Nash *et al. Fire Ecology* (2026) 22:40
https://doi.org/10.1186/s42408-026-00455-x

Fire Ecology

RESEARCH

Open Access

Invasion resistance varies by fuel break type in sagebrush ecosystems

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Abstract

Background Wildfire is an increasingly important driver of changes within sagebrush (*Artemisia* spp. L.) ecosystems of the western USA, often resulting in increased spread of exotic annual grasses, such as cheatgrass (*Bromus tectorum* L.), and subsequent losses of native vegetation and wildlife habitat. Fuel breaks— areas of land treated to reduce or redistribute fuel loads — are widely implemented to help prevent the spread of wildfires and provide areas to facilitate firefighting efforts. However, localized installation and maintenance of fuel breaks directly reduce or remove vegetation and may propagate the spread of exotic annual grasses into fuel break boundaries and surrounding areas, inadvertently weakening ecological resilience to disturbance. To investigate if exotic annual grass cover was associated with mowed or green strip fuel breaks across the sagebrush biome, we combined multiple data sources and methodologies. We used targeted field surveys and land-management agency monitoring data within a space-for-time substitution framework coupled with a progressive-change before-after control-impact (PC BACI) study design using historical remotely sensed vegetation cover data which allowed us to account for potential confounding effects of roads on annual grass cover.

Results Models using both field collected and remotely sensed vegetation indices estimated increases in exotic annual grass cover over time following mowed fuel break installation, and higher exotic annual grass cover closer to mowed fuel breaks. These increases in exotic annual grass occurred within, at 500 m and at 1000 m from mowed fuel breaks. However, we found variable patterns of exotic annual grass after green strip fuel break installation depending on the data source. No increase in exotic annual grass was indicated by either analysis at distances greater than 500 m from green strip fuel breaks. However, our remotely sensed and field data analyses disagreed on the direction of the association of exotic annual grass cover and green strip fuel breaks.

Conclusions Although fuel breaks are an important tool in managing wildland fire, our analysis underscores the importance of planting fire-resistant vegetation, rather than mowing alone, to reduce invasion by annual grasses within and around fuel breaks in sagebrush ecosystems. In addition, site characteristics that hinder the proliferation of exotic annual grasses could be evaluated when installing fuel breaks to minimize unintended effects of exotic annual grass on surrounding sagebrush habitat.

Keywords Wildfire, Exotic annual grass, Wildlife habitat, Sage-grouse, Pygmy rabbit

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Resumen

Antecedentes Los fuegos de vegetación representan un factor de cambio dentro de los ecosistemas de arbustales de artemisia (*Artemisia* spp. L.) del oeste de los EEUU. Estos fuegos resultan frecuentemente en un incremento en la propagación de la especie exótica anual llamada *cheatgrass* (*Bromus tectorum* L.), que causa subsecuentes pérdidas en el hábitat de especies de vegetación nativa y de fauna. Las barreras de combustible, que son áreas de tierras tratadas para reducir o redistribuir los combustibles peligrosos, están ampliamente implementadas para ayudar a prevenir la propagación de los incendios, y proveer de áreas para facilitar los esfuerzos en el combate del fuego. Sin embargo, la ubicación, localización y el mantenimiento de estas barreras, si bien reduce directamente o remueve la vegetación, podría también acelerar la propagación de los pastos exóticos en el límite o en la cercanía de estas barreras, debilitando la resiliencia ecológica a los disturbios. Investigamos si la cobertura de los pastos anuales está asociada con vegetación segada o talada (i.e., cortada al ras), o con bandas de barreras a lo largo del bioma de artemisia. Lo hicimos usando datos de fuentes múltiples, incluyendo relevamientos direccionados a campo, datos de monitoreo de agencias de manejo de tierras, y productos de cobertura de suelos basados en datos de sensores remotos, usando un diseño (PC BACI), que tiene en cuenta el espacio de tiempo para la substitución dentro de un cambio progresivo en el control del impacto entre el antes y el después del mismo, y que tuvo en cuenta también los efectos de confusión que generan las rutas o caminos.

Resultados Los modelos que usaron tanto los datos colectados a campo como los índices derivados de datos de sensores remotos estimaron incrementos en la cobertura de pastos anuales en el tiempo luego de haber segado la vegetación para la instalación de las barreras y una mayor cobertura de estas anuales en las cercanías a estas barreras. Estos incrementos de los pastos anuales ocurrieron dentro de las barreras, a 500 m y a 1000 metros de ellas. Desde luego, encontramos patrones variables de pastos exóticos luego de la instalación de las barreras entre los dos análisis realizados. Ambos análisis no estimaron incrementos en los pastos anuales a 500 m o más de las barreras de combustibles verdes. Sin embargo, nuestro PC BACIPS y los datos de campo no concuerdan en la dirección de la asociación entre la cobertura de pastos exóticos anuales y la instalación de barreras dentro de las bandas de combustibles verdes.

Conclusiones Aunque las barreras de combustibles son herramientas importantes para el manejo de fuegos de vegetación, nuestro análisis subraya la importancia de plantar vegetación resistente al fuego en vez de cortar al ras la vegetación existente en estas barreras, para reducir la invasión de pastos anuales dentro y en los alrededores de las barreras de combustibles en ecosistemas de artemisia. Adicionalmente, las características de sitio que puedan ocultar la proliferación de pastos exóticos podrían ser avaluadas cuando estas barreras sean instaladas, de manera de minimizar efectos no deseados de pastos anuales exóticos en los alrededores del hábitat de ecosistemas de artemisia.

Background

Wildland fire is currently one of the most prevalent disturbances in sagebrush ecosystems (Crist et al. 2023). This disturbance has become more frequent, with some areas burning more than three times in the past 40 years in a system that historically experienced fire return intervals of over 100 years (Bukowski and Baker 2013). Mechanisms for increases in fire frequency include higher rates of anthropogenic ignitions that correspond with an expanding human "footprint" into wildlands (Hawbaker et al. 2013), extreme weather fluctuations due to climate change (Abatzoglou and Kolden 2011), and a continued proliferation of flammable, exotic annual grasses that initiate and sustain a synergistic grass-fire cycle that precludes native sagebrush recovery (D'Antonio and Vitousek 1992). In addition to general increases in fire frequency, megafires, defined as those which burn > 100,000 acres, are occurring more frequently (Crist et al. 2023). Larger and more frequent fires are driving a new era of conservation challenges for rangeland management in the sagebrush biome, as several sagebrush obligate species of conservation concern have experienced millions of acres of habitat loss due to wildland fire, including the greater sage-grouse (*Centrocercus urophasianus* Bonaparte, 1827; hereafter sage-grouse) (Coates et al. 2016; O'Neil et al. 2020) and pygmy rabbit (*Brachylagus idahoensis* Merriam, 1891) (Larrucea and Brussard 2008), among others. These species have received substantial conservation investment over recent decades, but a single fire can negate years of conservation progress, particularly when burned sagebrush communities subsequently transition into exotic annual grasslands (Pilliod et al. 2021; Mozelewski et al. 2024) that provide insufficient habitat for sagebrush obligate wildlife species (Rottler et al. 2015; Brussee et al. 2022).

