Rangeland Ecology & Management 98 (2025) 399–413

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: www.elsevier.com/locate/rama

Climate Change Vulnerabilities and Adaptation Strategies for Land Managers on Northwest US Rangelands ☆

Anna T. Maher [1,*], Holly R. Prendeville [2], Jessica E. Halofsky [3], Mary M. Rowland [4], Kirk W. Davies [5], Chad S. Boyd [5]

[1] *USDA Forest Service Pacific Northwest Research Station, Northwest Climate Hub, Portland, OR 97204, USA*
[2] *USDA Forest Service Pacific Northwest Research Station, Northwest Climate Hub and Western Wildland Environmental Threat Assessment Center, Portland, OR, USA*
[3] *USDA Forest Service Pacific Northwest Research Station, Northwest Climate Hub and Western Wildland Environmental Threat Assessment Center, Olympia, WA, USA*
[4] *USDA Forest Service, Pacific Northwest Research Station, La Grande, OR, USA*
[5] *USDA Agricultural Research Service, Burns, OR, USA*

ARTICLE INFO

Article history:
Received 15 March 2023
Revised 19 April 2024
Accepted 29 April 2024

Key Words:
Adaptation
Climate change
Natural resource management
Northwest
Rangeland

ABSTRACT

Rangelands around the globe are experiencing management challenges associated with existing and emerging stressors, including more frequent and severe fires, woody species expansion, annual grass invasion, heavy, repeated growing season grazing, and climate change. Disturbance is an essential part of rangeland systems. Yet climate change is likely to affect rangelands most directly by increasing the likelihood, severity, and extent of long term, negative impacts from disturbance. We conducted a synthesis of key vulnerabilities to climate change for Northwest US rangelands. These rangelands are projected to become warmer and drier this century, with episodes of more extreme droughts and higher likelihood of more severe fires affecting larger areas. Many of the vulnerabilities identified in our synthesis, such as increased frequency of fire and invasive grass proliferation, can have lasting effects, leading to "undesirable transformations" (substantial and persistent changes in vegetation composition and reductions in ecosystem services). For example, larger, more severe fires have led to the rapid loss of critical Greater sage-grouse habitat and diminished forage production capacity for livestock in some areas, lowering provisioning of ecosystem services, increasing fire management costs, and impacting rural livelihoods. Rangeland managers need guidance connecting climate change projections to on-the-ground management actions. We conclude from our synthesis of climate change vulnerabilities that supporting rangeland recovery is an important climate adaptation approach on Northwest rangelands. Proactive climate adaptation strategies (e.g., supporting soil health and vegetation) and example practices (e.g., establishing climate-adapted perennial plant species) are presented according to key action areas: prepare for, respond to, and recover from disturbance. Identifying specific adaptation needs at more local scales, like the management unit level, may be further refined through proactive planning and experimentation in collaborative settings that allow for resource pooling and foster learning.

Introduction

Rangelands are complex social and ecological landscapes (Bruno et al. 2020) that support wildlife, livestock, and humans and provide the foundation for many livestock operations, pastoralists, and other ecosystem services (Reid et al. 2014; Hoover et al. 2020; Maestre et al. 2022). These large expanses of land can comprise hundreds to thousands of hectares in which land managers typically use extensive (e.g., livestock grazing and prescribed fire) rather than intensive (e.g., seeding, irrigation, and soil amendments) management practices (ESA 2023). Globally, rangelands are facing many common management challenges due to shifting disturbance regimes, including woody and invasive plant expansion, increased fire severity, and legacy effects of heavy grazing (Archer et al. 1995; Belnap et al. 2012; Timm Hoffman et al. 2019; Godde et al. 2020; Hoover et al. 2020). Climate change is increasing temperatures globally and changing the quantity and timing of avail-

☆ This work was supported in part by the US Department of Agriculture (USDA) Forest Service Western Wildland Environmental Threat Assessment Center, USDA Northwest Climate Hub and by an appointment to the Science Education Programs at National Institutes of Health (NIH), administered by Oak Ridge Associated Universities (ORAU) through the US Department of Energy Oak Ridge Institute for Science and Education.

* Correspondence: Dr Anna T. Maher, USDA Forest Service Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331, USA.
E-mail address: anna.maher@usda.gov (A.T. Maher).

https://doi.org/10.1016/j.rama.2024.04.012
1550-7424/Published by Elsevier Inc. on behalf of The Society for Range Management.

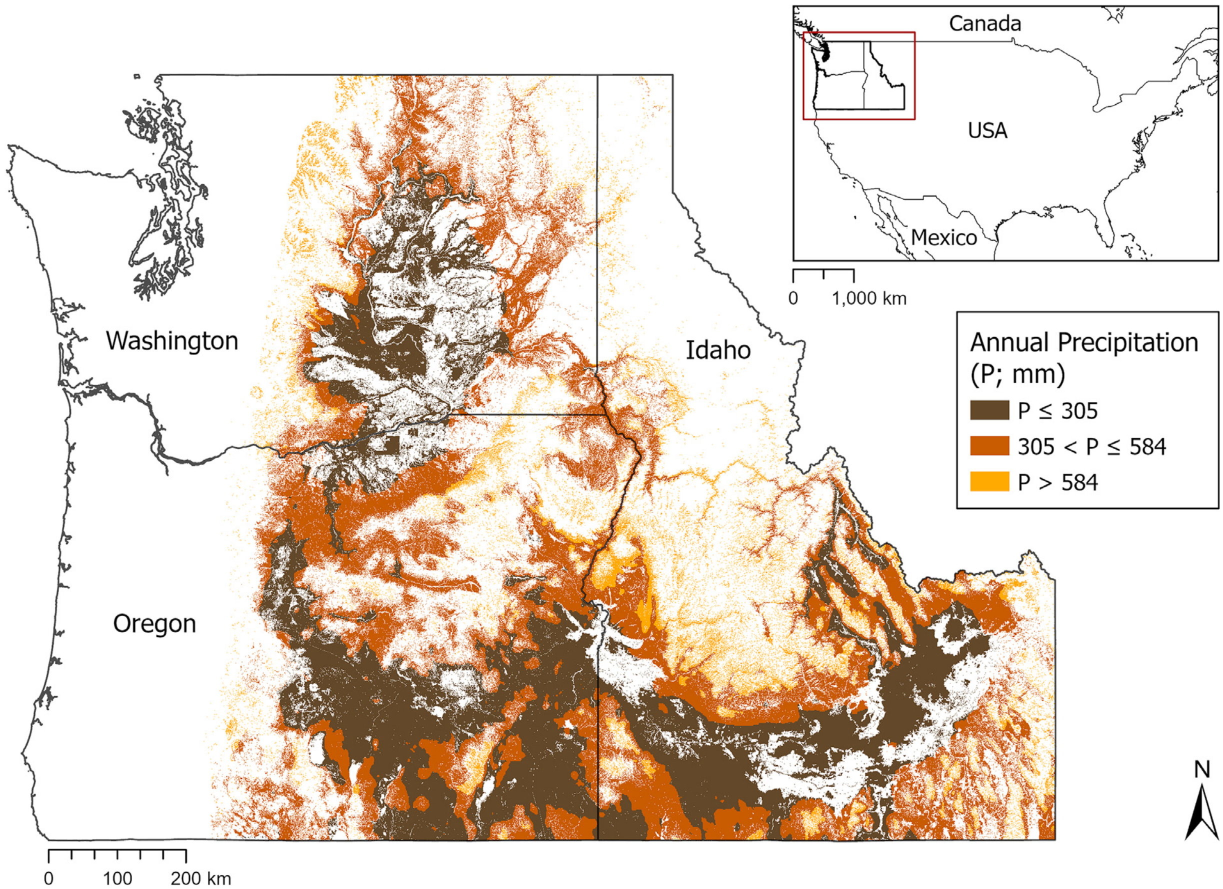

Figure 1. Northwest rangelands extent and precipitation. Rangelands comprise 21.9 million hectares in the Northwest USA (Reeves and Mitchell 2011; USDA 2018) and the majority (90%) receive 584 mm or less (area in dark orange and brown) of average annual precipitation (30 year normal; PRISM 2022). Small rangeland areas not meeting the designation of "dry domain" according to Baileys Ecoregions (Bailey 2016) were determined to be outside the study area and therefore were excluded from the map. Semiarid climates have been defined as having less than 500 mm and at least 250 mm of average annual precipitation (Huang et al. 2016). Average annual precipitation is one of several measures in the literature that have been used to differentiate between climate zones (Huang et al. 2016).

able water on rangelands (Mirzabaev et al. 2022), thus affecting the sustainability of wildlife, vegetation, and human communities.

Northwest US rangelands (including portions of Idaho, Oregon, and Washington; Fig. 1), like many rangeland areas around the world, have been challenged by multiple factors that have reduced their sustainability and have left them more vulnerable to future climate change effects. Some of these factors include invasive annual grasses and pinyon-juniper (*Pinus-Juniperus* spp.) expansion (Davies et al. 2011, 2021b; Morford et al. 2022), loss of active burning by indigenous peoples (McAdoo et al. 2013; Dalton and Fleishman 2021; Hessburg et al. 2021; STACCWG 2021), historical heavy, repeated growing season grazing (Davies et al. 2009; Davies and Boyd 2020), and increased drought incidence and severity, including snow drought (May et al. 2018; Dalton and Fleishman 2021). On rangelands, these factors lengthen fire seasons, increase fire size and frequency (Chambers et al. 2017b; May et al. 2018), and are associated with several large fires this century in the Northwest (DOI-BLM 2016; Davies et al. 2017; May et al. 2018; Vose et al. 2019). Such factors are causing some areas of Northwest rangelands to experience rapid loss of critical habitat for wildlife species (Krosby et al. 2020; WGA 2022), including core habitat for Greater sage-grouse (*Centrocercus urophasianus*; DOI-BLM 2016; Pilliod et al. 2021; Germino et al. 2022), designated as a near-threatened species globally (BirdLife International 2016).

While many of these challenges are not exclusive to the Northwest, vital management solutions may come from examining the Northwest area's vulnerabilities to climate change effects. These systems are reliant upon public and private interconnected pastures and wet meadows, semiarid shrublands and grasslands, and forested grazing lands. These lands are essential to sustaining fisheries and recreation (Charnley et al. 2018; Kantor et al. 2019), subsistence harvesting and gathering, cultural traditions, rural communities, and wildlife. These lands are also important for livestock production, with about 19 million hectares (77% of which are estimated to be publicly owned) providing forage for beef cattle (Maher et al. 2020). Climate change has the potential to increase resource scarcity (e.g., forage and water) in these systems, making it more difficult to balance social and ecological needs.

Past syntheses on the topic of climate change and US rangelands have focused on other regions (Joyce et al. 2013; Polley et al. 2013; McCollum et al. 2017; Balachowski et al. 2018) or emphasized intensive agriculture and private producer impacts (Yorgey et al. 2017; Neibergs et al. 2018) over those of broader public and private rangeland ecosystems and related services. With climate change, existing management challenges on Northwest rangelands (e.g., invasive grasses and fire) are anticipated to intensify over broad areas (Chambers and Pellant 2008; Creutzburg et al. 2015; Halofsky et al. 2018a), necessitating additional and larger-scale collaborative adaptation efforts. Fortunately, economic, cultural, and environmental interest in Northwest rangelands creates significant opportunity for collaborative solutions to address these management challenges. For instance, recovery efforts from the 2015 Soda Fire in parts of southern Idaho and eastern Oregon have demonstrated successful interagency, state, and private coordination and collaboration (Meredith and Brunson 2021; Meredith et al. 2021; Germino et al. 2022). Public–private partnerships have also supported active investment in restoration and future sustainability of Northwest rangelands (Charnley et al. 2018; Smith et al. 2022).

Northwest rangelands are vulnerable to climate change effects (Cartwright et al. 2020; Dalton and Fleishman 2021) and are affected by past management legacies that influence disturbance regimes and management options (Galbraith and Anderson 1971; Davies et al. 2009, 2018a; Boyd 2022). This suite of challenges creates an urgent need to effectively implement collaborative, climate-change-informed solutions. The purpose of this paper is to inform this need through providing: 1) a synthesis of the scientific literature on climate change vulnerabilities on Northwest rangelands, and 2) examples of climate adaptation management strategies that can address these vulnerabilities in proactive and collaborative ways on private and public rangelands. To this end, geographically relevant climate change assessments and papers cited therein were reviewed; we also reviewed the current literature on rangeland management, including grazing management, restoration practices, and related challenges in the Northwest. Ultimately, this paper aims to integrate information across several areas of science and management to offer actionable adaptation strategies for Northwest rangeland managers in a changing climate.

Northwest Rangelands in a Changing Climate

Geographic focus

Northwest US rangelands include areas primarily east of the Cascade Mountain range in Oregon (~9.5 million hectares) and Washington (~3.4 million hectares) and much of Idaho (~8.9 million hectares) in the United States (Reeves and Mitchell 2011; Fig. 1). These vast arid to semiarid cold deserts, edged by forests, are characterized by highly variable precipitation, which falls primarily as snow in the winter (Chambers and Pellant 2008). Ninety percent of Northwest rangelands receive an estimated 584 mm of average precipitation (30 year normal) or less each year (Reeves and Mitchell 2011; PRISM Climate Group 2022); half of that 90% (~10 million hectares) receives less than 306 mm of precipitation per year. Common vegetation on these rangelands includes salt desert shrub, sagebrush (*Artemisia*) steppe, sagebrush semiarid desert, and pinyon and juniper woodlands (Chambers and Pellant 2008).

Rangeland recovery

Rangeland ecosystems support a multitude of ecosystem services (Havstad et al. 2007; Maher et al. 2021) and characteristically fluctuate between different plant communities through disturbance (e.g., fire, drought, herbivory, wind; Pellant et al. 2020). These fluctuations are typically referred to as community transitions. Disturbance processes, such as fire, may promote diversity and provide many other benefits as well. However, rangelands also rely upon postdisturbance recovery (i.e., historically typical timeframes for recovery prior to the next disturbance) of plant communities and soils to support ecosystems and their provision of services. Plant communities can undergo substantial and persistent changes in vegetation composition as the result of changed disturbance frequencies and intensities outside of those in which the plants and plant communities have evolved (McIver et al. 2010; Rau et al. 2011; Dettweiler-Robinson et al. 2013a; Joyce et al. 2013; Hoover et al. 2020). “Undesirable transformation” is a term used herein to describe substantial and persistent changes in vegetation with significantly reduced ecosystem services, as can occur with exotic, invasive annual grasses. Disturbance history, together with ecological site characteristics, strongly influence rangeland recovery from disturbance by affecting surface water and soil retention, plant cover, and biological soil crusts (hereafter termed biocrusts; Belnap and Eldridge 2001; Booth and Tueller 2003; Miller et al. 2013; Edwards et al. 2019) and may also inform predictions of vulnerability to climate change effects. Although rangeland assessment and recovery strategies exist (Booth and Tueller 2003; Sheley et al. 2010; Weber and Gokhale 2011; Herrick et al. 2012; Pellant et al. 2020, Meehan et al. 2021), many factors are impeding recovery efforts on Northwest rangelands (Pilliod et al. 2021). While Northwest rangeland ecosystems have evolved under specific disturbance frequencies and intensities, in many areas, these regimes are understood to have changed since European arrival (Boyd 2022). Increases in fuel load quantity and fuel connectivity, driven largely by invasive species, have led to more frequent and larger fires, thus impairing mutualistic relationships between native plants (bunchgrasses and shrubs) and biocrusts, as well as other recovery mechanisms (Belnap and Eldridge 2001; Dettweiler-Robinson et al. 2013a). Climate change introduces potential additional changes in frequency and intensity of disturbance and added stress (Root et al. 2023). Understanding climate change effects as they relate to stress and disturbance on rangelands helps to identify climate change vulnerabilities and create effective adaptation strategies and practices.

