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REVIEW

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Review of fuel treatment effects on fuels, fire behavior and ecological resilience in sagebrush (*Artemisia* spp.) ecosystems in the Western U.S.

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Abstract

Background Sagebrush ecosystems are experiencing increases in wildfire extent and severity. Most research on vegetation treatments that reduce fuels and fire risk has been short term (2–3 years) and focused on ecological responses. We review causes of altered fire regimes and summarize literature on the longer-term effects of treatments that modify (1) shrub fuels, (2) pinyon and juniper canopy fuels, and (3) fine herbaceous fuels. We describe treatment effects on fuels, fire behavior, ecological resilience, and resistance to invasive annual grasses.

Results Our review revealed tradeoffs in woody fuel treatments between reducing canopy fuels vs. increasing understory herbaceous vegetation (fuels) and fire behavior. In pinyon-juniper expansion areas, all treatments decreased crown fire risk. Prescribed fire and cut and broadcast burn treatments reduced woody fuels long-term but had higher risk of invasion. Mechanical treatments left understory vegetation intact and increased native perennial plants. However, cut and leave treatments increased downed woody fuel and high-intensity wildfire risk, while cut and pile burn and mastication caused localized disturbances and annual grass invasion. Ecological outcomes depended on ecological resilience; sites with warm and dry conditions or depleted perennial native herbaceous species experienced lower recovery and resistance to invasive annual grasses. In invasive annual grass dominated areas, high-intensity targeted grazing reduced fine fuels but required retreatment or seeding; in intact ecosystems with relatively low shrub cover, dormant season targeted grazing reduced fine fuel and thus fire spread. Preemergent herbicides reduced annual grasses with differing effects in warm and dry vs. cool and moist environments.

Conclusions The information largely exists to make informed decisions on treatments to mitigate effects of wildfire and improve ecological resilience at local, project scales. Primary considerations are the short- vs long-term tradeoffs in fuels and fire behavior and thus fire severity and the likely ecological response.

Keywords Sagebrush, Pinyon-juniper, Invasive annual grasses, Fuels, Fire behavior, Ecological resilience, Prescribed fire, Mechanical fuel treatments, Targeted grazing, Herbicide treatments

Resumen

Antecedentes Los ecosistemas de arbustales de artemisia (Artemisia spp.) están experimentando aumentos de incendios tanto en extensión como en severidad. La mayoría de las investigaciones sobre tratamientos de reducción del combustible y por ende del riesgo de incendios, han sido de corto plazo (2 a 3 años) y enfocados en respuestas

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ecológicas. Revisamos las causas de la alteración de los regímenes de fuegos y resumimos la literatura sobre los efectos a largo plazo de los tratamientos que modifican 1) los combustibles de arbustos; 2) los combustibles en los doseles de juníperos y pinos piñoneros, y 3) combustibles herbáceos finos. Describimos los efectos de los tratamientos sobre los combustibles, el comportamiento del fuego, la resiliencia ecológica, y la resistencia a la invasión de pastos anuales.

Resultados Nuestra revisión reveló compensaciones en los tratamientos de material combustible leñoso entre la reducción de los combustibles del dosel vs un incremento en los combustibles herbáceos superficiales y el comportamiento del fuego. En las áreas de expansión del pino piñonero y del junípero, todos los tratamientos redujeron el riesgo de fuego de copas. Los tratamientos de quemas prescriptas y de corte, desparramado del combustible y su posterior quema, redujeron los combustibles leñosos a largo plazo, pero tuvieron un mayor riesgo de invasión. Los tratamientos mecánicos dejaron la vegetación del sotobosque intacta, y se incrementó la cantidad de especies perennes nativas. Sin embargo, los tratamientos de corta y abandono de los restos in situ incrementó la carga de estos combustibles y aumentó el riesgo de fuegos de alta intensidad, mientras que el corte, apilado y posterior quema, y el triturado causaron disturbios localizados y la invasión de pastos anuales. Los resultados ecológicos dependieron de la resiliencia ecológica; sitios con condiciones secas y cálidas o con escasa vegetación herbácea nativa experimentaron una recuperación más lenta y menor resistencia a la invasión de pastos anuales. En áreas dominadas por especies de pastos anuales invasores, el pastoreo aplicado a una alta intensidad redujo la cantidad de combustibles finos, pero requirió de resiembra posterior; en ecosistemas intactos con una cobertura relativamente baja de arbustos, el pastoreo aplicado durante la etapa de dormancia, redujo la cantidad de combustibles finos y por ende la velocidad de propagación del fuego. Los herbicidas de pre-emergencia redujeron los pastos anuales con efectos diferentes entre ambientes secos y cálidos vs templados y fríos.

Conclusiones La información existente es profusa como para tomar decisiones de manejo sobre los tratamientos que permitan mitigar los efectos de los fuegos de vegetación y mejorar así la resiliencia ecológica a escala local o de proyecto. Los consideraciones primarias deben enfocarse en las compensaciones de corto y largo plazo tanto en los combustibles como en el comportamiento del fuego, y por ende en la severidad del fuego y sus posibles respuestas ecológicas.

Introduction

A strong impetus exists for implementing fuel treatments to reduce fire hazard and risk in sagebrush (*Artemisia* spp.) ecosystems. Between 2000 and 2020 more area burned across the western US from wildfires in shrubland and herbaceous ecosystems (56%) than in forested, tree-dominated landscapes (44%) with the shrubland and herbaceous ecosystems experiencing increasing trends in area burned, number of burned patches, and fire sizes (Crist 2023). In sagebrush-dominated landscapes (Jeffries and Finn 2019), wildfires burned > 9 million ha (22.3 million acres) from 1984 to 2020, primarily in the Northern Basin and Range, Snake River Plain, and Central Basin and Range ecoregions (Fig. 1) (Crist et al. 2023).

Altered fire regimes interact with other anthropogenic and ecosystem perturbations, driving widespread transformation to alternative ecological states (Fusco et al. 2019; Ellsworth et al. 2020; Davies et al. 2021a, b). Progressive urban and exurban expansion and associated infrastructure, land conversion to agriculture, and oil and gas development (Knick et al. 2011) are resulting in a high number of human-caused fire starts and increased fire frequency (Fusco et al. 2016). In parallel, invasion and expansion of invasive annual grasses and forbs are creating continuous and highly flammable fine fuelbeds with longer fire seasons (Bradley et al. 2018), and resulting in type conversion to invasive annual grasslands (Fusco et al. 2019; Smith et al. 2021). In addition, native pinyon pine (*Pinus* spp.) and juniper (*Juniperus* spp.) trees (pinyon-juniper) are expanding into sagebrush ecosystems (Morford et al. 2022) and depleting native shrub and herbaceous understory species (Miller et al. 2019). In the initial phases of expansion, surface fuels are reduced but continued stand infilling and tree growth results in a new strata of crown fuel, increased threat of high severity crown fires, and the potential for conversion to alternative states (Miller et al. 2019). The fuel-related changes occurring in sagebrush ecosystems are exacerbated by elevated CO_2 which is projected to increase herbaceous production (fine fuels) in many areas (Zimmer et al. 2021) and climate warming which is already causing longer fire seasons and more severe fire weather (Abatzoglou and Kolden 2013, Abatzoglou et al. 2016, 2018).

Consequences of altered fire regimes include a rising risk to lives, homes, communities, and infrastructure (USDA 2022a). Increasing economic costs are resulting

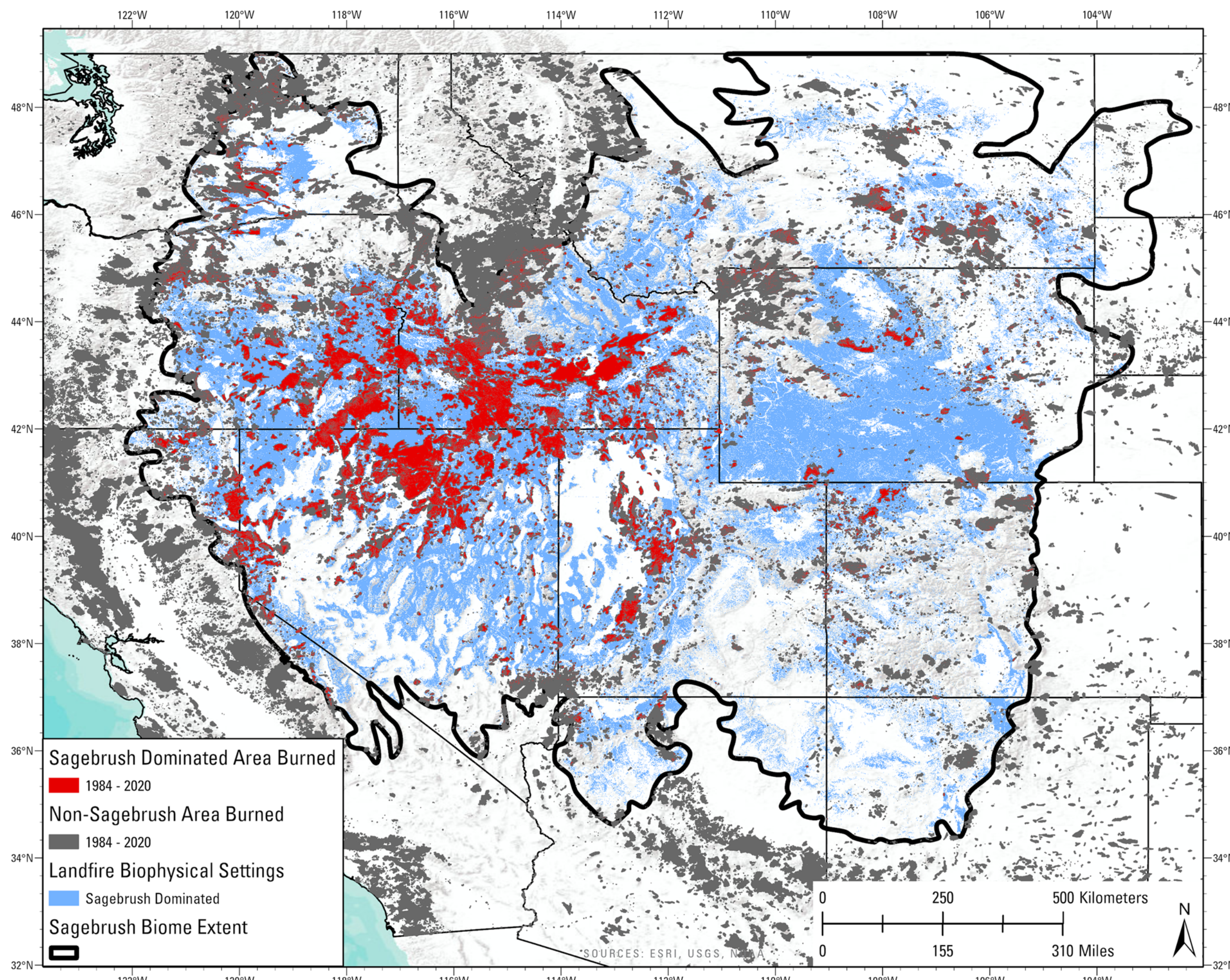

Fig. 1 Sagebrush-dominated area that burned across the sagebrush biome from 1984 to 2020. LANDFIRE Biophysical Settings (BpS; US Geological Survey 2014) were used to identify sagebrush-dominated areas, and wildfire perimeters (Welty and Jeffries 2021) were used to determine the area burned. Red areas depict where fires burned in sagebrush-dominated communities, which are shown in light blue. Dark gray represents the area burned either outside of the sagebrush biome or within the sagebrush biome that is not a sagebrush-dominated BpS, such as forests, woodlands, and other shrublands. Figure from Crist et al. 2023

from home and property loss, depreciated property values, emergency services, and fire suppression as well as a loss of ecosystem services and the need for long-term landscape restoration (Barrett et al. 2018). Loss of habitat is resulting in declining populations of many sagebrush-dependent species, such as the greater sage-grouse (*Centrocercus urophasianus*), and increasing the risk of listings under the U.S. Endangered Species Act (Coates et al. 2016; Remington et al. 2021).

Altered fire regimes and ecosystem transitions to alternative states are not unique to sagebrush ecosystems, and new policies and funding to increase capacity to prevent and suppress wildfires and to restore ecological resilience (Table 1) are resulting in implementation of vegetation management treatments across the sagebrush biome and elsewhere in the USA (USDA 2022b). Many of these treatments can be defined as fuel treatments, which are implemented to reduce or redistribute burnable material with the goal of decreasing fire spread rates, intensities, and/or severities (Reinhardt et al. 2008; Hood et al. 2022) (see Table 2 for definitions of the terms used in this review). In sagebrush ecosystems, the primary objective of fuel treatments is to decrease woody or fine fuels in a manner that has reliable and durable effects on fire behavior (Miller et al. 2013, 2019). However, a secondary objective of these same treatments is often to improve ecological resilience to disturbances like wildfires and resistance to invasive plants (Miller et al. 2013, 2019). For example, in sagebrush ecosystems experiencing pinyon and juniper expansion prescribed fire and mechanical

Table 1 Recent federal policies and funding initiatives for fire suppression, fire prevention, and prefire fuels mitigation

• National Cohesive Wildland Fire Management Strategy (Cohesive Strategy; USDA and USDOI 2014)—Established guidelines for wildfire response preparedness, improving vegetation and fuel management, facilitating prefire mitigation activities, and preventing human-caused ignitions. The Cohesive Strategy acknowledged that vegetation and fuel management was challenging because it involves designing and prioritizing the locations of fuel treatments not only to decrease fire risk, but also to meet resource objectives and improve the resilience of rangelands and forests
• An Integrated Rangeland Fire Management Strategy (Rangeland Strategy; USDOI 2015)—developed in response to USDOI Secretary Order 3336, *Rangeland Fire Prevention, Management and Restoration*. The Rangeland Strategy emphasized protecting core habitat for Greater sage-grouse and building resilience to wildfire and resistance to invasive annual grasses. Key aspects include working at landscape scales, promoting collaboration across boundaries, and improving prevention, fire suppression, and ecosystem restoration
• The Wildfire Crisis Strategy (USDA Forest Service 2022) builds on the Cohesive Strategy and directs the Forest Service to work with partners to focus fuels and forest health treatments strategically and at appropriate scales using the best available science. Under the Wildfire Crisis Strategy, as many as 20 M acres of National Forest System lands and 30 M acres of other Federal, State, Tribal and private lands would be treated over the next 10 years. A range of fuels and forest management activities will be implemented, including mechanical thinning and prescribed fire, followed by maintenance treatments at intervals of 10 to 15 years
• The Infrastructure Investment and Jobs Act (IIJA 2021) provides nearly $3 billion for hazardous fuel reductions and restoration, and the Forest Service's landscape investment plan (USDA Forest Service 2022b) targets several watersheds in the sagebrush biome for fuel and fire management treatments

treatments, such as cut and leave, are often implemented both to reduce woody fuels and the risk of crown fire and to increase native shrubs and herbaceous plants so to increase resilience and resistance and prevent transitions to undesirable alternative states postfire (McIver et al. 2010; Chambers et al. 2014b).

In recent decades, hundreds of vegetation management treatments have been implemented in sagebrush ecosystems with the objectives of reducing fuels and fire risk and/or increasing resilience and resistance (Pilliod et al. 2017). Recent reviews of treatments conducted in sagebrush ecosystems specifically to reduce fuels have provided general overviews of a variety of fuel treatments (Shinneman et al. 2023) or concentrated on fuel breaks (Shinneman et al. 2018, 2019). Most of the available literature on treatments conducted to reduce fuels focuses on the ecological effects, and relatively little information exists on the longer-term (>3 years) effects of treatments on fuels and future fire behavior (Miller et al. 2013, 2019).

Here, we focus on the effects of treatments that modify vegetation and fuels in sagebrush ecosystems and emphasize the longer-term consequences for fuels and fire behavior. We first review the causes of altered fire regimes in sagebrush landscapes. We then summarize literature on treatments in sagebrush ecosystems that modify (1) shrub fuels, (2) pinyon and juniper canopy fuels, and (3) fine herbaceous fuels. We discuss the effects of these treatments on fuels, fire behavior, and resilience and resistance. We conclude by highlighting knowledge gaps and research needs to support implementation of current federal policies.

Factors driving altered fire regimes in sagebrush landscapes

The primary influences on all fire regimes are climate, topography, soils, vegetation types, and plant functional groups (Fig. 2) (Bradstock 2010). Fire occurrence in any given year is a function of fuels (biomass), conditioning of those fuels for burning (fuel moisture), fire weather (antecedent drought, wind speed and direction, etc.), and ignitions (Fig. 2) (Bradstock 2010). Changes in fire regimes can result from changes in the composition of plant functional groups (Syphard et al. 2017; Bradley et al. 2018), the amount, structure, continuity, and conditioning of biomass for burning (Littell et al. 2009), and ignitions, both human and lightning caused (Fusco et al. 2016). Fire size and severity is strongly influenced by fire weather and fire behavior (Bradstock 2010) and ongoing shifts in climate and fire weather are altering fire regimes (Abatzoglou and Kolden 2013; Stavros et al. 2014).