The growing threat of wildland fires in sagebrush ecosystems has prompted management actions aimed at reducing the probability of fires and limiting their impacts when they do occur. Fuel breaks are a widely implemented technique to aid in wildfire containment in sagebrush ecosystems (Merriam et al. 2006; Shinneman et al. 2019). Fuel breaks are alterations in fuel characteristics that allow for easier control of wildfires (Shinneman et al. 2019; National Wildfire Coordinating Group 2024). These treatments are commonly implemented as a network of linear features intended to spatially isolate wildfire spread by providing areas to conduct backburning or other control methods, in addition to passively reducing flame heights (Shinneman et al. 2019). Typically, fuel breaks in non-forested rangelands are characterized into three main types: mowed, green strips, and brown strips. Mowed fuel breaks are the most common type in the sagebrush biome and are created by physically mowing the existing vegetation to reduce fuel heights to ~15–30 cm (Shinneman et al. 2019; Weise et al. 2024). Green strips are the second most common fuel break treatment and typically involve physically or chemically treating fuel loads while aiming to replace the existing vegetation with introduced (typically non-native) perennial species (Shinneman et al. 2019; Weise et al. 2024). The planted perennials are comprised of grass or shrub species that maintain relatively high moisture content later into the fire season and are able to effectively outcompete invasion by exotic species. Although fuel breaks can be constructed in a variety of strategic locations, both mowed and green strip treatments are predominately installed next to roads capable of providing access to firefighting vehicles, usually implemented in widths of 90–180 m (often on both sides of a road), and require regular maintenance, such as re-mowing or herbicide application, to remain effective (Shinneman et al. 2019). Brown strips are generally less common than mowed or green strips and are characterized by total removal of vegetation to maintain bare soil conditions (requiring regular retreatment), typically constructed as narrow strips (~6–10 m wide) along heavily used roadways where human-caused ignitions are more frequent (Shinneman et al. 2019). Other methods to create fuel breaks, such as targeted grazing and prescribed fire, are less frequently used (Boyd et al. 2023; Clark et al. 2023; Tanaka et al. 2023).

The installation of fuel breaks can benefit disturbance-adapted species through a variety of potential impacts to the environment, including the introduction of non-native seeds to the landscape in and around the fuel break from construction equipment used for mowing and seeding (Merriam et al. 2006), and the removal of existing vegetation and biocrust community cover due to soil disturbance from treatment actions (Pyke et al. 2014; Condon and Pyke 2018; Condon and Gray 2019). Following disturbance, invasive grasses rapidly reestablish, outcompeting slower-growing native perennials and sagebrush. Invasion by annual grasses into patchy landscapes characteristic of sagebrush shrublands has fundamentally altered fire regimes by increasing the amount and continuity of fine fuels across the landscape, creating a continuous layer of easily ignitable biomass (Balch et al. 2013; Reisner et al. 2013). Invasive annual grasses also readily recolonize following wildfire, reinforcing a grass–fire feedback cycle (D'Antonio and Vitousek 1992; Brooks 2008; Balch et al. 2013; Pilliod et al. 2017), most pronounced in areas with low ecological resilience, defined as a community's ability to maintain or recover its composition and structure after a disturbance, and ability to resist invasion from more ignitable annual grasses (Condon et al. 2011; Chambers et al. 2014; Crist et al. 2023). As such, Shinneman et al. (2019) suggested that the invasion of non-native annual grasses into fuel breaks and surrounding areas is likely an important potential ecological cost associated with fuel break installation and maintenance.

Some methods used in fuel break creation, such as mowing of vegetation, have been followed by increases in non-native annual herbaceous vegetation in sagebrush systems (Potts and Stephens 2009; Davies et al. 2011; Pyke et al. 2014; Shinneman et al. 2019). In California, non-native plant abundances were 200% higher in fuel breaks installed across a variety of habitat types when compared to surrounding areas (Merriam et al. 2006). Furthermore, fuel breaks in California chaparral and coastal scrub habitat (the closest analogues to shrub-dominated sagebrush ecosystems in the habitats sampled) were more likely to contain non-native plants than fuel breaks in forest or woodland habitat (Merriam et al. 2006). Cheatgrass (*Bromus tectorum* L.) and red brome (*B. rubens* L.) were the two most common non-native species in Californian fuel breaks (Merriam et al. 2006) and *Bromus* species such as cheatgrass are invaders of many sagebrush shrublands as well (Smith et al. 2022). The relationship between fuel break installation and exotic annual grass cover has been primarily studied in local contexts and relatively short timeframes, leaving uncertainty in long-term effects across the large spatial extent of the sagebrush biome (Germino et al. 2024; Germino and Watt 2025, but see Roche et al. 2024).

Within the Great Basin, expanding the current fuel break network to protect sagebrush ecosystems was identified as a priority by the U.S. Department of the Interior (U.S. Department of the Interior 2016; Bureau of Land Management 2020). However, at the time little was known about both the effectiveness of fuel breaks and the potential ecological impacts of widespread fuel break

installation (Weise et al. 2023; Roche et al. 2024; Germino et al. 2024). As such, decisions regarding optimal placement of fuel breaks often lacked empirical support, largely because scientific studies informing potential benefits (e.g., reduced fire spread, protected habitat) and ecological costs (e.g., exotic invasion, fragmented habitat) were limited. Weise et al. (2023) empirically estimated fuel break effectiveness across the sagebrush biome and found that fuel breaks had a 58% success rate at stopping wildfire spread overall. Local vegetation characteristics, weather, and distance to roads were all significantly associated with fuel break success, highlighting the importance of the local context in which fuel breaks are placed (Weise et al. 2023). While managers have important local ecological knowledge and landscape-level information on where to place fuel breaks to maximize success, there remains great utility in compiling data on fuel break effects to increase our understanding of the ecological consequences of these management actions.

To address this information gap, we used targeted field surveys, land-management agency monitoring data, and remotely sensed vegetation measures to examine connections between fuel break installation and exotic annual grass across the sagebrush biome. In our first analysis, we utilized a space-for-time substitution approach (Lovell et al. 2023) with agency monitoring and targeted field surveys to estimate if exotic annual grass cover was associated with mowed or green strip fuel breaks, while accounting for fuel break age and distance from the treatment. By combining multiple datasets, we were able to draw inferences across broad spatial and temporal scales. However, separating the effects of fuel breaks from other disturbances is difficult in large-scale analyses of exotic annual grasses as correlations between grasses and fuel breaks may reflect other factors, such as fire history or anthropogenic disturbance. To address these confounding effects, we also carried out a progressive-change before-after control-impact paired series (PC BACIPS) analysis (Thiault et al. 2017) of remotely sensed vegetation indices at a subset of locations to estimate if cover of annuals increased after fuel break installation relative to controls. By comparing changes at impact sites to paired control sites across time, this approach provided time-dependent estimates of fuel break treatment effects on exotic annual grasses while accounting for background fluctuations in the environment, including potential confounding effects of roadsides (Nielsen et al. 2011; Manier et al. 2014), where fuel breaks are often placed. The implementation of the progressive change variation of a BACIPS analysis also allowed for estimation of impacts that were not immediate (Thiault et al. 2017). For both analyses, we hypothesized that exotic annual grass cover would be higher closer to fuel breaks and would increase over time. In addition, we hypothesized that mowed fuel breaks would be more heavily invaded by exotic annual grasses than green strip fuel breaks. Lastly, we hypothesized that mowed fuel breaks would be associated with increases of exotic annual grass cover across larger distances from the edge of the treatment than green strip fuel breaks. If observed, this could be due to relative increases in propagule pressure from the hypothesized higher invasion severity of mowed fuel breaks. Estimating the effects of fuel break installation on exotic annual grass cover can help improve optimization of fuel break placement by prioritizing sites that are most likely to experience fuel break success (Weise et al. 2023) while minimizing increases in exotic annual grasses.

Methods

Study area

We examined patterns of exotic annual grass near fuel breaks within the sagebrush biome (as defined by Doherty et al. 2022), a large area consisting of portions of 13 states in the Western US characterized by landscapes with open vegetation communities dominated by shrubs of the genus *Artemisia* (Fig. 1). Sagebrush ecosystems are characterized by a patchwork of both public and private lands with livestock grazing as the predominant land use (Copeland et al. 2023). Precipitation occurs primarily in the cool season, although substantial climatic gradients exist across this wide-ranging biome. The Great Basin ecoregion, which spans portions of Nevada, Oregon, California, Idaho, and Utah, is more arid and contains more burned area than other portions of the sagebrush biome (Crist et al. 2023).