Climate change vulnerabilities

Temperature and precipitation

Annual temperature and aridity have increased in the last century and are projected to continue to increase as the climate changes, though the rate and magnitude of change depend upon future greenhouse gas emissions (Halofsky and Peterson 2017; May et al. 2018; Snyder et al., 2019). Midcentury climate projections for the Northwest show an increase in annual average temperature of 2.6°C under a higher emissions scenario, representative concentration pathway 8.5 (RCP 8.5; Edwards et al. 2019), and summers are projected to become warmer and drier this century (Polley et al. 2013; Briske et al. 2015; Palmquist et al. 2016 – RCP 8.5; Vose et al., 2019 – RCP 8.5). Between 1895 and 2011, the Great Basin and Columbia Plateau ecoregions saw temperature increases ranging from 0.7°C to 1.4°C, with a greater increase in the southern Great Basin than in the northern portion (Snyder et al. 2019). Changes in temperatures in these areas have increased more in the winter and at night, and resulted in fewer cold snaps, more frost-free days and nights, and more heatwaves (Snyder et al. 2019). Temperature increases can cause heat stress on plants, wildlife, and livestock, and influence plant phenology. Both earlier green-up and senescence are already being observed or are projected for important grass forage species (Brown et al. 2022; Zimmer et al. 2022).

Climate change also affects the timing and quantity of available water on rangelands. Recent increases in temperature have reduced average annual snowpack (Mote et al. 2018; Snyder et al. 2019; Fig. 2) and led to earlier snowmelt (Mote et al. 2019). Declines in snowpack and earlier snowmelt mean more runoff in spring and less water in summer for livestock watering systems, irrigation, and stream flows. Earlier snowmelt leads to lower stream flows in the summer, which can stress livestock and reduce the survival of wildlife and coldwater fish populations (Mote et al. 2018; Halofsky et al. 2020).

While climate projections for the Northwest indicate a slight increase in average annual precipitation, along with more intense rain events, intensifying droughts and longer periods of dryness in the summer months are also projected (May et al. 2018; Edwards et al. 2019; Dalton and Fleishman 2021). These factors, together with annual variation in the El Niño-Southern Oscillation and decadal variation in the Pacific Decadal Oscillation cycles, are anticipated to increase incidences of extreme wet and dry periods (Dalton and Fleishman 2021). Increased variability in meteorological conditions may make livestock management more difficult than

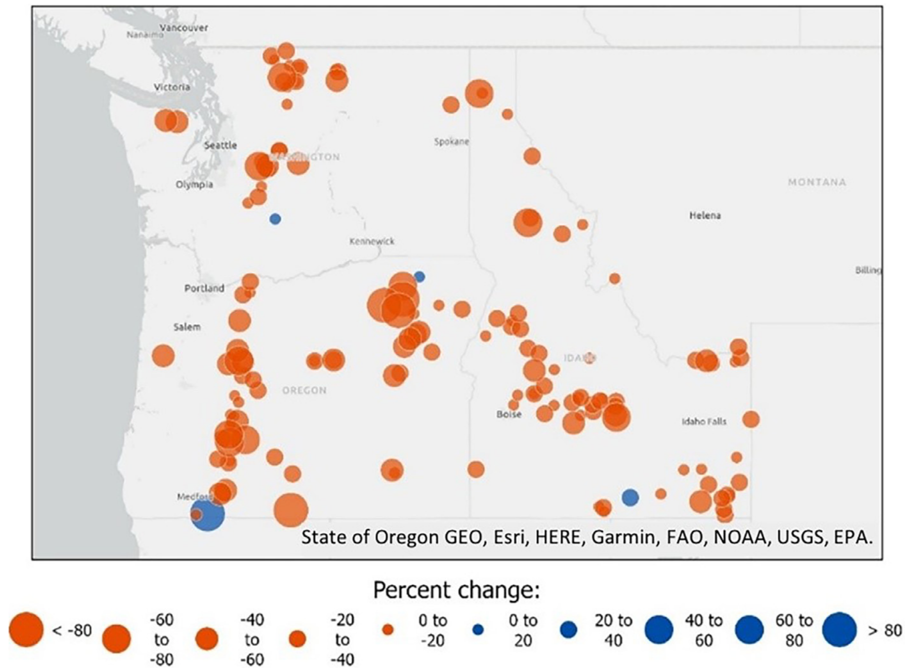

Figure 2. Trends in April snowpack in Idaho, Oregon, and Washington, 1955–2020, data source: https://www.epa.gov/climate-indicators/climate-change-indicators-snowpack, map created by Janelle Christensen, USDA Northwest Climate Hub.

directional change because the former is, by definition, less predictable, and therefore more difficult to plan for.

Higher average and extreme temperatures as well as changes in snowmelt and precipitation timing can directly impact livestock production (Yorgey et al. 2017; Gowda et al. 2018; Vose et al. 2019) and wildlife (Charnley et al. 2018; Rangwala et al. 2021). For example, drought can require sudden destocking or hay feeding (Coppock 2011). Under climate change, increasing heat loads can also increase water demand from livestock while, concurrently, surface water sources become increasingly scarce (Reeves et al. 2017). Also, heat stress can lead to reduced body condition and decreased fertility in livestock (Reeves et al. 2017; Neibergs et al. 2018).

Water and soils

In Northwest rangelands, climate change is likely to impact the availability of water needed for native perennial plant survival and recovery (Hernandez et al. 2017). Semiarid rangelands are particularly sensitive to changes in temperature and precipitation (Mirzabaev et al. 2022), as water is a limiting resource. Soil moisture is driven by soil type interacting with precipitation and temperature (Bradley et al. 2016). Potential evapotranspiration is projected to increase globally, and soil moisture declines are projected to continue (Mirzabaev et al. 2022; Stevenson et al. 2022). Changes in the timing of precipitation and snow melt may reduce soil water availability during the summer months, particularly in riparian areas (Dwire et al. 2018). Increased conifer expansion, such as western juniper (*Juniperus occidentalis* spp. *occidentalis* Hook.), can also reduce available water for vegetation (Kormos et al. 2017; Ray et al. 2019).

The ability for soils to retain water is also likely to be affected. Climate change, precipitation and temperature impacts on biocrusts may be similar to those observed from physical disturbance (Ferrenberg et al. 2015; Edwards et al. 2019). Further, severe fires are known to have long-term negative impacts on biocrusts and soil (Edwards et al. 2019; O'Connor and Germino 2021), as does conifer expansion (Pierson et al. 2007; Chambers et al. 2017a) and annual grass invasion (Ponzetti et al. 2007; Dettweiler-Robinson et al. 2013b). Loss of biocrusts can increase soil erosion, decrease infiltration, and increase evaporation (Dettweiler-Robinson et al. 2013a; Ellsworth et al. 2024). Furthermore, climate change projections of more intense rainfall may lead to increases in postfire soil loss (Edwards et al. 2019). In combination, these factors can make rangelands in the Northwest more susceptible to drought.

Vegetation change and loss

Native vegetation is important for ecosystem services (wildlife habitat, livestock forage production, etc.) and is vulnerable to climate change effects. Climate change in the Northwest is expected to reduce the ability of native plants to compete with invasive plant species. Drought impacts can shorten the growing season and decrease rangeland productivity (Izaurralde et al. 2011; Polley et al. 2013; May et al. 2018; Balachowski et al. 2018). Changes in snowpack, precipitation timing, and historical fire regimes affect native plant recovery (Bates et al. 2006; Zeppel et al. 2014; Chambers, 2015; Boyd 2022). These changes in stress and disturbance will create unprecedented opportunities for the expansion of invasive plant species. Restoration success following severe and large fires is reduced due to low competitive capabilities of native grass and forb seedlings (Chambers et al. 2017b), especially in the context of more frequent, extensive droughts. Native plant vulnerability to fire and invasion varies with site climatic characteristics (temperature and moisture; Chambers et al. 2019; Boyd 2022), proximity to vectors of invasive plant spread and ignition sources (Fusco et al. 2022), abundance of native perennial grass species and biocrusts (Sheley et al. 2010; Chambers et al. 2014b; Pellant et al. 2020; Davies et al. 2021b), plant dispersal mechanisms (Davies and Sheley 2007), and functionality of ecological processes (James et al. 2010; Leffler and Sheley 2012).

Climate change is likely to provide more favorable conditions for grasses and woody species that do well with warmer, drier climates and more frequent fire (Izaurralde et al. 2011; Creutzburg et al. 2015; Ruppert et al. 2015; Bradley et al. 2016;

Fryer 2017; Innes 2022; Snyder et al. 2019; Chambers et al. 2019; Smith et al. 2021). Invasive annual grass species outcompete native grasses given frequent fire activity and dry summers (Davies and Nafus 2013; Snyder et al. 2019; Boyd 2022), conditions which are more typically found at low to mid-elevations. Cheatgrass (*Bromus tectorum* L.) is the most common invasive annual grass in the Northwest, and its spread is likely facilitated by increased spring moisture followed by low summer moisture (Bradley et al. 2016). Cheatgrass has an additional competitive advantage over native grasses during summer droughts because of its spring peak production (Bradley and Mustard 2005; Bradley et al. 2016).

In addition to cheatgrass, there are several plant species that may affect native vegetation due to changes in climate. Ventenata (*Ventenata dubia* (Leers) Coss*;* Kerns et al. 2020; Ridder et al. 2022) is currently invading Northwest ecosystems and creates fuel for fires, increasing grass-fire cycles (Fryer 2017; Innes 2022; Dalton and Fleishman 2021). Future changes in climate may make climates more suitable for Ventenata expansion (Adhikari et al. 2022). Medusahead (*Taeniatherum caput-medusae* (L.) Nevski*)* is an invasive annual grass expanding in the Great Basin region (Nafus and Davies 2014; Davies and Boyd, 2018; Snyder et al. 2019). The success of this grass, as well as Ventenata, may be at least partly due to a warming climate (Snyder et al. 2019). Tamarisk (*Tamarix* spp.) is another invasive plant that is predicted to expand in the Northwest by the end of this century, significantly altering the composition and structure of many riparian corridors (Halofsky and Peterson 2017; Kerns et al. 2009). Additionally, significant expansions and density increases in conifers this century have been projected (Creutzburg et al. 2015; Halofsky et al. 2019). These expansions typically affect mid- to high-elevation areas and lengthen fire return intervals, leading to more severe fires that can promote establishment of invasive grasses (Chambers et al. 2017b; Davies et al. 2021b; Pilliod et al. 2021).

Fire

Climate change is expected to increase fire frequency and severity over large areas in the Northwest. Recent extreme fire years in the Northwest have been associated with high summer temperature and precipitation anomalies (Mote et al. 2019), and these anomalies are anticipated to become more frequent with climate change. Median burn size on rangelands in the Northwest has been projected to increase two to three times for a 1°C increase in temperature (Ojima et al. 2014; Littell et al. 2018). Ocean-atmospheric oscillation cycles, together with climate change factors, may also increase the likelihood of more extreme wet years followed by more extreme dry years (Dalton and Fleishman 2021). This phenomenon may be particularly important for the likelihood of fire on rangelands (Smith et al. 2023). Fires can be driven by fine fuels that accumulate in wet conditions in the 1 to 3 years prior to fire onset (Chambers et al. 2014b; Bradley et al. 2016; Pilliod et al. 2017; Snyder et al. 2019; Smith et al. 2023). Drought incidences this century have supported increased fire activity (Dalton and Fleishman 2021; Mirzabaev et al. 2022; Stevenson et al. 2022). Increasing drought and altered fire regimes make postfire vegetation and biocrust recovery difficult, thus further perpetuating declines in rangeland ecosystem goods and services (Sankey et al. 2013; Shriver et al. 2018; Davies et al. 2021b; O'Connor and Germino 2021; Pilliod et al. 2021).

Climate change effects are likely to increase the range and abundance of invasive annual grasses and exacerbate grass fire cycles in the Northwest. Large, severe fires on rangelands are typically attributed to fuel accumulations (Davies et al. 2021b). These fires can initiate repeated burns that perpetuate disturbance (Davies et al. 2021b) and facilitate the decline of native perennial grasses and shrubs and continued spread of invasive annual grasses (Chambers et al. 2014a; Davies et al. 2021b). Evidence from 1990 to 2020 shows that invasive annual grasses are occurring at higher elevations in the Northern Basin and Range and the Snake River Plains areas, with the greatest elevations being reached on south-facing slopes (Smith et al. 2021). Cheatgrass in particular is known for high variability in production that follows closely with variability in precipitation, filling vegetation interspaces to increase fuel continuity, and senescing (browning down and becoming flammable) earlier in the season, thus perpetuating and benefiting from fire cycles (Davies and Nafus 2013).

Climate change impacts on woodlands or forested areas can also have important effects on adjacent or intermixed Northwest rangelands areas (Haugo et al. 2019). In forested systems, the frequency and extent of fires are projected to increase under a warming climate (Halofsky et al. 2020). Historically, warm and dry conditions corresponded with larger fires in Northwest forests, and fire area burned is expected to increase with warmer and drier conditions in the future (Halofsky et al. 2020). Vast forested areas in eastern Oregon, eastern Washington, and central Idaho have also been affected by mountain pine beetle (*Dendroctonus ponderosae* Hopkins; May et al. 2018). Trees stressed by drought are more susceptible to insect attack, and thus insect-driven mortality will likely continue to affect large areas of forest and their fuel characteristics in the future. Such shifts in forested disturbance regimes can result in a higher probability of fire and spread of undesirable plants on rangelands intermixed with or adjacent to forests.

Impacts from interacting stressors in social and ecological landscapes

Recent extreme droughts in the Northwest shed light on existing vulnerabilities in these social and ecological landscapes (Mote et al. 2016, 2018; May et al. 2018; Vose et al. 2019, Dalton and Fleishman 2021). Shorter-term impacts from the 2014–2015 drought included reduced irrigation water, increased heat stress for livestock, reduced forage quantity and quality, increased fish mortality due to low flows in streams and rivers, and drought-related wildfires affecting hundreds of thousands of hectares (DOI-BLM 2016; May et al. 2018; Vose et al. 2019). Similar impacts were reported in 2021 following the driest March to May since 1924 (the second driest on record) and above-normal temperatures (NIDIS 2021; Bumbaco et al. 2022). The majority of livestock pastures and rangelands were also reported to be in poor to very poor condition (~91% in Washington) by the end of the summer in 2021 due to dry conditions (NASS 2021; NDMC 2021a).

Dry summer months like those that occurred during the 2014–2015 drought may occur more often by mid-century (Marlier et al. 2017; Dalton et al. 2017; Dalton and Fleishman 2021), increasing the importance of better understanding the long-term consequences of these interacting effects. Periods of reduced forage can result in competition between wildlife and livestock and increase the potential for longer term impacts, such as reduced long-term forage production potential, in some areas (Stewart et al. 2002; Coe et al. 2004; Kohl et al. 2023). This can also have potential consequences for riparian areas and adjacent streams, as drought and heat can drive cattle, feral horses, and wildlife to streams during summer when stream flows are at their lowest (Bailey, 2004; Roever et al. 2015; Boyd et al. 2017a; Charnley et al. 2018; Roper and Saunders 2021).

