which may have occurred in the absence of the linear fuel breaks (Johnston et al. 2025).

Fire scenario	AUMs lost in fire	Forage replacement cost–private lease (2 yr)	Forage replacement cost–hay (2 yr)
2019 Pothole	11 650	$403 336	$1 415 220
~3× larger (FARSITE)	33 783	$1 169 619	$4 101 950
2× larger	22 002	$761 743	$2 671 495
1.5× larger	16 892	$584 809	$2 050 975

Abbreviations: animal unit months (AUMs), year (yr).

Simulated outcomes of the 2019 Pothole Fire suggest that the cost savings from reduced fire size due to LFBs exceed both the implementation and 10-year maintenance costs of the Jarbidge LFB segments in southern Idaho. Our analysis supports the economic viability of investing in fuel breaks in strategic locations, demonstrating that the long-term financial benefits outweigh the initial and ongoing expenditures for the BLM. Our analysis further highlights significant implications for livestock operations affected by federal grazing land closures following wildfire. Long-term, it is not feasible for livestock producers to absorb the costs associated with repeated closures of allotments and the need for finding replacement forage to maintain the herd size.

We acknowledge that our study focused on monetary cost and cost savings, overlooking potentially important impacts that LFBs may have on wildlife habitat and recreational opportunities. Long-term analysis of improvements in ecological conditions resulting from wildfire protection in fire-prone areas was also not addressed or discussed as part of this research. Complementary analyses will be required to address these implications.

Conclusions

The first part of this study compared vegetation in LFBs that were subjected to targeted or allotment cattle grazing, or not grazed at all, to the adjacent landscape. The goal of the management strategies was to create and maintain less flammable fuel beds in LFBs. Linear fuel breaks where existing vegetation was removed via herbicide, desired species were seeded, a 1-year post-seeding rest period was observed, followed by resumed allotment style cattle grazing, and an imazapic treatment within 5 years of seeding were the most successful at creating and maintaining a potentially less flammable fuel bed compared to the adjacent landscape and to linear fuel breaks employing other management strategies. Linear fuel breaks treated with imazapic tended to have higher weed cover (not including invasive annual grasses) compared to the adjacent landscape and the linear fuel breaks not treated with imazapic. The main weed species observed where imazapic had been applied were Russian thistle and tall tumble mustard; each of these species reduces forage value and increases fire hazard, thus additional management tactics (such as targeted grazing with sheep and goats and/or additional herbicide treatments) should be explored for controlling these species. It is important to note that the adjacent landscape in this study was early successional sagebrush steppe dominated by perennial and annual grasses and forbs with low/no shrub cover. Larger differences in vegetation and fuel properties would be expected in a comparison between the vegetation in the LFBs and the adjacent landscape in a mid or late successional stage of sagebrush steppe.

Pairwise comparisons between wildland fuels in areas within and outside of LFBs in this study support the idea that linear fuel breaks in sagebrush and grass-dominated rangelands of the Northern Great Basin have created safer and more effective spaces for wildfire suppression activities. Further, due to the increase in safety and suppression effectiveness, wildfires that interact with linear fuel breaks are smaller and we estimate that tens of thousands of hectares have been saved from burning due to the presence and use of linear fuel breaks over the last 35 years. These findings support continued installation and use of linear fuel breaks in rangelands as a tool for combating the increased fire frequecy brought on by invasive annual grasses, climate change, and land use changes.

Our economic analysis of the 2019 Pothole Fire in the Twin Falls BLM District of southern Idaho suggests that LFBs aid in controlling and reducing the costs of wildfire; they are a worthwhile investment for public land managers and for the rural economy of the region. Continued research on the strategic placement of LFBs and potential ecological effects will further enhance understanding of wildfire management and wildfire's effects on ecology and economy in fire-prone landscapes.

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

In this section we identify planned or completed scientific/technical publications or science delivery activities. We include the date of delivery and work with relevant regions in the Fire Science Exchange Network.

Articles in peer-reviewed journals

Johnston, A., Johnston, K., Lee, K.D. 2025. Cost-Effectiveness of Linear Fuel Breaks in Wildfire Management: A Case Study from Southern Idaho. *Rangeland Ecology and Management.* 103: 406-416.

Johnston K.M., L.C. Jones, T.S. Prather, E.K. Strand. Evaluation of Management Activities for Creating and Maintaining Desired Linear Fuel Break Fuel Beds in South-Central Idaho. *in preparation for Fire Ecology.*

Johnston K.M., T.S. Prather, E.K. Strand. Remote sensing of fuel moisture through the growing season in sagebrush steppe. *in preparation for Fire Ecology.*

Touchette, M., E.K. Strand, T.S. Prather. Fire Behavior Modeling of Management Approaches for Linear Fuel Breaks. *in preparation for Fire Ecology* or *Rangeland Ecology and Management.*

Graduate thesis/dissertation

Johnston Kayla 2024. Evaluation of Linear Fuel Break Systems and Using Remote Sensing Data to Estimate Live Fuel Moisture Content in South-Central Idaho. Dissertation. University of Idaho, Moscow, Idaho. https://verso.uidaho.edu/esploro/outputs/doctoral/Evaluation-of-Linear-Fuel-Break-Systems/996671147401851