Fuel break data

We acquired fuel break treatment data from a Comprehensive Fuel Breaks Database (Weise et al. 2024) compiled for the western U.S. spanning 1953 to 2018. Fuel breaks were represented as polygons, with each record in the database containing information including treatment type (Mowed, Green, Brown, Other), year of treatment, number of previous treatments, and whether the fuel break was maintained. We specified maintenance regimes as binary (maintained/not maintained), as records of maintenance histories for treatments were inconsistently available. We classified a fuel break as "maintained" if it had more than one treatment record. The database contained 1776 recorded fuel break treatments, 87% of which occurred between 2000 and 2018. Mowed fuel break treatments were most prevalent (56.7%), followed by green (27.6%), other (7.8%), and

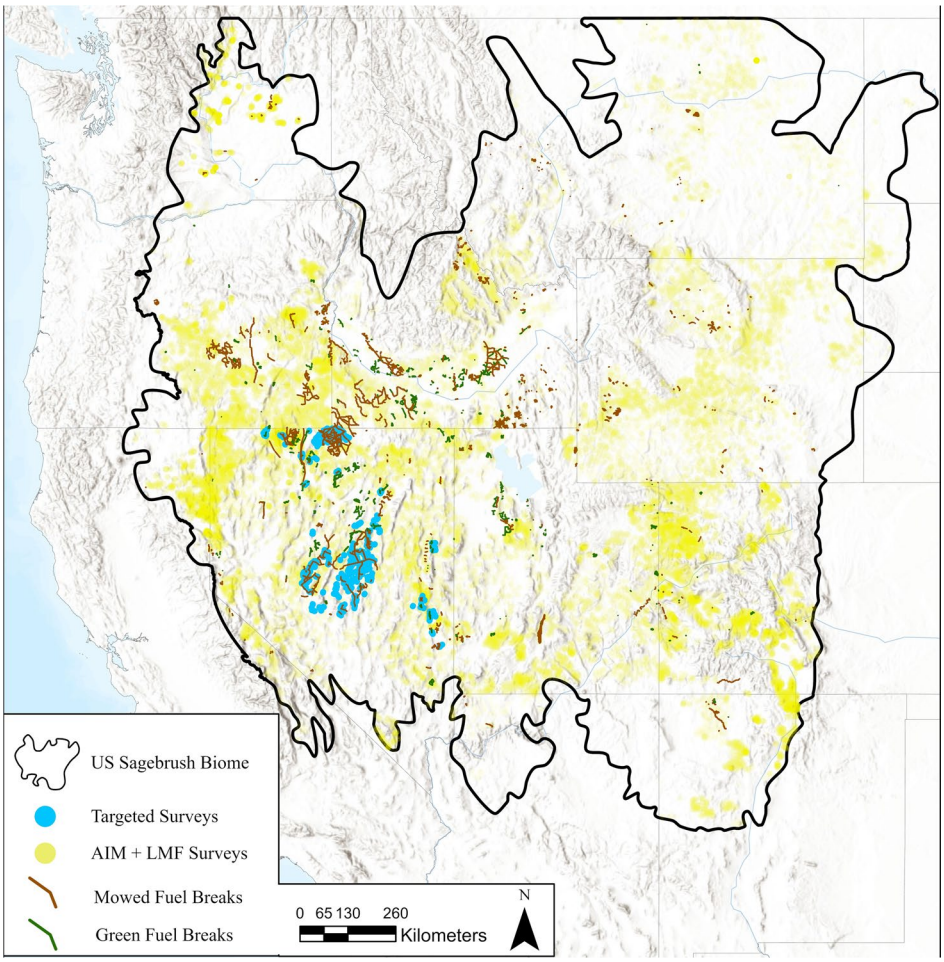


Fig. 1 Map of fuel breaks and survey locations within the sagebrush biome of the United States. Targeted fuel break surveys were conducted from 2019 to 2022. Bureau of Land Management Assessment Inventory and Monitoring (AIM) and Landscape Monitoring Framework (LMF) vegetation surveys occurred from 2004 to 2022. Basemap source: ESRI

brown (7.1%). We restricted our analysis to mowed and green strip fuel breaks, which comprised the majority (84.3%) of fuel break treatments.

Part 1: space for time substitution analysis

Vegetation data compilation

We obtained on-the-ground vegetation measurements across the study extent from the Bureau of Land Management's (BLM) Assessment Inventory and Monitoring Strategy (AIM) and Landscape Monitoring Framework (LMF) (Herrick et al. 2022). We compiled 52,109 vegetation surveys from 2004 to 2022, with the majority of LMF surveys and all AIM surveys occurring between 2011 and 2022. Vegetation metrics from AIM and LMF surveys (hereafter AIM surveys) used in this study were generated using line-point-intercept (LPI) methods, where the presence of a plant species is recorded at a set number of points along linear transects and divided by the number of points to calculate percent cover (Herrick et al. 2022). We subset the compiled data to those points that occurred within the sagebrush biome, as defined by Doherty et al. (2022), to focus on fuel break effects within our region of interest (Fig. 1). We then used the fuel breaks database to identify AIM sampling locations that occurred within 1 km of a mowed or green strip fuel break treatment polygon after that fuel break was installed and were not within 1 km of any other fuel break treatment polygon to prevent potential confounding influences of multiple treatments. For each vegetation sampling point, we defined fuel break age as the difference between the year of vegetation measurement and the fuel break installation year and calculated the distance from treatment using the `sf` package in `R` (Pebesma 2018). Of the available vegetation metrics, we selected an all-hits measure of annual grass cover (AH_AnnGrassCover) to represent exotic annual grass cover

at the sampling location (Herrick et al. 2022). In the Great Basin, annual grass cover is widely used as a proxy for exotic annual grasses, as non-native species such as cheatgrass, medusahead (*Taeniatherum caput-medusae* (L.) Nevski*)*, and ventenata (*Ventenata dubia* (Leers) Coss. & Durieu) dominate the annual grass component, whereas native annual grasses occur at low abundance and limited distribution (Chambers et al. 2014; Smith et al. 2022).

Targeted survey data collection

We conducted targeted vegetation surveys at 62 fuel breaks in the Great Basin from 2019 to 2022 to investigate potential ecological effects of fuel break installation in sagebrush ecosystems (Fig. 1). We subset the comprehensive fuel break dataset based on underlying ecological resilience (e.g., ability for the ecosystem to recover following disturbance) and resistance to invasive vegetation (R&R; Maestas et al. 2016), which combines soil moisture and temperature metrics to create three categories (1 = high, 2 = moderate, and 3 = low). We focused on R&R classes 2 and 3 as they were most susceptible to exotic annual grass. In addition, we subset fuel breaks to those which were classified as mowed or green strip fuel breaks, on public land, accessible by roads, not near cliffs or other unsafe terrain features, and whose LANDFIRE (Rollins 2009) existing vegetation type was classified as Wyoming big sagebrush (*A. tridentata wyomingensis* Beetle & A. M. Young). We subset our targeted field surveys to those that were not within 1 km of any other fuel break to align with our AIM subset criteria and reduce the effect of overlapping fuel break treatment effects. Vegetation characteristics were measured using LPI methods adapted from the BLM AIM framework. LPI surveys were conducted inside of fuel breaks, at the edge of fuel breaks, and at 200, 400, 500, 600, 800, and 1000 m from the fuel break. Fuel break age was calculated as described for AIM surveys and distance from the fuel break was measured in the field. We calculated the percent cover of annual grass at each transect using an all-hits criterion to generate comparable measures of exotic annual grass cover to AIM surveys (Herrick et al. 2022).