Climate change may compress grazing seasons (Neibergs et al. 2018), as drought occurs more often or worsens, which may affect rural livelihoods and result in additional interacting stressors (Scheffer et al., 2015). Temperature changes, drought, and dominance of invasive annual grasses all result in earlier summer forage senescence, which is projected to increase, as is earlier phenology (Zimmer et al. 2022). Yet, for livestock producers, especially those grazing public lands, changing the beginning of the grazing season

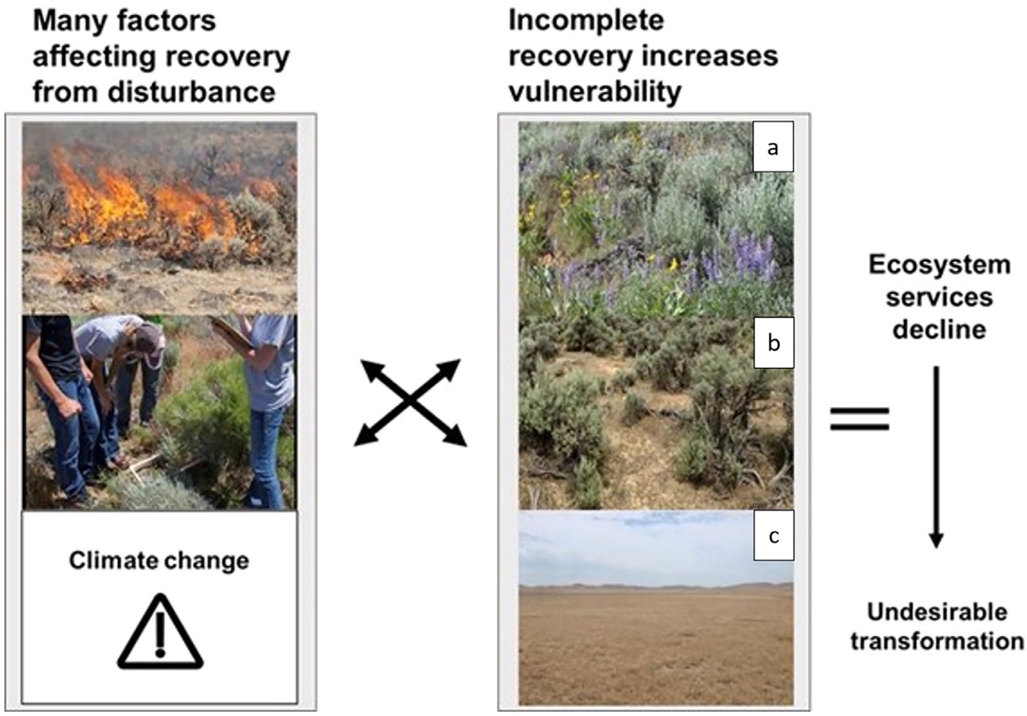

Figure 3. Incomplete recovery of Northwest rangelands from disturbances such as drought and fire can occur due to invasive annual grasses, past and current management, climate change, or other factors. This can make rangeland ecosystem services progressively more vulnerable to these disturbances. This can lead to persistent degradation (e.g., undesirable transformation to invasive annual grass monocultures). For example, (a) diverse and productive rangelands that provide many ecosystem services may experience (b) increasing bare ground in the interspaces between shrubs following one or multiple disturbances, leading to (c) opportunities for undesirable vegetation, such as cheatgrass, to proliferate. Photos left-hand side: fire in sagebrush by Kirk Davies (top left), rangeland management youth training day in southern Idaho by Charity Parks USDA Forest Service (middle left), and photos on the right-hand side: diverse sagebrush ecosystem (top right), annual grass invaded sagebrush ecosystem (middle right), annual grass monoculture (bottom right), by Kirk Davies.

may be undesirable or difficult due to factors such as soil moisture that determine sustainable livestock turn-out dates or time-consuming administrative adjustments (Charnley et al. 2018). Destocking earlier in the season can help to counteract effects from drought (Thurow and Taylor 1999; Holechek et al. 2011) and fire (Wright et al. 1979; DOI-BLM 2007; Meredith and Brunson 2021) but can also have extreme, long-lasting financial impacts for livestock producers (Torell et al. 2010; Maher et al. 2013; Torell et al. 2014; Neibergs et al. 2018; Maher 2019; Runge et al. 2019). In addition to short-term concerns about rural livelihoods, these financial impacts may lead producers to substitute private land when forage is limited on public lands, adding grazing stress to private lands. For example, producers have been known to graze their cattle on private lands when public land grazing is unavailable following large fires, and this has precluded important rehabilitation opportunities on private land (Meredith and Brunson 2021). Such factors can reduce the viability of ranching and increase the likelihood of rangeland conversion to croplands or other forms of land conversion and fragmentation (Runge et al. 2019).

Feedbacks on rangelands

Climate change effects on Northwest rangelands, such as those from periods of extended dryness or increased fire activity, will likely compound over time. Degraded rangelands, specifically those with compacted soil with less organic matter and structure, retain less water and experience vegetation changes (e.g., Rau et al. 2011; Nagy et al. 2021). These rangelands can be slower to recover from stress and disturbance and therefore more vulnerable to subsequent climate change effects.

As degradation and vulnerability to climate change increase, so will the likelihood of "undesirable transformation" to altered or new plant communities with persistent reductions in ecosystem services (Fig. 3). As more droughts and fires occur with climate change, shallow-rooted vegetation systems that are less able to maintain stable, productive vegetation communities are more likely to prevail (Ruppert et al. 2015; Boyd 2022). Some areas of Northwest rangelands may therefore change rapidly from diverse systems that support multiple uses to monocultures of invasive annual grasses and/or more barren landscapes. Such systems provide poor-quality habitat and highly variable forage, impacting wildlife and rural livelihoods. An important role for management in a changing climate is to reduce the likelihood of this undesirable transformation by using effective climate adaptation strategies that support rangeland recovery.

Climate adaptation strategies and practices

Incorporating climate change projections and information about related vulnerabilities into land management within Northwest rangelands can increase management effectiveness; management that is based on this information is referred to herein as "proactive." Supporting rangeland recovery with proactive strategies and practices is an important climate adaptation approach on Northwest rangelands. The following proactive strategies (e.g., improve hydrological function) and practices were developed from the scientific literature and taken or adapted from the Climate Change Adaptation Library (Table 1; AP 2022). This adaptation library is the product of science-management partnerships in the Northwest (and across the western United States) that were focused on climate change vulnerabilities and adaptation (Halofsky et al. 2018c). We divide proactive climate adaptation strategies and practices further into action areas: preparing for (before), responding to (during), and recovering from (after) disturbance.

Table 1
Facilitating rangeland recovery with proactive strategies and practices is an important climate adaptation approach on Northwest rangelands. These strategies (underlined) and related practice examples are presented according to action area (italics): prepare for, respond to, and recover from disturbance. The adaptation information comes from the scientific literature and the Climate Change Adaptation library (AP 2022). The library was developed primarily through workshops held with scientists, agency land managers, landowners, and others to explicitly create climate change vulnerability assessments and adaptation actions. This information was then reviewed by technical experts for scientific credibility through the peer review process (Halofsky et al. 2018b, 2018c).

Approach: Ensure that rangelands recover from disturbance Example strategies and practices
Prepare for disturbance Rangeland assessment • Determine plant community composition and changes over time (trends) • Monitor drought and disturbances Improve hydrologic function • Maintain or restore natural flow regime to buffer against future changes • Protect wetlands and spring-fed streams that maintain higher summer flows • Address water loss at water diversions and ditches • Control pinyon-juniper expansion to minimize water demand and maintain sagebrush Support soil health and vegetation • Maintain soil organic matter and perennial plant vigor and diversity, e.g., plant diverse, climate-adapted perennial species • Consider opportunities for changing grazing distribution, timing, intensity, and duration to sustain appropriate quantities of leaf litter and promote root regrowth • Identify locations where late-season grazing has minimal effects • Facilitate grazing rest for rangeland recovery, e.g., develop forage reserve systems • Co-manage wildlife and domestic ungulates with wildlife specialists to sustain vegetation communities Address the chronic problems of increased fire risk • Plan and prepare for greater burn area • Identify and actively manage areas at risk for severe fire • Consider fuel treatment needs and practices, especially after high fine-fuel production years • Implement invasive annual grass management, including early detection and rapid response
Respond to disturbance Adjust grazing management, provide immediate fire response • Monitor within season while using local knowledge and frequently updated decision-support tools to determine when to move livestock from pasture to pasture or to previously established forage reserves • Hold regular agency-producer meetings • Coordinate with Rangeland Fire Protection Associations and other community partners
Recover from disturbance Immediately take stock of disturbance effects and employ technologies to establish climate-adapted perennial vegetation • Identify disturbance impacts and implement appropriate actions such as: delayed grazing; planting diverse, climate-adapted perennial species; and applying treatments to control invasives • Assess drought and fire response to understand what went well and what could have gone better • Use combined re-vegetation methods, multiple years of planting, and the latest technologies to improve establishment

Prepare for disturbance

Rangeland Assessment

Monitoring existing and developing fire and water issues is facilitated by rangeland health indicators, for example, the Interpreting Indicators of Rangeland Health protocol (Pellant et al. 2020) and the Threat-Based Land Management approach (Johnson et al. 2019). These frameworks are designed specifically for rangeland assessment. Both short-term (e.g., stubble height, foliar cover) and long-term indicators (e.g., perennial grass basal cover and density) on rangelands are important to understanding changes in plant communities (Herrick et al. 2012). Moreover, they can facilitate creation of proactive management planning (e.g., identify locations where late-season grazing has minimal effects) and iterative decision-making strategies that aim to reduce uncertainty in management outcomes over time. Developing additional climate change-informed indicators may also be important (e.g., soil moisture, fuel loads, snow cover and residence time, and shifts in green-up and senescence timing). In addition to on-the-ground monitoring, on-line decision-support tools (e.g., the Rangeland Analysis Platform) can be used to identify vegetation cover and production changes over time (Jones et al. 2018, 2021; Allred et al. 2021; RAP 2022; Smith et al. 2023).

Improve hydrologic function

Practices that improve hydrologic functioning can be critical for minimizing climate change effects on water availability. Identified practices include reconnecting floodplains with streams, as well as restoring riparian areas and American beaver (*Castor canadensis*) populations (Halofsky et al. 2018a). Practices that restore natural stream flows, protect spring-fed streams and wetlands, and/or address water management and soil loss can minimize the impacts from reduced snowpacks and earlier snow melt (Halofsky and Peterson 2017; Halofsky et al. 2019). Controlling conifer expansion also supports grasses through minimizing water demand and protecting against soil erosion and issues with water infiltration (Pierson et al. 2007; Kormos et al. 2017; Halofsky et al. 2018a; Ray et al. 2019).

Support soil health and perennial vegetation

Supporting existing perennial plant vigor and planting climate-adapted, perennial plant species can be important climate adaptation practices (Halofsky and Peterson 2017; Halofsky et al. 2018a; Ellsworth et al. 2024).[1] In contrast to deep-rooted perennial grasses, annual grasses can make rangelands more vulnerable to climate change effects. For example, cheatgrass invasion can deplete water early in the growing season that is needed by perennials during the summertime (Melgoza et al. 1990). However, established perennial bunchgrasses can have extensive root systems and access to water lower in the soil than annual grasses, thereby promoting resistance to invasion (Germino et al. 2022) and better sustaining forage production and wildlife habitat during drought (Ruppert et al. 2015). Accounting for locally adapted, intraspecific variation when planting can improve establishment rates (Baughman et al. 2019). Making efforts prior to the next drought or fire may help limit postdisturbance competition with invasive plants.

Investing in flexible grazing management systems over some more conventional grazing systems can help to minimize climate effects on existing vegetation and soils (Charnley et al. 2018; Neibergs et al. 2018; Peterson and Halofsky 2018). Grazing can be used to sustain the appropriate amount of leaf litter, soil organic

[1] At smaller scales, soil amendments may be practical and effective but such methods on expansive rangelands are infeasible and likely to be ineffective or even counterproductive in the presence of invasive annual grasses.

matter, and ground cover (Davies et al., 2014; Neibergs et al. 2018; Vose et al. 2019). This is typically done by modifying the distribution, timing, intensity, and duration of grazing (Neibergs et al. 2018) and may require fencing, virtual fencing, range riding, or other means of controlling livestock movement. To gain or maintain access to forage, grazing systems may require investing in upland water systems (e.g., stock wells) to improve animal distribution and/or forage reserve networks for livestock (White and Conley 2007; Kachergis et al. 2014; Charnley et al. 2018; Neibergs et al. 2018; Maher 2019). The United States Department of Agriculture Natural Resources Conservation Service Environmental Quality Incentives Program provides technical assistance on privately owned lands and may ameliorate the costs for these investments (Maher et al. 2023). Beef cattle stocker/yearling production options can also increase flexibility and minimize costly forage demand and supply mismatches for cow-calf operations, though it may increase other costs or risks to production (Torell et al. 2010; Ruff et al. 2016; Reeves et al. 2022; Cummings et al. 2023). Finally, planning for potential overlap in resource demands of wild, feral, and domestic species in time and space during droughts creates grazing and wildlife management systems that are better adapted to climate change (Stewart et al. 2002; Coe et al. 2004; Roever et al. 2015; Halofsky and Peterson 2017; Roper and Saunders 2021; Kohl et al. 2023).

Address the chronic problem of increased fire risk

Preparing for more frequent fire while limiting the spread of invasive plant species can be supported through actions taken prior to disturbance events (Davies et al. 2021b; Boyd 2022). Information about the likelihood of postfire recovery potential helps to identify vulnerable plant communities. Postfire recovery potential varies with prefire community composition, site climatic characteristics, and elevation (Pyke et al. 2013; Chambers et al. 2019; Cartwright et al. 2020; Davies et al. 2021b). Effective fire management in a changing climate includes planning and preparing for greater burn area (Halofsky and Peterson 2017), identifying and actively managing areas at risk for severe fire (Halofsky and Peterson 2017; Halofsky et al. 2018a; Halofsky et al. 2019), weed management, and creating vegetation mosaics that help limit fire size (Halofsky et al. 2018a). For example, perennial grasses under shrubs can be more vulnerable to fire effects than those in interspaces (Boyd et al. 2015), suggesting a need for structural diversity in plant communities in a changing climate. Planning treatments across large areas can help to identify defendable fuel breaks, more comprehensive fuel reduction strategies, and opportunities to minimize treatment-related habitat fragmentation impacts (Pyke et al. 2010; Maestas et al. 2016; Shinneman et al. 2018; Shinneman et al. 2019). Fire breaks serve to disrupt fuel continuity, accumulation, and volatility, thus reducing fire intensity and rate of spread while also providing refugia for suppression resources in fast-moving fires (Wollstein et al. 2022). Online wildfire prediction tools like the Great Basin Rangeland Fire Map (RAP 2022; Smith et al. 2023) can inform strategic fuels reduction approaches.

Invasive plant management can reduce the likelihood of perpetuating the grass-fire feedback loop and maximize postdisturbance rangeland recovery potential. Minimizing potential vectors for invasive grass and forb species seed spread and ignition sources help to reduce establishment of invasive annual grasses (Chuong et al. 2016; Fusco et al. 2022). Early detection and rapid response is a popular method for many emerging invasive plant species threats (Chambers et al. 2017a; Halofsky et al. 2018b). Using biological controls, herbicides, mechanical treatments, education, and targeted grazing are all important practices to consider for managing existing invasive plants (Halofsky et al. 2018a, 2018b; Lake and Minteer 2018). Ecologically Based Invasive Plant Management provides a step-by-step framework for management of invasive plants on rangelands (Leffler and Sheley 2012; Halofsky et al. 2018b).

The use of prescribed and managed fire may be particularly complex in the presence of invasive annual grass species (Pyke et al. 2010; Miller et al. 2013) and to accommodate wildlife habitat needs (Boyd et al. 2017b). Management in these cases may require prescribed fire surrogates (mimicking changes associated with fire; Miller et al. 2013) and/or pre- or post-fire herbicide application (Halofsky and Peterson 2016; Mealor, 2016; Halofsky and Peterson 2017). A combination of fire and cutting treatments may be most effective for conifers, as prescribed fire can have greater than two times the treatment life of mechanical treatments only (Boyd et al. 2017b; Davies et al. 2019). Informed timing (e.g., burning during dormant season versus later in summer) can also improve native plant response to avoid flushes of invasives after treatment (see Pyke et al. 2010; Miller et al. 2013 for guidance). However, managers may need to watch for changes in dormant season timing that may be occurring with climate change (Munson and Long 2017).

Respond to disturbance

Adjust Grazing Management and Provide Immediate Fire Response

Responding effectively to disturbance includes monitoring vegetation characteristics (e.g., forage and fuel production), using frequently updated decision-support tools, and accessing fire response resources. Short-term indicators, such as stubble height or utilization levels, can inform timely response throughout the year (Herrick et al. 2012). Livestock grazing management adjustments during the grazing season are commonly practiced and important, but additional and/or significant adjustment may be needed during drought, fire, flood, or other disturbances. Online decision-support tools that are updated frequently (weekly or biweekly) and/or provide predictions, for example the US Drought Monitor (NDMC 2021b), Phenomap (Schrader-Patton et al. 2024), Fuelcast (Jones et al., 2021; Reeves et al. 2021), the Wallowa County Livestock Early Warning System, and the Rangeland Analysis Platform: Production Explorer feature, can further inform grazing and wildlife management in these situations. Some of these tools also provide near-term forecasts of forage production. Regular agency-producer meetings that use these tools and communicate additional observations during drought may support timely communication and grazing adjustment needs. If forage reserve systems have been previously established, they may be an important option during this time (Maher 2019). Additionally, coordination with community-based organizations such as Rangeland Fire Protection Associations during fires can help to provide improved wildfire response and minimize immediate impacts (Wollstein et al. 2022).

