Chapter L. Climate Adaptation

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Executive Summary

Increases in the frequency and magnitude of extreme climate events in the 21st century likely will create more ecologically significant droughts (especially hot droughts) and floods than experienced in the recent past. However, because there is substantial variability across climate projections among models, across seasons, and across space, the models help with understanding possible scenarios and possible outcomes affecting ecosystems and humans. All 10 climate models examined in this chapter project increases in temperature, and the magnitude of increase (1–3 degrees Celsius [°C; 1.8–5.4 degrees Fahrenheit (°F)] between 2020 and 2050, 2–5 °C [3.6–9.0 °F] or as much as 3–7 °C [5.4–12.6 °F] for 2070–2100) is reasonably consistent across seasons and locations, whereas approximately 90 percent of these models indicate slight increases in precipitation.

The interaction of rising temperatures and potential modest increases in precipitation are expected to influence patterns of drought and moisture availability within the sagebrush (*Artemisia* spp.) biome. Cool-season recharge of soil moisture is likely to be sustained, although more precipitation will come as rain, potentially resulting in higher moisture availability earlier in the year. However, warmer temperatures will prompt earlier soil drying, leading to longer periods of hot and dry conditions in summer. Climate projections indicate that large decreases in the abundance of sagebrush will occur in the hottest and driest regions within the sagebrush biome, but the geographic extent of loss is uncertain. Furthermore, potential increases in the abundance of cheatgrass (*Bromus tectorum*) are likely in cooler, wetter parts of that species' range, and decreases are likely in the hottest and driest parts of its range. However, those hot and dry locations may be vulnerable to invasion by other nonnative annuals such as red brome (*B. rubens*). Fewer days with precipitation in summer and declines in overall summer precipitation have likely contributed to recent increases in the amount of sagebrush burned. In the next 30–40 years, longer and hotter fire seasons, and more extreme fire weather are predicted to lead to a significant increase in the probability of very large fires, particularly in the Pacific Northwest.

The ecological importance of riparian zones, seeps, springs, and other wetlands are disproportionately large relative to their size. Similarly, climate change and other anthropogenic impacts on mesic systems may affect ecosystem function disproportionately, especially if these systems serve as local buffers and climate refugia. Native animal species' ability to persist as climate changes likely will depend on their phenotypic plasticity and evolutionary rates. Land use, including human appropriation of water and activities that fragment native vegetation or open space, may further constrict adaptive responses. Climate-driven stresses also are likely to impact the capacity to support herds of domestic livestock, although human intervention in breeding, nutrition, and movement may reduce the effects of climate change on livestock compared to the effects on most native species. Climate adaptation strategies include informed selection of seed sources for restoration and consideration of resistance and resilience information when prioritizing areas for restoration or other management.

Introduction

Average annual temperature over the contiguous United States has increased by 0.7 degrees Celsius (°C; 1.2 degrees Fahrenheit (°F) for the period 1986–2016 compared to 1901–1960 (Vose and others, 2017). Warming temperatures, increased frequency of heat waves, and possibly drought have likely contributed to longer fire seasons, more extreme fire weather, and consequently, larger amounts of sagebrush (*Artemisia* spp.) burned each year. Future climate warming and alterations in timing of seasonal precipitation may impact the distribution of sagebrush and invasive plants, and further increase the frequency and severity of fires and duration of fire seasons. The degree and spatial extent of these impacts of warming climates on the sagebrush biome will depend on the degree and rate of warming and changes in timing and amount of precipitation.

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Climate Change Trajectories and Impacts

Climate Projections

Details on projected changes in climate across several ecoregions encompassing the sagebrush biome are provided by Chambers and others (2017a; see sec. 5.2 and app. 3). Representative concentration pathways (RCPs) are scenarios used for global climate projections. These scenarios include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover (see https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html).

In this chapter, the results are summarized for a representative set of climate models that simulate two general climate scenarios: moderate increases in greenhouse gas emissions (RCP4.5) and more substantial increases (RCP8.5). Over the entire sagebrush biome, climate models simulating both RCPs project average increases in temperature of 1–3 °C (1.8–5.4 °F) in the near term (2020–2050) and increases in average temperatures of 2–5 °C (3.6–9.0 °F) under RCP4.5 and 3–7 °C (5.4–12.6 °F) under RCP8.5 in the far term (2070–2100). The models project that the greatest average temperature increases (more than 6 °C [10.8 °F] from 2070 to 2100 under RCP8.5) will occur in the center and far northeastern edge of the current range of big sagebrush (*A. tridentata*). Winter temperature increases are projected to be greatest in the northeastern part of big sagebrush range. Spring temperature increases, by contrast, are projected to be greatest in the central and southern part of the range.

Climate-change projections for precipitation in the sagebrush biome, and virtually all biomes, are more uncertain than projections of temperature change. Although the median projections indicate increasing mean annual precipitation—with the greatest increase (approximately 20 percent under RCP8.5) by the end of the century—different models project changes from a slight (less than [<] 10 percent) decrease to a 50 percent increase. Spring precipitation is projected to increase most in the northeastern part of the range of big sagebrush, and summer precipitation is projected to increase most in the southern and western range of big sagebrush. Most climate models project that the proportion of precipitation falling between May and October will decrease, especially in the northern part of the region. Projected historical and future values of these and other climate variables are available at https://www.sciencebase.gov/catalog/item/5850549ae4b0f24ebfd9368f.

A recent study described the current and projected 21st century climate changes at approximately 900 sites (Palmquist and others, 2016a), representing the current distribution of big sagebrush (Schlaepfer and others, 2012a). This study examined climate projections from 10 general circulation models (GCMs), a number likely to represent greater than (>) 80 percent of the variation in all climate models in CMIP5 (Coupled Model Intercomparison Project Phase 5—data source for climate data; McSweeney and Jones, 2016). The GCMs that were selected represent the most independent (Knutti and others, 2013) and best performing (for the western United States; Rupp and others, 2013) subset of GCMs. For these 900 sites, the mean annual temperature from 1980 to 2010 averaged 6.7 °C (44 °F) and is projected to increase 2.7 °C (4.9 °F) by 2030–2060 (range among 10 climate models used in this study: 1.9–3.3 °C [3.4–5.9 °F]) and 5.4 °C (9.7 °F) by 2070–2100 (ranges 4.7–6.5 °C [8.5–11.7 °F]). Mean annual precipitation at these sites averaged 353 millimeters (mm; 13.9 in.) from 1980 to 2010 and is projected to increase by 27 mm (1.1 in.) from 2030 to 2060 (ranges from −23 to 74 mm [−0.9–2.9 in.]; 90 percent of models projected increasing precipitation) and 45 mm (1.8 in.) from 2070 to 2100 (ranges from 1 to 156 mm [<1.0–6.1 in.]).

Climate Distributions and Extremes

Elevated temperature extremes have already been documented for the western United States and Canada (Vose and others, 2017), and projections suggest that rising temperatures in coming decades will be accompanied by continued increases in heat wave frequency and severity (Wuebbles and others, 2014). Similarly, the length of intervals without precipitation has increased over the past several decades (Groisman and Knight, 2008; Diffenbaugh and others, 2017) and is projected to continue increasing in the 21st century, especially in the southern part of the sagebrush biome (Polade and others, 2014). These dry intervals, combined with rising temperatures, will result in longer, hotter droughts in the western United States and Canada (Dai, 2013), including the sagebrush biome (Palmquist and others, 2016b). Simultaneous with increased severity of droughts, the frequency and severity of major precipitation events has been increasing and is projected to continue increasing in coming decades (Pfahl and others, 2017; Prein and others, 2017).

Soil Temperature and Moisture

Sagebrush ecosystems are characterized by a cool-season recharge of soil moisture (Schlaepfer and others, 2012b), so potential changes in winter precipitation as snow (especially when accompanied by rising temperatures) may alter patterns of moisture availability during the growing season. Furthermore, changes in snowpack dynamics are heavily influenced by temperature, so projections are relatively consistent among climate models. In their examination of representative big sagebrush sites, Palmquist and others (2016b; fig. L1) found that an average of 74 percent of precipitation currently falls as rain and that rising temperatures under RCP8.5 are projected to increase that proportion by 8 percent during 2030–2060 (range among climate models: 5–13 percent) and by 16 percent during 2070–2100 (range: 14–18 percent). Average maximum snow-water equivalent at these sites is projected to decrease from 45 mm (1.8 in.) in 1980–2010 to 31 mm (1.2 in.) in

2030–2060 (range: 20–39 mm [0.8–1.5 in.]) and 18 mm (0.7 in.) in 2070–2100 (range: 11–24 mm [0.4–0.9 in.]). These changes alter patterns of soil moisture, leading to increases in the amount of water available to plants during spring and decreases in the amount of water available to plants during summer. This may lead to overall longer warm-season dry soil periods.