In sagebrush ecosystems that are not influenced by pinyon-juniper expansion, shrub and herbaceous surface fuels interact with fire weather to influence the propensity for wildfires (Fig. 3). As shrub or fine fuel loadings increase, less severe weather conditions are required for fire to spread (Cheney and Sullivan 2008; Rego et al. 2021). Progressive increases in woody fuels can occur due to management actions such as fire suppression (e.g., Minnich 2001) and increases in fine fuel loading and continuity can occur following annual grass invasion (Fig. 3) (Strand et al. 2014). Fire behavior (i.e., rate of spread, flame length, reaction intensity) increases as fuel moisture decreases and herbaceous fuels cure (Ellsworth et al. 2022). Climate warming may increase extreme fire weather conditions and reduce the influence of fuel loads and continuity (Abatzoglou and Williams 2016).

Fuel composition, structure, and arrangement before either a wildfire or a fuel treatment influences subsequent fuels and ecological conditions (Chambers et al. 2014a, b; Strand et al. 2014). Negative relationships between abundance of native shrub (woody fuels) and herbaceous cover (fine fuels) often occur due to competition for water and nutrients (Leffler and Ryel 2012). Following a fire or fuel treatment, increases in shrub cover may occur over time with reestablishment and

Table 2 Definitions of terms used frequently in this review

Ecological resilience—the capacity of ecosystems to reorganize and regain fundamental structure, processes, and functioning (i.e., recover) when altered by stresses and disturbances, such as altered fire regimes (Holling 1973; Scheffer 2009)

Fire behavior—the manner in which a fire reacts to the influences of fuel, weather, and topography (USDA 2023)

• Flame length—the length of flames in a fire front measured along the slant of the flame from the midpoint of its base to its tip (USDA 2023)
• Fire intensity—the heat energy released during phases of a fire as determined by the amount and rate of fuel consumption (USDA 2023)
• Fire spread—the rate at which a fire moves across the landscape as influenced by factors such as the amount and arrangement of fine surface fuels, fuel moisture, wind, and slope (USDA 2023)
• Reaction intensity—the rate of heat release per unit area of the flaming front; typically used in fire behavior models and expressed as kilowatts per square meter per minute (Byram 1959; Keeley 2009)

Fire severity—the impacts of fire on ecological processes, soil, flora, and fauna; degree to which an ecosystem has been altered or disrupted by fire (USDA 2023)

Fuel treatments—vegetation management treatments implemented to reduce or redistribute burnable material and decrease fire spread rates, intensity, and/or severity (Reinhardt et al. 2008; Hood et al. 2022). In sagebrush ecosystems, fuel treatment objectives typically include: (1) decrease woody or fine fuels in a manner that has reliable and durable effects on fire behavior; and (2) improve ecological resilience and resistance to nonnative invasive plants (Miller et al. 2013, 2019)

• ***Cut and leave—***felling pinyon and juniper trees and leaving the downed trees and slash on the site (Miller et al. 2019)
• ***Cut and broadcast burn—***felling pinyon and juniper trees and then reducing the amount of downed wood fuels remaining on the soil surface by broadcast burning to burn the entire area (Miller et al. 2019)
• ***Cut and pile burn—***felling pinyon and juniper trees and then reducing the amount of downed woody fuels remaining on the soil surface by piling and burning the downed trees and slash (Miller et al. 2019)
• ***Herbicides to control shrubs—***applying an herbicide, typically Tebuthiuron (Spike 20P®), that kills shrubs and converts standing live shrub fuels into standing dead fuels in the short term and to downed woody debris and duff in the long term (Ellsworth et al. 2022; Pyke et al. 2022)
• ***Mastication***—mechanical treatment implemented to convert vertical canopy material from pinyon and juniper trees to chipped or shredded woody surface fuel distributed across the treated area using a rotary head or horizontal drum masticator (Vitorelo et al. 2009; Kreye et al. 2014)
• ***Preemergent herbicides to control invasive annuals***—applying an herbicide, typically Imazapic or Indaziflam (Rejuvra®), to decrease emergence and establishment of nonnative invasive annual grasses and prevent development of annual grass fire cycles (Terry et al. 2021, Davies et al. 2019, Courcamp et al. 2022a, 2022b, Pyke et al. 2022)
• ***Prescribed fire***—intentionally igniting a fire in accordance with applicable laws, policies, and regulations to reduce woody fuels and/or improve ecological resilience and resistance to nonnative invasive plants (Miller et al. 2013, 2019)
• ***Mowing—***mechanical thinning treatment implemented in sagebrush-dominated ecosystems that shifts woody fuel from the shrub canopy to the soil surface by mowing the shrubs with a rotary cutter to a height of about 20 to 35 cm above the soil surface (Davies et al. 2012a; Derner et al. 2014; Pyke et al. 2022)
• ***Targeted grazing—***application of a specific kind of livestock at a determined season, duration, and intensity to accomplish defined vegetation or landscape goals (Launchbaugh and Walker 2006)
  ○ ***Dormant season targeted grazing***—grazing by livestock during Nov–Apr with the objective of reducing fine fuels and fire spread. Used in areas dominated by invasive annual grasses and forbs (Schmelzer et al. 2014; Perryman et al. 2020) and in areas dominated by native shrubs and herbaceous species (Davies et al. 2021a, b, 2022)
  ○ ***High-intensity targeted grazing***—grazing of sagebrush ecosystems dominated by invasive annuals with cattle or sheep at high utilization rates to reduce fine, herbaceous fuels and control invasive annual grasses (Diamond et al. 2009, 2012)

Pinyon-juniper expansion phases I, II, III—phase I: trees are present but shrubs and herbs are the dominant vegetation influencing ecological processes; phase II: trees are codominant with shrubs and herbs and all three vegetation layers influence ecological processes; phase III: trees are the dominant vegetation on the site and the primary plant layer influencing ecological processes (Fig. 6) (Miller et al. 2019)

Resistance to invasion—a function of the abiotic and biotic attributes and ecological processes of an ecosystem that limit the population growth of an invading species (D'Antonio and Thomsen 2004)

Timelag fuels—total wildland fuels are all plant material, living and dead, that can be consumed by fire in a worst-case scenario. Dead woody fuel is commonly separated into diameter size classes: < ¼ in. (1-h fuel), ¼–1 in. (10-h fuel), 1–3 in. (100-h fuel), and > 3 in. (1000-h fuel) because of the rate at which they equilibrate with changing atmospheric relative humidity. Fuel size class influences the likelihood of consumption during fire and impacts fire intensity, severity, and spread

growth of sagebrush and/or with removal of perennial grass due to livestock grazing (Harniss and Murray 1973; Adler et al. 2005; Hanna and Fulgham 2015). Removal of perennial grass increases soil water and nutrient availability (Chambers et al. 2007), which can enhance establishment and growth of sagebrush (Chambers et al. 2017b, Chambers 2021).

The resilience and resistance of sagebrush ecosystems following treatments to remove woody fuels is highly dependent on the relative abundance of perennial native herbaceous species (Chambers et al. 2014a, b, Bansal and Sheley 2016, Ellsworth and Kauffman 2017, Wainwright et al. 2020, Ellsworth et al. 2024). Higher shrub cover can increase mortality of understory perennial native herbaceous species if burned (Miller et al. 2013), as woody fuels burn at higher intensities (Hulet et al. 2015). Native perennial grasses are the primary competitors with invasive annual grasses, and low cover of these species following fuel treatments heightens the probability of invasive annual grass density and cover increasing in areas with relatively

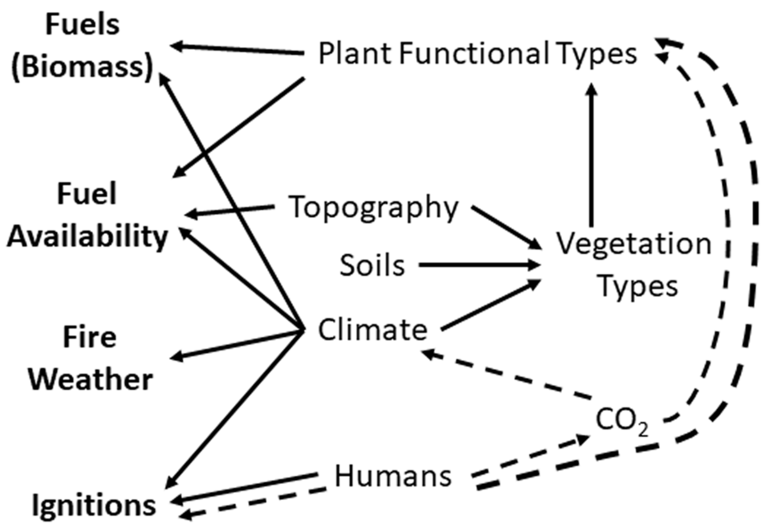

Fig. 2 Influences of abiotic and biotic factors (climate, soils, vegetation types, plant functional types) on fire regimes via four "switches" (fuels, fuel availability [amount, structure, continuity], fire weather, and ignitions). Plant functional types have similar responses to the environment and effects on ecosystem functioning. Potential effects of changing climate, human activity, and atmospheric CO_2 are indicated by dashed lines. Figure modified from Bradstock 2010

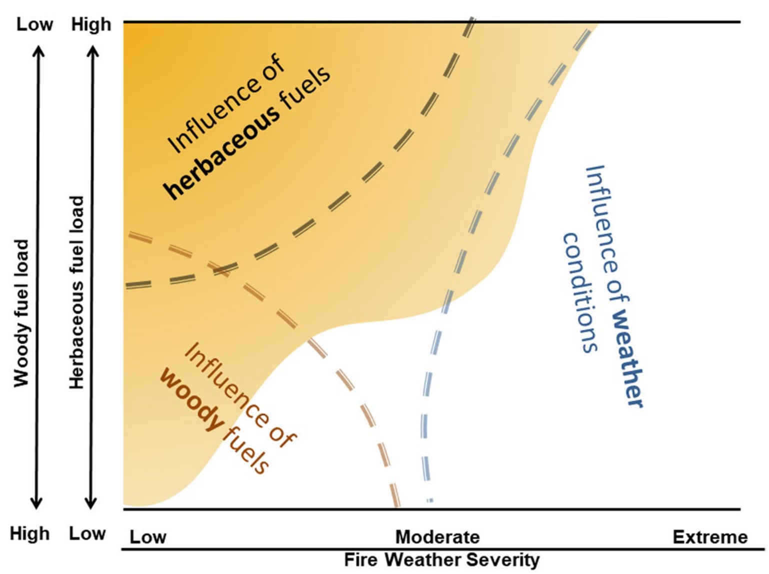

Fig. 3 A conceptual model of the interaction of herbaceous and shrub (woody) fuels with fire weather severity in sagebrush ecosystems that are not experiencing pinyon-juniper expansion. Fuel composition is displayed on the *y*-axis and fire weather condition is displayed on the *x*-axis. Low fire weather severity is characterized by high fuel moistures, high relative humidity, low temperature, and low wind speeds, while extreme fire weather is characterized by the opposite conditions. As shrub fuel loading increases (low on the *y*-axis) or fine fuel loading increases (high on the *y*-axis), fuel continuity increases, and less severe fire weather is required for large wildfires. Annual grasses, represented by the area in yellow in the upper left, produce fine fuels that can fill interspaces between native fuels (shrubs and grasses) and are particularly problematic. Extreme fire weather conditions, which are projected to increase in the future, can override the influence of fuel loads and continuity. Figure modified from Strand et al. (2014)

low resistance (Chambers et al. 2007, 2014b; Davies et al. 2008). Low relative abundance of perennial herbaceous species combined with dense shrub or flammable fine fuels from invasive annual grasses, can increase recovery time, alter species composition, and place the ecosystem at risk of developing an invasive grass fire cycle and converting to invasive annual grass dominance (Fig. 4).

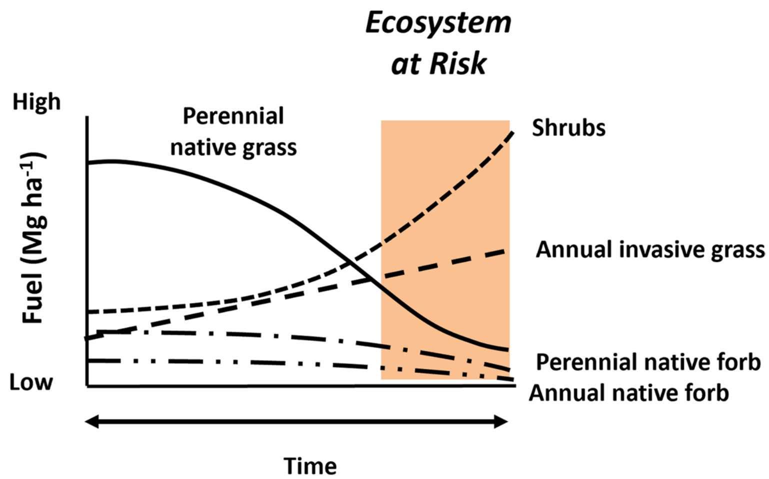

Fig. 4 A conceptual model of the changes in fuel types over time in sagebrush-dominated ecosystems that are not experiencing pinyon-juniper expansion. Increases in shrub fuels over time occur due to a combination of succession, fire suppression, or livestock grazing and may result in decreases in perennial native grasses, perennial native forbs, and annual native forbs. In warmer and drier ecosystems with relatively low resilience and resistance, perennial native grasses and forbs decrease while invasive annual grasses increase. Ecosystems with high levels of shrub and/or invasive annual grass fuels are at risk of transitioning to alternative states dominated by the invaders after wildfires or management treatments that remove shrubs as indicated by the shaded area

Expansion of pinyon and juniper into sagebrush-dominated ecosystems further increases woody fuel loads and elevates the risk of high severity fire over time (Miller et al. 2019). In intact ecosystems, succession is initiated by wildfires that remove fire-intolerant shrubs and trees. Postfire, the system is typically dominated by grasses and forbs (Fig. 5) (Barney and Frishknecht 1974; Miller and Heyerdahl 2008; Strand and Bunting 2023). Shrubs increase over time as sagebrush establishes and root-sprouting shrubs regrow. Establishment of pinyon and juniper is facilitated by the shrubs, which often serve as nurse plants for the trees (Chambers et al. 1999, 2001; Urza et al. 2019). Pinyon and juniper trees are highly competitive with native shrubs, grasses, and forbs for available soil water (Roundy et al. 2020) and nutrients (Bates and Davies 2017), as indicated by greater availability of these resources after tree removal, and increases in tree density and cover can cause progressive decreases in understory species (Fig. 5) (Miller et al. 2000; Strand and Bunting 2023). Three phases of tree expansion have been described (Table 2, Fig. 6) (Miller et al. 2005, 2019). Relative tree dominance in the later phases of tree expansion is highly dependent on site conditions, and phases can be quantified using perennial cover to calculate a total tree dominance index (TDI) (Williams et al. 2017).

Fuel loads change along a successional gradient in areas experiencing pinyon-juniper expansion (e.g., Yanish 2002). In later stages of woodland development, increased amounts of woody fuels in tree crowns and accumulation of dead biomass in the tree canopy and on the ground elevate the possibility of crown fires and therefore the risk of high fire severity, which can increase understory plant mortality and have detrimental effects on soils (Miller et al. 2019). This effect was observed along a successional gradient from shrub dominance to developed woodlands characterized by mountain big (*Artemisia tridentata* ssp. *vaseyana*) and low sagebrush (*A. arbuscula*) (Fig. 7) (Strand et al. 2013). Duff and litter that accumulate under juniper trees over time have been shown to contribute to increased fire severity (Weiner et al. 2016).

Recovery of pinyon-juniper expansion areas following tree removal treatments depends on the abundance of native perennial herbaceous species, woody fuel amount and type, and treatment severity (Miller et al. 2019). Consequently, treatments are most likely to be effective at restoring native shrub and grass communities in phase I and phase II which have lower tree biomass (Miller et al. 2019). There may be tradeoffs between understory restoration and fire risk because removal of tree and shrub species often increases understory herbaceous continuity and surface fuel loading (Dittel et al. 2018; Ellsworth et al. 2020; Williams et al. 2023). However, without fuel treatments, continued tree growth and infilling in expansion areas may ultimately result in a worst-case scenario—high-intensity crown fires with little or no residual understory to promote recovery (Miller et al. 2019; Strand and Bunting 2023; Williams et al. 2023).