Johnston Aaron 2024. An Economic Evaluation of Linear Vegetative Fuel Breaks and Wildfire in Southern Idaho. Master's Thesis. University of Idaho, Moscow, Idaho. https://verso.uidaho.edu/esploro/outputs/graduate/An-Economic-Evaluation-of-Linear-Vegetative/996671548901851

Touchette, Madeleine *in progress.* Fire Behavior Modeling of Management Approaches for Linear Fuel Breaks. Master's Thesis. University of Idaho, Moscow, Idaho. *Expected completion date May 2026.*

Conference symposium

We led a Special Session at the Society for Rangeland Management Annual Meeting in Boise in February 2023. The special session featured 17 oral presentations.

Special session title: The emerging urgency of fuel breaks: developing a better understanding of likely impacts on wildfire, plants, wildlife, and people

Special session description: To combat increasingly large and frequent fires in the Great Basin, thousands of miles of fuel breaks are being implemented as a key management strategy. This symposium will provide a synthesis of fuel break performance and their impact on rangeland ecology. Presentations will cover the following topics: 1) fuel break efficacy in modifying fuel loads, altering fire behavior, and limiting fire spread; 2) effects of fuel breaks on adjacent plant communities (including invasives) and wildlife; 3) fuel break design and treatment options (e.g., targeted grazing, herbicide application); and 4) management considerations of fuel breaks.

Traditional moderator: Eva Strand and Doug Shinneman
Virtual moderator: Tim Prather and Lisa Jones)
Invited presenters and presentation titles are listed in the symposium schedule below. Abstracts for each presentation can be provided upon request.

Table 12. Fuel breaks symposium SRM in Boise 2023, speakers and presentation titles.

Speaker	**Proposed Title**
Eva Strand and Doug Shinneman	Future direction of fuels science and management in sagebrush rangelands
Importance of fuel breaks	
Erik Kriwox (BLM)	"Fuel break management and maintenance considerations"
Kayla Johnston (University of Idaho)	"Evaluation of greenstrip linear fuel breaks in the Twin Falls BLM District (South-Central Idaho)"
Morgan Roche et al. (CSU)	"A spatial data synthesis of fuel breaks in relation to wildfire, invasive annual grasses, and sagebrush obligate wildlife"
Mike Guerry (RFPA/Idaho Rancher)	"Importance of fuel breaks during operations of a Rural Fire Protection Association"
Discussion	
Planning and assessment	
Jason Kreitler et al. (USGS)	"A return-on-investment approach for evaluating Great Basin fuel break priorities - Optimizing fuel break placement/implementation using fire behavior modeling and other spatial considerations"
Peter Coates et al. (USGS)	"Fuel break effectiveness linked to accessibility, environmental conditions, and treatment type in a

	retrospective assessment of wildfires across the western U.S.”
Matt Germino and Jake Price (USGS)	“Vegetation and modeled fire response to fuel breaks installed in and around recently burned areas: critical inference for breaking the annual-grass fire cycle”
Cali Roth et al. (USGS)	“A comprehensive fuels treatment database for novel inferences and applications in wildfire management across the western U.S.”
Jesse Young (USFS)	“The success of fuel breaks in the containment of large wildfires vary across fuel break and weather conditions”
Julie Heinrichs et al. (CSU)	“HexFire: Simulating fire spread and interactions with fuel breaks”
Karen Short (USFS)*	"Fuel break scenario planning informed by quantitative assessment of transmitted wildfire risk in the Great Basin, USA"
Erin Buchholtz et al. (USGS)*	“Assessing large landscape patterns of potential fire connectivity using circuit methods
Effects on plant communities and wildlife	
Francis Kilkenny (US Forest Service)	"Dynamics of forage kochia spread from fuel-break seedings in the Snake River Plain of Idaho, USA"
Steven Matthews-Sanchez et al. (USGS)	“Developing and evaluating fuel break performance metrics across spatiotemporal scales and for multiple risk factors in sagebrush landscapes of the Great Basin”
Susan McIlroy and Doug Shinneman (USGS)	“Fuel break treatment effects on plant communities and fuel loads across diverse fire histories in south central Idaho”
Julie Heinrichs et al. (CSU)	“Assessing the cover, connectivity and future proliferation of invasive fine fuels”
Jacob Powell (OSU)	“Vegetative Fuel Break Establishment and Effectiveness in the Columbia Plateau”
Closing Discussion	

Poster and oral conference presentations

Harrison G.R., E.K. Strand, T.S. Prather. 2023. Cheatgrass increases flammability of native perennial grasses in laboratory combustion experiments. Oral presentation. 76^{th} Annual meeting Society for Range Management, February 12-16, 2023, Boise, Idaho.

Johnston K., E.K. Strand, T.S. Prather. 2023. Evaluation of greenstrip linear fuel breaks in the Twin Falls BLM District (South-Central Idaho). Oral presentation. 76^{th} Annual meeting Society for Range Management, February 12-16, 2023, Boise, Idaho.