Soil temperature and moisture regimes in sagebrush ecosystems are used to assess resilience to disturbance and resistance to nonnative invasive species (Chambers and others, 2014b; Pyke and others, 2015b; Chambers and others, 2016b; Maestas and others, 2016; Chambers and others, 2017a). Recent work (Bradford and others, 2019) characterized the potential impact of climate change on the soil temperature and moisture variables that are the foundation of these assessments. Results suggest substantial increases in soil temperature that are reasonably consistent across climate models. Higher temperatures will expand the area of mesic (ranges from 8 to 15 °C [14.4–27.0 °F]) and thermic (ranges from 15 to 22 °C [27–39.6 °F]) soil temperatures while decreasing the area of cryic (ranges from 0 to 8 °C [0–14.4 °F]) and frigid (<8 °C [<14.4 °F]) temperatures, with the overall effect of decreasing the extent of areas with high resilience and resistance. Simultaneously, shifts toward cool season moisture lead to an increase in the area with cool-season (xeric) moisture conditions and a decrease in the area with warm season (ustic) conditions.

Plant Community Impacts

Single Species Approaches

Much of the research assessing the impact of climate change on sagebrush-dominated plant communities focuses on how precipitation or temperature may affect the distribution or abundance of a focal species (climate suitability models). The two species receiving most of the attention are big sagebrush and cheatgrass. The most common approach is to model current species distributions as a function of climate and other environmental drivers, then project future changes in habitat amount and quality as a function of projected changes in the environment. Studies applying this approach (for example, Schlaepfer and others, 2012a; Still and Richardson, 2015) to big sagebrush estimate declines of the species' occurrence in areas that are relatively low in elevation, warm, and dry (for example, the southern Great Basin and Colorado Plateau). Species' occurrence is estimated to increase in areas that are relatively high in elevation, cool, and wet (for example, montane areas and parts of the northern mixed prairie). Both Schlaepfer and others (2012a) and Still and Richardson (2015) projected substantial decreases in area for sagebrush.

However, similar studies that focused on cheatgrass abundance rather than occurrence found that precipitation seasonality had a greater influence (Bradley, 2010; Boyte and others, 2016; Brummer and others, 2016). Cheatgrass is

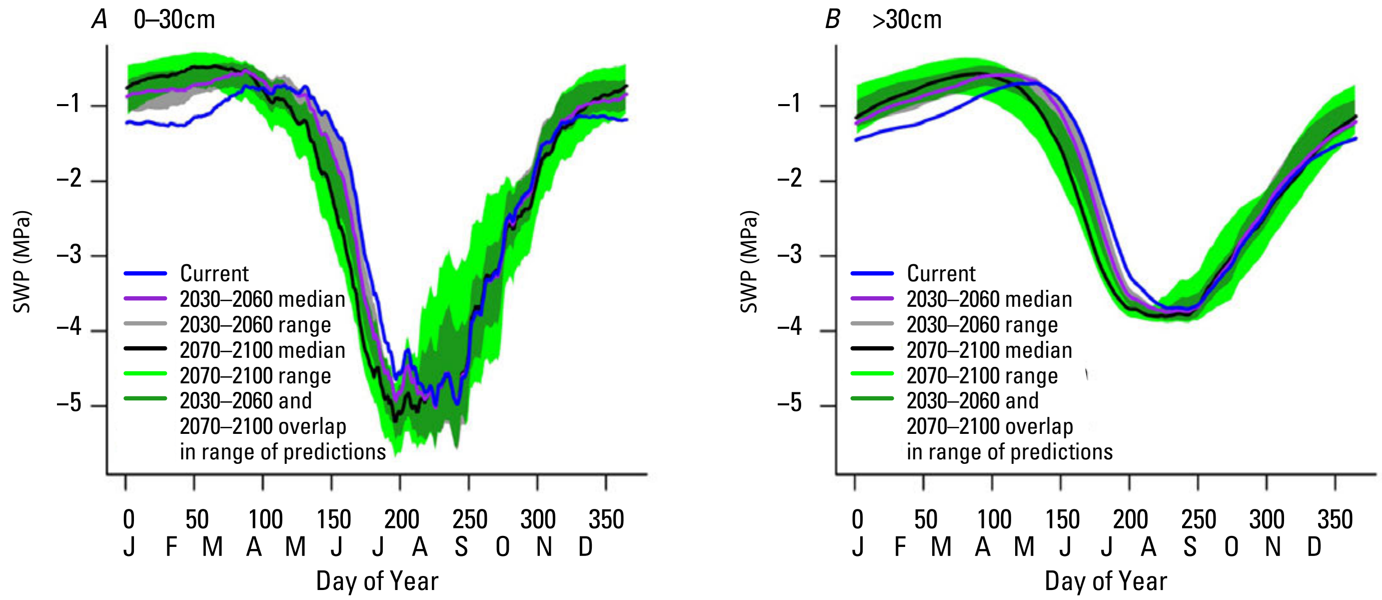

Figure L1. Mean daily soil water potential (SWP), based on 10 global circulation models (GSMs), for *A*, upper (0–30 centimeters [cm; 0–11.8 inches {in.}]) and *B*, lower (>30 cm [11.8 in.]) soil layers for current conditions (1980–2010), 2030–2060, and 2070–2100 across 898 sagebrush (*Artemisia* spp.) sites in the western United States. For 2030–2060 and 2070–2100, daily median values and the daily minimum and maximum values predicted from all 10 GCMs are shown. The overlap in the range of GCM predictions for 2030–2060 and 2070–2100 is in dark green. After Palmquist and others, 2016b. cm, centimeter; >, greater than; MPa, megapascals [pressure]; J, January; F, February; M, March; A, April: M, May; J, June; J, July; A, August; S, September; O, October; N, November; D, December.

currently most abundant in parts of the sagebrush biome with relatively hot and dry summers and where precipitation is received mostly during autumn and spring. The implication is that a change in precipitation seasonality could alter cheatgrass abundance, but predictions about changes in precipitation timing and amount are highly uncertain.

Climate suitability models depend heavily on potentially inaccurate assumptions, such as current distributions being in equilibrium with climate, and rarely provide information about abundance or the dynamics of climate change. Experiments can provide data that allow more direct inference about the effects of specific environmental drivers. Experimental manipulations of temperature and snowpack indicate that cheatgrass fitness likely increases as temperature increases (Concilio and others, 2013; Compagnoni and Adler, 2014a, 2014b; Blumenthal and others, 2016). Experimental manipulations to reduce winter and early spring precipitation limited increases in cheatgrass density (Prevéy and others, 2010a). Increasing winter precipitation through experimental irrigation greatly enhanced big sagebrush abundance over 20 years, provided soils were deep (> 1 meter [3.3 feet]; Germino and Reinhart, 2014).

A multimodel comparison of climate change impacts on sagebrush abundance (Renwick and others, 2018) yielded different inferences than the climate suitability models. Four models estimating the effects of climate change, including time series models (Kleinhesselink and Adler, 2018), mechanistic models (Schlaepfer and others, 2015), and a distribution model generated by Renwick and others (2018), were compared by Renwick and others (2018). The models were built with different data sources and reflected different underlying processes. The outputs consistently projected little change or an increase in sagebrush abundance over much of the species' current range, with decreases projected only in the hottest, driest parts. Both field measurements and modeling also have indicated that sagebrush and cheatgrass have substantial impacts on the microclimatic attributes of sites (Valayamkunnath and others, 2018) such as soil water availability, thereby affecting other plants in the community (Wilcox and others, 2012).

The study of physiological thresholds is another approach for learning about plant responses to climate. For example, the survival of different populations of sagebrush in common gardens is explained best by their adaptation to low temperature (Chaney and others, 2017; Lazarus and others, 2019). These thresholds for freezing damage may help explain patterns of mortality in sagebrush seedlings established from planting stocks after wildfire (Brabec and others, 2017; Lazarus and others, 2019). A response threshold to freezing temperatures also explains differences in the geographic distributions of cheatgrass and red brome (Salo, 2005; Bykova and Sage, 2012).

Impacts to Riparian Systems—Wetland and Meadow

Riparian zones, seeps, springs, and other wetlands make up a small proportion of the sagebrush biome, but they are essential to ecosystem function, the viability of many species of plants and animals, and numerous land uses. For example, about 80 percent of terrestrial animal species in the Great Basin (Thomas and others, 1979), including 66–75 percent of the breeding bird species (Martin and Finch, 1995), are associated with riparian areas for breeding, feeding, or shelter (for example, Dobkin and Wilcox, 1986; Krueper and others, 2003; Earnst and others, 2012).