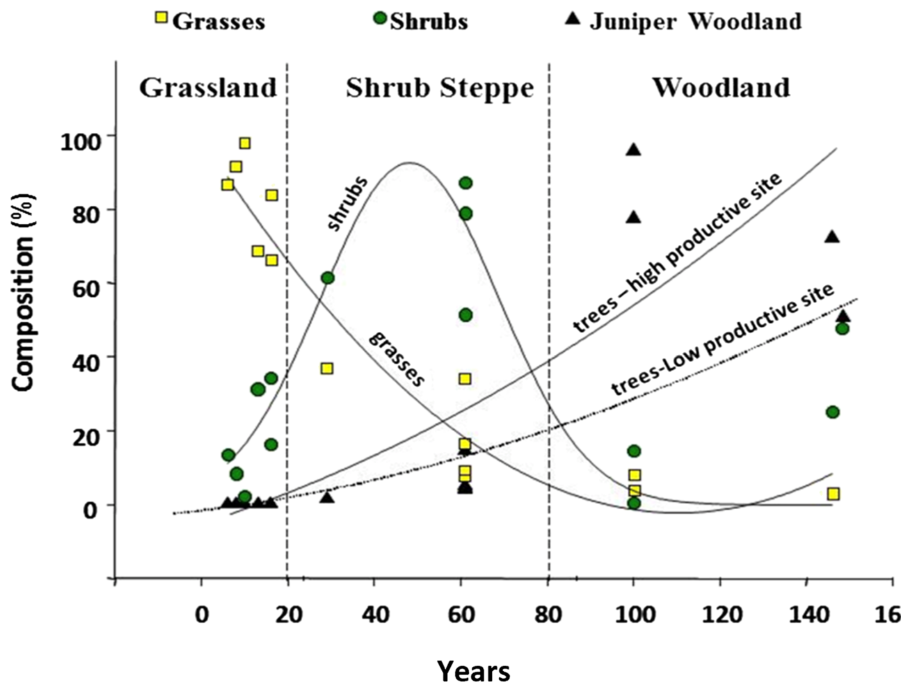

Fig. 5 Model of changes in percent composition of grasses, shrubs, and junipers in cool/moist mountain big sagebrush in northeastern California over time after fire (bottom) (Miller and Heyerdahl 2008). Successional trajectories follow this pattern across sagebrush ecosystems, but the time required to transition between stages varies by site conditions (Johnson and Miller 2006)

Treatments that modify shrub fuels

In sagebrush-dominated ecosystems with little pinyon-juniper expansion, treatments to reduce woody shrub fuels often include prescribed fire, mechanical thinning, and herbicide applications (Miller et al. 2013, 2019). These treatments can be used to break up continuous woody cover and provide anchor points for fire suppression (Bakker et al. 2012), increase native grass and forb cover, and improve sagebrush habitat (Miller et al. 2013).

Prescribed fire

Prescribed fire is used to reduce shrub fuel loads and restore herbaceous perennial vegetation in sagebrush-dominated ecosystems. Historically, this treatment was widely used but due to dual concerns about protecting greater sage-grouse habitat and preventing further spread of invasive annual grasses, its use is now generally limited to moderate to high resilience and resistance areas (Chambers et al 2014a, 2014b, 2017b). Several studies evaluated the relationships among fuel loads, environmental conditions, and fire behavior during prescribed fire in big sagebrush ecosystems (Table 3). Most burns were conducted during fairly mild conditions (low wind and moderate temperature and humidity) and pretreatment fuels were highly variable. A few general trends existed: rate of spread and flame length were higher in fall burns compared to spring burns, and flame length and rate of spread increased with increasing pretreatment shrub cover (Table 3, Schachtschneider 2016).

Prescribed fire can be effective at reducing total fuel loads initially because a large portion of both shrub and herbaceous fuels are consumed (Pyke et al. 2014; Wozniak and Strand 2019). In Wyoming big sagebrush sites across the long-term Sagebrush Treatment Evaluation Project's (SageSTEP) experimental network (http://www.SageSTEP.org) (McIver et al. 2010; McIver and Brunson 2014), prescribed fire reduced total fuel by more than half (Fig. 8) (Ellsworth et al. 2022). Most persistent fuel reductions came from removal of the shrub layer, which only recovered to 27% of control shrub fuels after 10 years. This is consistent with slow shrub recovery following prescribed fire across Wyoming big sagebrush communities (i.e., Wambolt and Payne 1986, Ellsworth and Kauffman 2010, Reis et al. 2019). In more productive mountain big sagebrush communities with higher resilience and resistance, shrub fuel recovery averaged 32 years in Montana (Lesica et al. 2007), though variable recovery times (15–100 years) were reported elsewhere (Nelson et al. 2014) due to differences in prefire site conditions, interspecific interactions (Chambers et al. 2021),

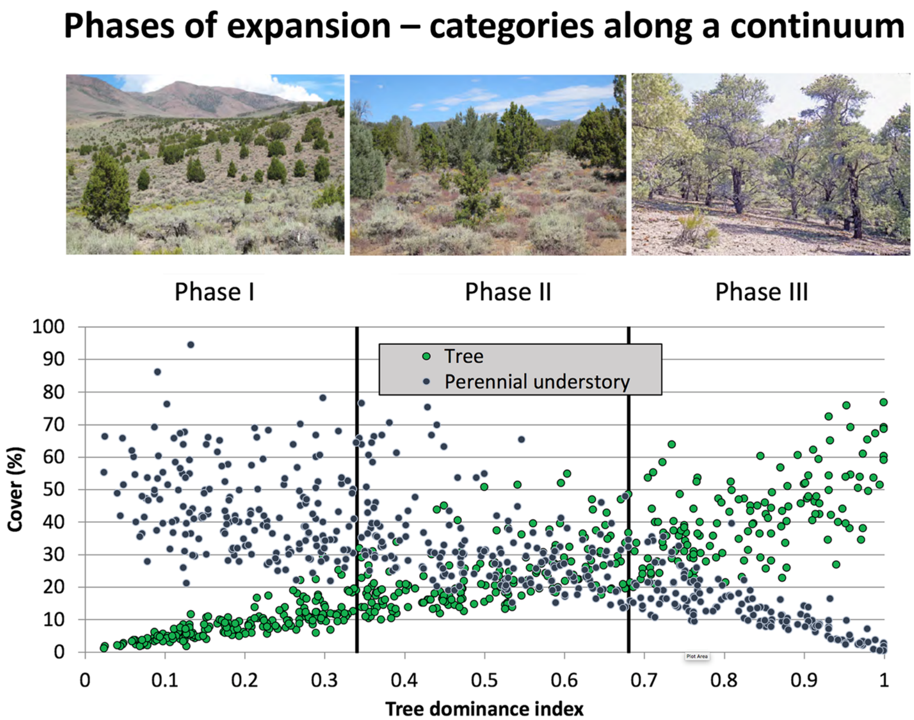

Fig. 6 The change in tree dominance across the phases of pinyon and juniper expansion. In phase I, trees are present but shrubs and herbs are the dominant vegetation influencing ecological processes; in phase II, trees are codominant with shrubs and herbs and all three vegetation layers influence ecological processes; in phase III, trees are the dominant vegetation on the site and are the primary influence on ecological processes (Miller et al. 2005). The tree dominance index (TDI) is used as a quantitative measure of the relative dominance of pinyon and juniper based on the proportion of tree canopy cover to the summation of shrub and perennial grass (or herb) cover and is calculated as: tree cover / [tree + shrub + tall perennial grass cover]. Figure from Miller et al. (2019)

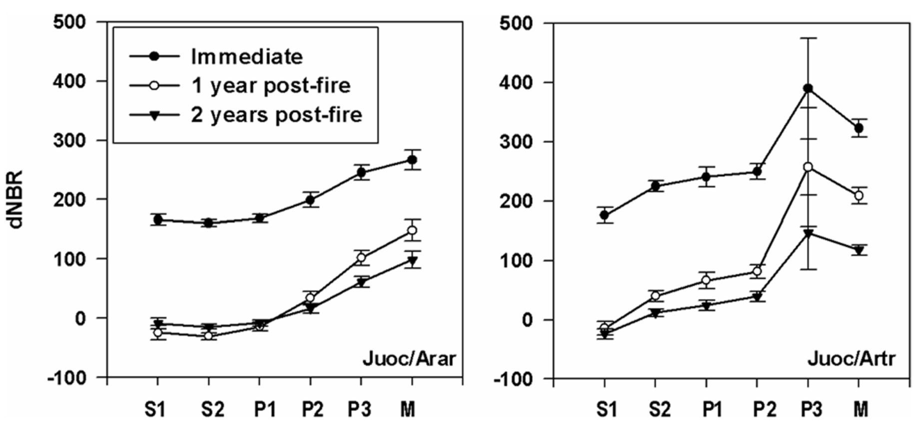

Fig. 7 Differenced normalized burn ratio (dNBR), an index of burn severity following wildfire, showing increases along a successional gradient from sagebrush to mature juniper in a western juniper and low sagebrush (Juoc/Arar) association as well as a western juniper and mountain big sagebrush (Juoc/Artr) association. Prefire successional stages are as follows: S1 = open sagebrush, S2 = closed sagebrush, and juniper expansion phase P1 = phase I, P2 = phase II, P3 = phase III, and M = Mature juniper. Adapted from Strand et al. (2013)

season of burn (Ellsworth and Kauffman 2017), and site productivity and seasonal climate (Chambers et al. 2014a; Nelson et al. 2014).

Prescribed fire treatments often result in trade-offs between reduction in woody fuel and increases in herbaceous fuel (grasses and forbs) by years 2–3 following shrub removal (Wrobleski and Kauffman 2003, Ellsworth and Kauffman 2017, Dittel et al. 2018; Ellsworth et al 2020, 2022). Across Wyoming big sagebrush sites in the SageSTEP experimental network, herbaceous

Table 3 Fuel loads, environmental conditions, and fire behavior metrics in big sagebrush ecosystems summarized from several studies. *Rx*prescribed; *PG* perennial grass

Reference	Fire type	Total fuels Mg ha^{-1}	Herbaceous fuels Mg ha^{-1} or % cover	Shrub fuels Mg ha^{-1} or % cover	Wind km/h	Ambient temp °C	Ambient RH %	Fuel moisture %	Flame length m	Spread rate m/min	Fireline intensity kW/m
Sapsis and Kauffman 1991*	Rx fire, fall	10.59	3.010	6.070	0–15	15–18	41–48	1-h: 8.9 10-h: 4.6	4.1	96	6441
Sapsis and Kauffman 1991*	Rx fire, spring	6.230	1.810	2.930	0–17	23–35	21–24	1-h: 7.4 10-h: 5.0	1.7	12	883
Wrobleski and Kauffman 2003	Rx fire, fall	NA	1.260–1.820	3.188–3.653	6.4–9.7	19–28	17–24	1-h: 4.4–6.5 10-h: 5.5–8.0	2.0–4.4	4.6–12	1,321
Ellsworth and Kauffman 2010	Rx fire, spring	6.890	9% PG cover	3%	3.6–7.2	17–28	28–53	1-h: 6–10	0.3–3.0	2.4–4.2	376
Ellsworth and Kauffman 2010	Rx fire, fall	6.550	9% PG cover	3%	0–10.8	7–12	41–55	1-h: 8–9	0.1–3.7	0.6–27.6	702
Ellsworth and Kauffman 2010	Rx fire, spring	9.980	17% PG cover	> 30%	3.6–14.4	14–24	30–54	1-h: 5–10	0.2–1.5	0.6–3	121
Ellsworth and Kauffman 2010	Rx fire, fall	8.980	14% PG cover	> 30%	0–7.2	6–11	53–60	1-h: 10–11	0.2–1.8	2.4–24.6	231
Schachtschneider 2016	Rx fire, fall	-	697	0.5%	3–8	23	20	1-h: 4–6	1.4	-	-
Schachtschneider 2016	Rx fire, fall	-	1.373	14.5%	3–8	22	20	1-h: 4–6	2.5	33	-
Schachtschneider 2016	Rx fire, fall	-	1.803	3.1%	3–8	22	31	1-h: 4–6	2.4	38.4	-
Schachtschneider 2016**	Rx fire, fall	-	0.346	38.9%	3–6	27	22	1-h: 4–6	4.4	70.8	-
Schachtschneider 2016**	Rx fire, fall	-	0.318	39.5%	3–8	27	20	1-h: 4–6	4.9	30	-
Bates et al. 2019	Rx fire, fall	-	0.350–0.480	13.8% shrub cover, 8% juniper cover	5–20	18–25	16–35	1-h: 8–12	-	-	-
Bates et al. 2019	Rx fire, fall	-	0.350–0.480	12% shrub cover, 21% juniper cover	5–20	16–35	16–35	1-h: 8–12	-	-	-
Davies and Bates 2020	Rx fire, fall	-	0.327–0.977	30% cover	2–10	6–11	33–43	Not reported	-	-	-

fuels were initially reduced by 40%, but exceeded that of controls by 74, 93, 117, and 61%, in years 2, 3, 6, and 10, respectively (Ellsworth et al. 2022) (Fig. 8). In the SageSTEP network, increases in herbaceous fuel were driven primarily by perennial deep-rooted grasses through year 6. In year 10, perennial cover returned to control levels and there was a concomitant increase in annual grasses (Pyke et al. 2022).

Fuel composition depended on the resilience and resistance (Chambers et al. 2014a), prefire plant composition, and disturbance history of the sites (Ellsworth and Kauffman 2017). Sites with large amounts of invasive grass before prescribed fire typically had high invasive herbaceous fuel following fire and could be at risk of type conversion to invasive grass fuel (Chambers et al. 2019). In contrast, prescribed fire in good condition, higher resilience sites typically had herbaceous fuels dominated by native, deep-rooted, perennial bunchgrasses (Davies et al. 2014; Ellsworth et al. 2016, Ellsworth and Kauffman 2017) and often higher postfire plant diversity (Bates et al. 2020). In mountain big sagebrush ecosystems with high resilience and resistance, perennial grass cover was lower in prescribed fire than controls initially, but perennial grass and forbs in burned plots were 1.5 to 2 times greater than in unburned plots from years 2 through 12 (Davies and Bates 2020). Cover of annual grass was generally low on these sites (<4%) but was higher in burned compared to control plots throughout the study.

Prescribed fire changes how future wildfires move through an area. Reduction in woody, shrub canopy fuels typically lowers modeled fire spread rate, flame length, and reaction intensity, a measure of the heat released by fire per unit area (Reis et al. 2019; Ellsworth et al. 2020, 2022). Modeled fire spread 1 year after prescribed fire in Wyoming big sagebrush was 75% lower than in untreated controls and remained lower for 10 years (Ellsworth et al. 2022). Modeled flame lengths were reduced by 55% relative to controls in the first year after burning and were still about 30% less than controls 10 years later. Similarly, Reis et al. (2019) and Wambolt and Payne (1986) showed large reductions in shrub cover following fire and slow recovery of the sagebrush canopy after 17–18 years, which resulted in persistent reductions in modeled fire behavior (Reis et al. 2019).

Mowing

Mowing is a type of mechanical thinning treatment used to alter sagebrush fuels that shifts woody fuel from the shrub canopy to the soil surface (Ellsworth et al. 2022). Mowing typically involves using a rotary cutter to reduce shrub height to about 20 to 35 cm above the soil surface (Davies et al. 2012a; Derner et al. 2014; Pyke et al. 2022). This type of mowing has been used to decrease big sagebrush cover, density, or height across the sagebrush biome (Wamboldt and Payne 1986, Watts and Wamboldt 1996, Davies et al. 2009; Swanson et al. 2016) and can

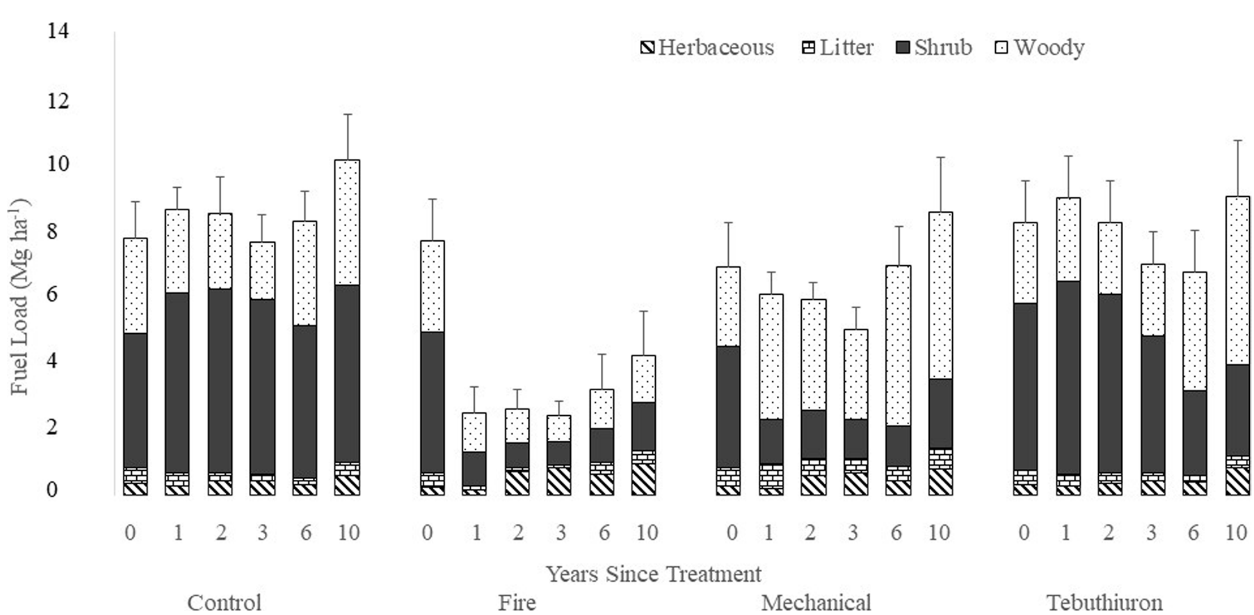

Fig. 8 Mean herbaceous, litter, shrub, and downed wood debris (woody) fuel in control, prescribed fire, mechanical, and tebuthiuron plots 0, 1, 2, 3, 6, and 10 years posttreatment at six Wyoming big sagebrush sites in the SageSTEP network. Error bars represent standard error for the total fuel load. Figure modified from Ellsworth et al. (2022)

reduce fuel for more than 10 years posttreatment (Ellsworth et al. 2022; Pyke et al. 2022).