Recover from disturbance

Immediately Take Stock of Disturbance Effects and Employ Technologies to Establish Climate-Adapted Perennial Vegetation

Postdisturbance recovery needs include taking stock of disturbance impacts and establishing climate-adapted perennial vegetation. Postdisturbance recovery efforts may be needed over multiple years to promote vegetation recovery. Monitoring of postdisturbance effects can help inform appropriate actions, including rest from grazing and restoration practices. As drought and fire increase with climate change, longer or more frequent grazing rest may be needed to support vegetation and soil recovery. To meet resting needs, livestock may need to be moved to other pastures within the same private grazing system or public allotment, from the public allotment to the base (private) property, or to public or private forage areas specifically reserved for these occasions. Within-pasture postdisturbance adjustment of livestock movement patterns through the use of virtual or temporary fencing may also be an important option in lieu of complete destocking (Boyd et al. 2022). This may also be a good time to reflect on the effectiveness of the disturbance response and the adequacy of recovery resources such as forage reserves.

Revegetation can be important after large fires or extensive drought that results in low perennial plant survival. As with preparing for disturbance, using a diverse mix of drought- and locally adapted species and genotypes can increase and sustain recovery success (Chambers et al. 2017b; Halofsky et al. 2018a, 2018b, 2018c; Baughman et al. 2019). Several years of seeding and combined re-vegetation methods may be needed to improve establishment success after fire, especially if drought persists (Davies et al. 2018b; Shriver et al. 2018, 2019). Decision-support tools are available that may improve postfire restoration success, for example the Short-term Ecological Drought Forecaster (USGS 2022) and the Climate Smart Restoration Tool (St. Clair et al. 2022). Urgent application of post-disturbance invasive plant management can be critical to support native plant and soil recovery (Halofsky et al. 2018a). New technologies are being developed to improve efficacy, including using pre-emergent herbicide together with activated carbon seed pelleting or coating to protect plantings from herbicide damage while allowing for control of exotic annuals immediately after fire (Madsen et al. 2014; Davies et al. 2017; Davies 2018; Clenet et al. 2019, 2020; Holfus et al. 2021).

Climate adaptation in practice

Incorporating climate change information into management has its benefits and challenges. The vulnerabilities and related adaptation strategies and actions identified herein can help guide management. Being informed about the effects of management actions today on future outcomes has the potential to limit unintended management outcomes (Albers, 1996; Albers and Goldbach, 2000; Marcot 2020). In the context of climate change, new conditions will occur that differ from past experiences, so ecosystems may respond differently to the same management than they did in the past. Land managers may therefore benefit from reconsidering their perception of risk considering climate change information. Specifically, considering future projections may lead to management actions that are better adapted to climate change.

Rangeland managers work across vast areas with finite resources to address many management needs, including preparing for, responding to, and recovering from disturbances. There are important trade-offs to consider when investing in one management need over another. Furthermore, uncertainty inherent in both climate change projections and management effectiveness can make it difficult for managers to incorporate climate change information into management (Heal and Kriström 2002; Pindyck 2007; Kundzewicz et al. 2018; Maas et al. 2020; Rangwala et al. 2021; Wardropper et al. 2021). For example, there can be substantial spatial and temporal variation in climate effects, and therefore estimates at only large scales can make it difficult to plan at the local level (Polley et al. 2013; Svejcar et al. 2016; Dierauer et al. 2019; Cartwright et al. 2020).

Collaborative efforts within the larger rangeland management community can help to achieve some of the benefits and to overcome some of the challenges associated with climate adaptation. Land managers partnering with scientists can help with science translation, planning, and data analysis (e.g., downscaling) as needed for improved decision making (Allen et al., 2011; Littell et al. 2012; Joyce and Millar 2014; Marcot 2020; Rangwala et al. 2021). For example, there are ongoing science-management partnership efforts working to identify climate vulnerabilities at more local scales (Rangwala et al. 2021), including place-based climate change vulnerability assessments (Halofsky et al. 2018c).

Within the context of the science–management partnership for climate adaptation, managers can play an integral role, including pooling resources, information gathering/sharing, and practice implementation. Intensifying invasive annual grasses and wildfire management challenges increase the benefits of engaging in larger-scale, collaborative adaptation efforts. There is also a growing recognition of the contribution that local, indigenous, intergenerational, and/or professional knowledge contributes to scientific knowledge and natural resource management (Knapp and Fernandez-Gimenez 2009a, 2009b; Littell et al. 2012; Marcot 2020; Reid et al. 2021; STACCWG 2021; Smith et al. 2022). On rangelands, some scientists have begun to work with managers, livestock producers, and/or indigenous peoples in more collaborative ways to address complex management challenges (Wilmer et al. 2018; Steen-Adams et al. 2019). In addition to providing intergenerational and practical knowledge, livestock producers can be important investors in rangelands (Briske et al. 2015; Collins 2019), provide a set of boots and eyes on the ground for management as issues like wildfire and invasive annual grasses unfold (WGA 2022), and may play an important role as "ecosystem engineers" in reducing fuel as a proactive strategy (Boyd et al. 2014; Bailey et al. 2019; Davies et al. 2021a, 2021b). Providing opportunities for managers to engage in such partnerships may therefore be an essential part of proactive climate adaptation on Northwest rangelands.

Multipartner land management studies that incorporate climate projections into planning and use timely observations to adjust management can grow the information base for climate adaptation in a management setting. For example, case studies of collaborative efforts can provide information about practice efficacy, benefits and costs of climate adaptation practices, and resource pooling opportunities (Charnley et al. 2018; Reeves et al. 2022), while identifying methods to increase the pace of learning (Wilmer et al. 2018; Derner et al. 2021). Collaborative experimentation and case study opportunities include virtual fencing for riparian and/or burned areas (Boyd et al. 2022), fine-fuel management (Davies et al. 2021b), improved seed planting methods (Davies et al. 2018b; Phillips et al. 2021), prefire and postfire invasive grass management (Mealor 2016), validating climate change-informed indicators, and development of water sources for wildlife and livestock (Charnley et al. 2018). In addition to learning, collaborative approaches in general have been found to foster planning, trust, and resource sharing which may alleviate many of the barriers to implementing effective climate adaptation (Timberlake and Schultz 2017; Charnley et al. 2018; Fernández-Giménez et al. 2019; McIver and Becker 2021; Reid et al. 2021; Timberlake et al. 2021). Ranchers, for example, may behave more proactively upon learning of positive management outcomes from short-term adaptations (Saliman and Petersen-Rockney 2022). Science–management partnerships may facilitate such observations, e.g., through lending data collection and analysis expertise.

Two recent efforts to address drought concerns serve as concrete examples of proactive management projects made possible through collaboration. The first effort is the creation of co-produced (federal agency and livestock producer) drought plans for Southwest National Forests; this was a long-term project organized by researchers from the University of Arizona to inform investment in and implementation of strategic grazing, while retaining management flexibility (Hawkes et al. 2018; Vose et al. 2019). This effort was separate from formal public agency management plans and theoretically, such drought plans are a guidance tool that can be updated more frequently if needed. Collaborators for this project included Tonto National Forest staff, livestock grazing permittees, US Forest Service leadership, and Gila County Cattle Growers Association. Planning collaboratively, iteratively, and multiple years ahead is critical to supporting climate adaptation approaches related to flexible grazing methods because of the level of investment, uncertainty, and cooperation needed (Charnley et al. 2018; Hawkes et al. 2018; Neibergs et al. 2018); this type of planning is also important for completing necessary procedures to get actions approved (e.g., 3–5 years to complete the National Environmental Policy Act process for developing water sources; Hawkes et al. 2018). Such co-produced plans may also provide important opportunities to use local and intergenerational knowledge and decision-support tools (Haigh et al. 2021), such as those using geospatial data (Hudson et al. 2021).

The second example is a riparian restoration project guided in part by the Blue Mountains Working Group in the Blue Mountains Ecoregion of eastern Oregon. Partnerships established specifically for that project have successfully implemented collaborative approaches to overcome several barriers to management innovation in public-lands grazing in riparian systems (Charnley et al. 2018). Among other beneficial outcomes, Bonneville Power Administration, the US Forest Service, livestock producers, and other partners worked together to share investment costs of new pasture fencing, riparian research exclosures, and upland water sources to support and evaluate sustainable livestock grazing in a riparian system that serves as habitat for fish listed under the Endangered Species Act (Charnley et al. 2018). These examples demonstrate the importance of leveraging the broader rangeland community to achieve proactive climate adaptation. However, the interest in collaborative projects such as these ebbs and flows. It can be much more difficult to sustain momentum with collaborative efforts if people believe that extreme disturbance and/or stressors are unlikely to occur again (Maas et al. 2020; WGA 2022), hence there is a vital need to continually incorporate climate change information into collaborative approaches and education programs.

Conclusions

Climate change is expected to have significant impacts this century on rangelands and the goods and services they provide. These impacts will be realized primarily through increased likelihood, severity, and extent of disturbances that affect rangeland recovery. With climate change, larger areas will be affected by disturbance, recovery times will be longer, and investment costs in recovery will be higher, all of which may lead to more degraded lands. Because of the multitude of factors affecting Northwest rangelands, including climate change, we cannot know with certainty to what extent management actions can reverse plant community change nor where such tactics make sense in a changing climate. A better understanding of the value of management that avoids undesirable transformation may be critical to decision-making moving forward.

In natural resource systems, our understanding of climate change vulnerabilities, resilience management, and restoration is changing. Management direction is moving from a focus on returning to historical conditions to managing according to a climate change-informed future so that these lands have a higher likelihood of rebounding from extreme and prolonged disturbances (Davies et al. 2009, 2021b; Falk and Millar 2016; Fischelli et al. 2016; Seidl et al. 2016; Urgenson 2017; Timberlake et al. 2018; Keane and Loehman 2019; Schuurman et al. 2020; Williams et al. 2021). This change points to a cultural shift to more proactive management options that guide and protect ecosystems through these changes. This shift also indicates an unprecedented need for collaborative goal setting and implementation at federal, state, tribal, private landowner, and community levels. However, as climate changes continue and more deleterious impacts occur, the opportunities for more proactive climate adaptation will diminish (Joyce et al. 2013). Awareness of climate projections and vegetation disturbance response helps land managers more accurately weigh the costs and benefits of engaging in climate adaptation activities and may lead to more proactive approaches (Maher 2019; Saliman and Petersen-Rockney 2022). Given these rapid changes and uncertainties, now is the time to take action to leverage available opportunities and reduce impacts from climate change on Northwest rangelands. Practices such as planting climate-adapted and diverse species mixes, creating habitat mosaics, and other methods to promote biodiversity and recovery are not new to landscape or rangeland ecology. However, the large-scale collaborative, proactive effort that is needed today is new for some. Such orchestrated approaches are more important now than ever before to the future sustainability of Northwest rangelands.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Anna T. Maher: Writing – original draft. **Holly R. Prendeville:** Writing – original draft. **Jessica E. Halofsky:** Writing – original draft. **Mary M. Rowland:** Writing – original draft. **Kirk W. Davies:** Writing – original draft. **Chad S. Boyd:** Writing – original draft.

Acknowledgments

We appreciate Hailey Hester's efforts in making Figure 1 and calculating rangeland acres. We also appreciate Janelle Christensen's efforts in making Figure 2.

Disclaimer

Mention of a proprietary product does not constitute a guarantee or warranty of the product by the USDA, the U.S. Government, or the authors and does not imply its approval to the exclusion of other products that may also be suitable. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the USDA. USDA is an equal opportunity provider and employer.

References

Adhikari, A., Mangold, J., Mainali, K.P., Rew, L.J., 2022. Climate change and more disturbed land-use types will further the invasion of a non-native annual grass, Ventenata dubia. Biological Invasions 25, 285–296. doi:10.1007/s10530-022-02913-4.

Albers, H.J., 1996. Modeling ecological constraints on tropical forest management: spatial interdependence, irreversibility, and uncertainty. Journal of Environmental Economics and Management 30 (1), 73–94. doi:10.1006/jeem.1996.0006.

Albers, H.J., Goldbach, M.J., 2000. Irreversible ecosystem change, species competition, and shifting cultivation. Resource and Energy Economics 22 (3), 261–280. doi:10.1016/S0928-7655(00)00034-8.

Allen, C.R., Fontaine, J.J., Pope, K.L., Garmestani, A.S., 2011. Adaptive management for a turbulent future. Journal of Environmental Management 92, 1339–1345. doi:10.1016/j.jenvman.2010.11.019.

Allred, B.W., Bestelmeyer, B.T., Boyd, C.S., Brown, C., Davies, K.W., Duniway, M.C., Ellsworth, L.M., Erickson, T.A., Fuhlendorf, S.D., Griffiths, T.V., Jansen, V., Jones, M.O., Karl, J., Knight, A., Maestas, J.D., Maynard, J.J., McCord, S.E., Naugle, D.E., Starns, H.D., Twidwell, D., Uden, D.R., 2021. Improving Landsat predictions of rangeland fractional cover with multitask learning and uncertainty. Methods in Ecology and Evolution 12, 841–849. doi:10.1111/2041-210X.13564.

AP (Adaptation Partners), 2022. Climate change adaptation library for the Western United States. U.S. Forest Service, Office of Sustainability and Climate, Pacific Northwest Research Station. Available at: http://adaptationpartners.org/library.php (Accessed 21 April 2022).

Archer, S., Schimel, D.S., Holland, E.A., 1995. Mechanisms of shrubland expansion: land use, climate or CO_2? Climatic Change 29, 91–99. doi:10.1007/BF01091640.

Bailey, D.W., 2004. Management strategies for optimal grazing distribution and use of arid rangelands. Journal of Animal Science 82, E147–E153.

Bailey, D.W., Mosley, J.C., Estell, R.E., Cibils, A.F., Horney, M., Hendrickson, J.R., Walker, J.W., Launchbaugh, K.L., Burritt, E.A., 2019. Synthesis paper: targeted livestock grazing: prescription for healthy rangelands. Rangeland Ecology & Management 72, 865–877. doi:10.1016/j.rama.2019.06.003.

Bailey, R.G., 2016. Bailey's ecoregions and subregions of the United States, Puerto Rico, and the U.S. Virgin Islands. Forest Service Research Data Archive, Fort Collins, CO doi:10.2737/RDS-2016-0003.

Balachowski, J., Alvarez, P., Kerr, A., Reyes, J., Xides, A., Choe, H., Peters, C., Brown, J., Roche, L., 2018. Climate vulnerability assessment of California rangelands. USDA California Climate Hub, Agricultural Research Service, University of California, Davis, Davis, CA, USA, p. 73. doi:10.32747/2018.6876398.ch.

Bates, J.D., Svejcar, T., Miller, R.F., Angell, R.A., 2006. The effects of precipitation timing on sagebrush steppe vegetation. Journal of Arid Environments 64, 670–697. doi:10.1016/j.jaridenv.2005.06.026.

Baughman, O.W., Agneray, A.C., Forister, M.L., Kilkenny, F.F., Espeland, E.K., Fiegener, R., Horning, M.E., Johnson, R.C., Kaye, T.N., Ott, J., St.Clair, J.B., Leger, E.A., 2019. Strong patterns of intraspecific variation and local adaptation in Great Basin plants revealed through a review of 75 years of experiments. Ecology and Evolution 9, 6259–6275. doi:10.1002/ece3.5200.

Belnap, J., Eldridge, D., 2001. Disturbance and recovery of biological soil crusts. In: Belnap, J., Lange, O.L. (Eds.), Biological soil crusts: structure, function, and management. Ecological studies, vol 150. Springer, Berlin, Heidelberg, Germany, pp. 363–383. doi:10.1007/978-3-642-56475-8_27.