The extent to which climate change will directly affect the area and configuration of riparian zones and other wetlands is difficult to project. Nevertheless, even if total precipitation changes little, increases in temperature (leading in part to increases in evapotranspiration) and decreases in the proportion of precipitation falling as snow will alter the amount of water availability seasonally and will likely intensify human appropriation of surface water and groundwater (Seager and others, 2007), particularly in the Great Basin part of the biome. Many sources of surface water throughout the Great Basin already are fully appropriated, and water is being reallocated from agricultural to domestic use as exurbanization spreads across the Intermountain West (Brown and others, 2005). Accordingly, the availability of water to support riparian functions, species, and uses is likely to decrease.

In some cases, land use has a stronger effect on riparian species and function than climate does, although the two types of causes interact. For example, recruitment of aspen (*Populus tremuloides*) in the northwestern Great Basin over the past century was much more strongly associated with grazing by domestic livestock than with climate (Beschta and others, 2014). The numerous springs and seeps that are supplied by groundwater, and species and communities in the surrounding areas, also will continue to be affected directly by human uses of water. Groundwater storage has not decreased appreciably over the past century in the Great Basin, and therefore, losses of groundwater are more likely attributable to land use than to climate change (Brutsaert, 2012).

Responses of terrestrial, riparian-associated species to climate change are difficult to project in part because changes in the structure and composition of riparian vegetation have different effects on different species (Strong and Bock, 1990; Dickson and others, 2009). For example, some species respond strongly to the extent of riparian areas, whereas others respond more strongly to the contiguity or fragmentation of riparian areas (Fahrig, 2013). Abundance and recruitment are likely more sensitive than species presence to changes in the amount or fragmentation of riparian cover (Fleishman and others, 2014). Moreover, many riparian areas in the Intermountain West are naturally fragmented. Species that evolved in naturally fragmented systems may have different responses to habitat area and fragmentation than species in human-fragmented systems. As climate changes, the microclimate in some riparian areas may provide a biological buffer from some effects of climate change. For instance, low-elevation ravines are cooler and wetter than surrounding areas and may provide refugia for limber pine (*Pinus flexilis*) in the Great Basin (Millar and others, 2018).

Biological Soil Crusts

Relatively few studies have attempted to assess the long-term impacts of changing climate on competitive interactions within sagebrush-dominated plant communities. One approach to evaluating the potential dynamics of future plant communities, an examination of competition for water by plant functional groups, identified several potential changes in biomass (Palmquist and others, 2018). In particular, biomass of big sagebrush was projected to decline by roughly 30–50 percent in the low-elevation, hotter, and drier areas by 2100, with smaller declines expected in the short term. By contrast, projections suggested that sagebrush biomass may increase by 20–30 percent in high-elevation, cool, and relatively wet locations.

Biological soil crust communities (BSCCs) occur between sparsely distributed woody plants in sagebrush ecosystems and can comprise large parts of the flora cover, particularly where herbaceous vegetation is lacking (Rutherford and others, 2017). The crusts, which are formed by algae, fungi, cyanobacteria, lichens, and bryophytes, occur in semiarid areas. They stabilize soils and increase nutrient cycling, water infiltration, and establishment of vascular plants (Root and others, 2017). With potential changes in climate—and therefore changes in fire regimes and potential invasion by nonnative plants—the species richness, abundance, and cover of BSCCs is likely to change, in turn affecting hydrological and biogeochemical functions (Rutherford and others, 2017). Consequences of a reduction in cover may include soil destabilization, increased albedo (reflection of sunlight), and increased redistribution of dust, all of which could increase rates of snowmelt (for example, Painter and others, 2018; Zhang and others, 2018).

Measurements of BSCCs at four sites in Idaho 12–16 years postfire suggested reductions in percent cover and abundance of several functional groups of plants (for example, squamulose lichens, vagrant lichens, and tall turf mosses), and a 65 percent reduction in species richness (Root and others, 2017). Although the study did not find that fires reduced the overall representation of functional groups of vascular plants, BSCCs require at least one to two decades to recover after fire. With potential changes in climate, and therefore fire regimes and invasion of nonnative species, BSCCs could experience multiple stresses.

Few studies have investigated how BSCCs may change owing to changes in climate. However, their functional importance in semiarid ecosystems is well understood (Ferrenberg and others, 2017), and therefore, manipulations can suggest some of the consequences if their cover, abundance, and composition change. For example, a 10-year study (2005–2015) in the Colorado Plateau established 20 different 5-square meter (m^2; 54 square foot [ft^2]) control sites and treatment sites in which water input and temperature were manipulated to simulate projected climate changes: a 1.2 mm (0.05 in.) increase in summer precipitation and a 2 °C (3.6 °F) temperature increase for 3 years followed by a 4 °C (3.6 °F) temperature increase for 7 years (Rutherford and others, 2017). Treatments were selected to meet climate model projections for 2098 (Christensen and others, 2004). The results indicated as much as a 33 percent increase in albedo in all three treatment types (increased water, increased temperature, and increased water and temperature), which resulted in loss of darkly pigmented, late succession species and increases in cyanobacteria (early successional, lightly pigmented species). Ecosystems and interactions among their biotic and abiotic elements are complex, but increases in the magnitude and rate of warming will likely have negative consequences in many semiarid ecosystems.

Climate Change as One of Multiple Interacting Stressors

The previously referenced studies focused on the direct effects of changes in precipitation or temperature on species and communities but did not address the potential for climate change to interact with—and exacerbate—additional threats to species such as land use change, biological invasions, and changes in fire dynamics. For example, Renwick and others (2018) projected increases in sagebrush abundance in cool, moist parts of the species' range. However, their models did not consider the possibility that warming also might cause an increase in cheatgrass abundance in the same locations, leading to increases in fire and, ultimately, substantial reductions in sagebrush abundance. Large increases in the abundance of cheatgrass and nonnative forbs occurred when sagebrush was experimentally removed from plots (Prevéy, 2010a, b). The effects were exacerbated in study locations where the most precipitation fell during winter (Prevéy and others, 2010a, b), which is projected for much of the core range of big sagebrush (Abatzoglou and Kolden, 2011). Such interactions could amplify, offset, or overwhelm the direct effects of precipitation and temperature on individual species, but little research exists to help understand these potential effects.

Effects of Climate Change on Wildfire

Sagebrush ecosystems are highly variable because they occur over large gradients of climate, topography, soils, vegetation types, and plant functional groups (fig. L2; see also chap. J, this volume). Fire occurrence in any given year is a function of fuels (biomass), the availability of those fuels for burning, fire weather, and ignition sources (Bradstock, 2010). Fire regimes can be altered by changes in the composition of plant functional groups, the amount and availability of biomass for burning (Abatzoglou and Kolden, 2013), and ignitions that are either caused by humans or lightning (Fusco and others, 2015). Invasion of nonnative annual grasses, which are highly flammable and increase fuel continuity, can alter plant functional group composition and increase the amount and availability of fuels following high-precipitation years. Fire size and intensity is strongly influenced by fire weather and fire behavior (Bradstock, 2010). Warmer and drier conditions are often required to decrease fuel moisture sufficiently for large wildfires to burn. Thus, increases in atmospheric carbon dioxide concentrations that result in changes in climate and fire weather (for example, longer and hotter fire seasons and more extreme fire weather) have the potential to influence fire regimes in sagebrush ecosystems (Abatzoglou and Kolden, 2013; Stavros and others, 2014).

Declines in summer precipitation and the number of days with measurable precipitation have likely been a primary driver of increases in area burned across the western United States (Holden and others, 2018). Recent analyses of fire patterns in pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) land-cover types in the semiarid western United States demonstrated that fire seasons started earlier and ended later from 1984 to 2013 in the Sierra Pacific, Central Basin and Range, and Mojave Basin and Range ecoregions (Board and others, 2018). In many of the ecoregions, the area burned during the fire season was related to temperature, precipitation, and soil moisture in the preceding year because of their effects on fine-fuel abundance (Abatzoglou and Kolden, 2011).