Following mowing treatments, herbaceous, downed wood, and litter fuel components often increase (Fig. 8) (Ellsworth et al. 2022). In the SageSTEP study, where Wyoming big sagebrush was mowed to height of about 35 cm, shrub cover was initially about 19% and shrub fuel was approximately 3.8 Mg ha^{-1} (Pyke et al. 2022). Mowing reduced shrub cover by about 50% (Pyke et al. 2022) and live shrub fuel by about 60% in the first post-treatment year (Ellsworth et al. 2022). Ten years later, live shrub fuel was still about 40% less than the pretreatment levels. Despite live shrub fuel decreases, the woody material generated during the mowing treatment was still present in the system: downed woody fuel increased by almost 60% in the year following mowing and was even higher in year 10 (Ellsworth et al. 2022) (Fig. 8). Herbaceous fuel had high interannual variability (Chambers et al. 2014b) but was significantly higher in year 10 post-treatment than at the beginning of the study (Ellsworth et al. 2022).

Across the SageSTEP network, mowing sagebrush reduced modeled rates of spread from about 11 m min^{-1} pretreatment to 4 m min^{-1} in the first year after treatment (Ellsworth et al. 2022). Rates of spread for the mowing treatment were lower than controls in year 10 but were similar to pretreatment values. Mowing decreased modeled flame lengths by about 1.5 m in the first year, and flame lengths remained lower than controls in year 10. Mowing decreased modeled reaction intensity by 50% compared to controls.

Effects of mowing on herbaceous fuels are related to the relative abundance of fuel types prior to treatment and the relative resilience and resistance of the site. In the Great Basin, a comparison of 76 paired, adjacent unmowed and mowed areas treated between 2001 and 2010 showed that cover of native perennial herbaceous species was likely to be higher than cover of invasive annual grasses after treatment, where the paired unmowed areas had greater cover of perennial grass, lacked cheatgrass, and had fewer invasive forbs (Swanson et al. 2016). Annual grasses and forbs increased over time following mowing of Wyoming big sagebrush in sites with dense shrubs and low perennial herbaceous cover prior to treatment (Davies et al. 2011, 2012a), as well as in relatively good ecological condition sites across the SageSTEP network (Chambers et al. 2021; Pyke et al. 2022). In contrast, Wyoming big sagebrush sites in the middle Rockies treated in the early 1960s had no increase in invasive annual herbaceous species and showed an increase in perennial grasses and forbs that persisted until sagebrush cover began to increase about 10 years later (Wamboldt and Payne 1986). Also, in dense mountain big sagebrush sites in the Northern Basin and Range ecoregion with sagebrush cover ranging from 26 to 34% and perennial grass densities averaging 25 individuals/m^2, there was no increase in invasive annual grass, and herbaceous cover, density, and production increased significantly compared with untreated controls (Davies et al. 2012b).

Herbicides

Herbicides that reduce sagebrush cover convert standing live shrub fuels to standing dead fuels in the short term and to downed woody debris and duff in the long term (Fig. 8) (Ellsworth et al. 2022; Pyke et al. 2022). One of the few herbicides that is still used occasionally to reduce or remove shrub fuels is Tebuthiuron (Spike 20P®), a nonselective herbicide that inhibits photosynthetic activity and kills woody plants. Native grasses and forbs, as well as sagebrush, can be reduced when the herbicide is applied at relatively high rates (0.6 to 1.1 kg ai ha^{-1}) (Whitson 1982; Whitson and Alley 1984).

Research at various sites showed that Wyoming big sagebrush cover decreased progressively with increasing rates of tebuthiuron; 0.11 to 1.1 kg ha^{-1} active ingredient (Wachocki et al. 2001, Olsen et al. 2002, McDaniel et al. 2005). Tebuthiuron applications resulted in long-term increases in native perennial grasses (fine fuels) in areas of the sagebrush biome that receive relatively more summer precipitation and have a higher proportion of warm season grasses, including the Big Horn Basin of Wyoming (Olsen et al. 2002) and northern New Mexico (McDaniel et al. 2005). Increases in annual grasses occurred at only a few sites and were attributed to environmental conditions and species composition prior to treatment. Although species richness did not appear to be reduced, gradual shifts in species composition occurred (Olsen and Whitson 2002) with unknown effects on ecosystem functioning. Rates of sagebrush (shrub fuel) recovery following treatment depended on environmental conditions. Applications of tebuthiuron to mountain big sagebrush sites in Utah resulted in the expected, short-term decrease in sagebrush, low to moderate increases in perennial grasses, and on sites with low initial perennial grass cover, large increases in weedy forb species (Wachocki et al. 2001, Dahlgren 2006).

In Wyoming big sagebrush SageSTEP sites, tebuthiuron (1.68 kg ha^{-1} active ingredient) was applied aerially and had a delayed effect on shrub response (Pyke et al. 2022). No effects on fuels were observed until year 6 when the initial live shrub fuel (5.4 Mg ha^{-1}) declined by about 50% (Fig. 8) (Ellsworth et al. 2022). Downed woody fuel increased as shrub mortality progressed and was greater than half of the total fuel load in year 10. Herbaceous fuels were highest in year 10 and were composed primarily of cheatgrass and annual forbs (Pyke et al. 2022). Litter fuels changed little over time. The tebuthiuron treatment had no effect on modeled rate of fire spread, flame length, or reaction intensity (Ellsworth et al. 2022). The increase in shrub ground fuels may contribute to more smoldering rather than flaming combustion and increase fire severity due to increased duration (Weiner et al. 2016).

Tradeoffs of shrub fuel treatments

Effects of treatments designed to modify shrub fuels on vegetation and fuel structure, fire behavior, and ecological response provide implications for fire management (Table 4). Our review indicates that prescribed fire is the most effective treatment at reducing total fuel load (Bernau et al. 2018; Ellsworth et al. 2022) and thus the likelihood of severe wildfire effects. Mowing had shorter-term effects on total fuel loads and modeled fire behavior but reduced reaction intensity for 10 years (Ellsworth et al. 2022). Tebuthiuron had no effect on either fuel load or modeled fire behavior (Ellsworth et al. 2022). All treatments increased herbaceous fuels; these were dominated primarily by annual invasive fuels in relatively warm and dry Wyoming big sagebrush sites and by perennial native grass and forb fuels in cooler and moister mountain big sagebrush sites (Davies et al. 2012b; Swanson et al. 2016). These findings indicated that prescribed fire followed by mowing are likely the most durable treatments because of longer-term (10-year) effects on fuels and/or fire behavior.

Ecological tradeoffs among the three treatments include effects on the posttreatment plant community and habitat for sagebrush-obligate species. The ecological site and plant community's inherent resistance to invasion and ecological condition largely determined treatment outcomes. Warm and dry sites with relatively low resilience and resistance were susceptible to invasion by annual grasses and forbs and tended to recover slowly (Davies et al. 2012a), even with relatively high initial amounts of competitive perennial grasses (Pyke et al. 2022). The invaders were most abundant after prescribed fire likely due to shrub mortality and an immediate release of water and nutrient resources (Roundy et al. 2020). Regardless of treatment, cooler and moister sites with relatively high resilience and resistance had increases in perennial native herbaceous species and limited invasion, except in dense shrublands with depleted understories. The relative cover of sagebrush and perennial herbaceous species strongly influence resilience to treatments (see Fig. 4) and should be a primary consideration in selecting treatment sites and posttreatment management strategies.

Loss of sagebrush can decrease habitat quality in areas managed for sagebrush-obligate species (Pyke et al. 2022). Fire is lethal to many species of sagebrush and high mortality can occur depending on how and when fire is applied (Miller et al. 2013). In areas with relatively high resilience, implementing patchy and incomplete burns that mimic historical fire patterns may prevent over-dense sagebrush stands and help maintain habitat (Ellsworth et al. 2016). Mowing can affect habitat if sagebrush height is below the requirements for sagebrush obligates like greater sage-grouse (Pyke et al. 2022). In addition, it is likely that mowing and tebuthiuron can affect habitat if downed woody debris and increases in invasive annuals impede wildlife.

Treatments that modify pinyon and juniper fuels

In sagebrush ecosystems experiencing pinyon-juniper expansion, treatments are used to decrease or redistribute canopy fuels with the objective of reducing fire risk or behavior (Miller et al. 2005). These treatments often increase the relative abundance of shrubs and/or native herbaceous species by reducing competition from trees. Common fuel treatments used in these ecosystems include prescribed fire and mechanical treatments — cutting the trees and leaving them in place, cutting and broadcast burning the slash, cutting and pile burning the slash, and masticating or shredding trees and leaving the debris in place (Miller et al. 2019). Available studies focus largely on the Northern Basin and Range, Central Basin and Range, and Snake River Plain ecoregions.

Prescribed fire

Effects of prescribed fire on short- and long-term fuel characteristics and future fire behavior depend on woody debris and canopy fuel consumption during the burn and subsequent understory vegetation response. Prescribed fire often reduces tree canopy cover (Miller et al. 2005; Rau et al. 2010; Davies et al. 2019), which can lower the risk of high-intensity crown fire and subsequent ecosystem losses (Williams et al. 2023). For example, a spring prescribed burn reduced canopy biomass by 56% and 1-h canopy fuels by 90% in a pinyon-juniper woodland (Rau et al. 2010). In the SageSTEP sites, pinyon and juniper density remained > 90% lower than untreated sites 10 years after burning (Wozniak and Strand 2019). Canopy loss typically increased with increasing pretreatment canopy cover and higher fire intensity (Strand et al. 2013; Bates et al. 2017; Wozniak and Strand 2019). Across western (*Juniperus occidentalis*) and Utah juniper (*Juniperus osteosperma*) sites, fuel reduction targets were most often met with 100% blackening and low-intensity prescribed fire (Bourne and Bunting 2011).

Prescribed burning in pinyon and juniper woodlands also decreases existing downed woody debris, especially 1- and 10-h fuels, although these effects vary across vegetation types and woodland phase and with time

Table 4 Effects of treatments to reduce shrub fuels in sagebrush ecosystems that are not experiencing pinyon-juniper expansion on vegetation and fuel structure, fire behavior, fire management implications, and ecological response

	Vegetation/fuel structure	Fire behavior	Fire management implications	Ecological effects
Prescribed fire	*Decreases fuel loads of all fuel types in years 1 and 2; subsequent increases vary by fuel type and depend on site conditions and initial species*	*Decreases in rate of spread until herbaceous fuels increase; longer-term reduction in flame length and reaction intensity dependent on shrub establishment and growth*	*Warmer and drier types with low resilience and resistance less likely to respond favorably than cooler and moister types*	*Ecological effects depend on ecological site type, relative resilience and resistance, and current ecological conditions*
Wyoming big sage	• High risk of increases in invasive annual grass and forb fuel • Slow sagebrush establishment and slow increase in woody fuels • Increases in woody fuels due to any root-sprouting shrubs	• Longer-term risk of increased rates of fire spread due to annual invaders • Flame length and rates of spread influenced more by herbaceous than woody fuel	• Low sagebrush cover and high perennial grass and forb cover lowers burn severity and promotes recovery • Risk of annual grass is very high on sites with low resistance and perennial herbaceous cover • Patchy burns may help maintain sagebrush habitat and promote recovery	• May reduce resilience to fire and resistance to invasion • Increases herbaceous and reduces shrub biomass • Recovery of ecosystem production and vegetation structure will likely be slow
Mountain big sage	• Lower risk of invasive annuals • Increases in perennial grasses and forbs likely • Higher probability of increases in sagebrush fuels over time due to more favorable establishment conditions • Increases in woody fuels due to any root-sprouting shrubs	• Rates of spread determined by recovery of perennial herbaceous fuels • Flame length and reaction intensity influenced by recovery of woody fuel	• Prefire vegetation is a good indicator of postfire effects • Risk of annual grass dominance if present before fire or perennial herbaceous vegetation is diminished • Patchy burns may help maintain sagebrush habitat and promote recovery	• May increase resilience to wildfire and resistance to invasion • Increases herbaceous and reduces shrub biomass • Ecosystem production returns to prefire conditions quickly (~ 2 years); vegetation structure in ~ 25–50 years
Mowing	*Shifts woody fuel from shrub canopy to herbaceous, downed wood, and litter layers*	*Reduction in rates of spread, flame lengths, and reaction intensity relative to controls*	*Potential for use in areas such as fuel breaks to provide anchor points for suppression*	*Ecological effects depend on ecological site type, resilience and resistance, relative cover of shrubs and perennial herbs*
Wyoming big sage	• High risk of increases in annual grasses and forbs • Slow establishment and growth of sagebrush	• Reduced flame lengths due to shorter fuelbed • Potential for higher rates of spread with increases in annual herbaceous fuels • May reduce reaction intensity (heat per unit area) but increase potential for smoldering	• Risk of increase in annual grasses is high if perennial herbaceous vegetation cover is low and sagebrush cover is high • Tradeoffs between decreasing flame lengths and increasing fire spread and intensity	• Unlikely to increase resilience to fire and resistance to invasion • Increases in annual grass likely under most conditions • Decreases in sagebrush cover and downed wood may reduce habitat quality
Mountain big sage	• Lower risk of annual invaders • Increases in perennial herbs likely • More rapid sagebrush establishment and growth and thus increases in woody fuels	• Shorter fuelbed resulting in reduced flame lengths • Increases in perennial herbaceous fuels may influence rates of spread • May reduce reaction intensity (heat per unit area) but increase potential for smoldering	• Increases in perennial herbaceous vegetation (fuel) likely • Tradeoffs between decreasing flame lengths and increasing fire spread and intensity • Less time sensitive and costly implementation compared to prescribed fire	• Fire surrogate that may increase resilience to wildfire and resistance to invasive annuals • Reductions in shrub biomass and increases in perennial native grasses and forbs • Effects on habitat quality unknown

Table 4 (continued)

	Vegetation/fuel structure	Fire behavior	Fire management implications	Ecological effects
Herbicides to suppress shrubs	*Converts live woody fuel to standing dead in short term and to downed woody debris and duff in the long term*	*No effect on the modeled rate of fire spread, flame length, or reaction intensity*	*No apparent benefits to fire management*	*Ecological effects depend on ecological site type, resilience and resistance, relative cover of shrubs and perennial herbs*
Wyoming big sage	• Delayed mortality of shrubs and reductions in woody fuels • Increases in invasive annual fuels over time likely	• Increases in downed woody fuel and invasive annual fuels over time • No effect on rates of spread, flame length or reaction intensity • Increased woody ground fuels may increase smoldering and decrease flaming combustion	• Risk of annual grass is high if perennial herbaceous vegetation cover is low • No benefits to fire management based on modeled fire behavior • Less time sensitive and costly implementation compared to prescribed fire	• Unlikely to increase resilience to fire and resistance to invasion • Invasive annual grass likely to increase over time • Decreases in sagebrush cover and downed wood may reduce habitat quality
Mountain big sage	• Delayed mortality of shrubs and reductions in woody fuels • Lower risk of invasive annual fuels • Increases in perennial grass and forb fuels over time possible	• Increases in perennial herbaceous and downed woody fuels over time • Effect on rates of spread, flame length and reaction intensity minimal • Increased woody ground fuels may increase smoldering and decrease flaming combustion	• Longer-term increases in perennial grasses and forbs likely • Fire behavior models from Wyoming big sage sites indicate no benefits to fire management • Less time sensitive and costly implementation compared to prescribed fire	• Fire surrogate that may increase resilience to wildfire and resistance to invasion • Reductions in shrub biomass and increases in perennial native grasses and forbs • Effects on habitat quality unknown

since treatment (Young et al. 2015; Bernau et al. 2018). Remaining downed woody debris may decrease over time as weathering breaks down charred surface 10-h fuels into smaller fuel classes in the first years after treatment (Young et al. 2015). However, burning often increases surface woody 100-h fuels when unconsumed branches from standing trees collect on the ground, especially in sites with high pretreatment canopy cover (Williams et al. 2023; Bernau et al. 2018; Young et al. 2015). This increase in 100-h fuels can result in an overall increase of downed woody debris after prescribed fire, especially in phase III woodlands (Fig. 9) (Williams et al. 2023). In the SageSTEP plots, changes in fire behavior after prescribed fire and cut and leave treatments were modeled using the Fuel Characteristic Classification System (FCCS) in the Fuel and Fire Tool (FFT) (Prichard et al. 2013). Following prescribed fire treatments, the modeled rate of fire spread increased by 21-fold and flame lengths were 1.0 m higher than controls at year 10 regardless of phase (Williams et al. 2023).