Environmental covariates

We aggregated a suite of environmental covariates to account for influences on exotic annual grass cover that could otherwise confound our ability to detect effects of fuel breaks. We calculated elevation from a 90-m digital elevation model (Rosen et al. 2000). We utilized the *SpatialEco* package in R (R Core Team 2023) to calculate heat load index (HLI) (Evans and Murphy 2023), which represents the influence of topography and aspect on insolation. We obtained average annual windspeed at 10 m above the surface from the National Renewable Energy Laboratory Wind Integration National Dataset Toolkit (Draxl et al. 2015) at a 2-km resolution, as high wind speeds can drive large wildfires and disperse seeds (Linn and Cunningham 2005; Applestein et al. 2022). We used the National Land Cover Database percent developed imperviousness time series dataset at a 30-m resolution (Yang et al. 2018) to represent anthropogenic disturbances and features within the landscape. We rasterized the time series of fire polygons compiled in the Combined Wildland Fire Datasets for the United States and certain territories: 1800s–present (Welty and Jeffries 2022), which contained fire data from 1985 to 2020 and the National Interagency Fire Center Wildland Fire Interagency Geospatial Services (WFIGS) Interagency Fire Perimeters for 2021–2022 fire perimeters (NIFC 2023). With this time series of rasterized polygons, we generated two time series of rasters that consisted of annual layers of (1) the number of burns across the full time series and (2) the last year a burn occurred during 1985–2022. We represented soil conditions using R&R layers from Maestas et al. (2016). We obtained precipitation, maximum temperature, minimum temperature, mean temperature, and minimum vapor pressure deficit (VPD) gridded data from the PRISM Climate Group at 4-km resolution (Daly et al. 2000). For each climate metric, we generated a seasonal mean value from December of the prior year, January, and February monthly means, to represent winter climate conditions that could provide soil moisture during spring that can influence the cover of exotic annual grass in that year (Boyte et al. 2015). We retrieved Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI) data from gridMET at a 4-km resolution (Abatzoglou 2013) and generated mean values for December–February as described for the PRISM climate datasets. Lastly, we obtained spring snow water equivalent (SWE; 01 March to 30 April) snowpack data from the Snow Data Assimilation System at a 1-km resolution (National Operational Hydrologic Remote Sensing Center 2004) to represent snow cover that would delay germination of exotic annual grasses. We extracted values from these covariates to the location of AIM surveys at the year vegetation measurements occurred. Continuous variables were standardized to their z-score, so that all covariates were on the same scale to ease interpretation of beta coefficients and aid in model fitting (Schielzeth 2010).

Model development

We specified a Bayesian ordered beta distributed (Kubinec 2023) generalized linear mixed model (GLMM) of exotic annual grass cover. The ordered beta distribution

provides a parsimonious modeling framework for zero-inflated beta-distributed data that aligned with our data structure (Kubinec 2023). Our model included a three-way interaction of interest, a binary variable indicating fuel break maintenance status, a set of environmental covariates, a random intercept term for year to account for underlying trends in exotic annual grass cover unrelated to fuel breaks, and a spatial grid random intercept term to account for uneven sampling across the sagebrush biome. We tested for a three-way interaction of fuel break type (green vs. mowed), fuel break age, and distance from the fuel break to estimate spatiotemporal patterns in exotic annual grass abundance at green and mowed fuel breaks. To generate our suite of environmental covariates, we included additive terms for all categorical covariates detailed in *Environmental Covariates*, above, and all continuous predictor variables that had Pearson pairwise correlation coefficients below $|r|=0.4$ (Zuur et al. 2010) to avoid potential issues due to multicollinearity. When two variables were correlated above our threshold, we generated a univariate generalized linear model (GLM) of exotic annual grass as predicted by each member of the correlated pair and retained the variable whose GLM had the lowest widely applicable information criterion (WAIC) score, a Bayesian model evaluation characteristic analogous to Akaike information criterion (AIC) (Vehtari et al. 2017). As exotic annual grass cover has been increasing over time in the sagebrush biome (Kleinhesselink et al. 2023), we included the year the vegetation measurement was recorded as a random intercept to account for this potentially confounding trend. We generated a 100-km spatial grid and assigned grid cell identity as a random intercept to account for uneven sampling intensity across the landscape, as recommended by the AIM program on their data access portal (Herrick et al. 2022). Thus, our final model structure was

$$\begin{aligned} &\textit{Exotic Annual Grass} \sim \textit{Fuel Break Type} \\ &\times \textit{Fuel Break Age} \times \textit{Distance to Fuel Break} \\ &+ \textit{Maintenance Status} + \textit{Environmental Covariates} \\ &+ (1|\textit{Year}) + (1|\textit{Spatial Grid ID}) \end{aligned}$$

We fit our model with STAN (Carpenter et al. 2017) using the *ordbetareg* R package (Kubinec 2023) and ran 3 chains with 50,000 iterations each, with 25,000 iterations discarded as burn-in, and thinned chains by every 10th sample, resulting in 7500 draws retained for inference. We assessed model convergence by visually inspecting trace plots and ensuring all parameters had an R-hat value of <1.1 (Gelman and Rubin 1992). To assess how well the model represented the observed data, we conducted posterior predictive checks, which involved generating data from the fitted model and checking for consistency between the simulated values and the actual data (Kubinec 2023).

Part 2: time series analysis

A progressive-change before-after control-impact paired series (PC BACIPS) analysis takes paired time series of a response variable of interest at control and impact sites as input and fits a set of competing models to estimate whether the change in the relative difference (e.g., the before-after control-impact, or BACI ratio) over time is best represented by a step, linear, asymptotic, or sigmoidal function (Thiault et al. 2017). Each of these functions represents a different hypothesis about the effect of the perturbation of interest over time. Step changes reflect an immediate and one-time change in the response variable, linear changes reflect an intensifying effect over time, asymptotic changes reflect an effect that attenuates over time, and sigmoidal changes reflect an effect that is initially delayed but intensifies before attenuating again. We utilized paired time series of annual herbaceous cover from the Rangeland Analysis Platform (RAP; Jones et al. 2018) at fuel breaks and control sites to estimate if fuel break treatments precede larger increases in exotic annual grass relative to control sites.

Control and impact site selection

We used locations that were delineated as impact and control sites for our targeted field surveys to investigate potential ecological effects of fuel breaks for the PC BACIPS analysis focal locations (Fig. 1). Therefore, the criteria for selecting fuel breaks followed the criteria of the targeted fuel break field surveys described above. In addition, visiting a subset of these sites in the field allowed us to confirm fuel break presence to avoid spatial inaccuracies obscuring relationships. Control sites were selected with the same criteria as fuel breaks, but as opposed to being located on a fuel break, they were within 300–1000 m of a road (to help account for the phenomena that fuel breaks typically co-occur with roads) and within 2–5 km of a fuel break, similar to the targeted fuel break field surveys for control sites. In addition to controls occurring at sites near roads, the temporal separation of road installation and fuel break treatment allows for the disentanglement of these effects with before-after comparisons. These criteria accounted for confounding effects of roads and reduced unwanted variation between control and treatment sites to better estimate effects of fuel breaks themselves (Nielsen et al. 2011; Manier et al. 2014).