Generalized linear models and statistically downscaled climate projections for two representative concentration pathways (RCP4.5 and 8.5) projected significant increases in the probability of very large wildfires during the mid-21st century (2031–2060; >20,234 hectares [ha; 50,000 acres];

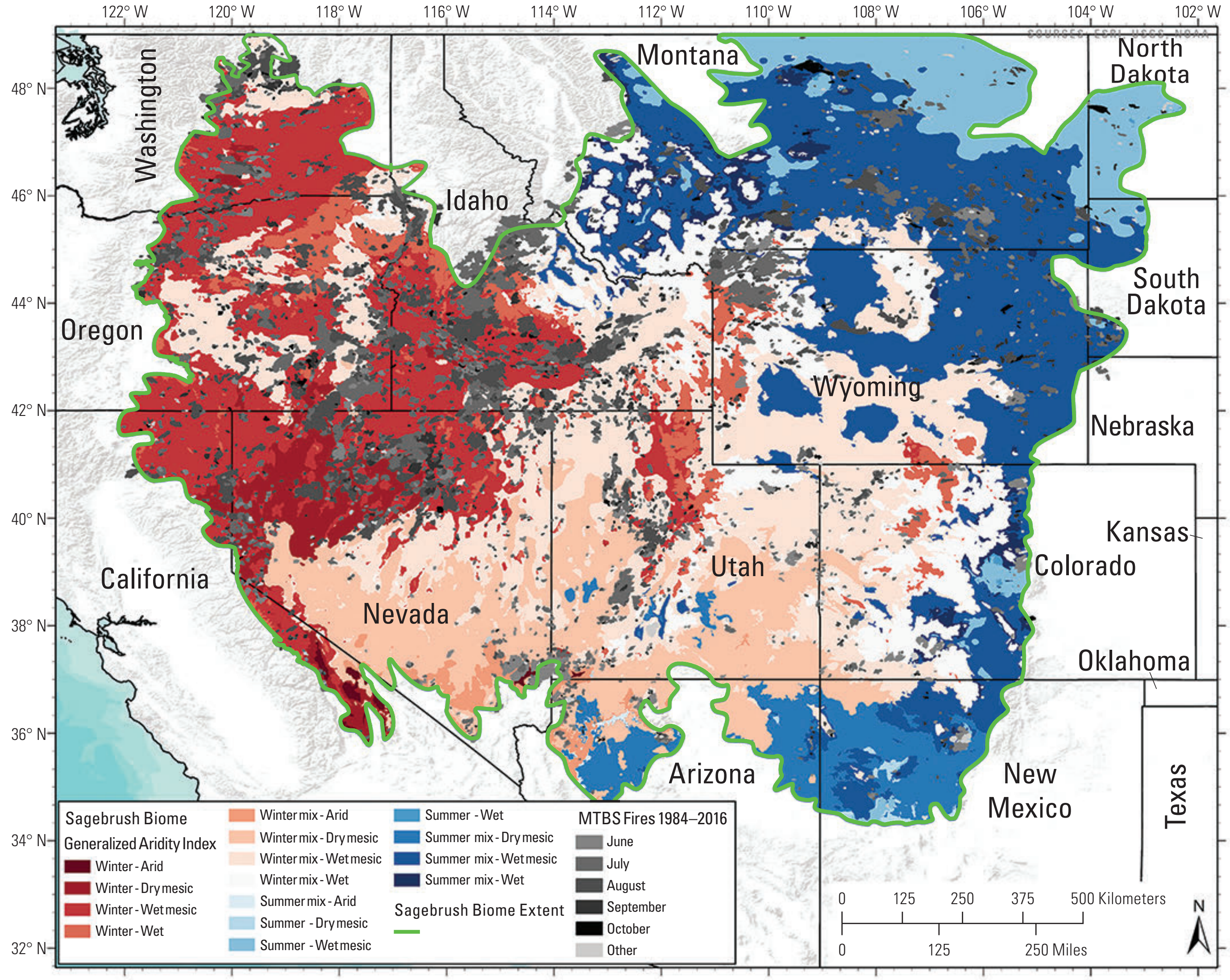

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Figure L2. A generalized aridity index customized for the sagebrush (*Artemisia* spp.) biome (adapted from Dobrowski and others, 2013) based on the timing of precipitation (winter or summer) using 30-year normal annual values (from PRISM Climate Group, 2019), overlaid with the locations of large fires that occurred during 1984–2016 (from Monitoring Trends in Burn Severity, 2018).

Stavros and others, 2014). In mesic areas such as the Pacific Northwest, model agreement was high, and the occurrence of weeks with very large wildfires in a given year was 2–2.7 times more likely. The number of weeks with at least one very large wildfire in fuel-limited systems, such as the western Great Basin, was only 1.3 times greater, but model agreement was low. Therefore, increases in the likelihood of very large wildfires are greater in areas where fire is associated with unusually hot and dry conditions, such as the Pacific Northwest, than in areas where fire is related to conditions in previous years, such as much of the western Great Basin.

Wildlife and Livestock Impacts

Wildlife Impacts and Adaptive Capacity

Conservation planning for climate change, including climate-change vulnerability assessment, has tended to focus on population climate exposure rather than on species sensitivity and adaptive capacity (Butt and others, 2016). Adaptive capacity and land use are likely to have a substantial effect on responses to climate change of native animals in the region in which sagebrush dominates, including but not limited to big sagebrush, black sagebrush (*A. nova*), low sagebrush (*A. arbuscula*), and silver sagebrush (*A. cana*). Species adapt in response to environmental changes (Thomas and others, 1996; Skelly and others, 2007), and these adaptations may be rapid (on the order of years) or slow (on the order of decades; MacDonald and others, 2008; Willis and MacDonald, 2011). Adaptive responses may reflect phenotypic plasticity (the ability of individuals to increase their probability of survival and reproduction by responding to environmental cues), dispersal ability, or adaptive evolution (Reed and others, 2011; Beever and others, 2016). Plasticity is heritable, and therefore can also evolve. Species with relatively high phenotypic plasticity are generally more resilient to environmental change, including climate change, than those with relatively little plasticity (Møller and others, 2008; Willis and others, 2008).

The explicit study of the extent of phenotypic plasticity in wild animals and the extent to which such plasticity is adaptive is rare (Hall and Chalfoun, 2019). An understanding of underlying genetic variation in traits related to persistence as climate changes is even more limited (Culp and others, 2017). The development of new genomic resources, however, may facilitate a better understanding of the adaptive potential of species (Oyler-McCance and others, 2016). Such resources now exist for several species that inhabit sagebrush-dominated areas (Oh and others, 2019). For example, genomic analyses revealed evidence of adaptive variation in genes linked to heat stress, response to viral pathogens, and digestion of plant defense compounds (such as those in sagebrush) in Gunnison sage-grouse (*Centrocercus minimus*; Zimmerman and others, 2019). The extent to which this variation may affect the ability of species to adapt to increasing temperatures or to potential climate-induced changes to its habitat is uncertain. Phenotypic plasticity, however, may be more strongly associated with whether populations persist in the face of climate change than with evolutionary capacity (Dawson and others, 2011).

Many of the animal species that currently inhabit the Intermountain West persisted through relatively rapid and substantial changes in climate and land cover over tens of thousands of years. However, the anticipated rate of widespread climate change from 2010 to 2100 generally exceeds that documented in paleoecological records from the past approximately 2 million years. Therefore, some populations or species, especially those with relatively long generation times, may not be able to evolve genetically with the current pace of climate change (Hoffmann and Sgrò, 2011; Sih and others, 2011). Some species that inhabit open, exposed environments in deserts, including those that occupy relatively low-elevation sagebrush steppe in the United States and Canada, may be among the most vulnerable to changes in climate because they may already be close to their physiological limits (Vale and Brito, 2015).

Changes in climate variability may affect phenology—the timing of seasonal biological events (Parmesan and Yohe, 2003; Gienapp and others, 2013). For example, differences among species in phenological responses to climate variability may affect species interactions including competition, predation, symbiosis, and disease (Yang and Rudolf, 2010). Both plasticity and topographic heterogeneity may reduce the likelihood that asynchronous phenology will reduce the viability of species in the Intermountain West. Additionally, phenological changes may be more likely at relatively high and mesic elevations than at relatively low and xeric elevations (Fleishman and others, 2013).

Livestock Impacts and Adaptive Capacity

Climate-driven stresses on domestic livestock have the potential to reduce the number of young produced or the amount of weight gained (Thornton and others, 2009; Gaughan and Cawdell-Smith, 2015; Rojas-Downing and others, 2017) and therefore to reduce farm or ranch income. This issue is receiving increased attention in both scientific and agricultural communities. Adaptation in this case is largely human-mediated and involves the selection of livestock breeds with traits that are resilient to contemporary and projected climate (for example, heat tolerance; also body size and "muscling"). Adaptation also involves modified management strategies (for example, grazing rotations, stocking rates, protein supplements) that aid in climate response.

Climate change may also impact livestock production by causing an increase in the frequency and severity of droughts and floods, which may reduce available forage and lead to changes in grazing management. Existing programs to help producers manage drought, such as grass banks, drought insurance, more flexible operations (yearlings rather than cow-calf operations), seasonal drought forecasts, and spatial bet-hedging strategies, will become even more important (Finch and others, 2016).

Indirect Climate Impacts

One of the greatest ways in which climate change in arid biomes may affect wildlife and livestock is indirect, from human appropriation of surface water and groundwater. Although per capita municipal water use is declining across much of the western United States, human populations are increasing, and the production of food and energy in the region generally requires considerable inputs of fresh water (Udall, 2013). It is likely that increases in temperature and changes in the timing and amount of snow across the sagebrush biome will reduce water availability for both humans and animals, even if the total amount of precipitation remains fairly constant.