Although often undesirable for sagebrush-obligate species, reductions in shrub and sagebrush cover following prescribed fire are common (Williams et al. 2017, 2020; Bernau et al. 2018). Decreases in shrubs can contribute to decreased flame lengths and fire intensity for a time after prescribed fire (Ellsworth et al. 2022) but increases in downed woody fuels coupled with recovery of understory shrubs and herbaceous fuels can increase fire behavior and effects longer-term. While sprouting shrubs can increase to above pretreatment cover within 5 years of prescribed burning (Huffman et al. 2013; Williams et al. 2017), sagebrush recovery depends on site conditions and can take decades to return to prefire levels (Pieper and Wittie 1990; Urza et al. 2017, 2021). However, in more productive mountain big sagebrush sites with a seed source, burning can promote sagebrush establishment (Davies and Bates 2016; Chambers et al. 2017b).

Woody fuel treatments can have unintended consequences for future fire characteristics if prescribed fire increases fine fuel loads and continuity. Prescribed burning in woodlands generally decreased herbaceous vegetation 1–2 years posttreatment followed by increases in years 3–10 (Young et al. 2015; Bernau et al. 2018). However, responses varied depending on fire characteristics (e.g., season of burn and fire intensity), woodland phase, time since burning, and site characteristics. In burned western juniper woodlands, herbaceous cover was 200–250% higher than in unburned controls 3–6 years postfire (Bates et al. 2019). Live fine fuel loading was 300 to > 400% higher 2 and 10 years following treatment in pinyon and juniper expansion areas across the SageSTEP sites with the greatest proportionate increases occurring with the highest pretreatment canopy cover (Bernau et al. 2018; Wozniak and Strand 2019; Wozniak et al. 2020). Burning increased invasive annual herbaceous cover to varying degrees in these woodlands initially but perennial tall grasses increased across pretreatment canopy covers by 3–6 years following treatment (Miller et al. 2014; Williams et al. 2017).

Annual grass invasion following prescribed burning can increase fine fuel loads and continuity, particularly on warmer and drier pinyon-juniper expansion sites with lower resilience and resistance (Chambers et al. 2014b). Canopy removal, soil disturbance, and increased soil moisture and nutrients following woody fuel reduction can elevate both perennial native and invasive annual grass growth and reproduction (Zouhar et al. 2008; Ross et al. 2012; Bates et al. 2017; Roundy et al. 2020) leading to higher fine fuel loads. In the SageSTEP sites, cheatgrass cover was generally higher in prescribed fire than untreated or cut and leave sites (Freund et al. 2021). In warmer and drier burned sites, cheatgrass cover increased from 3 to 10 years after treatment and as pretreatment tree cover increased (Freund et al. 2021). Cooler and moister SageSTEP sites generally had lower cover of cheatgrass after prescribed fire, particularly with high pretreatment tree cover (~ 20%) where increases in perennial native grasses appeared to offset increases in cheatgrass (Freund et al. 2021). In contrast, in relatively cool and moist phase II western juniper sites, bunchgrass declined initially by 78% after prescribed fire but recovered over time; in phase II sites, bunchgrass decreased by 95% and the site was dominated by cheatgrass in years 3–9 after fire (Bates et al. 2011, 2013).

Cut and leave

Cut and leave treatment involves cutting individual trees and leaving them on the site. Cutting of standing trees reduces the risk of crowning and torching in a future wildfire (Williams et al. 2023). However, cut trees left on the site significantly increase the woody fuel load of the site, potentially altering future surface fire behavior and effects (Fig. 9) (Bernau et al. 2018; Wozniak and Strand 2019; Williams et al. 2023). Two years after treatment of SageSTEP woodland sites, no increase in 10-h woody fuel load was detected in phase I, while 10-h woody fuels were 36–141% higher in phase II sites; in phase III woodlands, 10-h woody debris approximately doubled in western juniper and pinyon-juniper and increased fourfold in Utah juniper (Bernau et al. 2018). Woody fuels of the 100-h size class increased by a factor of 1.5 in phase I, two- to fourfold in phase II, and four- to five-fold in phase III (Bernau et al. 2018). Ten years after treatment of SageSTEP woodland sites, average downed woody fuel loads were higher on treated sites: 8.4 Mg ha^{-1}in treated phase I woodlands compared to 3.4 Mg ha^{-1} pretreatment, and

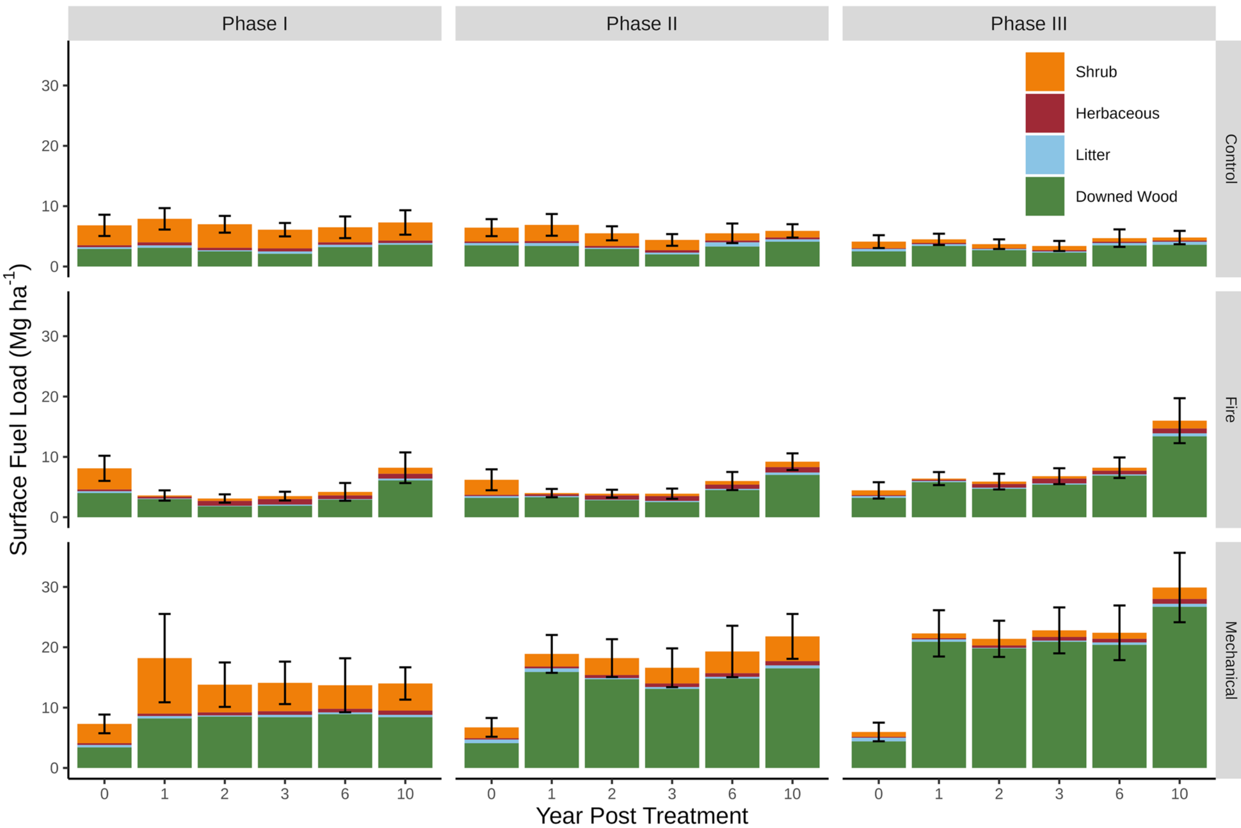

Fig. 9 The response of surface fuels to prescribed fire and a mechanical cut and leave treatment averaged across ten sites within the SageSTEP woodland network in Oregon, northern California, Nevada, and Utah. Shown are the mean shrub, herbaceous, litter, and downed woody fuel (Mg ha^{-1}) in control (top), prescribed fire (center), and mechanical treatment (bottom) plots for woodland phases I (left), II (center), and III (right) in years 0, 1, 2, 3, 6, and 10 posttreatment. Total surface fuels averaged 6.23 Mg ha^{-1} across all plots prior to treatments and did not change by year 10 in control plots. In contrast, total surface fuels were 11.13 Mg ha^{-1} across prescribed fire plots ($p < 0.01$) and 21.9 Mg ha^{-1} across mechanical plots ($p < 0.01$) in year 10. Figure from Williams et al. (2023)

26.7 Mg ha^{-1} in treated phase III woodlands compared to 4.4 Mg ha^{-1} pretreatment (Williams et al. 2023).

Live shrub fuels increase over time following cut and leave treatments in expanding woodlands. No differences existed in shrub fuel loads between cut and leave and untreated controls 2 years after treatment across the SageSTEP sites (Bernau et al. 2018). After 10 years, shrub fuel loads averaged 4.5 Mg ha^{-1} compared to 3.2 Mg ha^{-1} pretreatment in phase I woodlands and more than doubled in phase III woodlands, increasing from 0.8 to 1.9 Mg ha^{-1} (Williams et al. 2023).

Treatment response in herbaceous fuels can vary over time. In the SageSTEP study, significant increases in herbaceous fuels occurred 2 years following cut and leave treatments in phase II and III woodlands, but no change was detected in phase I woodlands (Bernau et al. 2018). Ten years posttreatment, herbaceous fuels increased from 0.30 Mg ha^{-1} pretreatment to 0.56 Mg ha^{-1} in phase I woodlands and from 0.16 to 0.52 Mg ha^{-1} in phase III woodlands in this study (Williams et al. 2023).

The large increase in surface fuels following cut and leave treatments in SageSTEP sites resulted in increased modeled fire behavior (Fig. 10) (Williams et al. 2023). Across all 10 SageSTEP sites, modeled flame length at 50th percentile windspeeds increased 3.8-fold and fire rate of spread increased 15-fold compared to pretreatment and untreated controls (Williams et al. 2023). At 80th percentile windspeeds, reaction intensity projections in cut and leave treatment plots were double that of control plots 10 years after treatment when fully cured herbaceous fuels were assumed. While there were increases in surface fire behavior with cut and leave treatments, crown fire risk was eliminated with both prescribed fire and mechanical treatments for at least 10 years posttreatment.

Most studies reported increases in perennial understory vegetation following cut and leave treatments (Miller et al. 2019). Cutting increases the nutrients and soil water on the site and can lengthen the growing season by two or more weeks (Bates et al. 2000, 2017; Roundy et al. 2014b, 2020). Invasive annual grasses may increase after cutting treatments, especially on warmer and drier sites with relatively low resistance to invasion (Bates et al. 2000, 2017; Miller et al. 2014; Roundy et al. 2014a).

In late woodland development phases, cut and leave treatments can smother perennial understory vegetation leading to mortality (Miller et al. 2019). Large amounts of woody fuels increase risk of smoldering, soil heating, and additional plant mortality should a wildfire occur. Smaller trees (< 0.5 m) are generally left untreated which allows the woodland to regenerate quicker than after prescribed burning which kills most seedlings. However, regeneration is generally slow in the Great Basin and average tree cover was < 1% 10 years after treatment in phase I and II woodlands and 1–2% 10 years after treatment in phase III woodlands (Wozniak and Strand 2019).

Cut and slash burning

Cut and slash burning treatments involve felling the trees and then reducing the amount of downed wood fuels remaining on the soil surface by (1) piling and burning the downed trees and slash (cut and pile burn) or (2) broadcast burning the downed trees and slash (cut and broadcast burn) (O'Connor et al. 2013; Bates et al. 2014, 2016, 2017; Redmond et al. 2014). Differences exist in the effects of removal of pinyon-juniper slash by pile burning or broadcast burning on subsequent fuels, fire behavior, and ecological responses.

There is little research on how cut and slash management treatments alter fuel loads and especially potential fire behavior in expansion woodlands. As a rough approximation of the difference in fire behavior between cut and leave treatments in the SageSTEP network and potential cut and pile burn treatments, we first modeled fire behavior using actual fuels data from cut and leave treatments. We then removed 90% of downed wood fuels of all size classes from the model inputs to approximate cut and remove treatments and re-ran the model simulations. Results suggested that the modeled rate of spread increases slightly relative to untreated controls by removing downed woody fuels (Fig. 10A), likely due to an increase in herbaceous and shrub fuels over time. However, modeled reaction intensities are likely lower in cut and pile burn treatments relative to cut and leave treatments (Fig. 10B), which could reduce treatment severity (Haskins and Gehring 2004).

In cut and pile burn treatments, the relative resilience and resistance of the sites are primary determinants of treatment outcomes. In a cool and moist site with mountain big sagebrush and Idaho fescue experiencing western

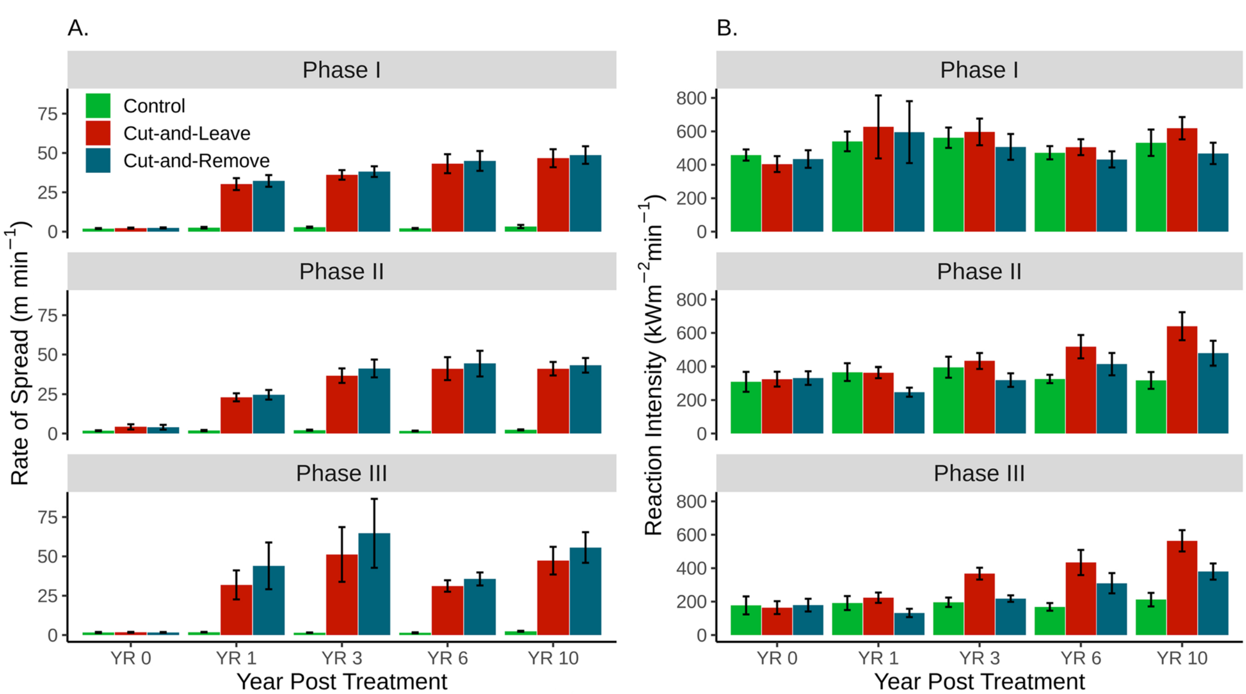

Fig. 10 Simulated differences in rate of spread (**A**) and reaction intensity (**B**) between cut and leave (red), cut and remove (blue) and untreated control (green) treatments in sagebrush ecosystems experiencing pinyon and juniper expansion. Field data used in modeling was from the SageSTEP network treatment plots at time 0 (pretreatment) and years 1, 3, 6, and 10 posttreatment. Fire behavior modeling used the Fuel Characteristic Classification System (FCCS) in the Fuel and Fire Tool (FFT) (Prichard et al. 2013). Figure adapted from Williams et al. (2023)

juniper expansion, a cut and pile burn had higher cover of the perennial grasses, Sandberg bluegrass (*Poa secunda*) and large bunchgrasses than a broadcast burn 4 years after treatment (O'Connor et al. 2013). The cut and pile burn also had slightly lower cover of cheatgrass, although neither site had cover above 6% (O'Connor et al. 2023). Following cut and pile burning in a warmer and drier big sagebrush site with western juniper expansion in central Oregon, sites with relatively high invasive annual grass abundance pretreatment showed large increases in invasive annual grasses in both pile disks and skid trails (Kerns and Day 2014). Seeding with native species (cultivar, locally sourced, and no seed) were not effective in mitigating the increase in invasive grass (Kerns and Day 2014) reflecting the difficulty of establishing native species following cut and pile burn treatments in these warmer and drier ecosystems (Havrilla et al. 2017).