Remotely sensed vegetation data

We obtained time series of annual forb and grass percent cover (hereafter, annual herbaceous cover) during 1984–2022 at a 30-m resolution using RAP (Jones et al. 2018). We selected RAP products as they more closely track on-the-ground vegetation measurements from AIM than other remotely sensed measures of rangeland vegetation such as RCMAP or LandCart (Applestein and Germino 2023). We verified that RAP annual herbaceous cover was a robust proxy for exotic annual grass cover by extracting RAP annual herbaceous cover values to each field survey point from the year the survey point was collected and calculated the Pearson correlation coefficient between the field and remotely sensed vegetation measure (Pearson 1895). To reduce known issues with pixel-to-pixel variability in remotely sensed vegetation indices, we calculated the mean annual herbaceous percent cover within a 100-m buffer centered on each control or impact location (Rigge et al. 2025).

PC BACIPS model formulation

We ran three separate PC BACIPS models, control versus inside a fuel break, control versus 500 m from a fuel break, and control versus 1000 m from a fuel break, for mowed and green strip fuel breaks to estimate the extent of potential influences of fuel break installation on annual herbaceous cover. We adapted methods from Thiault et al. (2017) to accommodate differences in the date of installation of fuel breaks. The implementation of each model was identical, with only the location of the 100-m buffer selected for measuring annual herbaceous cover varying (inside, at 500 m, and at 1000 m from the break). First, we paired each fuel break to the closest control site of the same R&R class using the st_nearest function in the R package *sf* (Pebesma 2018; R Core Team 2023). We determined the year of fuel break installation using the comprehensive fuel breaks database and designated all years before installation as the before period and all other years after fuel break installation as the after period. We then generated impact:control ratios (R_{CI}) of the percent cover of annual herbaceous cover (*AHC*) for each pair (k) of impact and control sites for every year of the time series (j).

$$R_{CI_{kj}} = AHC_{\text{impact}_{kj}} / AHC_{\text{control}_{kj}}$$

To generate a reference level for before intervention conditions ($R_{\text{Reference Before}_s}$), the mean of the impact:control ratio for each site (s) was generated across all years in the before period of length b years.

$$R_{\text{Reference Before}_s} = \frac{\sum_1^b R_{CI\text{Before}_{sb}}}{b}$$

Next, the impact:control ratio for every year in the after period (h) was divided by that site's (s) before impact:control ratio to generate an estimate of the change in the magnitude of this ratio after the intervention.

$$R_{BACI_{sh}} = \frac{R_{CI\ \text{After}_{sh}}}{R_{\text{Reference Before}_s}}$$

Finally, for each of the three PC BACIPS models, we fit four competing models with different functional forms to the time series of BACI values generated in the steps above: a step change, linear change, asymptotic change, and sigmoidal change using *minpack.lm* (Elzhov et al. 2013) and *nls2* R (Grothendieck 2013) packages for fitting non-linear models (Thiault et al. 2017). We measured the performance of each model using AIC_c (Burnham and Anderson 2002). We calculated AIC weights (Burnham and Anderson 2002) to estimate the relative likelihood of each model being the best among a set of candidate models. The model with the highest AIC weight was the top performing model. We then compared the top model and its estimated effect size between distances to understand the spatial pattern of the potential impact of fuel breaks on exotic annual grass cover. We examined the sensitivity of model results to the endpoint of the time series modeled, as data points near the edges of the observed range of values can have outsized leverage in regression models (Chatterjee and Hadi 1986). We re-ran each model with the last 5 years of the time series removed and compared the results to the models of the full time series. Lastly, as PC BACI ratios reflect changes in a response relative to controls and not necessarily an absolute increase or decrease at impact sites, we examined the underlying trend in remotely sensed annual forbs and grass at both impact and control sites to estimate acceleration, deceleration, or opposing trend of any change occurring at the control sites. We provide code (Nash et al. 2026) and data (Coates et al. 2026) to fit our models through USGS GitLab and ScienceBase. All analyses were conducted using R version 4.2.3 (R Core Team 2023).

Results

Space-for-time results

Our final model consisted of 876 observations of exotic annual grass cover, and after identifying the more informative variables among correlated predictors, included fixed effects of elevation, PDSI, precipitation, impervious surface cover, mean wind speed, minimum temperature, VPD, HLI, maintenance status, R&R class, number of times burned, plus a three-way interaction of distance from the fuel break, fuel break age, and fuel break type. Random effects included a random intercept term for year and a random intercept term for spatial grid ID. Of

Table 1 Standardized beta coefficients and 95% credible intervals estimated from the space-for-time substitution model for environmental covariates that were strongly associated with exotic annual grass cover at survey locations associated with fuel breaks in the sagebrush biome collected from 2004 to 2022. Note that coefficient estimates are on the logit scale. Interactions are represented using an asterisk (*)

Variable	Coefficient (logit scale)	95% Credible interval
Elevation	−0.74	[−0.97, −0.52]
PDSI	0.25	[0.11, 0.41]
Count of prior burns	0.14	[0.04, 0.25]
Winter precipitation	0.14	[0.01, 0.28]
Green treatments (intercept)	−2.01	[−2.66, −1.37]
Mowed treatments	−0.61	[−0.97, −0.24]
Distance	0.08	[−0.06, 0.23]
Fuel break age	−0.22	[−0.35, −0.09]
Distance * mowed	−0.24	[−0.50, 0.02]
Treatment age * mowed	0.64	[0.21, 1.05]
Distance * fuel break age (green)	0.03	[−0.06, 0.12]
Distance * fuel break age * mowed	−0.39	[−0.71, −0.06]

the 876 observations, 59% were from the AIM dataset and 41% were from our targeted surveys. Posterior predictive checks showed adequate fit, with proper identification of zero versus nonzero cover values, and moderately low to high cover values, with greater deviance at very low cover values. Parameter estimates and credible intervals for variables for which the 95% credible intervals did not include 0 are presented in Table 1. Of the environmental covariates, elevation was most strongly associated with exotic annual grass cover, with exotic annual grass cover decreasing as sites increase in elevation. PDSI, the number of times a site burned, and winter precipitation were positively associated with exotic annual grass cover. We detected strong interactions between fuel break type, fuel break age, and distance to the fuel break (Fig. 2). For green strip fuel breaks, exotic annual grass decreased with fuel break age, regardless of distance to fuel break. We did not detect patterns of increasing exotic annual grass with proximity to green strip fuel breaks. Overall, mowed fuel breaks had less exotic annual grass cover than areas with green strip fuel breaks, but exotic annual grass increased over time near mowed fuel breaks. Exotic annual grasses increased at farther distances as fuel break age increased (Fig. 2). We did not detect strong associations between exotic annual grass cover and any other predictors (95% Credible Interval [CrI] overlapped zero).

Time series results

We calculated a Pearson correlation coefficient of 0.79 between our remotely sensed and field-based measures of exotic annual grass cover and thus concluded that our remotely sensed measure was a strong proxy. Our final PC BACIPS dataset was comprised of 167 pairs of impact and control sites with a minimum of 4 years

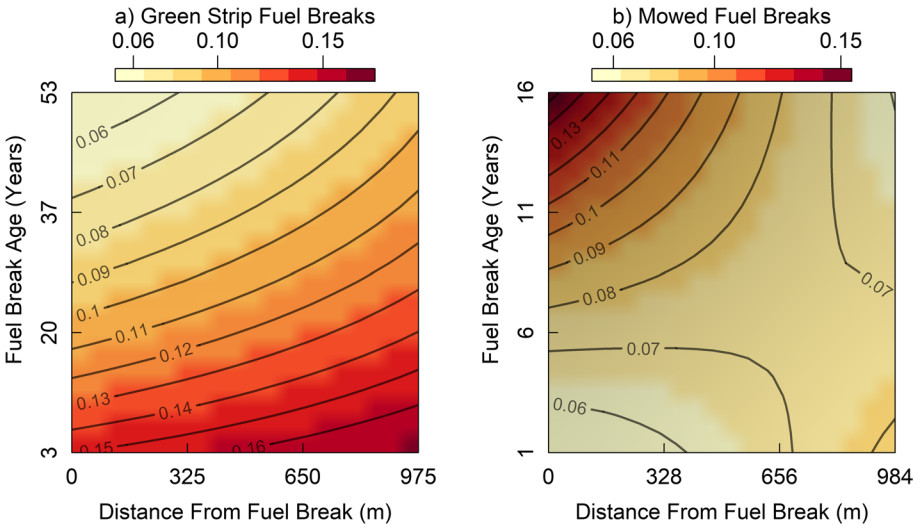


Fig. 2 Estimated exotic annual grass cover at green (**a**) and mowed fuel breaks (**b**) derived from the space-for-time substitution model using survey data collected in the sagebrush biome from 2004 to 2022. Panels reflect the interaction between fuel break age and distance from the fuel break with all other covariates held at their mean values. Topographic lines reflect predicted exotic annual grass percent cover for each combination of fuel break age and distance. The color ramp represents higher (darker colors) and lower (lighter colors) cover of annual grass, respectively. Note the different y and *x*-axis scales