Belnap, J., Ludwig, J.A., Wilcox, B.P., Betancourt, J.L., Dean, W.R.J., Hoffmann, B.D., Milton, S.J., 2012. Introduced and invasive species in novel rangeland ecosystems: friends or foes? Rangeland Ecology & Management 65, 569–578. doi:10.2111/REM-D-11-00157.1.

BirdLife International, 2016. Centrocercus urophasianus. The IUCN Red List of Threatened Species 2016: e.T22679503A92816586. https://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22679503A92816586.en (Accessed 19 December 2022).

Booth, D.T., Tueller, P.T., 2003. Rangeland monitoring using remote sensing. Arid Land Research and Management 17, 455–467. doi:10.1080/713936105.

Boyd, C.S., 2022. Managing for resilient sagebrush plant communities in the modern era: we're not in 1850 anymore. Rangelands 44, 167–172. doi:10.1016/j.rala.2022.02.002.

Boyd, C.S., Beck, J.L., Tanaka, J.A., 2014. Livestock grazing and sage-grouse habitat: impacts and opportunities 20. Journal of Rangeland Applications 1, 58–77.

Boyd, C.S., Davies, K.W., Collins, G, 2017a. Impacts of feral horse use on riparian vegetation within the sagebrush steppe. Rangeland Ecology & Management 70, 411–417. doi:10.1016/j.rama.2017.02.001.

Boyd, C.S., Davies, K.W., Hulet, A., 2015. Predicting fire-based perennial bunchgrass mortality in big sagebrush plant communities. International Journal of Wildland Fire 24, 527–533. doi:10.1071/WF14132.

Boyd, C.S., Kerby, J.D., Svejcar, T.J., Bates, J.D., Johnson, D.D., Davies, K.W., 2017b. The sage-grouse habitat mortgage: effective conifer management in space and time. Rangeland Ecology & Management 70, 141–148. doi:10.1016/j.rama.2016.08.012.

Boyd, C.S., O'Connor, R., Ranches, J., Bohnert, D.W., Bates, J.D., Johnson, D.D., Davies, K.W., Parker, T., Doherty, K.E., 2022. Virtual fencing effectively excludes cattle from burned sagebrush steppe. Rangeland Ecology & Management 81, 55–62. doi:10.1016/j.rama.2022.01.001.

Bradley, B.A., Curtis, C.A., Chambers, J.C., 2016. Bromus response to climate and projected changes with climate change. In: Germino, M.J., Chambers, J.C., Brown, C.S. (Eds.), Exotic brome-grasses in arid and semiarid ecosystems of the Western US. Springer Series on Environmental Management. Springer International Publishing, Cham, Switzerland, pp. 257–274. doi:10.1007/978-3-319-24930-8_9.

Bradley, B.A., Mustard, J.F., 2005. Identifying land cover variability distinct from land cover change: cheatgrass in the Great Basin. Remote Sensing of Environment 94, 204–213. doi:10.1016/j.rse.2004.08.016.

Briske, D.D., Joyce, L.A., Polley, H.W., Brown, J.R., Wolter, K., Morgan, J.A., McCarl, B.A., Bailey, D.W., 2015. Climate-change adaptation on rangelands: linking regional exposure with diverse adaptive capacity. Frontiers in Ecology and the Environment 13, 249–256. doi:10.1890/140266.

Brown, C.L., Coe, P.K., Clark, D.A., Wisdom, M.J., Rowland, M.M., Averett, J.P., Johnson, B.K., 2022. Climate change effects on understory plant phenology: implications for large herbivore forage availability. Environmental Research: Ecology 1, 011002. doi:10.1088/2752-664X/ac7fb0.

Bruno, J.E., Jamsranjav, C., Jablonski, K.E., Dosamantes, E.G., Wilmer, H., Fernández-Giménez, M.E., 2020. The landscape of North American Rangeland Social Science: a systematic map. Rangeland Ecology & Management 73, 181–193. doi:10.1016/j.rama.2019.10.005.

Bumbaco KA, Rogers MH, O'Neill LW, Hoekema DJ, Raymond CL, 2022. 2021 Pacific Northwest Water Year Impacts Assessment. A collaboration between the Office of the Washington State Climatologist, Climate Impacts Group, Oregon State Climatologist, Idaho Department of Water Resources, and NOAA National Integrated Drought Information System. 45 p. Available at: https://www.drought.gov/sites/default/files/2022-02/PNW-Water-Year-Impacts-Assessment-2021.pdf (Accessed 19 December 2022).

Cartwright, J.M., Littlefield, C.E., Michalak, J.L., Dobrowski, S.Z., 2020. Topographic, soil, and climate drivers of drought sensitivity in forests and shrublands of the Pacific Northwest, USA. Scientific Reports 10, 18486. doi:10.1038/s41598-020-75273-5.

Chambers, J., 2015. Seeding big sagebrush successfully on intermountain rangelands, Great Basin Factsheet Series. Available at: https://www.sagegrouseinitiative.com/wp-content/uploads/2015/11/10_GBFS_seeding_sagebrush.pdf (Accessed 14 September 2022).

Chambers, J.C., Beck, J.L., Bradford, J.B., Bybee, J., Campbell, S., Carlson, J., Christiansen, T.J., Clause, K.J., Collins, G., Crist, M.R., Dinkins, J.B., Doherty, K.E., Edwards, F., Espinosa, S., Griffin, K.A., Griffin, P., Haas, J.R., Hanser, S.E., Havlina, D.W., Henke, K.F., Hennig, J.D., Joyce, L.A., Kilkenny, F.M., Kulpa, S.M., Kurth, L.L., Maestas, J.D., Manning, M., Mayer, K.E., Mealor, B.A., McCarthy, C., Pellant, M., Perea, M.A., Prentice, K.L., Pyke, D.A., Wiechman, L.A., Wuenschel, A., 2017a. Science framework for conservation and restoration of the sagebrush biome: linking the Department of the Interior's Integrated Rangeland Fire Management Strategy to long-term strategic conservation actions, Part 2 Management Applications (No. RMRS-GTR-389). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, USA, p. 237. doi:10.2737/RMRS-GTR-389.

Chambers, J.C., Bradley, B.A., Brown, C.S., D'Antonio, C., Germino, M.J., Grace, J.B., Hardegree, S.P., Miller, R.F., Pyke, D.A., 2014a. Resilience to stress and disturbance, and resistance to Bromus tectorum L. invasion in cold desert shrublands of Western North America. Ecosystem 17, 360–375. doi:10.1007/s10021-013-9725-5.

Chambers, J.C., Brooks, M.L., Germino, M.J., Maestas, J.D., Board, D.I., Jones, M.O., Allred, B.W., 2019. Operationalizing resilience and resistance concepts to address invasive grass-fire cycles. Frontiers in Ecology and Evolution 7, 185. doi:10.3389/fevo.2019.00185.

Chambers, J.C., Maestas, J.D., Pyke, D.A., Boyd, C.S., Pellant, M., Wuenschel, A., 2017b. Using resilience and resistance concepts to manage persistent threats to sagebrush ecosystems and greater sage-grouse. Rangeland Ecology & Management 70, 149–164. doi:10.1016/j.rama.2016.08.005.

Chambers, J.C., Pellant, M., 2008. Climate change impacts on northwestern and intermountain United States rangelands. Rangelands 30, 29–33. doi:10.2111/1551-501X(2008)30[29:CCIONA]2.0.CO;2.

Chambers, J.C., Pyke, D.A., Maestas, J.D., Pellant, M., Boyd, C.S., Campbell, S.B., Espinosa, S., Havlina, D.W., Mayer, K.E., Wuenschel, A., 2014b. Using resistance and resilience concepts to reduce impacts of invasive annual grasses and altered fire regimes on the sagebrush ecosystem and greater sage-grouse: A strategic multi-scale approach (No. RMRS-GTR-326). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, USA doi:10.2737/RMRS-GTR-326.

Charnley, S., Gosnell, H., Wendel, K.L., Rowland, M.M., Wisdom, M.J., 2018. Cattle grazing and fish recovery on US federal lands: can social-ecological systems science help? Frontiers in Ecology and the Environment 16, S11–S22. doi:10.1002/fee.1751.

Chuong, J., Huxley, J., Spotswood, E.N., Nichols, L., Mariotte, P., Suding, K.N., 2016. Cattle as dispersal vectors of invasive and introduced plants in a California Annual Grassland. Rangeland Ecology & Management 69, 52–58. doi:10.1016/j.rama.2015.10.009.

Clenet, D.R., Davies, K.W., Johnson, D.D., Kerby, J.D., 2019. Native seeds incorporated into activated carbon pods applied concurrently with indaziflam: a new strategy for restoring annual-invaded communities? Restoration Ecology 27, 738–744. doi:10.1111/rec.12927.

Clenet, D.R., Davies, K.W., Johnson, D.D., Kerby, J.D., 2020. Herbicide protection pods (HPPs) facilitate sagebrush and bunchgrass establishment under imazapic control of exotic annual grasses. Rangeland Ecology & Management 73, 687–693. doi:10.1016/j.rama.2020.07.002.

Coe, P.K., Johnson, B.K., Stewart, K.M., Kie, J.G., 2004. Spatial and temporal interactions of elk, mule deer and cattle. In: Transactions of the 69th North American Wildlife and Natural Resources Conference, pp. 656–669.

Collins, A.C., 2019. Demographics, motivations, and experiences of producers participating in the environmental quality incentives program and the conservation stewardship program (Order No. 13880743). Master's thesis. University of Wyoming. Dissertations & Theses @ University of Wyoming. Available at: http://libproxy.uwyo.edu/login/?url=https://search-proquest-com.libproxy.uwyo.edu/docview/2297180150?accountid=14793 (Accessed 13 March 2023).

Coppock, D.L., 2011. Ranching and multiyear droughts in Utah: production impacts, risk perceptions, and changes in preparedness. Rangeland Ecology & Management 64, 607–618. doi:10.2111/REM-D-10-00113.1.

Creutzburg, M.K., Halofsky, J.E., Halofsky, J.S., Christopher, T.A., 2015. Climate change and land management in the rangelands of central Oregon. Environmental Management 55, 43–55. doi:10.1007/s00267-014-0362-3.

Cummings, D.B., Groves, J.T., Turner, B.L., 2023. Assessing the role of systems thinking for stocker cattle operations. Veterinary Sciences 10, 69. doi:10.3390/vetsci10020069.

Dalton, M.M., Dello, K.D., Hawkins, L., Mote, P.W., Rupp, D.E., 2017. The third Oregon climate assessment report. Oregon Climate Change Research Institute, College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. Available at: https://pnwcirc.org/sites/pnwcirc.org/files/ocar3_finalweb.pdf (Accessed 13 March 2023).

Dalton, M., Fleishman, E. (Eds.), 2021. Fifth Oregon climate assessment. Oregon Climate Change Research Institute, Oregon State University, Corvallis, OR, USA. Available at: https://oregonstate.app.box.com/s/7mynjzhda9vunbzqib6mn1dcpd6q5jka (Accessed 13 March 2023).

Davies, K.W., 2018. Incorporating seeds in activated carbon pellets limits herbicide effects to seeded bunchgrasses when controlling exotic annuals. Rangeland Ecology & Management 71, 323–326. doi:10.1016/j.rama.2017.12.010.

Davies, K.W., Bates, J.D., Boyd, C.S., O'Connor, R., Copeland, S., 2021a. Dormant-season moderate grazing prefire maintains diversity and reduces exotic annual grass response postfire in imperiled artemisia steppe. Rangeland Ecology & Management 79, 91–99. doi:10.1016/j.rama.2021.08.002.

Davies, K.W., Boyd, C.S., 2018. Longer-term evaluation of revegetation of medusahead-invaded sagebrush steppe. Rangeland Ecology & Management 71, 292–297. doi:10.1016/j.rama.2018.02.001.

Davies, K.W., Boyd, C.S., 2020. Grazing is not binomial (i.e., grazed or not grazed): a reply to Herman. Bioscience 70, 6–7. doi:10.1093/biosci/biz138.

Davies, K.W., Boyd, C.S., Bates, J.D., 2018a. Eighty years of grazing by cattle modifies sagebrush and bunchgrass structure. Rangeland Ecology & Management 71, 275–280. doi:10.1016/j.rama.2018.01.002.

Davies, K.W., Boyd, C.S., Beck, J.L., Bates, J.D., Svejcar, T.J., Gregg, M.A., 2011. Saving the sagebrush sea: an ecosystem conservation plan for big sagebrush plant communities. Biological Conservation 144, 2573–2584. doi:10.1016/j.biocon.2011.07.016.

Davies, K.W., Boyd, C.S., Madsen, M.D., Kerby, J., Hulet, A., 2018b. Evaluating a seed technology for sagebrush restoration across an elevation gradient: support for bet hedging. Rangeland Ecology & Management 71, 19–24. doi:10.1016/j.rama.2017.07.006.

Davies, K.W., Leger, E.A., Boyd, C.S., Hallett, L.M., 2021b. Living with exotic annual grasses in the sagebrush ecosystem. Journal of Environmental Management 288, 112417. doi:10.1016/j.jenvman.2021.112417.

Davies, K.W., Madsen, M.D., Hulet, A., 2017. Using activated carbon to limit herbicide effects to seeded bunchgrass when revegetating annual grass-invaded rangelands. Rangeland Ecology & Management 70, 604–608. doi:10.1016/j.rama.2017.04.004.

Davies, K.W., Nafus, A.M., 2013. Exotic annual grass invasion alters fuel amounts, continuity and moisture content. International Journal of Wildland Fire 22, 353. doi:10.1071/WF11161.

Davies, K.W., Rios, R.C., Bates, J.D., Johnson, D.D., Kerby, J., Boyd, C.S., 2019. To burn or not to burn: comparing reintroducing fire with cutting an encroaching conifer for conservation of an imperiled shrub-steppe. Ecology and Evolution 9, 9137–9148. doi:10.1002/ece3.5461.

Davies, K.W., Sheley, R.L., 2007. A conceptual framework for preventing the spatial dispersal of invasive plants. Weed Science 55, 178–184. doi:10.1614/WS-06-161.

Davies, K.W., Svejcar, T.J., Bates, J.D., 2009. Interaction of historical and nonhistorical disturbances maintains native plant communities. Ecological Applications 19, 1536–1545. doi:10.1890/09-0111.1.

Davies, K.W., Vavra, M., Schultz, B., Rimbey, N., 2014. Implications of longer term rest from grazing in the sagebrush steppe. Journal of Rangeland Applications 1, 14–34.

Derner, J.D., Augustine, D.J., Briske, D.D., Wilmer, H., Porensky, L.M., Fernández-Giménez, M.E., Peck, D.E., Ritten, J.P., 2021. Can collaborative adaptive management improve cattle production in multipaddock grazing systems? Rangeland Ecology & Management 75, 1–8. doi:10.1016/j.rama.2020.11.002.

Dettweiler-Robinson, E., Bakker, J.D., Grace, J.B., 2013a. Controls of biological soil crust cover and composition shift with succession in sagebrush shrub-steppe. Journal of Arid Environments 94, 96–104. doi:10.1016/j.jaridenv.2013.01.013.

Dettweiler-Robinson, E., Ponzetti, J.M., Bakker, J.D., 2013b. Long-term changes in biological soil crust cover and composition. Ecological Processes 2, 5. doi:10.1186/2192-1709-2-5.

Dierauer, J.R., Allen, D.M., Whitfield, P.H., 2019. Snow drought risk and susceptibility in the western United States and Southwestern Canada. Water Resources Research 55, 3076–3091. doi:10.1029/2018WR023229.

DOI-BLM (U.S. Department of the Interior, Bureau of Land Management), 2007. Emergency fire rehabilitation handbook. BLM, Washington, DC, USA, p. 80. Available at: https://www.blm.gov/sites/blm.gov/files/uploads/Media_Library_BLM_Policy_Handbook_h1742-1.pdf (Accessed 14 September 2022).