The persistence of downed woody material where pinyon and juniper are cut without follow-up burning of either distributed slash or slash piles may have implications for tree regeneration and treatment durability. In northeastern Oregon, there was a twofold increase in juniper seedlings and saplings beneath unburned juniper piles (Dittel et al. 2018). Winter burns and unburned sites left saplings (< 1.5 m) and seedlings, but higher-intensity spring and early fall burns following cut treatments effectively controlled juniper regeneration through 5 years posttreatment (Bates et al. 2014).

Broadcast burning, like prescribed fire, is often a more severe treatment than pile burning because of decreases in fire-intolerant species, like *A. tridentata*, and the potential for larger and more immediate increases in soil resources that can promote invasion by annual grasses and forbs (O'Connor et al. 2013; Bates et al. 2017). In a cool, wet big sagebrush-Idaho fescue association and a warm dry big sagebrush-bluebunch wheatgrass association in southeast Oregon, increases in inorganic N (NO_3, NH_4^+), phosphorus ($H_2PO_4^-$), and potassium (K^+) occurred in both cut and leave and cut and broadcast burn treatments, but the increases were delayed for cut and leave (Bates et al. 2017). The increases in N, P, and K tended to occur within the first 2 years for treatments conducted in April and September and were greatest in severely burned debris and canopy zones (Bates et al. 2017). Other studies indicate that responses to treatments may also be influenced by greater solar radiation at the soil surface, which may increase establishment microsites (Redmond et al. 2014) and decreases in soil aggregate stability, an indicator of overall soil quality (Ross et al. 2012). In the southeast Oregon study, soil inorganic N concentrations were positively correlated with invasive annual grass cover (Bates et al. 2017).

The vegetation response and thus fuel composition following cut and broadcast burn treatments is highly dependent on treatment timing and fire severity. In the Oregon study above, the cool, wet big sagebrush-Idaho fescue association was generally resistant to annual grasses after juniper removal treatments with native plants dominating even in the highly impacted debris and canopy zones of a higher severity September burn 4 (O'Connor et al. 2013) and 7 years (Bates et al. 2016) posttreatment. In contrast, the warm dry big sagebrush-bluebunch wheatgrass association had lower resistance and resilient; thus, invasive annual grasses were a major component of the understory especially when tree and slash burning was high severity (Bates et al. 2016). Similarly, relatively warm, two needle pinyon (*Pinus edulis*) and Utah juniper sites on the Colorado Plateau showed a flush of annual invasive forbs 2 years after broadcast burning and seeding treatments (Redmond et al. 2014). In the Oregon study, broadcast burns conduced in April and September resulted in moderate to high fire severity in stump and felled tree zones; all fuels up to the 1000-h fuel class were consumed and herbaceous perennials were largely eliminated (Bates et al. 2014, 2016). In contrast, burning in January, when fuel moisture and relative humidity were high and temperatures cooler, reduced disturbance severity in stump and felled tree zones, which maintained perennial herbaceous understories and prevented or limited the presence of invasive annuals (Bates et al. 2014, 2016).

Mastication

Mastication treatments convert vertical canopy material from trees to chipped or shredded woody surface fuel distributed across the treated area (Vitorelo et al. 2009; Kreye et al. 2014). Two types of masticators are common, the rotary head and horizontal drum (Vitorelo et al. 2009). The primary objective of mastication is to reduce vertical fuel continuity and crown fire potential with the expectation of reducing fireline intensity, rate of spread, and flame length (Kreye et al. 2014). Masticated fuels have a high concentration of compacted 1-h (size class < 0.64 cm) and 10-h (0.64–2.54 cm) woody fuel particles (Kane et al. 2009; Knapp et al. 2011; Kreye et al. 2011). Fuel moisture and drying of the fuels may be highly variable given the variability in particle size, compaction, and depth within the fuelbed (Jin and Chen 2012).

Changes in shrub and herbaceous fuels after mastication are closely related to pretreatment tree cover (Young et al. 2015; Wozniak et al. 2020). In pinyon-juniper expansion areas in Utah, both shrub and herbaceous fuel loads increased across pretreatment tree covers ranging from 10 to 40% in 1 to 10 years posttreatment (Fig. 11) (Wozniak et al. 2020). The increases in herbaceous fuels were due to increases in both cheatgrass and perennial native grasses and forbs. In Utah juniper sites in Utah, masticated sites had lower seedling establishment of a native perennial grass (bluebunch wheatgrass; *Pseudoroegneria spicata*) and cheatgrass likely due to increased cover from masticated-juniper debris (Young et al. 2013a). However, both species had more tillers and greater biomass than the untreated controls due to higher soil water and available nitrogen compared to untreated controls (Young et al. 2013b; Roundy et al. 2014b).

Mastication increases woody fuel loadings on the soil surface, particularly if the treatment is implemented in later woodland expansion phases (Fig. 11, Table 5). Mean woody fuel load in untreated phase I stands was 5.7 Mg ha^{-1} for pinyon-juniper stands, 5.2 Mg ha^{-1} for Utah juniper stands and 3.6 Mg ha^{-1} for western juniper stands (Wozniak and Strand 2019). Masticated fuels decreased over time and the fuel properties changed as the fuelbed aged. Ten years after mastication in pinyon-juniper woodlands in Utah with initial tree cover of 5–15%, the 1-h woody fuels decreased from 3.4 ± 2.2 to 0.9 ± 0.8 Mg ha^{-1}, with tree cover of 15–25% the decrease was from 7.0 ± 4.5 to 2.2 ± 1.4 Mg ha^{-1}, and with 25–50% tree cover, it was from 10.9 ± 4.5 to 3.1 ± 2.1 Mg ha^{-1} (Table 5) (Wozniak et al. 2020). No significant decreases in 10, 100 or 1000-h fuels were observed over the 10-year period (Table 5).

Kreye et al. (2014) summarized fire behavior when burning masticated conifer and shrub fuels in the laboratory and field. Flame lengths in the laboratory ranged from 0.12 to 1.70 m with longer flame lengths associated with lower fuel moisture (range 2.5–16.0%) and greater fuel load (range 10 to 169 Mg ha^{-1}) indicating that fuelbed load, depth, and bulk density impact fire behavior (Kreye et al. 2013). Similar flame lengths (0.26 to 1.88 m) were reported when burning masticated fuelbeds in field settings (Kreye et al. 2014) with higher variability due to differences in wind speed, additional fuels such as herbaceous or shrub patches, and variable ages of the fuel beds. Higher flame lengths (> 2.5 m) were observed when standing shrubs or herbaceous vegetation occurred in the burn (Kreye and Kobziar 2015) or at higher wind speeds (Moore et al. 2020). In the field, rates of fire spread on masticated sites varied between 0.44 and 5.9 m min^{-1} for headfires, while backing fires were orders of magnitude slower (0.06–0.09 m min^{-1}) (Kreye et al. 2014). Differences between fire rate of spread and fuel and fire characteristics were difficult to discern because of varying conditions (wind speed, relative humidity, fuel loading, fuel bed depth, and fuel moisture).

Masticated fuels observed during wildfires suggest that they burn at lower intensity and at slower rates than untreated fuels (Kreye et al. 2014), thereby perhaps enhancing fire suppression efforts. Difficulties during holding and mop-up can occur because of the longer duration of combustion and increase in smoldering and smoke production (Bass et al. 2012; Kreye et al. 2014). High winds can blow burning masticated particles across firelines (Bass et al. 2012). Prolonged smoldering has been observed to increase duff consumption, soil heating, and root injury. For example, Busse et al. (2005) documented that masticated fuel depths of 7.5 cm or greater

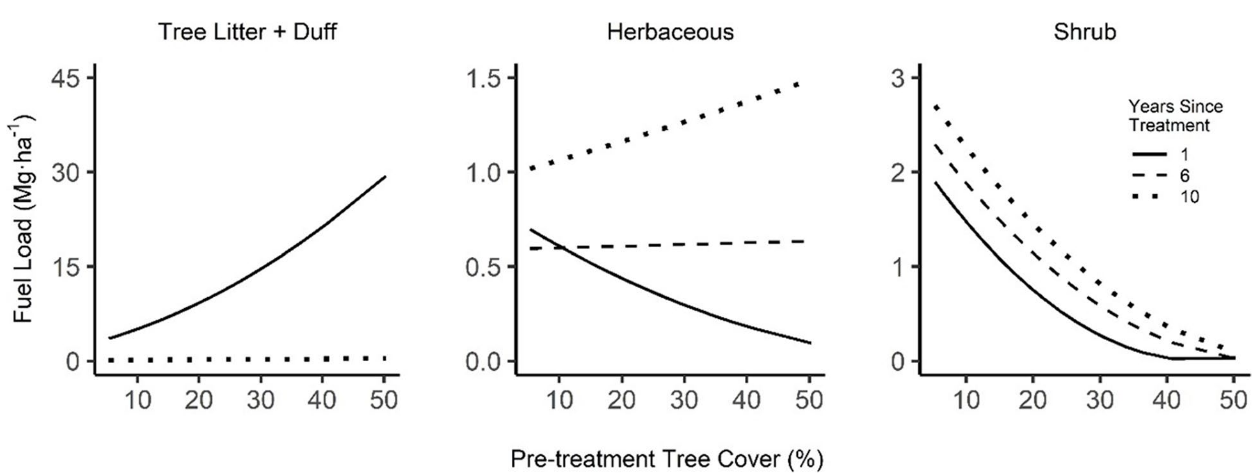

Fig. 11 Model-based estimates of the tree litter + duff, herbaceous, and shrub median fuel loads (Mg/ha) across a gradient of pretreatment tree cover at 1, 6, and 10 years after mastication. Data are for sites along a north to south gradient in western Utah experiencing Utah juniper and Colorado pinyon pine expansion. The mean (± SE) increase was 413.4 ± 110.4% in herbaceous fuel load and 232 ± 61.4% in shrub fuel load from 1 to 10 years posttreatment. Note: tree litter + duff fuel loads were not collected (nor estimated) at 6 years posttreatment. Figure from Wozniak et al. (2020)

Table 5 Means + standard deviations of fuel loads (Mg ha^{-1}), bare ground cover (%), and tree density (stems ha^{-1}) within mastication plots with tree cover ranges of 5–15%, 15–25%, and 25–50%. Data are for sites along a north to south gradient in western Utah experiencing Utah juniper and Colorado pinyon pine expansion. From Wozniak et al. 2020

Response variable	Years posttreatment	Pretreatment tree cover range (%)		
		5–15	15–25	25–50
1-h DWD fuel load (Mg ha^{-1})	1	3.39 ± 2.16	7.04 ± 4.46	10.87 ± 4.49
	5–6	1.67 ± 1.59	3.68 ± 2.87	5.38 ± 1.68
	10	0.89 ± 0.81	2.23 ± 1.44	3.12 ± 2.06
10-h DWD fuel load (Mg ha^{-1})	1	1.93 ± 1.11	4.44 ± 1.70	6.62 ± 2.22
	5–6	2.17 ± 1.16	3.68 ± 1.89	4.46 ± 2.15
	10	2.57 ± 2.28	3.98 ± 2.23	5.46 ± 2.96
100 + 1000-h DWD fuel load (Mg ha^{-1})	1	1.37 ± 2.13	1.59 ± 2.84	4.01 ± 2.95
	5–6	0.56 ± 0.62	1.24 ± 1.61	2.58 ± 3.27
	10	0.94 ± 1.05	1.90 ± 3.07	3.70 ± 3.60
Tree litter + duff (Mg ha^{-1})	1	5.27 ± 2.72	10.59 ± 3.03	15.96 ± 6.82
	5–6	-	-	-
	10	0.34 ± 0.59	0.33 ± 0.43	0.53 ± 1.02
Herbaceous fuel load (Mg ha^{-1})	1	0.72 ± 0.28	0.37 ± 0.20	0.30 ± 0.20
	5–6	0.65 ± 0.29	0.60 ± 0.39	0.70 ± 0.40
	10	1.02 ± 0.35	1.43 ± 0.64	1.20 ± 0.42
Shrub fuel load (Mg ha^{-1})	1	1.84 ± 1.62	0.86 ± 0.70	0.29 ± 0.51
	5–6	2.16 ± 1.60	1.69 ± 1.21	0.39 ± 0.33
	10	2.66 ± 1.95	1.68 ± 1.31	0.76 ± 0.58
Total fuel load (Mg ha^{-1})	1	14.53 ± 5.38	24.43 ± 7.74	32.38 ± 11.17
	5–6	-	-	-
	10	8.41 ± 4.83	12.02 ± 7.12	13.23 ± 7.07
Bare ground cover (%)	1	27.57 ± 11.37	30.51 ± 8.84	28.42 ± 7.91
	5–6	22.68 ± 6.09	21.29 ± 7.31	17.93 ± 9.40
	10	22.98 ± 6.98	20.13 ± 5.58	17.04 ± 5.36
Tree density (stems ha^{-1})	1	91.8 ± 85.1	81.6 ± 91.2	77.9 ± 111.7
	5–6	202.9 ± 176.9	170.3 ± 172.3	161.1 ± 187.7
	10	219.7 ± 161.6	193.6 ± 190.3	159.2 ± 207.9

could produce temperatures above 60 °C, the lethal temperature threshold for plants, as deep as 10 cm below the soil surface.