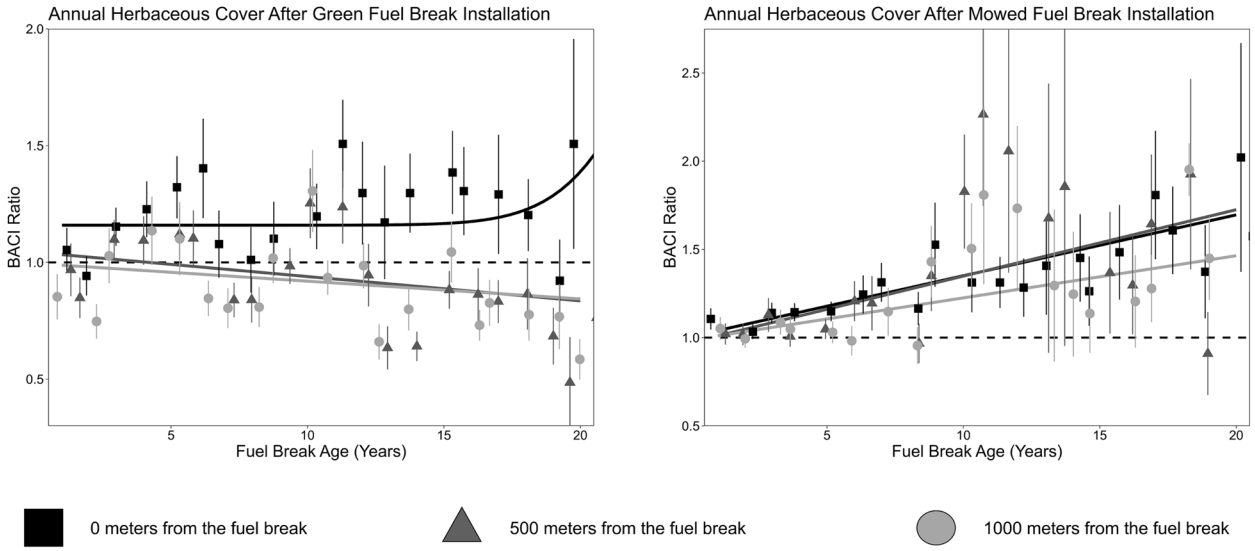


Fig. 3 Trends in mean annual BACI (Before-After Control Impact) ratios at green (left panel) and mowed (right panel) fuel breaks estimated from Progressive Change BACIPS models using remotely sensed vegetation data from sagebrush biomes spanning 1984 to 2022. The dotted horizontal line at 1 represents no effect, while a BACI (before-after-control-impact) ratio above one represents greater increases in the impact sites relative to the controls. Annual mean BACI ratios are represented by points (inside square, 500 m triangle, 1000 m circle) and standard error bars, with decreasing darkness representing further distances

pre-treatment and a maximum of 31 years of after-treatment data. We analyzed green and mowed fuel break sites separately to assess whether mowed fuel breaks exhibited different spatiotemporal patterns of annual herbaceous cover than green strip fuel breaks (Fig. 3). Our BACIPS dataset had fewer green strip fuel breaks, with 31 pairs of green strip fuel breaks and control sites. We detected a positive sigmoidal trend inside green strip fuel breaks, with initial exotic annual grass values 1.15 times control site values that further increased around 15 years after treatment. This model had 100% AICc weight, with the step (0%), asymptotic (0%), and sigmoidal (0%) models having less support. We detected a negative linear trend at 500 m from green strip fuel breaks of 0.99 times control site annual herbaceous cover per year ($\beta = -0.01$, $p = 0.005$) with an initial value 1.04 times control site cover. This model had 97% AICc weight, with the step (3%), asymptotic (0%), and sigmoidal (1%) models generating less support. At 1000 m from green strip fuel breaks, the linear model was most supported (47%) over the step (34%), asymptotic (16%), and sigmoidal (4%) models, but detected a marginal decline over time ($p = 0.06$).

Of the 167 site pairs, our dataset contained 136 pairs of mowed and control sites. Inside mowed fuel breaks (0 m), we detected a significant linear trend in annual herbaceous cover of 1.034 times control sites per year ($\beta = 0.034$, $p < 0.001$). The linear model was supported (67.3% AICc weight) over the step (0%), asymptotic (18%), and sigmoidal (14%) models. At 500 m from mowed fuel breaks, we estimated a significant linear increase of 1.037 times control site annual herbaceous cover per year, which was 99% supported over the linear (0%), asymptotic (0.5%), and sigmoidal (0%) models. At 1000 m from mowed fuel breaks, we estimated a significant linear increase of 1.024 times control site annual herbaceous cover per year, which was supported (91% AICc weight) over the linear (0%), asymptotic (8%), and sigmoidal (0%) models.

In our endpoint sensitivity analyses, we found that the top model was the same type and effect direction in the full time series and the time series truncated by 5 years for all models except both the inside and 1000 m green strip fuel break results. Inside green strip fuel breaks, we found a linear increase was supported when the time series was truncated by 5 years, as opposed to a sigmoidal increase. At 1000 m from green strip fuel breaks, we found that the top performing model (step change) was within 2 AICc of our null model, supporting no effect relative to controls, as opposed to a marginally significant decline. All three distances of the mowed fuel break models supported linear increases, in agreement with the full time series analyses.

After visualizing the raw trends in annual forbs and grass at both impact and control sites, we found that sites experienced a high degree of interannual variability; but generally, impact and control sites were experiencing a trend of increasing annual herbaceous cover

(Figures S1–S6). Therefore, the positive BACI ratios estimated in our three mowed models and inside green model support an acceleration of annual herbaceous cover expansion at impact sites compared to control sites. Negative BACI ratios estimated in the 500 m and 1000 m green models reflect a deceleration of invasion at impact sites compared to control sites.

Discussion

We estimated the relationship between exotic annual grass cover and fuel break installation across both space and time using targeted field surveys, land-management agency monitoring data, and remotely sensed vegetation cover data. We structured our analysis into two sub-analyses, a correlational space-for-time analysis (Lovell et al. 2023) using targeted field surveys and BLM AIM vegetation surveys, and a progressive change before-after control impact paired series time series analysis (Thiault et al. 2017) to account for potential confounding effects of roads. Across both analyses, we found spatial and temporal patterns in exotic annual grass cover that varied in relation to fuel break presence, type, and fuel break age. In addition, we found that fire frequency was positively associated, and elevation was negatively associated with the cover of exotic annual grasses, which has been broadly documented across the western US (D'Antonio and Vitousek 1992; Brooks et al. 2004; Barker et al. 2019; Smith et al. 2022). We found that exotic annual grass cover was positively associated with winter precipitation, which corroborates past findings (Bradley and Mustard 2005; Boyte et al. 2015).