DOI-BLM (U.S. Department of the Interior Bureau of Land Management), 2016. Soda fire emergency stabilization and rehabilitation, Idaho and Oregon. Owyhee Field Office Marsing, ID. Available at: https://www.blm.gov/sites/blm.gov/files/Program_FishandWildlife_WildllifeIdahoSodaFireESR_StatusReport.pdf (Accessed 13 March 2023).

Dwire, K.A., Mellmann-Brown, S., Gurrieri, J.T., 2018. Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. Climate Services 10, 44–52. doi:10.1016/j.cliser.2017.10.002.

Edwards, B.L., Webb, N.P., Brown, D.P., Elias, E., Peck, D.E., Pierson, F.B., Williams, C.J., Herrick, J.E., 2019. Climate change impacts on wind and water erosion on US rangelands. Journal of Soil and Water Conservation 74, 405–418. doi:10.2489/jswc.74.4.405.

Ellsworth, L.M., Gutierrez Yee, L., Dittel, J.W., Sanchez, D.M., Antoninka, A., 2024. Sagebrush-associated bunchgrasses drive invasion resistance in a greenhouse experiment. Rangeland Ecology & Management 92, 24–33. doi:10.1016/j.rama.2023.09.004.

ESA (Ecological Society of America). Rangeland Ecology. Available at: https://www.esa.org/rangeland/ (Accessed 3 June 2024).

Falk, D.A., Millar, C.I., 2016. The influence of climate variability and change on the science and practice of restoration ecology. In: Palmer, M.A., Zedler, J.B., Falk, D.A. (Eds.), Foundations of restoration ecology. Island Press/Center for Resource Economics, Washington, DC, USA, pp. 484–513. doi:10.5822/978-1-61091-698-1_17.

Fernández-Giménez, M.E., Augustine, D.J., Porensky, L.M., Wilmer, H., Derner, J.D., Briske, D.D., Stewart, M.O., 2019. Complexity fosters learning in collaborative adaptive management. Ecology and Society 24 (2), 29. doi:10.5751/ES-10963-240229.

Ferrenberg, S., Reed, S.C., Belnap, J., 2015. Climate change and physical disturbance cause similar community shifts in biological soil crusts. Proceedings of the National Academy of Sciences of the United States of America 112, 12116–12121. doi:10.1073/pnas.1509150112.

Fisichelli, N.A., Schuurman, G.W., Hoffman, C.H., 2016. Is 'resilience' maladaptive? Towards an Accurate lexicon for climate change adaptation. Environmental Management 57, 753–758. doi:10.1007/s00267-015-0650-6.

Fryer, J.L., 2017. *Ventenata dubia*, in: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available at: https://agr.mt.gov/_docs/weeds-docs/usda-ventenata-dubia.pdf (Accessed 24 January 2022).

Fusco, E.J., Balch, J.K., Mahood, A.L., Nagy, R.C., Syphard, A.D., Bradley, B.A., 2022. The human–grass–fire cycle: how people and invasives co-occur to drive fire regimes. Frontiers in Ecology and the Environment 20 (2), 117–126. doi:10.1002/fee.2432.

Galbraith, W.A., Anderson, E.W., 1971. Grazing history of the northwest. Journal of Range Management 24, 6. doi:10.2307/3896056.

Germino, M.J., Torma, P., Fisk, M.R., Applestein, C.V., 2022. Monitoring for adaptive management of burned sagebrush-steppe rangelands: addressing variability and uncertainty on the 2015 Soda Megafire. Rangelands 44, 99–110. doi:10.1016/j.rala.2021.12.002.

Godde, C.M., Boone, R.B., Ash, A.J., Waha, K., Sloat, L.L., Thornton, P.K., Herrero, M., 2020. Global rangeland production systems and livelihoods at threat under climate change and variability. Environmental Research Letters 15, 044021. doi:10.1088/1748-9326/ab7395.

Gowda, P.H., Steiner, J., Olson, C., Boggess, M., Farrigan, T., Grusak, M.A., 2018. Chapter 10: Agriculture and rural communities. Impacts, risks, and adaptation in the United States: the fourth national climate assessment, volume II. U.S. Global Change Research Program, Washington, DC, US doi:10.7930/NCA4.2018.CH10.

Haigh, T., Hayes, M., Smyth, J., Prokopy, L., Francis, C., Burbach, M., 2021. Ranchers' use of drought contingency plans in protective action decision making. Rangeland Ecology & Management 74, 50–62. doi:10.1016/j.rama.2020.09.007.

Halofsky, J., Peterson, D., 2016. Climate change vulnerabilities and adaptation options for forest vegetation management in the northwestern USA. Atmosphere 7, 46. doi:10.3390/atmos7030046.

Halofsky, J.E., Peterson, D.L. (Eds.), 2017, Climate change vulnerability and adaptation in the Blue Mountains. Gen. Tech. Rep. PNW-GTR-939. USDA, Forest Service, Pacific Northwest Research Station, Portland, OR, USA, p. 331 p. doi:10.2737/PNW-GTR-939.

Halofsky, J.E., Peterson, D.L., Dante-Wood, S.K., Hoang, L., Ho, J.J., Joyce, L.A. (Eds.), 2018b. Climate change vulnerability and adaptation in the Northern Rocky Mountains, part 1 and 2 (No. RMRS-GTR-374). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA doi:10.2737/RMRS-GTR-374PART2.

Halofsky, J.E., Peterson, D.L., Harvey, B.J., 2020. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. Fire Ecology 16, 4. doi:10.1186/s42408-019-0062-8.

Halofsky, J.E., Peterson, D.L., Ho, J.J., 2019. Climate change vulnerability and adaptation in south-central Oregon (No. PNW-GTR-974). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA doi:10.2737/PNW-GTR-974.

Halofsky, J.E., Peterson, D.L., Ho, J.J., Little, N.J., Joyce, L.A. (Eds.), 2018a. Climate change vulnerability and adaptation in the Intermountain Region, part 1 and 2 (No. RMRS-GTR-375). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA h t tps://doi.org/10.2737/RMRS-GTR-375PART1 doi:10.2737/RMRS-GTR-375PART2.

Halofsky, JE, Peterson, DL, Prendeville, HR, 2018c. Assessing vulnerabilities and adapting to climate change in northwestern U.S. forests. Climate Change 146, 89–102. doi:10.1007/s10584-017-1972-6.

Haugo, R.D., Kellogg, B.S., Cansler, C.A., Kolden, C.A., Kemp, K.B., Robertson, J.C., Metlen, K.L., Vaillant, N.M., Restaino, C.M., 2019. The missing fire: quantifying human exclusion of wildfire in Pacific Northwest forests, USA. Ecosphere 10 (4), e02702. doi:10.1002/ecs2.2702.

Havstad, K.M., Peters, D.P.C., Skaggs, R., Brown, J., Bestelmeyer, B., Fredrickson, E., Herrick, J., Wright, J., 2007. Ecological services to and from rangelands of the United States. Ecological Economics 64, 261–268. doi:10.1016/j.ecolecon.2007.08.005.

Hawkes, K.L., McClaran, M.P., Brugger, J., Crimmins, M.A., Howery, L.D., Ruyle, G.B., Sprinkle, J.E., Tolleson, D.R., 2018. Guide to co-developing drought preparation plans for livestock grazing on southwest national forests. The University of Arizona College of Agriculture & Life Sciences: Cooperative Extension, p. 80. Available at: https://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1764-2018.pdf (Accessed 1 August 2024).

Heal, G., Kriström, B., 2002. Uncertainty and climate change. Environmental and Resource Economics 22 (1/2), 3–39. Available at: https://link.springer.com/article/10.1023/A:1015556632097 (Accessed 1 August 2024).

Hernandez, M., Nearing, M.A., Al-Hamdan, O.Z., Pierson, F.B., Armendariz, G., Weltz, M.A., Spaeth, K.E., Williams, C.J., Nouwakpo, S.K., Goodrich, D.C., Unkrich, C.L., Nichols, M.H., Holifield Collins, C.D., 2017. The rangeland hydrology and erosion model: a dynamic approach for predicting soil loss on rangelands. Water Resources Research 53, 9368–9391. doi:10.1002/2017WR020651.

Herrick, J.E., Duniway, M.C., Pyke, D.A., Bestelmeyer, B.T., Wills, S.A., Brown, J.R., Karl, J.W., Havstad, K.M., 2012. A holistic strategy for adaptive land management. Journal of Soil and Water Conservation 67, 105A–113A. doi:10.2489/jswc.67.4.105A.

Hessburg, P.F., Prichard, S.J., Hagmann, R.K., Povak, N.A., Lake, F.K., 2021. Wildfire and climate change adaptation of western North American forests: a case for intentional management. Ecological Applications 31 (8), e02432,1-15. doi:10.1002/eap.2432.

Holechek, J.L., Pieper, R.D., Herbel, C.H., 2011. Range management principles and practices, 6th ed. Prentice-Hall, New York, NY, USA, pp. 269–276.
Holfus, C.M., Rios, R.C., Boyd, C.S., Mata-González, R., 2021. Preemergent herbicide protection seed coating: a promising new restoration tool. Rangeland Ecology & Management 76, 95–99. doi:10.1016/j.rama.2021.02.005.
Hoover, D.L., Bestelmeyer, B., Grimm, N.B., Huxman, T.E., Reed, S.C., Sala, O., Seastedt, T.R., Wilmer, H., Ferrenberg, S., 2020. Traversing the wasteland: a framework for assessing ecological threats to drylands. BioScience 70, 35–47. doi:10.1093/biosci/biz126.
Huang, J., Ji, M., Xie, Y., Wang, S., He, Y., Ran, J., 2016. Global semi-arid climate change over last 60 years. Climate Dynamics 46, 1131–1150. doi:10.1007/s00382-015-2636-8.
Hudson, T.D., Reeves, M.C., Hall, S.A., Yorgey, G.G., Neibergs, J.S., 2021. Big landscapes meet big data: Informing grazing management in a variable and changing world. Rangelands 43, 17–28. doi:10.1016/j.rala.2020.10.006.
Innes, R.J., 2022. *Ventenata dubia*, in: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available at: https://www.fs.usda.gov/database/feis/plants/graminoid/vendub/all.html (Accessed 11 June 2024).
Izaurralde, R.C., Thomson, A.M., Morgan, J.A., Fay, P.A., Polley, H.W., Hatfield, J.L., 2011. Climate impacts on agriculture: implications for forage and rangeland production. Agronomy Journal 103, 371–381. doi:10.2134/agronj2010.0304.
James, J.J., Smith, B.S., Vasquez, E.A., Sheley, R.L., 2010. Principles for ecologically based invasive plant management. Invasive Plant Science and Management 3, 229–239. doi:10.1614/IPSM-D-09-00027.1.
Johnson, J., Cahill, M., Boyd, C., Schroeder, V., Foster, L., Sitz, A., Kerby, J., Svejar, T. Cupples, J., 2019. Threat-based land management in the northern Great Basin: a manager's guide. Available at: https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw722.pdf (Accessed 3 June 2024).
Jones, M.O., Allred, B.W., Naugle, D.E., Maestas, J.D., Donnelly, P., Metz, L.J., Karl, J., Smith, R., Bestelmeyer, B., Boyd, C., Kerby, J.D., McIver, J.D., 2018. Innovation in rangeland monitoring: annual, 30 m, plant functional type percent cover maps for U.S. rangelands, 1984–2017. Ecosphere (Washington, D.C) 9, 1–19. doi:10.1002/ecs2.2430.
Jones, M.O., Robinson, N.P., Naugle, D.E., Maestas, J.D., Reeves, M.C., Lankston, R.W., Allred, B.W., 2021. Annual and 16-day rangeland production estimates for the western United States. Rangeland Ecology & Management 77, 112–117. doi:10.1016/j.rama.2021.04.003.
Joyce, L.A., Briske, D.D., Brown, J.R., Polley, H.W., McCarl, B.A., Bailey, D.W., 2013. Climate change and North American rangelands: assessment of mitigation and adaptation strategies. Rangeland Ecology & Management 66, 512–528. doi:10.2111/REM-D-12-00142.1.
Joyce, L.A., Millar, C.I., 2014. Improving the role of vulnerability assessments in decision support for effective climate adaptation, in: Sample, V.A.; Bixler, R.P., (Eds.), Forest Conservation and Management in the Anthropocene: Conference Proceedings. Proceedings (No. RMRS-P-71). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA. p. 245-271
Kachergis, E., Derner, J.D., Cutts, B.B., Roche, L.M., Eviner, V.T., Lubell, M.N., Tate, K.W., 2014. Increasing flexibility in rangeland management during drought. Ecosphere (Washington, D.C) 5, 77. doi:10.1890/ES13-00402.1.
Kantor, S., Wisdom, M., Johnson, B., 2019, Seeking ground less traveled: elk responses to recreation. Science findings 219. In: Mazza, R. (Ed.). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA, p. 5. Available at: https://research.fs.usda.gov/treesearch/58484 (Accessed 1 August 2024).
Keane, R.E., Loehman, R., 2019. Historical range and variation (HRV). In: Manzello, S.L. (Ed.), Encyclopedia of wildfires and wildland-urban interface (WUI) fires. Springer International Publishing, Cham, Switzerland, pp. 1–12. doi:10.1007/978-3-319-51727-8_255-1.
Kerns, B.K., Naylor, B.J., Buonopane, M., Parks, C.G., Rogers, B., 2009. Modeling tamarisk (Tamarix spp.) habitat and climate change effects in the northwestern United States. Invasive Plant Science and Management 2, 200–215. doi:10.1614/IPSM-08-120.1.
Kerns, B.K., Tortorelli, C., Day, M.A., Nietupski, T., Barros, A.M., Kim, J.B., Krawchuk, M.A., 2020. Invasive grasses: a new perfect storm for forested ecosystems? Forest Ecology and Management 463, 117985. doi:10.1016/j.foreco.2020.117985.
Knapp, C.N., Fernandez-Gimenez, M.E., 2009a. Knowledge in practice: documenting rancher local knowledge in northwest Colorado. Rangeland Ecology & Management 62, 500–509. doi:10.2111/08-175.1.
Knapp, C.N., Fernandez-Gimenez, M.E., 2009b. Understanding change: integrating rancher knowledge into state-and-transition models. Rangeland Ecology & Management 62, 510–521. doi:10.2111/08-176.1.
Kohl, M.T., Cleveland, S., Merkle, J., Proffitt, K.M., Rowland, M.M., Wisdom, M.J., 2023, Elk and Rangelands. In: McNew, L.B., Dahlgren, D.K., Beck, J.L. (Eds.). Rangeland wildlife ecology and conservation, Springer, Cham, Switzerland, pp. 703–733. doi:10.1007/978-3-031-34037-6_20.
Kormos, P.R., Marks, D., Pierson, F.B., Williams, C.J., Hardegree, S.P., Havens, S., Hedrick, A., Bates, J.D., Svejcar, T.J., 2017. Ecosystem water availability in juniper versus sagebrush snow-dominated rangelands. Rangeland Ecology & Management 70, 116–128. doi:10.1016/j.rama.2016.05.003.
Kundzewicz, Z.W., Krysanova, V., Benestad, R.E., Hov, Ø., Piniewski, M., Otto, I.M., 2018. Uncertainty in climate change impacts on water resources. Environmental Science & Policy 79, 1–8. doi:10.1016/j.envsci.2017.10.008.
Krosby, M., Davis, K., Rozance, M.A., Bagley, A., Dohrn, C., Lyons, D., Swensen, K., McClure, M., Walls, C., 2020. Managing post-fire, climate-induced vegetation transitions in the northwest: a synthesis of existing knowledge and research needs. Northwest Climate Adaptation Science Center, University of Washington, Seattle, WA, USA. https://nwcasc.uw.edu/wp-content/uploads/sites/23/2021/03/DEEP_DIVE_2020_REPORT.pdf.
Lake, E.C., Minteer, C.R., 2018. A review of the integration of classical biological control with other techniques to manage invasive weeds in natural areas and rangelands. BioControl 63, 71–86. doi:10.1007/s10526-017-9853-5.
Leffler, A.J., Sheley, R.L., 2012. Adaptive management in EBIPM. Rangelands 34, 44–47. doi:10.2111/RANGELANDS-D-12-00053.1.
Littell, J.S., McKenzie, D., Wan, H.Y., Cushman, S.A., 2018. Climate change and future wildfire in the western United States: An ecological approach to nonstationarity. Earth's Future 6, 1097–1111. doi:10.1029/2018EF000878.
Littell, J.S., Peterson, D.L., Millar, C.I., O'Halloran, K.A., 2012. U.S. National Forests adapt to climate change through science–management partnerships. Climate Change 110, 269–296. doi:10.1007/s10584-011-0066-0.
Maas, A., Wardropper, C., Roesch-McNally, G., Abatzoglou, J., 2020. A (mis)alignment of farmer experience and perceptions of climate change in the U.S. inland Pacific Northwest. Climate Change 162, 1011–1029. doi:10.1007/s10584-020-02713-6.
Madsen, M.D., Davies, K.W., Mummey, D.L., Svejcar, T.J., 2014. Improving restoration of exotic annual grass-invaded rangelands through activated carbon seed enhancement technologies. Rangeland Ecology & Management 67, 61–67. doi:10.2111/REM-D-13-00050.1.
Maestas, J., Pellant, M., Okeson, L., Tilley, D., Havlina, D., Cracroft, T., Brazee, B., Williams, M. and Messmer, D., 2016. Fuel breaks to reduce large wildfire impacts in sagebrush ecosystems. Boise, ID, USA: Plant Materials Technical Note 66. https://www.wlfw.org/wp-content/uploads/2016/03/idpmctn16_tn66fuelbreaks-1.pdf.
Maestre, F.T., Le Bagousse-Pinguet, Y., Delgado-Baquerizo, M., Eldridge, D.J., Saiz, H., Berdugo, M., Gozalo, B., Ochoa, V., Guirado, E., García-Gómez, M., Valencia, E., 2022. Grazing and ecosystem service delivery in global drylands. Science 378, 915–920. doi:10.1126/science.abq4062.
Maher, A.T., 2019. Identifying opportunities for collaboration in resilience-based management: coordinating rancher and land manager incentives [dissertation]. Oregon State University, Corvallis, OR, USA. Available at: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/fj2367760 (Accessed 26 July 2024).
Maher A.T, Maczko, K.A., Taylor, D.T., Tanaka, J.A., 2020. National and state economic values of cattle ranching and farming-based ecosystem services on federal and private lands in the U.S. (B-1367). 154 p. Available at: https://www.wyoextension.org/publications/Search_Details.php?pubid=2052 (Accessed 3 June 2024).
Maher, A.T., Quintana Ashwell, N.E., Maczko, K.A., Taylor, D.T., Tanaka, J.A., Reeves, M.C., 2021. An economic valuation of federal and private grazing land ecosystem services supported by beef cattle ranching in the United States. Translational Animal Science 5 (3), txab054. doi:10.1093/tas/txab054.
Maher, A.T., Quintana Ashwell, N.E., Tanaka, J.A., Ritten, J.P., Maczko, K.A., 2023. Financial barriers and opportunities for conservation adoption on U.S. rangelands: a region-wide, ranch-level economic assessment of NRCS-sponsored Greater Sage-grouse habitat conservation programs. Journal of Environmental Management 329, 116420. doi:10.1016/j.jenvman.2022.116420.
Maher, A.T., Tanaka, J.A., Rimbey, N., 2013. Economic risks of cheatgrass invasion on a simulated eastern Oregon ranch. Rangeland Ecology & Management 66, 356–363. doi:10.2111/REM-D-10-00126.1.
Marcot, B.G., 2020. The science and management of uncertainty: dealing with doubt in natural resource management. CRC Press, Boca Raton, FL, USA.
Marlier, M.E., Xiao, M., Engel, R., Livneh, B., Abatzoglou, J.T., Lettenmaier, D.P., 2017. The 2015 drought in Washington State: a harbinger of things to come? Environmental Research Letters 12, 114008. doi:10.1088/1748-9326/aa8fde.
May, C., Luce, C.H., Casola, J.H., Chang, M., Cuhaciyan, J., Dalton, M., Lowe, S.E., Morishima, G.S., Mote, P.W., Petersen, A.S., Roesch-McNally, G., York, E.A., 2018. Q17 1353 Chapter 24: Northwest. Impacts, risks, and adaptation in the United States: the fourth national climate assessment, volume II. U.S. Global Change Research Program, Washington, DC, USA doi:10.7930/NCA4.2018.CH24.
McAdoo, J.K., Schultz, B.W., Swanson, S.R., 2013. Aboriginal precedent for active management of sagebrush-perennial grass communities in the Great Basin. Rangeland Ecology & Management 66, 241–253. doi:10.2111/REM-D-11-00231.1.
McCollum, D.W., Tanaka, J.A., Morgan, J.A., Mitchell, J.E., Fox, W.E., Maczko, K.A., Hidinger, L., Duke, C.S., Kreuter, U.P., 2017. Climate change effects on rangelands and rangeland management: affirming the need for monitoring. Ecosystem Health and Sustainability 3, e01264. doi:10.1002/ehs2.1264.
McIver, C.P., Becker, D.R., 2021. An empirical evaluation of the impact of collaboration on the pace and scale of national forest management in Idaho. Forest Science 67 (1), 49–59. doi:10.1093/forsci/fxaa040.
McIver, J.D., Brunson, M., Bunting, S.C., Chambers, J., Devoe, N., Doescher, P., Grace, J., Johnson, D., Knick, S., Miller, R., Pellant, M., Pierson, F., Pyke, D., Rollins, K., Roundy, B., Schupp, E., Tausch, R., Turner, D., 2010. The Sagebrush Steppe Treatment Evaluation Project (SageSTEP): a test of state-and-transition theory (No. RMRS-GTR-237). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, USA doi:10.2737/RMRS-GTR-237.
Mealor, B., 2016. Webinar: strategic cheatgrass management in sagebrush ecosystems. University of Wyoming, Sheridan Research and Extension Center, Sheridan, WY, USA. Available at: https://www.sagegrouseinitiative.com/webinar-strategic-cheatgrass-management-in-sagebrush-ecosystems/ (Accessed 30 Dec 2022).