Tradeoffs of pinyon and juniper fuel treatments

Synthesizing effects of treatments to reduce pinyon and juniper fuels on vegetation and fuel structure, fire behavior, and ecological response provides implications for fire management (Table 6). All treatments were effective at reducing tree canopy cover and lowering the risk of high-intensity crown fire. Prescribed fire reduced surface fuel loads in phase I and II woodlands for up to 10 years and can decrease modeled fire intensity in phase I for 10 years and in phase II for 3–6 years (Williams et al. 2023). Cut and broadcast burn may have similar effects depending on season of burn (Bates et al. 2016). A tradeoff for all treatments is that increases in shrub and especially herbaceous fuels following tree removal can elevate the rate of fire spread (Williams et al. 2023). Increases in herbaceous fuels were often largest in prescribed fire treatments. Compared to other treatments, cut and leave greatly increases surface fuels with progressively larger increases from phase I through phase III. The increase in woody surface fuels and to a lesser degree herbaceous fuels increases modeled fire intensity, flame length, and especially rate of spread in cut and leave treatments (Williams et al. 2023). Cut and pile burn treatments appear to be a better option than cut and leave due to reduced canopy and woody surface fuels, except in the early phases of tree expansion where cut and leave treatments have less effect on fuels and fire behavior. In cut and pile burn treatments increases in both shrub and herbaceous fuels occur over time and are associated with potential increases in surface

Table 6 Effects of treatments to reduce woody fuels in sagebrush ecosystems experiencing pinyon-juniper expansion on vegetation and fuel structure, fire behavior, fire management implications, and ecological response

	Vegetation/ Fuel Structure	Fire Behavior	Fire Management Implications	Ecological Effects
Prescribed fire	• Reduces canopy fuels and woody debris for > 10 years with the greatest reductions occurring with higher pretreatment canopy cover • Decreases fire-intolerant shrubs for > 10 years, but increases sprouting shrubs and herbaceous species (fine fuels) 2–3 years posttreatment	• Reduces crowning and eliminates crown transmission for > 10 years • Reduces modeled reaction intensity with low canopy fuels (phase I), and for a shorter time with moderate (phase II) canopy fuels • Increases in shrub and herbaceous fuels over time may result in increases in rate of spread and flame length • High productivity years may increase fire behavior	• Treatment in phase I or II before declines in perennial grasses and forbs allow prescribed burns to carry and increase recovery potential • Patchy prescribed fire in moderate to high resilience and resistance areas may benefit habitat • Decreases in trees and shrubs may facilitate suppression activities, but greater rate of spread due to increased herbs may create challenges	• Loss of fire-intolerant shrubs, which may be slow to recover on warmer and dryer sites • Increases in perennial grasses and forbs typical after 2–3 years • High risk of invasive annual grasses in warm and dry lower resilience and resistance sites and where perennial grasses and forbs are depleted
Cut and leave	• Reduces canopy fuels but leaves significant woody fuel loads on site that increase with increases in pretreatment tree canopy cover • Increases sagebrush, other shrubs, and herbaceous species with the largest increases in sites with higher pretreatment canopy cover • High amounts of downed wood can smother understory species	• Reduces risk of crowing and crown transmission • Modeled flame length, rate of spread, and reaction intensity increase due to large amounts of surface woody fuels • Fire behavior increases over time as cover of surface shrub and herbaceous fuels increase	• Treatments in phase I have the most beneficial effects for fire suppression and site recovery • High flame length, rate of spread, and reaction intensity due to increased surface fuels in phases II and III may increase fire suppression challenges • Failure to remove seedlings and saplings requires follow-up treatment	• Retaining shrubs, native perennial grasses, and forbs can improve habitat for sagebrush species • Increases in invasive annual grasses may occur depending on resilience and resistance, degree of disturbance, and initial cover of perennial grasses and forbs
Cut and broadcast burn	• Removes tree canopy fuels by cutting down trees and broadcast burning of slash • Decreases fire-intolerant shrubs in the short term, but sprouting shrubs increase after 1–2 years • Typically increases herbaceous species (fine fuels)	• Reduces risk of crowing and crown transmission • Effects on flame length, rate of spread, and fire intensity are likely similar to prescribed fire depending on timing of burns • High productivity years may promote growth of herbaceous species and increase fire behavior	• Removes high amounts of slash in later tree expansion phases • Fire severity may be high in spring or fall, but can be decreased by burning slash in winter • Treatment longevity is relatively high as small trees are killed	• Fire-intolerant shrubs are killed and may be slow to recover on warmer and drier sites • Increases in perennial grasses and forbs typical after 2–3 years, but risk of invasive annual grasses is high in warm and dry lower resilience and resistance sites and where perennial grasses and forbs are limited
Cut and pile burn	• Removes tree canopy fuels, typically by pile burning of slash • Results in increases in native herbaceous and/or annual fuels depending on site conditions • Leaving unburned piles may promote tree recruitment, but pile burn disks may be invasion sources	• Reduces risk of crowing and crown transmission • Modeled flame length, rate of spread, and reaction intensity may increase over time due to increases in fine fuels • High productivity years may promote invasion in pile burns and increase fire behavior	• Treatment longevity is related to the abundance of residual seedlings and saplings • Seedling burn disks, preferably with native species, may be desirable to minimize burn scars and invasive plant species	• Cover of shrubs as well as native perennial grasses and forbs typically increase • Increases in invasive annual grasses may occur depending on resilience and resistance, degree of disturbance and initial cover of perennial grasses and forbs

Table 6 (continued)

	Vegetation/ Fuel Structure	Fire Behavior	Fire Management Implications	Ecological Effects
Mastication	• Redistributes tree canopy fuels to the ground surface with a high abundance of compacted 1-h and 10-h woody fuel size classes • Typically results in an increase in sagebrush, other shrubs, and herbaceous species over time • Large amounts of masticated fuels can smother understory species	• Reduces crowing and crown transmission and appears to reduce fire intensity and rate of spread • Small and compacted fuels may result in a longer duration of combustion and therefore increased smoldering and smoke production	• Wildfires that burn at lower intensities and at a slower rate may enhance fire suppression efforts • Increased smoke production and high winds that blow burning masticated particles across fire lines may increase suppression challenges	• Cover of shrubs and native perennial grasses and forbs typically increase • Increases in invasive grasses may occur depending on resilience and resistance, degree of disturbance and initial cover of perennial grasses and forbs • Prolonged smoldering during wildfires may increase duff consumption, soil heating, and root injury

fire intensity, flame length, and rate of spread relative to untreated controls. Mastication results in a high abundance of compacted 1- and 10-h woody fuel surface fuels. These fuels appear to burn at lower intensity and at a slower rate (Kreye et al. 2014), but prolonged smoldering may result in increased duff consumption, soil heating, and root injury (Busse et al. 2005).

Posttreatment vegetation response depends on pretreatment cover of trees and shrubs, cover and composition of herbaceous vegetation, and ecological site characteristics (Chambers et al. 2014a; Miller et al. 2014, 2019). Prescribed fire and cut and broadcast burn, especially in fall, are more severe treatments because of the loss of fire-intolerant shrubs and potential mortality of native bunchgrass, which can result in the largest increases in invasive annuals (Bates and Davies 2016; Chambers et al. 2021). Treatment outcomes are generally most favorable (1) where resilience and resistance of the site is categorized as moderate or higher, (2) in expansion phases I and II, and (3) where sufficient perennial grasses and forbs exist to outcompete invasive annuals and promote recovery (Miller et al. 2014, 2019; Bates and Davies 2016; Chambers et al. 2017a, 2017c, 2023c; Crist et al. 2019).

Cut and leave, cut and pile burn, and mastication are less severe treatments ecologically than prescribed fire and cut and broadcast burn because the understory shrubs and perennial herbaceous species are left intact (Chambers et al. 2021). Recovery of the understory is still greatest in the early phases of woodland expansion and with adequate native perennial herbaceous species (Miller et al. 2019). In addition, treatment is possible in sites with moderately low as well as higher resilience and resistance because of the intact understory (Miller et al. 2019; Chambers et al. 2023c).

All mechanical treatments have tradeoffs. Cut and leave treatments in expansion phases II and III can decrease the longer-term ecological integrity of the site due to large increases in woody surface fuels (Fig. 9) and risk of high severity fire but these effects are minimized in phase I (Williams et al. 2023). Increases in invasive annuals may be promoted by cut and broadcast burn treatments as a result of broadcast burning of slash (O'Connor et al. 2013) and by cut and pile burn due to skid trails or pile burns requiring pretreatment assessment of relative resistance to invasive annuals and possibly posttreatment seeding (Redmond et al. 2014). Mastication may result in smothering residual plants and reducing seedling establishment in shredded piles, and like the other treatments, increase the potential for invasive plants due to competitive release again requiring pretreatment assessment of site conditions and potentially posttreatment seeding (Young et al. 2013a).

Treatments that modify annual herbaceous fuels

Treatments to reduce invasive annual grasses and thus fine fuels have been conducted primarily in Wyoming big sagebrush ecosystems and include targeted grazing by livestock as well as preemergent herbicide treatments. Targeted grazing is the application of a specific kind of livestock at a determined season, duration, and intensity to accomplish defined vegetation or landscape goals (Launchbaugh and Walker 2006). In sagebrush landscapes targeted grazing with cattle or sheep can be used to reduce fine, herbaceous fuels and to control invasive annual grasses. Targeted grazing has the potential to alter landscape-scale fire behavior by creating fuel breaks, increasing the safety and effectiveness of fire-suppression operations, and decreasing the extent of wildfire spread (Maestas et al. 2016a, b; Shinneman et al. 2019). Preemergent herbicides can be used to reduce fine fuels by decreasing establishment of invasive annual grasses and forbs (Pyke et al. 2014).

Targeted grazing

High-intensity targeted grazing is typically used in areas dominated by annual grasses to reduce herbaceous fuel loads (Diamond et al. 2009, 2012). High-intensity spring grazing by cattle removed 80 to 90% of cheatgrass biomass (Diamond et al. 2009, 2012) and by sheep removed 71 to 83% of all fine fuels (Mosley 1996). The decreases in cheatgrass biomass due to a single year of cattle grazing reduced flame length and rate of spread and a second year of grazing reduced biomass and cover to the degree that the fuels no longer carried fire (Diamond et al. 2009). The cheatgrass seed bank was reduced by spring grazing, but spring grazing followed by fall burning was more effective than either treatment alone in reducing seed bank density (Diamond et al. 2012).

Dormant season targeted grazing (Nov–April) can be used to reduce herbaceous fuels and fire spread during subsequent fire seasons (Schmelzer et al. 2014; Davies et al. 2021a, b, 2022). Autmn grazing in areas dominated by invasive annual grasses removed significant amounts of cheatgrass standing crop (79, 80, 79, and 58%) over four successive years with variable precipitation (Schmelzer et al. 2014). Cumulatively, 0.675 Mg ha^{-1} were removed reducing the fuels carried over to the next year. Although fall grazing did not affect perennial grass density, biomass of introduced crested wheatgrass increased on grazed plots (Schmelzer et al 2014). Grazing in fall reduced the cheatgrass seed bank to about 50% (3,432 ± 2,513 seeds m^{-2}) compared to ungrazed areas (7187 ± 1569 seeds m^{-2}), but sufficient seed numbers remained to result in a rapid increase in seed densities if grazing were stopped (Perryman et al. 2020).

Dormant season targeted grazing in intact native ecosystems also can reduce fine fuels and fire spread. Most studies on effects of dormant season targeted grazing in intact ecosystems on fuels are from sites in southeastern Oregon characterized by Wyoming big sagebrush and Thurber's needle grass (*Achnatherum thurberianum*) with relatively low resilience and resistance (Davies et al. 2015a, b, 2017, 2022). These sites received about 250 to 280 mm of precipitation annually and had initial covers of about 10% shrubs, 20% total herbaceous, and 20% litter.

Dormant season targeted grazing with moderate utilization (40 – 60% of available forage removed) for a single year reduced herbaceous fuel cover, continuity, height, and biomass and increased fuel moisture (Davies et al. 2015a). Prescribed burns applied the following fall showed that grazed areas had lower burn temperatures than ungrazed areas (Davies et al. 2015b). The rate of fire spread was 3.2 times faster (about 0.24 m s^{-1} vs. 0.08 m s^{-1}), while flame length was nearly four times greater (2.4 m vs 0.8 m) in ungrazed than grazed areas (Davies et al. 2015b). Over a 5-year period after fire, perennial bunchgrass biomass, but not density, was slightly higher in grazed than ungrazed plots (Davies et al. 2021a, b). In unburned plots, annual grass cover and biomass varied among years but increased in both grazed and ungrazed treatments averaging approximately 3% on grazed and 6% on ungrazed plots at the end of the study (Davies et al. 2022). Cover of large bunchgrasses was higher on grazed plots initially and remained higher during the study; there was no difference between treatments in bunchgrass density or cover and density of the perennial grass, Sandberg bluegrass (*Poa secunda*) (Davies et al. 2022). Overall, dormant season grazing with moderate utilization had minimal effects over time, but because no pretreatment data were presented, it was not possible to clearly separate site vs. treatment differences.

A comparison of effects of fall grazing, spring grazing, and no grazing on fuels and fire behavior showed that both grazing treatments decreased fine fuel biomass, cover, and height, and increased fuel moisture, thereby decreasing ignition probability and initial fire spread compared to the ungrazed treatment (Fig. 12a, b) (Davies et al. 2017). Modeled probability of initial fire spread was sixfold greater in fall-grazed than spring-grazed treatments when evaluated in August (Fig. 12b), likely because grazing in fall had little influence on the subsequent year's plant growth. However, spring grazing likely also had a greater effect on perennial native vegetation.

Effects of different levels of herbaceous biomass removal (low [15–30%], moderate [40–55%], high [60–75%]) during the growing season by cattle on fire ignition and initial fire spread were evaluated at a similar Wyoming big sagebrush site with relatively low shrub cover (Orr et al. 2022). Growing season grazing reduced fine fuel loads and increased bare ground, which at moderate- and high-grazing, reduced fire ignition and spread relative to controls. Fuel moisture varied among years but was generally higher with moderate- and particularly high-intensity grazing. Total herbaceous, perennial, and litter fuels also varied among years, but were generally lowest in moderate followed by high-intensity grazing. Total area burned as well as maximum and average fire spread were generally lower in grazed treatments than in controls but did not differ among grazing intensities.

A separate study in southern Idaho evaluated effects of cattle grazing in summer and fall at zero, low (25–35%), and moderate (50–60%) grazing utilization levels on fire behavior in big sagebrush communities that varied in shrub cover and understory species (Schachtschneider 2016). Shrub canopy cover had highly significant effects on flame length and rate of spread ($p < 0.01$) and was positively correlated with both flame length and rate of spread when evaluated across grazing utilization levels (Fig. 13) (Schachtschneider 2016). Grazing utilization had an effect on flame length and rate of spread, but relationships were difficult to discern. Shrub canopy cover appeared to be the primary factor driving flame length and rate of spread above shrub covers of about 20% (Schachtschneider 2016, also see Britton et al. 1981). This relationship contradicts suggestions that areas with higher shrub cover require higher-intensity livestock grazing to prevent fire spread (Orr et al. 2022). In addition, higher grazing intensity, especially during the growing season, may result in progressive increases in sagebrush and other shrubs, decreases in perennial herbaceous species, and a loss of resilience and resistance over time (Fig. 4). Therefore, cattle grazing to reduce fine fuels is likely limited to areas with relatively low shrub cover due to the potential of fire to carry through the shrub canopy.

Preemergent herbicides

Imazapic is a pre- to early emergence herbicide that has been widely used to decrease emergence and establishment of invasive annual grasses and prevent development of annual grass fire cycles. Effectiveness of Imazapic in suppressing invasive annual grass fuels depends on timing and rate of application and initial suppression effectiveness can vary widely (Mangold et al. 2013). Applying Imazapic shortly after emergence at a rate of 105 to 141 g ha^{-1} active ingredient provides consistent, short-term (1–3 years) control of cheatgrass (Elserod and Rudd 2011; Davison and Smith 2007; Mangold et al. 2013; Pyke et al. 2014; Morris et al. 2017). Imazapic reduces multiple invasive annual grass species

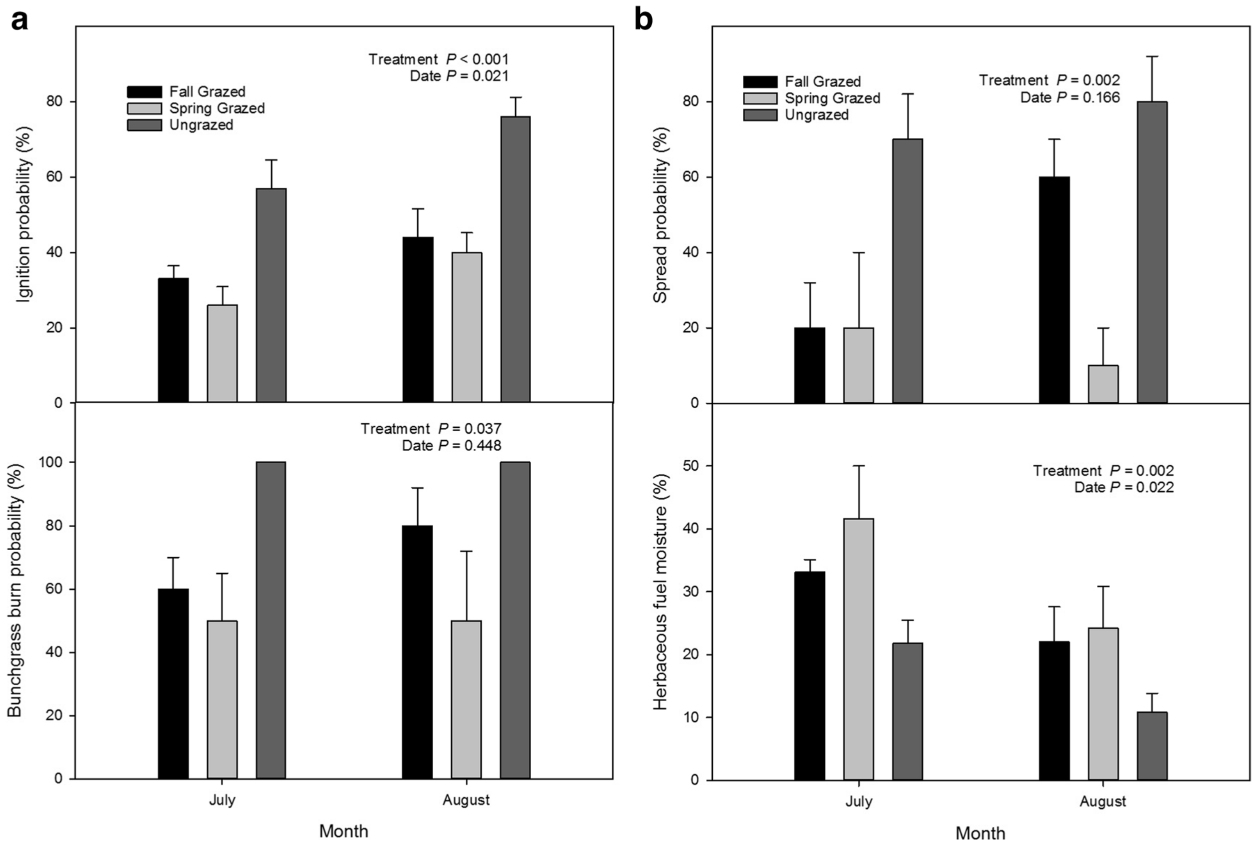

Fig. 12 Mean (± s.e.) ignition and burn probability (**a**) and fire spread probability and herbaceous fuel moisture (**b**) expressed as a percentage in July and August for fall-grazed, spring-grazed, and ungrazed treatments. Fall-grazed was grazed in the prior fall; spring-grazed was ungrazed in the prior fall and also grazed in spring before sampling. Ungrazed was not grazed in the prior fall or spring before sampling. Data are from Wyoming big sagebrush and bunchgrass sites with an average of 21% shrub cover west of Burns, OR. Figure from Davies et al. (2017)

including cheatgrass (Pyke et al. 2022), medusahead (*Taeniatherum caput-medusae*) (Bekedam 2004; Davies et al. 2015c, 2018; Donaldson and Germino 2022), and ventenata (*Ventenata dubia*) (Davies and Hamerlynck 2019). However, without effective restoration seeding, invasive grass abundance may return to initial or higher levels within a few years (Davies et al. 2019; Pyke et al. 2022), and may stimulate secondary invasion by invasive tall forbs (Donaldson and Germino 2022).