As noted above, climate change interacts with other environmental changes that function as stressors to many species, including changes in land use, species composition, and disturbance processes. Although the scientific community continues to explore whether native species with similar evolutionary histories, life-history traits, and vegetation associations have similar and predictable responses to environmental change, empirical evidence is limited. The greatest good for the greatest number of native species will likely be accomplished by actions that follow first principles of conservation, such as minimizing loss and fragmentation of natural ecosystems by human activities and minimizing the creation of hard edges between vegetation types. In the sagebrush biome, maintaining riparian ecosystems may be especially beneficial to a high proportion of native taxa.

Diseases and Impacts to Wildlife and Humans

As climate and land use continue to change, the distribution, frequency, and virulence of infectious diseases that are either carried by or expressed in native wild animals, domestic animals, and humans across the sagebrush biome are also expected to change. Infectious diseases are the product of interactions among hosts, pathogens, and vectors, and changes in climate may directly affect the distribution, life cycle, and physiological status of hosts (Gallana and others, 2013). However, given the complexity of systems and possible adaptations, there is no consensus on how infectious diseases may respond to climate changes (Liang and Gong, 2017). The physiological changes in hosts may include phenotypic acclimation or genotypic adaptation, but with many interactions and stressors, nonlinear responses of infectious diseases to changing climates are likely (Gallana and others, 2013). Changes in temperature, precipitation, and humidity affect vector abundance and transmission of pathogens. Land use, pollution, and social and economic systems also change in response to climate change, which can affect the geographic and temporal distribution of infectious diseases (Algeo and others, 2014).

In the western United States, fleas and rodents serve as vectors of sylvatic plague (*Yersinia pestis*), which can spread to pets and humans. Prairie dogs (*Cynomys* spp.) are the most common vector in the western United States. Models suggest general reductions of the plague in prairies in the United States but indicate potential shifts of the bacteria to higher latitudes and elevations (Algeo and others, 2014). Chronic wasting disease occurs primarily in the western United States among elk (*Cervus canadensis*), mule deer (*Odocoileus hemionus*), and white-tailed deer (*O. virginianus*). Climate-driven changes in these species' ranges may increase the frequency of their interactions with other ungulates, such as woodland caribou (*Rangifer tarandus caribou*; Algeo and others, 2014).

Hantavirus pulmonary syndrome occurs when humans contact Hantavirus particles associated with feces of murid rodents, such as deer mice (*Peromyscus maniculatus*), which most commonly occurs in the southwestern United States (Algeo and others, 2014). The occurrence of hantavirus pulmonary syndrome fluctuates with population cycles of deer mice, which are responsive to El Niño events. Therefore, climate changes will likely affect distributions and population cycles of deer mice (Algeo and others, 2014) and may increase the occurrence of hantavirus pulmonary syndrome in humans.

West Nile virus (*Flavivirus* spp.), which currently occurs on every continent except Antarctica, causes neurological symptoms in birds (notably greater sage-grouse [Walker and Naugle, 2011]), horses (*Equus caballus*), and humans. Mosquitoes (mainly those of the genus *Culex*) are the primary vectors of West Nile virus. Ticks are a much less common vector (Hoover and Barker, 2016). Temperature and the availability of overwintering sites play a major role in population sizes of mosquitoes. The incidence of West Nile virus has increased significantly since 1996. Given a scenario of RCP4.5 in 2070, West Nile virus is likely to expand across all continents (Hoover and Barker, 2016). Similarly, an assessment of potential risks of West Nile virus in southwestern Wyoming, north-central Montana, and possibly northeastern Wyoming, given six projections of climate in 2030 suggested that transmission is likely to increase in July and August (Schrag and others, 2011).

Climate Change Adaptation

Vulnerability and Adaptation Concepts

Climate vulnerability, the degree to which a system is susceptible to adverse effects of climate change—which may include climate variability and extremes (Intergovernmental Panel on Climate Change, 2007)—can be estimated at a variety of ecological, spatial, and temporal scales with standard vulnerability assessments (Glick and others, 2011). Vulnerability is a function of the sensitivity of a particular system to climate changes, its exposure to those changes, and its capacity to adapt (Intergovernmental Panel on Climate Change, 2007). The potential of natural and human systems to adapt to climate change can be increased by promoting ecological resilience; maintaining ecological function, including ecosystem services; and supporting other elements of biological diversity (Glick and others, 2009). Given the uncertainties associated with projecting future climates and with the adaptive capacity of species and ecological function, some traditional adaptive management approaches are well-suited to guide resource management in response to climate change.

Ecological Models Incorporating Climate

Many modeling approaches aim to characterize historical, current, and future interactions between climate and ecological condition. Climate envelope models are projections of changes in the distributions of individual species (such as sagebrush [Schlaepfer and others, 2012a], cheatgrass [Bradley and others, 2016], or birds [Langham and others, 2015]) under different climate change scenarios. This family of models assume that species-environment relations are spatially homogeneous and permanent (Parra and Monahan, 2008) and, at least implicitly, that climate is the primary driver or limiting factor of species' distributions. Also, these models rarely account for heterogeneity in topography and microclimate that is common across the Intermountain West and which affects the distributions of numerous taxonomic groups (for example, Weiss and others, 1988; Frey and others, 2016). Models that reflect these assumptions can overestimate the distributions of species that are locally adapted (Reed and others, 2011) and underestimate species' capacity for adaptation (Visser, 2008; Chevin and others, 2010; Reed and others, 2013). Furthermore, future values of climate variables may be outside the boundaries of values during the period of observation. Values outlying the boundaries would thereby increase the uncertainty of projections based on associated statistical models.

Climate change velocity models (Carroll and others, 2015; Hamann and others, 2015) evaluate the exposure of an organism to climate change. Climate velocity is calculated by dividing the rate of climate change by the rate of spatial climate variability to hypothesize a speed at which species must migrate over the surface of Earth to maintain constant climate conditions. Forward velocity models measure the distance from a single location (potential source of organisms) to multiple future destinations and focus on species or populations. In other words, these models measure the speed at which an organism would need to move to maintain the same climate niche.

Backward velocity models consider the distance between multiple locations or sources and a single future destination and therefore focus on sites (for example, where source genotypes currently are located [time *t*] that will be climatically matched with an area of interest at time *t*+1; Carroll and others, 2015). Velocity modeling approaches are limited by poorly understood relations between climate and species plasticity, and although they explicitly account for variation in local topography, they generally assume distance is a proxy for climate exposure and ignore climate-topographic gradients that may hinder or prevent species movement (Dobrowski and Parks, 2016).

Applying Concepts in the Sagebrush Biome

Coarse-Resolution Approaches

A number of vulnerability assessments have been developed for the sagebrush biome (app. L1; table L1.1). Assessments of climate impacts tend to focus on either specific ecosystem components or questions (such as a single species response, see above) or hypothesize generalized responses to climate change and related drivers of change. The former often are published in the peer-reviewed literature, whereas the latter generally appear in agency reports. The U.S. Department of the Interior (DOI) Bureau of Land Management [BLM] initiated rapid ecoregional assessments (REAs) that covered nearly the full extent of the sagebrush biome. Individual States have also evaluated climate-change threats in State Wildlife Action Plans. For example, Idaho identified species of greatest conservation need; evaluated threats, including those resulting from climate change; and recommended management strategies and actions (Idaho Department of Fish and Game, 2017). An assessment of vegetation responses in the sagebrush biome was provided by Reeves and others (2018a) as part of a set of fairly general vulnerability assessments led by the U.S. Department of Agriculture (USDA) Forest Service (Forest Service; for example, Halofsky and others, 2018a, b).

BLM conducted REAs (https://landscape.blm.gov/geoportal/catalog/REAs/REAs.page) for many of the ecoregions in the conterminous United States where sagebrush is a dominant species. From 2010 to 2015, authors of the REAs collated much of the available digital information on the past or projected effects of change agents (fire, development, nonnative invasive species, and climate) and conservation elements (coarse-resolution elements include major resources or ecosystems, fine-resolution elements were species) to address management questions, such as how a certain conservation element may respond to interactions among certain change agents. The analysis team for each REA convened with land managers and scientists to create a conceptual model of the response of the various conservation elements to change agents and to establish management questions. The management and science team then reviewed each step of the REA process, from data gathering to analysis and reporting. Not all REAs addressed the effects of change agents and adaptation potential in a consistent manner, which precludes applying them collectively to draw inferences across the entire sagebrush biome.