Meehan, M.A., O'Brien, P.L., Hecker, G.A., Printz, J.L., 2021. Integrating rangeland health and stream stability in assessments of rangeland watersheds. Rangeland Ecology & Management 75, 104–111. doi:10.1016/j.rama.2020.12.005.

Melgoza, G., Nowak, R.S., Tausch, R.J., 1990. Soil water exploitation after fire: competition between Bromus tectorum (cheatgrass) and two native species. Oecologia 83, 7–13. doi:10.1007/BF00324626.

Meredith, G.R., Brunson, M.W., 2021. Effects of wildfire on collaborative management of rangelands: a case study of the 2015 soda fire. Rangelands 44 (5), 306–315. doi:10.1016/j.rala.2021.03.001.

Meredith, G.R., Brunson, M.W., Hardegree, S.P., 2021. Management innovations for resilient public rangelands: adoption constraints and considerations for interagency diffusion. Rangeland Ecology & Management 75, 152–160. doi:10.1016/j.rama.2021.01.002.

Miller, R.F., Chambers, J.C., Pyke, D.A., Pierson, F.B., Williams, C.J., 2013. A review of fire effects on vegetation and soils in the Great Basin region: response and ecological site characteristics (No. RMRS-GTR-308). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, USA doi:10.2737/RMRS-GTR-308.

Mirzabaev, A., Stringer, L.C., Benjaminsen, T.A., Gonzalez, P., Harris, R., Jafari, M., Stevens, N., Tirado, C.M., Zakieldeen, S., 2022. Cross-chapter paper 3: Deserts, semiarid areas and desertification. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (Eds.), Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2195–2231. doi:10.1017/9781009325844.020.

Morford, S.L., Allred, B.W., Twidwell, D., Jones, M.O., Maestas, J.D., Roberts, C.P., Naugle, D.E., 2022. Herbaceous production lost to tree encroachment in United States rangelands. Journal of Applied Ecology 59 (12), 2971–2982. doi:10.1111/1365-2664.14288.

Mote, P.W., Abatzoglou, J., Dello, K.D., Hegewisch, K., Rupp, D.E., 2019. Fourth Oregon climate assessment report. Oregon Climate Change Research Institute. occri.net/ocar4.

Mote, P.W., Li, S., Lettenmaier, D.P., Xiao, M., Engel, R., 2018. Dramatic declines in snowpack in the western US. npj Climate and Atmospheric Science 1, 2. doi:10.1038/s41612-018-0012-1.

Mote, P.W., Rupp, D.E., Li, S., Sharp, D.J., Otto, F., Uhe, P.F., Xiao, M., Lettenmaier, D.P., Cullen, H., Allen, M.R., 2016. Perspectives on the causes of exceptionally low 2015 snowpack in the western United States. Geophysical Research Letters 43. doi:10.1002/2016GL069965.

Munson, S.M., Long, A.L., 2017. Climate drives shifts in grass reproductive phenology across the western USA. The New Phytologist 213, 1945–1955. doi:10.1111/nph.14327.

Nafus, A.M., Davies, K.W., 2014. Medusahead ecology and management: California Annual Grasslands to the Intermountain West. Invasive Plant Science and Management 7, 210–221. doi:10.1614/IPSM-D-13-00077.1.

Nagy, R.C., Fusco, E.J., Balch, J.K., Finn, J.T., Mahood, A., Allen, J.M., Bradley, B.A., 2021. A synthesis of the effects of cheatgrass invasion on US Great Basin carbon storage. J Appl Ecol 58, 327–337. doi:10.1111/1365-2664.13770.

NASS (National Agricultural Statistics Service), 2021. Crop progress and condition report, September 20, 2021. Available at: https://www.nass.usda.gov/Statistics_by_State/Washington/Publications/Crop_Progress_&_Condition/index.php (Accessed 17 May 2022).

NDMC (National Drought Mitigation Center) and Partners, 2021a. United States drought monitor. University of Nebraska-Lincoln. Available at: https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?West (Accessed 15 September 2021).

NDMC (National Drought Mitigation Center) and Partners, 2021b. United States drought monitor. University of Nebraska-Lincoln. Available at: https://droughtmonitor.unl.edu/ (Accessed 21 September 2021).

Neibergs, J.S., Hudson, T.D., Kruger, C.E., Hamel-Rieken, K., 2018. Estimating climate change effects on grazing management and beef cattle production in the Pacific Northwest. Climate Change 146, 5–17. doi:10.1007/s10584-017-2014-0.

NIDIS (National Integrated Drought Information System) and partners, 2021. Drought status update for the Pacific Northwest. Available at: https://www.drought.gov/drought-status-updates/drought-status-update-pacific-northwest-2 (Accessed 15 September 2021).

O'Connor, R.C., Germino, M.J., 2021. Comment on: Grazing disturbance promotes exotic annual grasses by degrading soil biocrust communities. Ecological Applications 31 (7), e02277. doi:10.1002/eap.2277.

Ojima, D.S., Iverson, L.R., Sohngen, B.L., Vose, J.M., Woodall, C.W., Domke, G.M., Peterson, D.L., Littell, J.S., Matthews, S.N., Prasad, A.M., Peters, M.P., 2014. Risk assessment. In: Peterson, D.L., Vose, J.M., Patel-Weynand, T. (Eds.), Climate change and United States forests. Springer, Dordrecht, the Netherlands, pp. 223–244. doi:10.1007/978-94-007-7515-2_9.

Palmquist, K.A., Schlaepfer, D.R., Bradford, J.B., Lauenroth, W.K., 2016. Spatial and ecological variation in dryland ecohydrological responses to climate change: implications for management. Ecosphere (Washington, D.C) 7, e01590. doi:10.1002/ecs2.1590.

Pellant, M., Shaver, P.L., Pyke, D.A., Herrick, J.E., Lepak, N., Riegel, G., Kachergis, E., Newingham, B.A., Toledo, D., Busby, F.E., 2020. Interpreting indicators of rangeland health, version 5, (Tech Ref No. 1734-6). U.S. Department of the Interior, Bureau of Land Management, National Operations Center, Denver, CO, USA.

Peterson, D.L., Halofsky, J.E., 2018. Adapting to the effects of climate change on natural resources in the Blue Mountains, USA. Climate Services 10, 63–71. doi:10.1016/j.cliser.2017.06.005.

Phillips, C.L., Meyer, K.M., Hanson, C.V., Biraud, S.C., Trippe, K.M., 2021. Manipulating rangeland soil microclimate with juniper biochar for improved native seedling establishment. Soil Science Society of America Journal 85, 847–861. doi:10.1002/saj2.20207.

Pierson, F.B., Bates, J.D., Svejcar, T.J., Hardegree, S.P., 2007. Runoff and erosion after cutting western Juniper. Rangeland Ecology & Management 60, 285–292. doi:10.2111/1551-5028(2007)60[285:RAEACW]2.0.CO;2.

Pilliod, D.S., Jeffries, M.I., Welty, J.L., Arkle, R.S., 2021. Protecting restoration investments from the cheatgrass-fire cycle in sagebrush steppe. Conservation Science and Practice 3 (10), e508. doi:10.1111/csp2.508.

Pilliod, D.S., Welty, J.L., Arkle, R.S., 2017. Refining the cheatgrass-fire cycle in the Great Basin: precipitation timing and fine fuel composition predict wildfire trends. Ecology and Evolution 7, 8126–8151. doi:10.1002/ece3.3414.

Pindyck, R.S. 2007. Uncertainty in environmental economics, working paper (12752), Nber Working paper series. 1, 45-65. Available at: https://www.nber.org/system/files/working_papers/w12752/w12752.pdf (Accessed 1 September 2022).

Polley, H.W., Briske, D.D., Morgan, J.A., Wolter, K., Bailey, D.W., Brown, J.R., 2013. Climate change and North American rangelands: trends, projections, and implications. Rangeland Ecology & Management 66, 493–511. doi:10.2111/REM-D-12-00068.1.

Ponzetti, J.M., McCune, B., Pyke, D.A., 2007. Biotic soil crusts in relation to topography, cheatgrass and fire in the Columbia Basin, Washington. The Bryologist 110, 706–722. doi:10.1639/0007-2745(2007)110[706:BSCIRT]2.0.CO;2.

PRISM Climate Group, Oregon State University. 2022. 30-year normal precipitation: annual, period: 1991-2020. Available at: https://prism.oregonstate.edu/normals/ (Dataset). (Accessed 7 June 2024).

Pyke, D.A., Brooks, M.L., D'Antonio, C., 2010. Fire as a restoration tool: a decision framework for predicting the control or enhancement of plants using fire. Restoration Ecology 18, 274–284. doi:10.1111/j.1526-100X.2010.00658.x.

Pyke, D.A., Pilliod, D.S., Chambers, J.C., Brooks, M.L., Grace, J., 2013. Fire rehabilitation effectiveness: a chronosequence approach for the Great Basin. JFSP Research Project Reports 85, 34. http://digitalcommons.unl.edu/jfspresearch/85.

Rangwala, I., Moss, W., Wolken, J., Rondeau, R., Newlon, K., Guinotte, J., Travis, W.R., 2021. Uncertainty, complexity and constraints: how do we robustly assess biological responses under a rapidly changing climate? Climate 9, 177. doi:10.3390/cli9120177.

RAP (Rangeland Analysis Platform), 2022. Available at: https://rangelands.app/ (Accessed 20 April 2022).

Rau, B.M., Johnson, D.W., Blank, R.R., Lucchesi, A., Caldwell, T.G., Schupp, E.W., 2011. Transition from sagebrush steppe to annual grass (Bromus tectorum): influence on belowground carbon and nitrogen. Rangeland Ecology & Management 64, 139–147. doi:10.2111/REM-D-10-00063.1.

Ray, G., Ochoa, C.G., Deboodt, T., Mata-Gonzalez, R., 2019. Overstory–understory vegetation cover and soil water content observations in Western Juniper Woodlands: a paired watershed study in central Oregon, USA. Forests 10, 151. doi:10.3390/f10020151.

Reeves, M.C., Bagne, K.E., Tanaka, J., 2017. Potential climate change impacts on four biophysical indicators of cattle production from Western US rangelands. Rangeland Ecology & Management 70, 529–539. doi:10.1016/j.rama.2017.02.005.