Imazapic appears to have less effect on persistence and resprouting of residual perennial species than invasive annuals at landscape scales (Applestein et al. 2018). However, various studies showed decreases in perennial species, such as Sandberg bluegrass following application of Imazapic (Pyke et al. 2022). Applying Imazapic prior to restoration seeding can negatively impact establishment of native shrubs (Owen et al. 2017) and perennial grasses (Shinn and Thill 2004), but may have a lesser effect on introduced species, such as crested wheatgrass (*Agropyron cristatum*), Siberian wheatgrass (*Agropyron fragile*), and forage kochia (*Bassia prostrata*) (Davies et al. 2015a, b, c, 2018).

Indaziflam (Rejuvra®) is a recently approved (2020) preemergent herbicide that inhibits seedling establishment and provides 3 to 4 years of control of invasive annual grass fuels. Indaziflam was approved for use on sites grazed by domestic livestock at a rate no higher than 73 g ha^{-1} (Seedorf et al. 2022). Indaziflam effectively controlled cheatgrass (e.g., Terry et al. 2021, Clark et al. 2020, Courcamp et al. 2022a, 2022b), ventenata (Hart and Mealor 2021), feral rye (*Secale cereale*) (Clark et al. 2020), and a nonnative annual forb (*Alyssum* spp.) (Meyer-Morey et al. 2021). However, Indaziflam had consistently negative effects on the seedbanks of native species, particularly native annual forbs (Meyer-Morey et al. 2021, Courcamp et al. 2022b). In seeding trials, both Indaziflam and Imazapic negatively affected seeded and residual species across a range of site conditions in Utah, decreasing bluebunch wheatgrass (*Pseudoroegneria spicata*) seedling emergence by 96 and 46%, and 2-year plant density by 91 and 65%, respectively, compared to non-herbicide

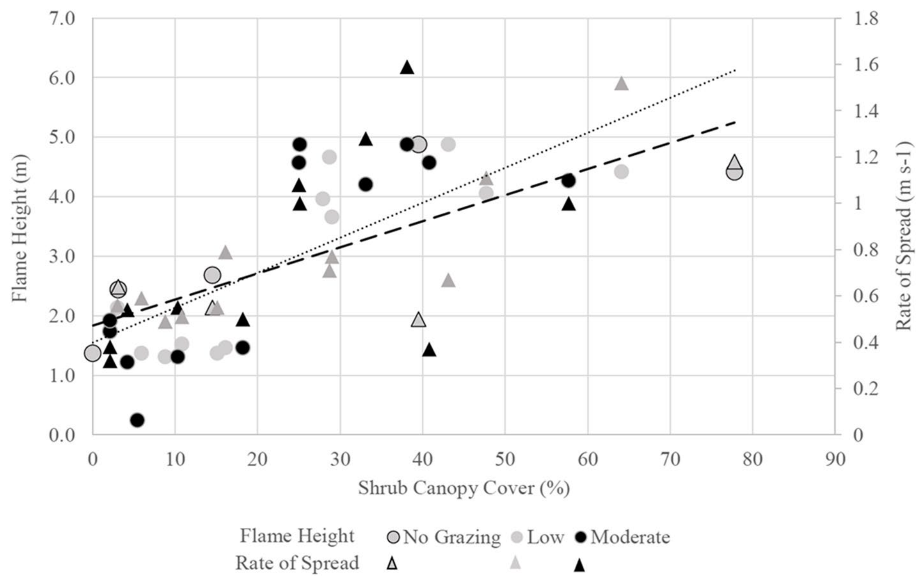

Fig. 13 Effects of shrub canopy cover on flame length and rate of spread across three grazing utilization levels (none, low [25–35%], and moderate [50–60%]) in Reynolds Creek, ID. Trend lines show that shrub canopy cover was positively correlated with both flame length (dotted line, R2 = 0.59) and rate of spread (dashed line, R2 = 0.44) when evaluated across grazing levels. Overall study results indicate that shrub canopy cover and not herbaceous fuel is likely the primary factor driving flame length and rate of spread above shrub covers of about 20%. Figure from Schachtschneider (2016)

treatments (Terry et al. 2021). Both herbicides reduced aboveground biomass of bluebunch wheatgrass by over 85% 2 years after treatment.

Neutral or positive effects of Indaziflam on established perennial grasses and forbs were observed in cooler and moister sagebrush and prairie ecosystems with native, remnant plant communities, and relatively high resilience and resistance. In mountain big sagebrush and bluebunch wheatgrass communities Indaziflam had little effect on perennial native grasses (Courcamp et al. 2022a). In more productive communities characterized by species such as Prairie sagewort (*Artemisia frigida*), western wheatgrass (*Pascopyrum smithii*), and green needlegrass (*Nassella viridula*), Indaziflam resulted in increases in perennial grasses (Clark et al. 2020; Hart and Mealor 2021). Litter intercepts herbicides during application and prescribed fire prior to application increased Indaziflam effectiveness in cool and moist communities dominated by western wheatgrass and by the introduced perennial grasses, Kentucky bluegrass (*Poa pratensis*) and Canada bluegrass (*Poa compressa*) (Seedorf et al. 2022).

The SageSTEP study evaluated interacting effects of Impazapic application with prescribed fire, mowing, and tebuthiuron application in Wyoming big sagebrush ecosystems. In the first 3 years after treatment, cheatgrass cover was reduced at least 63%, invasive annual forb cover by at least 45%, and unexpectedly, perennial grass cover by 49% (Pyke et al. 2014). Consequently, herbaceous fuels were decreased by 30% in years 2 and 3 posttreatments. Imazapic had no impact on total, shrub, litter, or downed woody fuel and there was no interaction among Imazapic and sagebrush treatments for any fuel component. However, Imazapic treatments reduced modeled rates of spread by an additional 0.5 m min^{-1} compared to plots receiving only shrub removal treatments (Ellsworth et al. 2022). Imazapic treatment effects on modeled fire behavior did not differ across shrub treatments or among years nor influence flame length or reaction intensity.

Tradeoffs of treatments that reduce annual herbaceous fuels

Effects of treatments that reduce herbaceous fuels on vegetation and fuel structure, fire behavior, and ecological response have important fire management implications (Table 7). Targeted grazing to remove invasive annual grass fuels in heavily invaded areas can be highly effective, but two or more years are needed to remove the seedbank and prevent subsequent increases if treatments cease (Schmelzer et al. 2014). To be viable over the long term, targeted grazing requires either repeated application or successfully seeding and establishing perennial species. In warmer and drier ecological types where targeted grazing is typically used, establishing perennial species is difficult and may require repeated entries (e.g., Knutson et al. 2014; Shriver et al. 2019).

Table 7 Effects of treatments to reduce herbaceous fuels on vegetation and fuel structure, fire behavior, fire management implications, and ecological response

	Vegetation/fuel structure	Fire behavior	Fire management implications	Ecological effects
Herbicides to reduce annual grass fuel				
Imazapic	• Decreases invasive annual fuels for 2–3 years • Invaders increase over time without successful restoration or repeated applications in areas dominated by invasive annuals • May reduce seeding success of native perennials with lesser effects on introduced grasses • Tradeoffs exist between reduced seedling establishment and invasive annual grass control	• Decreases rates of fire spread when used in conjunction with fuel treatments in relatively warm and dry areas	• Intended to decrease establishment and growth of annual grasses and forbs long enough for residual native herbs to recover and seeded species to establish • May prevent development of annual grass fire cycles where effective in promoting seeding success	• Imazapic is effective at reducing several annual grasses, but is only partially selective and may decrease residual native annual and perennial species as well as seeded species • Increases in relative resilience and resistance may occur where effects of controlling invasive annual grasses outweigh decreased seeding success and perennial grass recovery
Indaziflam	• Decreases native and invasive annual fuels for 3–4 years • Invaders increase over time without successful restoration or repeated applications in areas with abundant invasive annuals • Results in consistent decreases in native seedbanks, especially annuals • In remnant native systems, decreases perennial natives and reduces seeding success in relatively warm and dry areas; has neutral or positive effects in relatively cool and wet areas	• No data found, but likely decreases short-term fire ignition, flame length and fire spread in invasive annual dominated areas • May increase fire spread in remnant native communities where perennial herbaceous species increase	• Intended to decrease establishment and growth of invasive annual grasses and forbs long enough for residual native herbs to recover and seeded species to establish • Effects appear highly dependent on site conditions • Desired results are more likely in cool and moist areas that receive relatively high summer precipitation	• Indaziflam reduces the seed banks of both native and invasive grasses and forbs • In areas with relatively low resilience and resistance (warm and dry) it appears to reduce invasive species, seeded species, and residual perennial species • In areas with relatively high resilience and resistance (cool to cold and moist) it appears to reduce invasive species, and increase residual perennial forbs and especially grasses
Targeted grazing to reduce herbaceous fuel				
High-intensity targeted grazing	• High-intensity grazing in areas dominated by invasive annual grasses decreases fine fuels • Invasive annual grass biomass can be reduced by 70 to 90% • Residual native perennial herbaceous species may be further decreased	• Vegetation stays green longer reducing flame length and rate of spread • Repeated high-intensity grazing in spring may prevent fires from carrying	• High-intensity grazing will likely require enclosures or protein supplements to concentrate livestock • High-intensity grazing to create fuel breaks may decrease fire risk and aid fire-suppression operations	• High-intensity grazing of annual grass dominated areas can decrease invasive annual grass cover and seed banks • Native perennial herbaceous species also can be reduced • Return to a perennial community following high-intensity grazing requires active restoration
Dormant season targeted grazing	• Dormant season grazing decreases fine fuel carryover and increases fuel moisture in the following year • In intact Wyoming big sagebrush ecosystems moderate utilization appears to have minor effects on native herbaceous perennials	• Decreases in fine fuels with dormant season grazing may decrease fire ignition, flame length and fire spread where shrub fuels are relatively low • Greater flame length and fire spread is likely with higher shrub fuels (> 15%) regardless of reductions in herbaceous fuels	• Dormant season grazing that effectively reduces fine fuels, fire ignition, and fire spread may slow fire growth and aid suppression efforts	• Repeated fall (dormant season) grazing at low to moderate utilization rates appears to have relatively minor effects on composition of intact sagebrush ecosystems over time • Heavier dormant season grazing utilization rates or spring grazing has negative effects on perennial herbaceous species

Dormant season grazing to reduce herbaceous fuels and fire spread has promise but has been demonstrated for only a few ecological site types in southeastern Oregon with relatively low sagebrush cover. A primary tradeoff is that removal of herbaceous fuels by grazing reduces flame length and rate of spread only when shrub cover is relatively low (< 20%) (Fig. 13) (Schachtschneider 2016, Orr et al. 2022). Defining the conditions under which dormant season grazing is most likely to be successful in reducing fuels and fire spread is a logical next research step.

Preemergent herbicides can be highly effective at reducing invasive annuals, but there may be significant tradeoffs. Because their suppressive effects are short-lived, i.e., 1 to 3 years for Imazapic and 3 to 4 years for Indaziflam, successful regrowth or establishment of perennial species is required to inhibit the recovery of invasive annuals following treatment (Lazarus and Germino 2022). In addition, negative effects on seed banks, existing perennial plants, and newly seeded species, especially with Indaziflam, may decrease the ability to meet posttreatment objectives, particularly in warmer and drier sites.

Key research needs to effectively implement treatments that modify fuels

Additional research is needed to determine the most effective treatments for reducing fuels and fire hazard across the diverse vegetation types and ecological conditions in the sagebrush biome. A key aspect includes clarifying the tradeoffs of treatments that decrease woody fuels (shrubs and trees) but increase herbaceous fuels (native grasses and forbs) on future fuels and fire behavior vs. ecological resilience and resistance to invasive plants. Increases in herbaceous fuels posttreatment can elevate rate of spread and other fire behavior metrics, especially in pinyon-juniper expansion areas (Bunting et al. 1987; Williams et al. 2023). However, greater abundance of perennial herbaceous species may increase both ecological resilience and resistance to invasive annual grasses following subsequent wildfires (Chambers et al. 2014b, 2019). Thus, greater understanding is needed of the site characteristics and ecological conditions under which treatments that modify fuels are most effective in promoting the longer-term resilience and resistance of sagebrush ecosystems. Because both woody and herbaceous fuels typically increase over time after fuel treatments, an increased understanding of woody fuel treatment durability and appropriate retreatment intervals or treatment combinations also is needed.

Reducing fine fuels has the potential to minimize fire spread and aid fire suppression (Schmelzer et al. 2014). High-intensity targeted grazing reduced fine fuels in cheatgrass-dominated areas, but retreatment was required to prevent a rapid increase of the invader (Perryman et al. 2020). An understanding of how to restore perennial species following high-intensity grazing would increase the efficacy of this treatment. Dormant season targeted grazing reduced herbaceous fuel and fire spread in intact sagebrush ecosystems with relatively low shrub cover in southeastern Oregon and had minimal effects on native perennial herbaceous species (Davies et al. 2017, 2021a, 2022). However, a threshold of shrub cover (~ 20%) exists above which fire spread is driven by the shrubs and targeted grazing to remove herbaceous fuels has little effect on fire behavior (Britton and Sneva 1981; Schachtschneider 2016; Orr et al. 2022). This indicates that additional research is needed on the fuel characteristics under which dormant season targeted grazing to decrease herbaceous fuels is effective in reducing fire behavior and improving ecological resilience and resistance over a broader range of ecological types and fuel characteristics. Preemergent herbicides reduced annual grasses but had differing effects on perennial native and introduced species in warm and dry vs. cool and moist environments indicating a need to clarify the effects of preemergent herbicides across the diverse ecological types and conditions in the sagebrush biome.

Most research on the effects of fuel treatments has focused on single ecological types and study areas have been relatively small scale (McKinney et al. 2022). These studies provide a local understanding of individual sites and can inform adaptive strategies for implementing treatments to meet specific objectives (Dittel et al. 2023). However, we still lack the information needed to optimize the types and locations of treatments to reduce fuels and mitigate fire risk across broader spatial scales. Studies designed to evaluate the effects of fuel treatments across not only environmental gradients but also gradients of shrub or tree cover will help refine the conditions under which fuel treatments are most effective in promoting longer-term resilience and resistance. Developing landscape-scale spatial data of the dominant sagebrush associations, phases of pinyon-juniper expansion, and persistent woodlands (Chambers et al. 2023b) coupled with indicators of resilience and resistance (Maestas et al. 2016a, b; Chambers et al. 2023a) will help provide the understanding of likely treatment response needed to prioritize fuel treatment investments at landscape scales. An increased understanding of the effects of climate change on fuel treatment effectiveness and on fuel treatment prioritization is essential for mitigating fire risk as the atmosphere warms.

Conclusions

In most cases information exists to make informed decisions on treatments to mitigate the effects of wildfire and improve ecological resilience at local scales. Primary considerations are the short- and long-term effects on fuels and fire behavior and thus fire severity and the ecological response. To increase ecological resilience and resistance to nonnative annuals, treatments should be selected that minimize fire severity and the loss of desirable perennial species in subsequent wildfires. Additional research is needed to prioritize areas for management and determine optimal strategies across large sagebrush landscapes.

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Authors' contributions
JCC, EKS, and LME led the writing of the manuscript and contributed new figures and analyses. CMT, AKU, MRC, RFM, MCR, KCS, and CLM contributed to writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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