Fuel breaks are implemented using multiple methods with varying spatial extents and levels of disturbance, and thus the expected ecological impacts are not uniform (Shinneman et al. 2019). In concordance, we found that patterns of exotic annual grass cover differed between fuel break types across the sagebrush biome. Mowed fuel breaks, the most common fuel break type in the sagebrush biome, were associated with increasing exotic annual grass over time, with the rate of increase generally attenuating with distance from the fuel break. This spatiotemporal pattern is consistent with an invasion of exotic annual grass inside or near the mowed fuel break, with this grass then gradually spreading outwards into the surrounding landscape. Our time series analysis results revealed an effect of mowed fuel breaks on exotic annual grass distribution, regardless of road effects, wherein areas located inside, within 500 m, and within 1000 m of a mowed fuel break exhibited linear increases in exotic annual grass relative to controls over time. In both of our mowed fuel breaks analyses, exotic annual grass increases gradually declined in strength from the break to a distance of around 500 m and then weakened significantly after 500 m.

Our results align with previous research linking exotic annual grasses to vegetation disturbances within linear clearings. Increased exotic annual grasses have been observed near fuel breaks (Roche et al. 2024), after mowing in sagebrush communities (Davies et al. 2011), following fuel break construction in chaparral and coastal shrublands (Merriam et al. 2006), along fuel break edges in the sagebrush biome (Germino and Watt 2025), after pipeline corridor construction (Farrell et al. 2021; Terry and Adler 2024), and along powerline rights-of-way (Bradley and Mustard 2005). These studies suggest that vegetation disturbances occurring within linear corridors consistently promote exotic annual grass establishment and spread, supporting our observations. With longer post-treatment data, the patterns we observed will likely become more parsimoniously modeled as asymptotic increases, as exotic annual grass cover at these distances reaches carrying capacity. However, increases in exotic annual grass are not always observed outside treatments with mowed fuel break installation. Little evidence of annual grass increases was observed inside of or within 90 m of fuel breaks at 40 paired plots 5 years after the installation of mowed fuel breaks in previously burned areas in eastern Idaho (Germino et al. 2024). While most of our mowed fuel break on-the-ground vegetation measures occurred within 5 years of treatment, our dataset included observations up to 30 years post treatment, allowing for the detection of lagged effects from fuel break installation. In addition, our analyses included fuel breaks located across the sagebrush biome with different disturbance histories and climate conditions, including in warmer and drier portions of the Great Basin, compared to fuel breaks in the Soda Fire scar in western Idaho, as studied by Germino et al. (2024).

Green strip fuel breaks, the second most common fuel break type in the sagebrush biome, were associated with patterns of exotic annual grass that differed from mowed fuel breaks. Green strip fuel breaks were generally characterized by stable or declining exotic annual grass over time, in both the space-for-time and time series analyses. This pattern could be in part due to the establishment of planted perennials that define green strip fuel breaks. As these perennials develop both above and below ground, they may compete with annual grasses within treated areas, as intended, leading to reduced exotic annual grass cover compared to mowed breaks (Condon and Pyke 2018; Shinneman et al. 2019). Our two green strip fuel break analyses disagreed on the relationship of exotic annual grass in and very near green strip fuel breaks, with the space-for-time model supporting a decline over time, and the time series analysis supporting a sigmoidal

increase in annual grass, with ~15 years of a step increase that then accelerated. This discrepancy could be due to initial increases in exotic annual grass from the primary disturbance of fuel break installation and potential invasion after planted perennials fail (Heston et al. 2025) or maintenance is no longer conducted that is confounded by road effects in the space-for-time analysis. Overall, we found that green strip fuel breaks were installed in areas with higher exotic annual grass cover than mowed fuel breaks, which could be due to intentional non-random placement of these fuel break types in the landscape, with more resistant green strip fuel breaks being preferentially targeted in areas with higher invasion risk (Shinneman et al. 2019). Regardless, the lack of an observed increase in annual grasses over time within 1 km of green strip fuel breaks, even with a likely higher seed bank, supports green strip fuel breaks as less vulnerable to invasion than mowed fuel breaks.

Disentangling the influence of fuel breaks from other landscape disturbances is a substantial challenge when conducting large scale analyses of exotic annual grass and fuel breaks. Associations between exotic annual grass and fuel breaks detected in correlational space-for-time substitution analyses could be driven by other disturbances on the landscapes such as fires (wild or prescribed), especially if fuel breaks are installed in areas more likely to burn due to high exotic annual grass cover, where they have been shown to be more effective (Weise et al. 2023). In addition, roads alone have been shown to cause increased abundance of exotic annual grass into surrounding landscapes over time (Gelbard and Belnap 2003), and fuel breaks are often installed along roads, thus confounding the effects of these two variables. We addressed these issues by pairing our space-for-time analysis with a time series analysis that accounted for trends in exotic annual grass at similar untreated control sites to estimate increases in exotic annual grass due to fuel breaks themselves. We ensured that both control and impact sites did not occur within post-1985 fire footprints to avoid dramatic changes within the time series of vegetation that would not be properly reflected in both groups of sites. Additionally, we chose control sites near roads of the same travel volume and surface material to those of fuel break sites to control for underlying trends in exotic annual grass due to roads. As the installation of a fuel break typically occurs after a road, detecting a signal of increased exotic annual grass in the after period of our analysis supports that mowed fuel breaks contribute to increases in annual grass, in addition to likely effects of roads. Potentially, fuel breaks could exacerbate pre-existing exotic annual grass invasions along roadsides by widening the area of disturbance near roads, allowing for the development of higher propagule pressure along the edges of the break. These increases in seed bank could turn a small, but static exotic annual grass stand into a much larger and more competitive population that expands (Schantz et al. 2015). Using on-the-ground data such as AIM and remotely sensed data such as RAP, we were able to identify patterns of landscape change across a large spatial extent and disentangle coincident drivers of change in a landscape of multiple contemporaneous disturbances.

Undoubtedly, non-standardized application of treatments to install fuel breaks and maintenance activities that differ in the timing of their application, the intensity of application, and environmental context, lead to varying degrees of resistance between fuel breaks of the same type (Germino et al. 2024). Maintenance has been demonstrated to strongly influence the trajectory of exotic annual grasses within fuel treatments, with varied maintenance treatments of herbicide, hand cutting, mowing, and drill seeding leading to reductions, increases, and no difference in annual grass cover when compared to controls (Germino et al. 2024). These differing responses highlight the contextual nature of fuel break maintenance treatments, and how longer-term investigations of fuel break maintenance could add important detail on what treatments work to reduce exotic annual grass and for what temporal scale they are best suited.

We used remotely sensed annual herbaceous cover in our time series analysis, which includes cover other than exotic annual grasses. However, within our study area, cover of exotic annual grass and remotely sensed annual herbaceous cover products were highly correlated, suggesting that remotely sensed indices of annual herbaceous cover were not dominated by annual forbs. To resolve the limitations of our analyses, future work could address maintenance effects and species-level responses to fuel break installation, such as collecting repeated vegetation measures in the AIM framework both before and after fuel break installation and at control sites. This design would allow for a more precise understanding of what species of exotic annual grass respond most to fuel break installation and whether there are shifts in invading species as the fuel break ages. In addition, this design paired with maintenance treatments could quantify how much maintenance reduces exotic annual grass invasion and provide guidance on the appropriate maintenance effort for managers.