Johnston K., E.K. Strand, T.S. Prather. 2023. Evaluation of greenstrip linear fuel breaks in the

Twin Falls BLM District (South-Central Idaho). Oral presentation. 10th International Fire Ecology and Management Congress December 6, 2023, Monteray, California.

Harrison G.R., L.C. Jones, E.K. Strand, H. Quicke, T.S. Prather. 2022. Sagebrush Steppe Plant Community Response and Annual Grass Control After Aerial Application of Indaziflam. Oral presentation. 75th Annual meeting of the Western Society of Weed Science. March 7-10, 2022, Newport Beach, CA

Harrison G.R., T .P. Prather. E.K. Strand. 2022. Flammability of annual and perennial grasses of the Western US from green-up through senescence. Poster presentation. Association for Fire Ecology conference. Fire Ecology Across Boundaries: Connecting Science and Management October 4-7, 2022, Florence, Italy.

Johnston, K., E.K. Strand, T .P. Prather. 2022. Evaluating Grazing Strategies for Fuels Management in Linear Fuel Breaks of South-Central Idaho (USA). Poster presentation. Association for Fire Ecology conference. Fire Ecology Across Boundaries: Connecting Science and Management October 4-7, 2022, Florence, Italy.

Johnston, A. 2024. A Cost-Benefit approach to analyzing economic viability of Rangeland Wildfire Fuel Breaks. Oral presentation. Society for Range Management in Reno, Nevada February 2024.

Touchette M.C., E.K. Strand, K.M. Johnson, L. Jones, and T.S. Prather. 2025. Fire Modeling of Techniques to Manage Linear Fuel Breaks Suggest Moderation of Fire Behavior. Poster presentation. 78th Western Society of Weed Science Annual Meeting, March 10-13, 2025, Seattle, Washington, USA.

Appendix C: Data and Metadata

Field data (raw and summarized) will be provided in Excel spreadsheets at Figshare at https://doi.org/10.6084/m9.figshare.31236367

The metdata is expected to be completed by May 15, 2026. A preliminary data archive has been created on Figshare, and the data will become publicly available on the publication date.

Appendix D: Photos

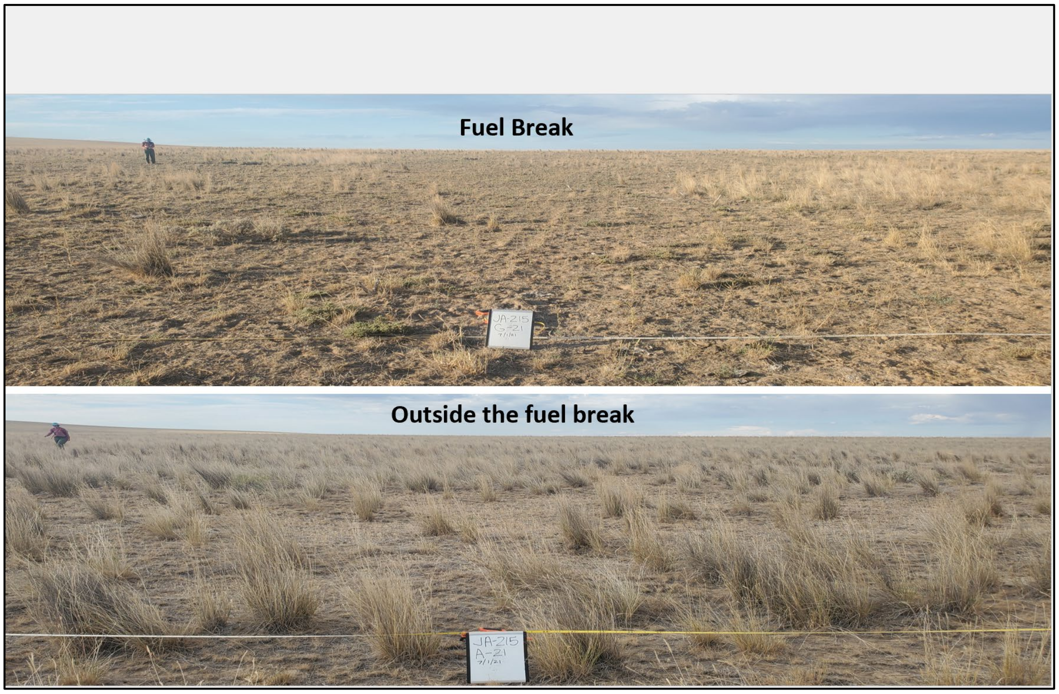

Photo 1. Inside and outside grazed fuel break. Early successional site, the area was burned in the Murphy Fire Complex in 2007. Photo credit: Kayla Johnston.

Photo 2. Ungrazed linear fuel break (left of fence) compared to cattle grazed linear fuel break (right of fence). Various levels of grazing intensity are used to maintain many linear fuel breaks across the Great Basin. Various levels of grazing intensity result in complex effects that can be positive, neutral, or negative. Photo credit: Kayla Johnston.

Photo 3. A linear fuel break near Bruneau, Idaho stays green (i.e. high moisture content & less flammable) later into summer than the surrounding vegetation. Photo credit: Kayla Johnston.