As an example of how climate was evaluated in some REAs, the Central Basin and Range REA provided watershed-level analyses on the overlap among climate responses; the existing distribution of invasive, nonnative grasses; and wildfire risk for several types of sagebrush communities as defined by LANDFIRE (for example, Intermountain Basin Montane Sagebrush Steppe, Intermountain Basins Big Sagebrush Shrubland, and Great Basin xeric mixed sagebrush shrubland; fig. L3).

Managing for Resilience and Resistance

Enabling ecosystem adaptation to climate changes and promoting ecosystem resilience to disturbance are essential for effective management (Chambers and others, 2019a, b). A widely used approach focuses on four types of climate adaptation strategies: resistance, resilience, response, and realignment (Millar and others, 2007; Halofsky and others, 2018a, b; Chambers and others, 2019c; Snyder and others, 2019). Resistance strategies aim to increase the capacity of ecosystems to retain their fundamental structure, processes, and functioning in the face of climate change-related stressors such as longer and hotter drought, more frequent and intense wildfire, outbreaks of insects at frequencies or magnitudes with which most native plants did not evolve, and diseases with which plants and animals did not evolve. Resistance strategies typically are only a short-term solution but often describe the intensive and localized management of rare and isolated species (Heller and Zavaleta, 2009). Resilience strategies aim to minimize the severity of climate change impacts by reducing climate vulnerability and increasing the capacity of ecosystem elements to adapt to climate change and its effects. Response strategies seek to facilitate spatially extensive ecological transitions in response to changing environmental conditions and may include realignment, which is the use of restoration practices to ensure ecosystem function in a changing climate.

Key steps in developing adaptation strategies and actions include obtaining the information on regional climate change projections, resource conditions, and threats; evaluating the relative resilience of ecosystems and high-value resources to climate change and interacting threats; prioritizing areas for management; developing and implementing adaptation strategies and actions; and monitoring the effectiveness of adaptation actions and adjusting management actions as needed (based on Peterson and others, 2011).

The approach used in the Science Framework for Conservation and Restoration (Chambers and others, 2017a; Crist and others, 2019) allows researchers to assess potential effects of climate change and interacting disturbances on sagebrush ecosystems and high-value resources (Chambers and others, 2019b). Geospatial analyses overlay key data to quantify and visualize the locations and extents of high-value species' habitats and resources, such as the probability of occurrence of breeding habitat for greater sage-grouse (*C. urophasianus*). Probable ecosystem response to disturbance and management treatments can be evaluated through a resilience and resistance index that is based on soil temperature and moisture regimes. Dominant threats can be assessed, such as cover of nonnative invasive annual grasses, burn probability, or density of active oil and gas wells. Climate change projections can be used to evaluate future suitability and potential interactions with invasive species and fire. These analyses and overlays can inform land managers' selection of management strategies and target areas for adaptive management.

Recent downscaled climate projections for the sagebrush biome are available (see Chambers and others, 2017a, app. 3). Also, current and future patterns in soil temperature and moisture regimes have been characterized for the sagebrush biome and provide information on how relative resilience to disturbance and management actions and resistance to nonnative invasive annual grasses are likely to change in sagebrush ecosystems (Bradford and others, 2019). Other important data layers are projections of changes in the distributions of individual plant species, such as sagebrush (Schlaepfer and others, 2012a) and annual grasses and forbs (Bradley and others, 2016; Jones, M.O., and others, 2018), under different climate change scenarios.

Climate change projections can be factored into land management prioritizations and strategies (Chambers and others, 2019a). If continued increases in climate change (for example, increases in temperature and shifts in the timing and amount of precipitation) and associated ecological responses are expected to be small, areas can be prioritized to support populations of a given species at ecoregional levels, and management can be used to build local resilience to climate change. If changes in climate are already documented and projected to be large (for example, rapid warming, uncertain snowpack, extreme drought in the next few decades), more proactive strategies may be needed to facilitate ecosystem adjustments.

Restoration

Principles and techniques for restoration of sagebrush ecosystems following fire or other disturbance are discussed in chapter R (this volume); this section provides a discussion of challenges to restoration posed by climate change. Threats such as colonization or expansion of nonnative plants and wildfires most likely will be exacerbated by warming and a higher proportion of precipitation falling in winter. Consequently, active restoration of plant communities to reduce fire occurrence—or to encourage establishment of desirable perennial plant species after fire—will become increasingly necessary. Fuel-reduction treatments and postfire

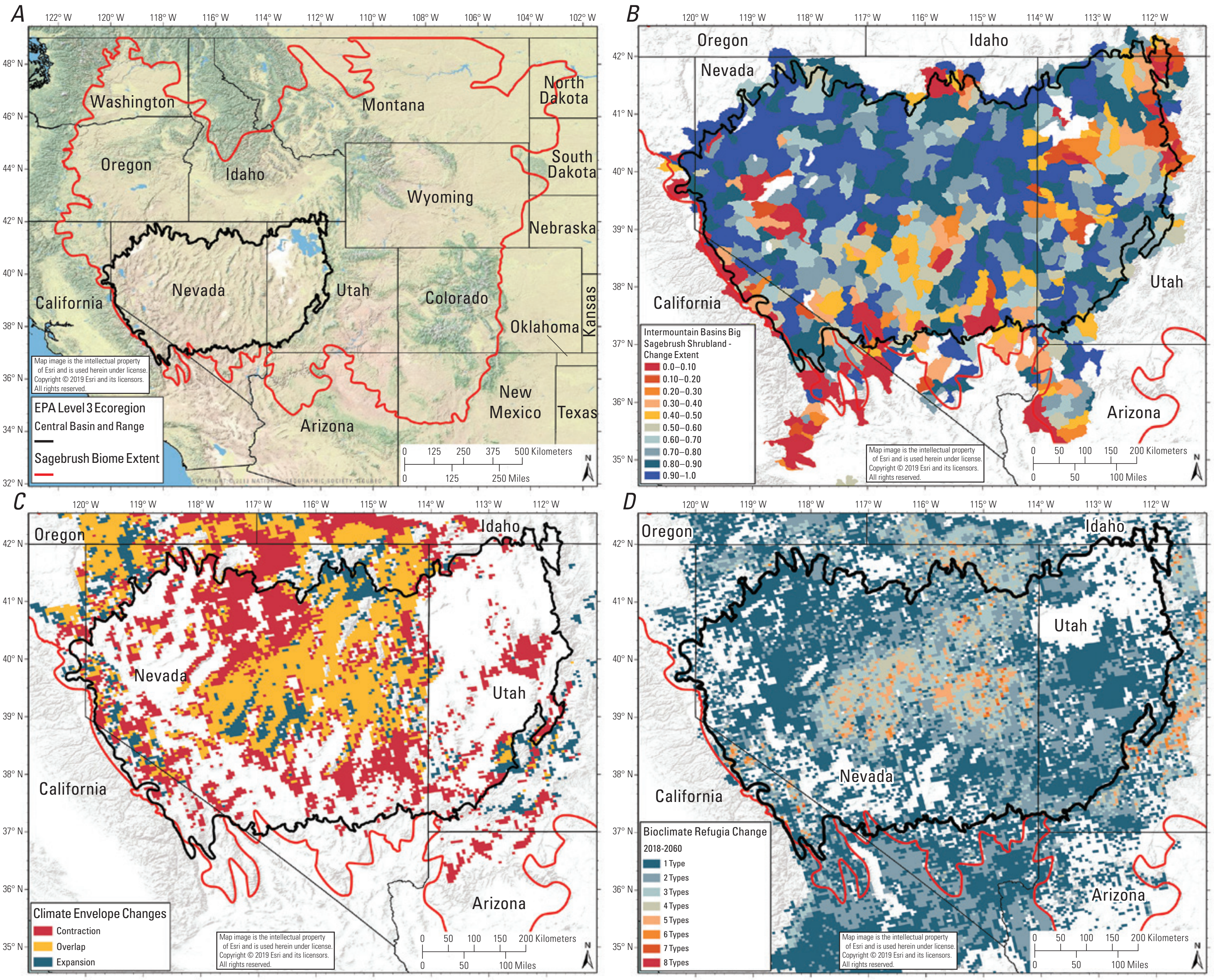


Figure L3. Maps showing *A*, aspects of a changing climate in the Central Basin and Range ecoregion and examples of climate change including *B*, percent change in the extent of Intermountain Basins Big Sagebrush (*Artemisia tridentata*) Shrubland; *C*, locations where the climate envelopes in which species currently occur may be located in the future; and *D*, different bioclimate refugia changes under predicted climate change (Bureau of Land Management, 2019d). EPA, Environmental Protection Agency.

restoration (including rehabilitation) will likely continue to be the largest investments into conservation of sagebrush ecosystems. From 1950 to 2017, more than 9,000 such land treatments were conducted over 3.8 million ha (9.3 million acres) in the Great Basin alone (Pilliod and others, 2017b). Three general considerations regarding climate are key in restoration:

- Climate affects the response of sites to restoration treatments and, conversely, restoration affects the response of sites to climate and the resilience of an ecosystem.
- Restoring perennial species and, potentially, increasing the genetic diversity of seeded or transplanted species may facilitate ecosystem functioning as the environment continues to change (Edwards and others, 2019).
- Consideration of climate during selection of treatments for particular objectives and locations increases the likelihood of success.