While fuel breaks are an important tool to manage wildland fire, unintended increases in exotic annual grass cover from fuel break installation could degrade the quality of the sagebrush-dependent wildlife habitat and grazing forage resource that they are designed to protect (Roche et al. 2024). In sagebrush ecosystems, wildfires were once limited by the natural spacing of native grasses

and shrubs, which broke up fuel continuity (Bukowski and Baker 2013). Invasive annual grasses readily colonize these gaps (Reisner et al. 2013), especially after fire, and dry out earlier than native plants (Chambers et al. 2017). This creates a continuous fuel layer resulting in shortened fire-return intervals and driving a reinforcing cycle of exotic grass invasion and more frequent, larger wildfires (D'Antonio and Vitousek 1992; Brooks 2008; Abatzoglou and Kolden 2011; Balch et al. 2013; Pilliod et al. 2017). Beyond increasing the frequency and extent of fires, exotic annual grasses have direct impacts on habitat quality for sagebrush-dependent wildlife species such as sage-grouse (Lockyer et al. 2015; Brussee et al. 2022). Following a wildfire, reductions in sagebrush cover can significantly diminish winter forage availability for both sage-grouse and pygmy rabbits, as their winter diets are often composed almost entirely of sagebrush (Pennington et al. 2016; Olsoy et al. 2022). Along with reductions in food resources, habitat conversion to annual grassland could likely reduce connectivity between remaining populations of species of conservation concern such as sage-grouse and pygmy rabbits (Harju et al. 2013; Dilts et al. 2023). Lastly, unintended increases in exotic annual grass cover could impact biological interactions, such as increasing densities of deer mice, *Peromyscus maniculatus* (Wagner, 1845), (Sanders and Chalfoun 2018), a nest predator of sagebrush songbird species of concern such as sage thrasher, *Oreoscoptes montanus* (Townsend, 1837) (Hethcoat and Chalfoun 2015). Monitoring for and actively managing unintended increases in exotic annual grass invasion near sensitive wildlife species habitat could allow for increased protection of these areas from wildfire while maintaining the vegetation community that the fuel break is intended to protect.

Despite the possibility that fuel breaks might lead to unintended increases in annual grasses, progress has been made in developing methods to control these species within the sagebrush biome, and these methods are currently employed for the maintenance of fuel breaks. Managers could implement seasonally specific, targeted grazing to reduce exotic annual grasses and maintain fuel breaks (Diamond et al. 2009; Lehnhoff et al. 2019; Perryman et al. 2020; Marchetto et al. 2021; Clark et al. 2023), while ensuring that grazing pressure allows for perennials to recover and competitively exclude annual grasses. In addition, application of herbicides such as imazapic, rimsulfuron, indaziflam, aminopyralid, and glyphosate can effectively reduce annual grasses, can be applied in or near fuel breaks, and do not harm biocrusts that increase resistance, although these treatments often have limited durations of effectiveness (Kyser et al. 2013; Rinella et al. 2014; Sebastian et al. 2016; Condon and Gray 2020; Terry et al. 2021; Lazarus and Germino 2022).

Along with post-treatment maintenance, site-based resistance and invasion status could be assessed when placing fuel breaks to minimize exotic annual grass invasion. For example, our space-for-time analysis supported previously described relationships of exotic annual grass increasing with lower elevations (Smith et al. 2022) and number of previous burns (D'Antonio and Vitousek 1992). This information could be used to optimize the placement of fuel break installation, prioritizing locations with greater resistance to cheatgrass. Conversely, managers could use remotely sensed vegetation indices such as the Rangeland Analysis Platform (RAP) (Jones et al. 2018) and the Rangeland Condition Monitoring Assessment and Projection (RCMAP) (Shi et al. 2022) to site fuel breaks in locations that have already been invaded with annual grass, as this may reduce the loss of intact sagebrush communities (Pastick et al. 2021). Siting fuel breaks in invaded areas could lead to higher fuel break success, as fine fuel cover has been associated with greater fuel break effectiveness, likely due to reduced flame lengths (Weise et al. 2023). Beyond evaluating existing exotic annual grass cover, managers can utilize spatially explicit predictions of abiotic factors driving resistance to exotic annual grass invasion both with and without fire to prioritize sites that are likely to resist cheatgrass if they remain unburned (Urza et al. 2024). These tools can be combined with maps of predicted fuel break success (Weise et al. 2023) to balance ecological tradeoffs between wildfire suppression and fuel break impacts (Roche et al. 2024).

Conclusions

Optimizing the placement of fuel management treatments such as fuel breaks could facilitate the protection of sensitive species in decline, such as sage-grouse and pygmy rabbit (Dudley et al. 2021; Dilts et al. 2023) and maximize the benefit of these treatments per dollar invested. We build on previous evidence that fuel breaks in shrub-dominated ecosystems can lead to increases in exotic annual grass (Merriam et al. 2006), and that fuel breaks are spatially coincident with exotic annual grass in the sagebrush ecosystem (Roche et al. 2024). We demonstrate that mowed fuel breaks were associated with increases in exotic annual grass cover relative to controls in sagebrush rangelands. Our results support the hypothesis that green strip fuel breaks are less vulnerable to invasion compared to mowed fuel breaks, enhancing their suitability for placement in uninvaded areas while simultaneously reducing the risk of exotic annual grass invasion. However, green strip fuel breaks can introduce non-native perennials that can spread beyond the fuel break itself (Gray and Muir 2013). These increases remained robust, even when accounting for

other associated disturbances, specifically roads. Tracking of management actions in databases such as the Land Treatment Digital Library (Pilliod et al. 2019) and Comprehensive Fuel Breaks Database (Weise et al. 2024) are critical for continued evaluation of fuel break installation and maintenance and for adaptively managing these treatments. Our results indicate that further research regarding management actions and their unintended consequences, and proactive fire risk reduction strategies, would benefit practitioners working to mitigate the impacts of fire to sagebrush ecosystems, especially if the climate in the western U.S. continues to warm and dry (Overpeck and Udall 2010).

Abbreviations

AIC_c	Akaike Information Criterion Corrected for Small Sample Sizes
AIM	Assessment, inventory, and monitoring
BACI	Before-After control impact
BLM	Bureau of Land Management
GLM	Generalized linear model
GLMM	Generalized linear mixed model
LMF	Landscape Monitoring Framework
LPI	Line point intercept
PCBACIPS	Progressive change before-after control impact paired series
PDSI	Palmer drought severity index
RAP	Rangeland Analysis Platform
R&R	Resistance and resilience
SPEI	Standardized Precipitation and Evapotranspiration Index
SPI	Standardized Precipitation Index
SWE	Snow water equivalent
WAIC	Widely Applicable Information Criterion
WFIGS	Wildland Fire Interagency Geospatial Services

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-026-00455-x.

Additional file 1: Supplementary Figs. 1–8.

Acknowledgements
We extend gratitude to all field technicians who collected vegetation data at fuel breaks. We thank Joe Atkinson for assistance in copy-editing the manuscript. We thank the Northern California District Office of the Bureau of Land Management for their support. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Authors' contributions
DJS, MAR, and PSC conceived the study; DJS, MAR, and PSC acquired funding for the project; ALN, BEB, CLW, SCW, SRM, SJD, MAR, and PSC acquired and processed the data; ALN, BEB, and PSC led the design of the data analysis; ALN led the data analysis; ALN and BEB carried out the data analysis, and ALN led the manuscript preparation. All authors contributed significantly to editing the manuscript and have approved the final manuscript.

Funding
This work was supported by JFSP Award L20PG00064, the Bureau of Land Management's Northern California District Office, USGS Ecosystems Mission Area, and USGS SERF Project 058.

Data availability
Data supporting this publication is available at USGS ScienceBase (https://doi.org/10.5066/P14WVZKB; Coates et al. 2026) and code to reproduce the analyses is available on GitLab (https://doi.org/10.5066/P13H9ADF; Nash et al. 2026).

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 25 April 2025 Accepted: 6 February 2026
Published online: 16 March 2026

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