Reeves, M.C., Hanberry, B.B., Wilmer, H., Kaplan, N.E., Lauenroth, W.K., 2021. An assessment of production trends on the Great Plains from 1984 to 2017. Rangeland Ecology & Management 78, 165–179. doi:10.1016/j.rama.2020.01.011.

Reeves, M.C., Hudson, T.D., Neibergs, J.S., Hall, S.A., Yorgey, G., 2022. Rancher-to-rancher case study series: increasing resilience among ranchers in the Pacific Northwest. Pacific Northwest Extension Publishing. Available at: https://csanr.wsu.edu/case-studies/ (Accessed 11 December 2022).

Reeves, M.C., Mitchell, J.E., 2011. Extent of coterminous US rangelands: quantifying implications of differing agency perspectives. Rangeland Ecology & Management 64 (6), 585–597. https://www.fs.usda.gov/treesearch/pubs/41872.

Reid, R.S., Fernández-Giménez, M.E., Galvin, K.A., 2014. Dynamics and resilience of rangelands and pastoral peoples around the globe. Annual Review of Environment and Resources 39, 217–242. doi:10.1146/annurev-environ-020713-163329.

Reid, R.S., Fernández-Giménez, M.E., Wilmer, H., Pickering, T., Kassam, K.-A.S., Yasin, A., Porensky, L.M., Derner, J.D., Nkedianye, D., Jamsranjav, C., Jamiyansharav, K., Ulambayar, T., Oteros-Rozas, E., Ravera, F., Bulbulshoev, U., Kaziev, D.S., Knapp, C.N., 2021. Using research to support transformative impacts on complex, "wicked problems" with pastoral peoples in rangelands. Frontiers in Sustainable Food Systems 4, 600689. doi:10.3389/fsufs.2020.600689.

Ridder, L.W., Morris, L.R., Day, M.A., Kerns, B.K., 2022. Ventenata (Ventenata dubia) response to grazing and prescribed fire on the Pacific Northwest bunchgrass prairie. Rangeland Ecology & Management 80, 1–9. doi:10.1016/j.rama.2021.09.003.

Roever, C.L., DelCurto, T., Rowland, M., Vavra, M., Wisdom, M., 2015. Cattle grazing in semiarid forestlands: habitat selection during periods of drought1. Journal of Animal Science 93, 3212–3225. doi:10.2527/jas.2014-8794.

Root, H.T., Chan, J., Ponzetti, J., Pyke, D.A., McCune, B., 2023. Long-term biocrust responses to wildfires in Washington, USA. American Journal of Botany 110 (12). e16261 1–15. doi: 10.1002/ajb2.16261.

Roper, B.B., Saunders, W.C., 2021. How cattle and wild ungulate use of riparian areas effects measures of streambank disturbance. Rangeland Ecology & Management 74, 32–42. doi:10.1016/j.rama.2020.08.009.

Ruff, S.P., Peck, D.E., Bastian, C.T., Cook, W.E., 2016. Economics of transitioning from a cow-calf-yearling operation to a stocker operation. Journal of the ASFMRA 55–76. Available at: http://ageconsearch.umn.edu (Accessed 13 March 2023).
Runge, C.A., Plantinga, A.J., Larsen, A.E., Naugle, D.E., Helmstedt, K.J., Polasky, S., Donnelly, J.P., Smith, J.T., Lark, T.J., Lawler, J.J., Martinuzzi, S., Fargione, J., 2019. Unintended habitat loss on private land from grazing restrictions on public rangelands. The Journal of Applied Ecology 56, 52–62. doi:10.1111/1365-2664.13271.
Ruppert, J.C., Harmoney, K., Henkin, Z., Snyman, H.A., Sternberg, M., Willms, W., Linstädter, A., 2015. Quantifying drylands' drought resistance and recovery: the importance of drought intensity, dominant life history and grazing regime. Global Change Biology 21, 1258–1270. doi:10.1111/gcb.12777.
Saliman, A., Petersen-Rockney, M., 2022. Rancher experiences and perceptions of climate change in the Western United States. Rangeland Ecology & Management 84, 75–85. doi:10.1016/j.rama.2022.06.001.
Sankey, J.B., Wallace, C.S.A., Ravi, S., 2013. Phenology-based, remote sensing of post-burn disturbance windows in rangelands. Ecological Indicators 30, 35–44. doi:10.1016/j.ecolind.2013.02.004.
Scheffer, M., Barrett, S., Carpenter, S.R., Folke, C., Green, A.J., Holmgren, M., Hughes, T.P., Kosten, S., van de Leemput, I.A., Nepstad, D.C., van Nes, E.H., Peeters, E.T.H.M., Walker, B., 2015. Creating a safe operating space for iconic ecosystems. Science 347, 1317–1319. doi:10.1126/science.aaa3769.
Schrader-Patton C., Grulke N.E., and Ott, J.P., 2024. TRM-CONUS PhenoMap. Available at: https://www.fs.usda.gov/wwetac/threat-map/TRMPhenoMap.php (Accessed 11 June 2024).
Schuurman, G.W., Hawkins-Hoffman, C., Cole, D.N., Lawrence, D.J., Morton, J.M., Magness, D.R., Cravens, A.E., Covington, S., O'Malley, R., Fisichelli, N.A., 2020. Resist–accept–direct (RAD): a framework for the 21st-century natural resource manager (no. 10.36967/nrr-2283597). National Park Service, Fort Collins, CO, USA doi:10.36967/nrr-2283597.
Seidl, R., Spies, T.A., Peterson, D.L., Stephens, S.L., Hicke, J.A., 2016. REVIEW: searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. The Journal of Applied Ecology 53, 120–129. doi:10.1111/1365-2664.12511.
Sheley, R., James, J., Smith, B., Vasquez, E., 2010. Applying ecologically based invasive-plant management. Rangeland Ecology & Management 63 (6), 605–613. doi:10.2111/REM-D-09-00187.1.
Shinneman, D.J., Aldridge, C.L., Coates, P.S., Germino, M.J., Pilliod, D.S., Vaillant, N.M., 2018. U.S. Geological Survey, p. 70. doi:10.3133/ofr20181034.
Shinneman, D.J., Germino, M.J., Pilliod, D.S., Aldridge, C.L., Vaillant, N.M., Coates, P.S., 2019. The ecological uncertainty of wildfire fuel breaks: examples from the sagebrush steppe. Frontiers in Ecology and the Environment 17, 279–288. doi:10.1002/fee.2045.
Shriver, R.K., Andrews, C.M., Arkle, R.S., Barnard, D.M., Duniway, M.C., Germino, M.J., Pilliod, D.S., Pyke, D.A., Welty, J.L., Bradford, J.B., 2019. Transient population dynamics impede restoration and may promote ecosystem transformation after disturbance. Ecology Letters 22, 1357–1366. doi:10.1111/ele.13291.
Shriver, R.K., Andrews, C.M., Pilliod, D.S., Arkle, R.S., Welty, J.L., Germino, M.J., Duniway, M.C., Pyke, D.A., Bradford, J.B., 2018. Adapting management to a changing world: warm temperatures, dry soil, and interannual variability limit restoration success of a dominant woody shrub in temperate drylands. Global Change Biology 24, 4972–4982. doi:10.1111/gcb.14374.
Smith, B.S., Unfried, J.K., Defrees, D.K.H., Wood, D.J., 2022. Prioritizing limited resources in landscape-scale management projects. Rangelands 44, 235–241. doi:10.1016/j.rala.2022.02.005.
Smith, J.T., Allred, B.W., Boyd, C.S., Davies, K.W., Jones, M.O., Kleinhesselink, A.R., Maestas, J.D., Morford, S.L., Naugle, D.E., 2021. The elevational ascent and spread of exotic annual grass dominance in the Great Basin, USA. Diversity & Distributions 28, 83–96. doi:10.1111/ddi.13440.
Smith, J.T., Allred, B.W., Boyd, C.S., Davies, K.W., Jones, M.O., Kleinhesselink, A.R., Maestas, J.D., Naugle, D.E., 2023. Where There's Smoke, There's Fuel: Dynamic Vegetation Data Improve Predictions of Wildfire Hazard in the Great Basin 89(1), 20-32. doi:10.1016/j.rama.2022.07.005.
Snyder, K.A., Evers, L., Chambers, J.C., Dunham, J., Bradford, J.B., Loik, M.E., 2019. Effects of changing climate on the hydrological cycle in cold desert ecosystems of the Great Basin and Columbia Plateau. Rangeland Ecology & Management 72, 1–12. doi:10.1016/j.rama.2018.07.007.
St. Clair, J.B., Richardson, B.A., Stevenson-Molnar, N., Howe, G.T., Bower, A.D., Erickson, V.J., Ward, B., Bachelet, D., Kilkenny, F.F, Wang, T., 2022. Seedlot selection tool and climate-smart restoration tool: web-based tools for sourcing seed adapted to future climates. Ecosphere (Washington, D.C) 13 (5), e4089. doi:10.1002/ecs2.4089.
Steen-Adams, M.M., Charnley, S., McLain, R.J., Adams, M.D., Wendel, K.L., 2019. Traditional knowledge of fire use by the confederated tribes of warm springs in the eastside cascades of Oregon. Forest Ecology and Management 450, 117405. doi:10.1016/j.foreco.2019.06.002.
STACCWG (Status of Tribes and Climate Change Working Group), 2021. In: Marks-Marino, D. (Ed.), Status of tribes and climate change report. Institute for Tribal Environmental Professionals. Northern Arizona University, Flagstaff, AZ, USA. Available at: http://nau.edu/stacc2021 (Accessed 1 September 2022).
Stevenson, S., Coats, S., Touma, D., Cole, J., Lehner, F., Fasullo, J., Otto-Bliesner, B., 2022. Twenty-first century hydroclimate: a continually changing baseline, with more frequent extremes. Proceedings of the National Academy of Sciences of the United States of America 119, e2108124119. doi:10.1073/pnas.2108124119.
Stewart, K.M., Bowyer, R.T., Kie, J.G., Cimon, N.J., Johnson, B.K., 2002. Temporospatial distributions of elk, mule deer and cattle: resource partitioning and competitive displacement. Journal of Mammalogy 83, 16. doi:10.1644/1545-1542(2002)083<0229:TDOEMD>2.0.CO;2.
Svejcar, T., Angell, R., James, J., 2016. Spatial and temporal variability in minimum temperature trends in the western U.S. sagebrush steppe. Journal of Arid Environments 133, 125–133. doi:10.1016/j.jaridenv.2016.06.003.
Thurow, T.L., Taylor, C.A., 1999. Viewpoint: the role of drought in range management. Journal of Range Management 52, 413–419.
Timberlake, T., Joyce, L.A., Schultz, C., Lampman, G., 2018. Design of a workshop process to support consideration of natural range of variation and climate change for land management planning under the 2012 planning rule (No. RMRS-RN-82). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, USA doi:10.2737/RMRS-RN-82.
Timberlake, T.J., Schultz, C.A., 2017. Policy, practice, and partnerships for climate change adaptation on US national forests. Climate Change 144, 257–269. doi:10.1007/s10584-017-2031-z.
Timberlake, T.J., Schultz, C.A., Evans, A., Abrams, J.B., 2021. Working on institutions while planning for forest resilience: a case study of public land management in the United States. Journal of Environmental Planning and Management 64, 1291–1311. doi:10.1080/09640568.2020.1817730.
Timm Hoffman, M., Rohde, R.F., Gillson, L., 2019. Rethinking catastrophe? Historical trajectories and modelled future vegetation change in southern Africa. Anthropocene 25, 100189. doi:10.1016/j.ancene.2018.12.003.
Torell, L.A., Murugan, S., Ramirez, O.A., 2010. Economics of flexible versus conservative stocking strategies to manage climate variability risk. Rangeland Ecology & Management 63, 415–425. doi:10.2111/REM-D-09-00131.1.
Torell, L.A., Rimbey, N.R., Tanaka, J.A., 2014. Ranch-level economic impacts of altering grazing policies on federal land to protect the greater sage-grouse (1258). Agricultural Extension Service, University of Wyoming.
Urgenson, L.S., 2017. Visions of restoration in fire-adapted forest landscapes: lessons from the collaborative forest landscape restoration program. Environmental Management 59, 338–353. https://link.springer.com/article/10.1007/s00267-016-0791-2.
USDA Forest Service Office of Sustainability and Climate. 2018. Extent of coterminous U.S. rangelands. Available at: https://data.fs.usda.gov/geodata/rastergateway/rangelands/index.php (Accessed 1 December 2024).
USGS, 2022. Ecological drought forecast tool for drylands. Available at: https://www.usgs.gov/news/ecological-drought-forecast-tool-drylands. (Accessed 22 June 2022).
Vose, J.M., Peterson, D.L., Luce, C.H., Patel-Weynand, T., 2019. Effects of drought on forests and rangelands in the United States: translating science into management responses (No. WO-GTR-98). U.S. Department of Agriculture, Forest Service, Washington, DC, USA doi:10.2737/WO-GTR-98.
Wardropper, C.B., Angerer, J.P., Burnham, M., Fernández-Giménez, M.E., Jansen, V.S., Karl, J.W., Lee, K., Wollstein, K., 2021. Improving rangeland climate services for ranchers and pastoralists with social science. Current Opinion in Environmental Sustainability 52, 82–91. doi:10.1016/j.cosust.2021.07.001.
Weber, K.T., Gokhale, B.S., 2011. Effect of grazing on soil-water content in semiarid rangelands of southeast Idaho. Journal of Arid Environments 75, 464–470. doi:10.1016/j.jaridenv.2010.12.009.
WGA (Western Governors' Association), 2022. Rangeland Fire Protection Associations, Working Lands, Working Communities Initiative, Roundtable VI, Idaho Workshop. Available at: https://www.youtube.com/watch?v=0N_ikcMl2H8 (Accessed 1 March 2022).
White, C., Conley, C., 2007. Grassbank 2.0: building on what we have learned from the Valle Grande Grassbank. Rangelands 29 (3), 27–30. doi:10.2458/azu_rangelands_v29i3_white.
Williams, J.W., Ordonez, A., Svenning, J.-C., 2021. A unifying framework for studying and managing climate-driven rates of ecological change. Nature Ecology & Evolution 5, 17–26. doi:10.1038/s41559-020-01344-5.
Wilmer, H., Derner, J.D., Fernández-Giménez, M.E., Briske, D.D., Augustine, D.J., Porensky, L.M., 2018. Collaborative adaptive rangeland management fosters management-science partnerships. Rangeland Ecology & Management 71, 646–657. doi:10.1016/j.rama.2017.07.008.
Wollstein, K., O'Connor, C., Gear, J., Hoagland, R., 2022. Minimize the bad days: Wildland fire response and suppression success. Rangelands 44 (3), 187–193. doi:10.1016/j.rala.2021.12.006.
Wright, H.A., Neuenschwander, L.F., Britton, C.M., 1979. The role and use of fire in sagebrush-grass and pinyon-juniper plant communities: a state of the art review (No. INT-58). US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, USA, p. 48 p.
Yorgey, G.G., Hall, S.A., Allen, E.R., Whitefield, E.M., Embertson, N.M., Jones, V.P., Saari, B.R., Rajagopalan, K., Roesch-McNally, G.E., Van Horne, B., Abatzoglou, J.T., Collins, H.P., Houston, L.L., Ewing, T.W., Kruger, C.E., 2017. Northwest U.S. Agriculture in a changing climate: collaboratively defined research and extension priorities. Frontiers in Environmental Science 5, 52. doi:10.3389/fenvs.2017.00052.
Zeppel, M.J.B., Wilks, J.V., Lewis, J.D., 2014. Impacts of extreme precipitation and seasonal changes in precipitation on plants. Biogeosciences 11, 3083–3093. doi:10.5194/bg-11-3083-2014.
Zimmer, S.N., Reeves, M.C., St. Peter, J.R., Hanberry, B.B., 2022. Earlier green-up and senescence of temperate United States rangelands under future climate. Modeling Earth Systems and Environment 8, 5389–5405. doi:10.1007/s40808-022-01389-4.