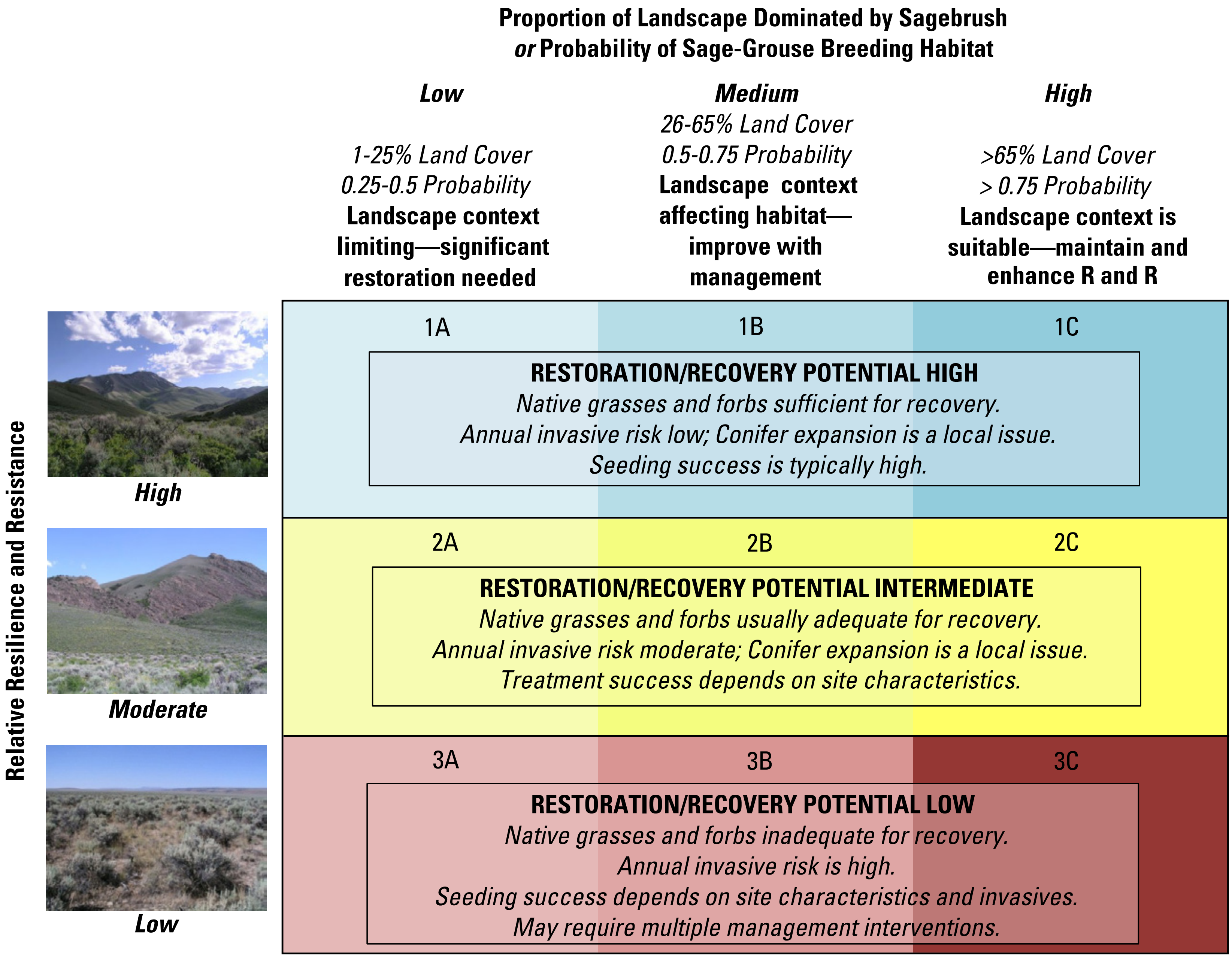
The resilience of sagebrush ecosystems or their ability to recover after disturbances, such as wildfire, and their resistance to invasion by nonnative plants is strongly affected by climate, soils, and attributes of the predisturbance plant community (chap. R, this volume, “Resilience and Resistance” sidebar; Chambers and others, 2014a, 2019b). The first consideration for climate adaptation when planning for restoration is prioritization of where treatments are conducted relative to spatial variation in vegetation and long-term climate. A resilience matrix allows land managers to consider both general and spatial resilience when prioritizing areas for management actions (fig. L4; Chambers and others, 2017a). The resilience matrix facilitates estimation of both (1) the locations where conservation and restoration activities are likely to have the greatest benefits and (2) the types of activities most likely to be effective. This decision tool will be most useful when applied in conjunction with an understanding of recent climate changes and projections for the future.

Long-term climate variation or directional changes in temperature, precipitation, and wind exert strong effects on restoration outcomes (Hardegree and others, 2018). Drought or unfavorable timing of precipitation relative to necessary temperatures for growth results in many seeding failures (for example, Brabec and others, 2015). Storm patterns are highly variable among years, and their timing relative to vegetation recovery strongly affects soil stability and restoration (for example, whether sowed seed germinates and transplants survive) via erosion from water or wind (Germino, 2015). Hydrological changes, including the delivery of annual precipitation in fewer but more intense events, are likely to exacerbate erosion and effectively reduce the hydrothermal time required for germination and seedling establishment (Roundy and others, 2018). Treatments such as herbicides, which are most commonly applied before seedlings emerge, are quite sensitive to the timing of application relative to temperature, moisture, and wind, and identifying suitable weather windows can be a considerable challenge.

Weather forecasting tools are increasingly available and can help determine when to apply treatments (chap. R, table R3, this volume). The National Weather Service Climate Prediction Center provides a 3-month outlook of weather and a suite of forecasting tools; the National Weather Service Fire Weather Center announces red flag warnings; the National Interagency Coordination Center provides Significant Wildland Fire Potential Outlooks (7-day and monthly); and a suite of forecasting tools are available on Dr. John Abatzaglou’s website (https://climate.northwestknowledge.net/RangelandForecast/index.php) at the University of Idaho and the Northwest Climate Toolbox (https://climatetoolbox.org/). There are practical limitations to timing postfire restoration treatments to optimize temperature and moisture, such as the fleeting availability of freshly burned and bare soil and emergency fire response funds. Repeat application of treatments such as seeding can be an important means of improving success regardless of weather after seeding. Any restoration treatment should be considered a learning opportunity given the uncertainty of its outcomes, particularly in relatively warm and dry sites (sites with low resilience and resistance) where multiple interventions over many years usually are necessary for success (for example, Shriver and others, 2018). Accordingly, an adaptive management cycle is essential (Wiechman and others, 2019).

Planting a selection of climatically appropriate seed sources, possibly from relatively warmer and drier areas, is a basic climate-adaptation strategy (Richardson and Chaney, 2018). The U.S. National Seed Strategy outlines key needs and steps for avoiding risks of climate maladaptation of seeded or planted species under current or future climate conditions. Given the extensive seedings that occur in sagebrush ecosystems, these concerns are very relevant. Seeds in these ecosystems are either wildland collected (for example, those of sagebrush and some forbs), wildland collected and then farm-reared to increase seed quantity (most forbs and many grasses), or developed from propagated lines and then widely available for use (for example, the Anatone cultivar of bluebunch wheatgrass [*Pseudoroegneria spicata*]).

Seeds of nonnative species also are commonly used in restoration (for example, crested wheatgrass [*Agropyron cristatum*], Lewis flax [*Linum lewisii*], clover [*Trifolium* spp.]). Use of nonnative species sometimes is rationalized based on their low cost and the severity of threat from nonnative grasses. Many of the species used in restoration seed mixes are widespread. They typically have high intraspecific diversity, and therefore it is important to obtain locally adapted subspecies (for example, Mahalovich and McArthur, 2004, for sagebrush). Furthermore, population-level variation may not be associated with subspecies identity but rather with adaptive variation, including local adaptation, which may be underestimated owing to the short duration of many common-garden experiments. This type of experiment occurs when seeds from different populations are planted in the same location to discriminate between genetic and environmental differences (for example, Germino and others, 2019).



Proportion of Landscape Dominated by Sagebrush
***or* Probability of Sage-Grouse Breeding Habitat**

Low
1-25% Land Cover
0.25-0.5 Probability
Landscape context limiting—significant restoration needed

Medium
26-65% Land Cover
0.5-0.75 Probability
Landscape context affecting habitat—improve with management

High
>65% Land Cover
> 0.75 Probability
Landscape context is suitable—maintain and enhance R and R

Relative Resilience and Resistance

High

1A 1B 1C

RESTORATION/RECOVERY POTENTIAL HIGH
Native grasses and forbs sufficient for recovery.
Annual invasive risk low; Conifer expansion is a local issue.
Seeding success is typically high.

Moderate

2A 2B 2C

RESTORATION/RECOVERY POTENTIAL INTERMEDIATE
Native grasses and forbs usually adequate for recovery.
Annual invasive risk moderate; Conifer expansion is a local issue.
Treatment success depends on site characteristics.

Low

3A 3B 3C

RESTORATION/RECOVERY POTENTIAL LOW
Native grasses and forbs inadequate for recovery.
Annual invasive risk is high.
Seeding success depends on site characteristics and invasives.
May require multiple management interventions.

Figure L4. Decision matrix for determining management strategies based on a landscape's resilience to fire and resistance to nonnative invasive annual grasses (rows) and spatial resilience and resources or habitat quality (columns). Adapted from Chambers and others (2017a). %, percent; >, greater than.

Local seed sources are often not an option for restoration of large burned areas, particularly for aerial seeding in the first year or two after fire. Provisional seed zones (Western Wildland Environmental Threat Assessment Center, https://www.fs.fed.us/wwetac/threat-map/TRMSeedZoneMapper.php) have climates similar to those of the burned areas and are useful first approximations for matching the climate of seed sources and planting sites (Bower and others, 2014). Empirical seed zones for a few species have been identified on the basis of common garden studies or genetic information and are the best available guidance for seed selection (Erickson and others, 2004; Johnson and others, 2013). Diversifying seed mixes may be another way to hedge against risks of maladaptation and the uncertainty of future climate. Diversification may be achieved either with multiple populations (seed lots) or propagated lines for a particular species or with multiple species of functional groups of interest (for example, Barr and others, 2017). The Seedlot Selection Tool (https://seedlotselectiontool.org/sst/) is useful for matching sources to planting areas.

Direct manipulation of soil moisture or temperature for restoration, such as with mulching, generally is not feasible for large treatment areas. Biological soil crusts can strongly affect the amount of water available to the soil, and spatially constrained trials have demonstrated that soil crusts can be restored in sagebrush ecosystems (Condon and Pyke, 2016). Efforts to determine whether the techniques can be applied over larger areas are underway. Aggregating seeds into pillows or coating them with hormones or other compounds that influence water absorption and retention can accelerate or delay the seasonal timing of germination (Madsen and others, 2016). Seeding sagebrush into areas among or within restoration projects that have favorable climate resulting from their topography, soils, or biological communities can mitigate climate stresses. For example, north-facing slopes or higher-elevation sites with fertile soils (organic content from prefire shrubs or from the absence of restrictive layers) and limited competition from grasses can result in a greater establishment of sagebrush from seed (Chambers and others, 2017a; Germino and others, 2018). Providing sufficient time for recovery of restored grasses and forbs by restricting grazing by domestic livestock or wild horses (*Equus caballus*) or burros (*E. asinus*) may enable these species to develop the size and root systems that are key for enduring drought.

Current Programs and Activities

Many resource management agencies are transitioning to climate adaptation (Smith and Travis, 2010; Archie and others, 2012; Center for Climate and Energy Solutions, 2012). Under Executive Order 13514 and in coordination with the Interagency Climate Change Adaptation Task Force (ICCATF), all Federal agencies are required to “manage the effects of climate change” (Center for Climate and Energy Solutions, 2012). Prominent Federal agencies that manage lands in the sagebrush biome, including the Forest Service; U.S. Department of the Interior, National Park Service; and U.S. Fish and Wildlife Service, have agency-wide strategic plans for climate adaptation, and the Departments of the Interior and Agriculture have department-level plans. These strategic plans continue to be used for general guidance, referenced for annual policy-level reporting and appear in land use planning documents (for example, see rapid ecoregional assessments, https://landscape.blm.gov/geoportal/catalog/REAs/REAs.page). However, institutional implementation has been slow (Kemp and others, 2015). Federal agency personnel reported that their organizations tend to adapt to climate change through existing management strategies that already are widely implemented (Kemp and others, 2015), in part because managers feel they lack consistent science, guidance, time, and resources to apply emerging adaptation practices. Between 33 and 56 percent of agency personnel surveyed reported that they did not know the degree to which climate change adaptation plans differ from prior management plans (Archie and others, 2012).

Federal resource management staff report actions consistent with these data. When weighed against uncertain future budgets and multiple resource objectives, treatments that cover large areas are often selected over treatments that cover small areas. The latter generally use more expensive, climate-adapted seed mixes. The extent at which treatments occur does not consider landscape climate change effects, but typically considers more localized data such as annual weather variation, antecedent conditions, local slope and aspect, and wild horse or livestock grazing management (that is, timing, season, and duration of use) in the vicinity.

Maintaining and enhancing ecological connectivity may be one of the more effective ways to ameliorate the consequences of climate change on plant and animal populations. Connectivity over extensive areas will be critical in enabling species’ ranges to shift in response to climate changes (Heller and Zavaleta, 2009) and to maintaining adaptive capacity via gene flow (Sexton and others, 2011). Research (for example, Buttrick and others, 2015; Crist and others, 2017; Cross and others, 2018) of spatially extensive connectivity and permeability has the potential to inform spatially explicit conservation that maximizes genetic and demographic persistence of sagebrush-associated species.

Each State Wildlife Action Plan (SWAP) revision relevant to the sagebrush biome identifies climate change as a factor for management consideration. Characterization of climate change varies among State plans, from direct threat to pervasive factor, and most SWAPs offer a set of climate adaptation strategies for consideration. Resource management in practice is more likely to be informed by climate adaptation principles than explicitly guided by them. Adaptations, when they occur, typically are integrated with—or modified from—traditional management activities. For example, managers are more likely to be cognizant of changing bird and pollinator behaviors and phenologies than changing climate patterns and, thus, may delay mowing as a result of observing extended nesting by grassland birds. These fine-resolution actions generally are not documented as climate adaptation.

Appendix L1. A Selection of Climate Vulnerability Assessments and Adaptation Strategies Relevant to the Sagebrush Biome

Table L1.1. A selection of climate vulnerability assessments and adaptation strategies relevant to the sagebrush (*Artemisia* spp.) biome.

[-, unspecified]

Title	Year	Geography	Relevant targets
Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats (https://www.fws.gov/greatersagegrouse/documents/Research/WAFWA_Conservation_assessment_2004.pdf)	2004	Badlands and Prairies, Great Basin, Northern Rockies, Southern Rockies, and Colorado Plateau	Sage-grouse, sagebrush
Using the NatureServe Climate Change Vulnerability Index—A Nevada Case Study (https://www.natureserve.org/biodiversity-science/publications/using-natureserve-climate-change-vulnerability-index-nevada-case)	2009	Great Basin	-
Management Planning in Light of Climate Change—Grassland Wildlife in the Great Plains LCC (https://www.cakex.org/sites/default/files/documents/Rowland%20LTA%20rally_10.3.10_GPLCC.pdf)	2010	Badlands and Prairies	Grasslands
Climate Adaptation Priorities for the Western States—Scoping Report (https://www.cakex.org/sites/default/files/documents/WesternGovernorsAssociation.pdf)	2010	Badlands and Prairies, Great Basin, Northern Rockies, Southern Rockies, and Colorado Plateau	All lands
Hydrologic Vulnerability of Sagebrush Steppe Following Pinyon and Juniper Encroachment (https://www.researchgate.net/publication/258498583_Hydrologic_Vulnerability_of_Sagebrush_Steppe_Following_Pinyon_and_Juniper_Encroachment)	2010	Badlands and Prairies, Great Basin, Northern Rockies, Southern Rockies, and Colorado Plateau	Hydrology
Managing Changing Landscapes in the Southwestern United States (https://www.cakex.org/sites/default/files/documents/TNC_Managing_Changing_Landscapes_SW.pdf)	2010	Great Basin; Southern Rockies and Colorado Plateau	Sagebrush species
Bear River Climate Change Adaptation Workshop Summary (https://www.cakex.org/sites/default/files/documents/SWCCI-BearRiver-Climate-Adaptation-Wkshp-FINAL-Report-Nov-2010.pdf)	2010	Great Basin	Wetlands
A Geospatial Assessment on the Distribution, Condition, and Vulnerability of Wyoming's Wetlands (https://www.sciencedirect.com/science/article/pii/S1470160X1000021X)	2010	Northern Rockies	Wetlands
Climate Change Vulnerability Assessments, Lessons Learned from Practical Experience—Practitioner's Responses to Frequently Asked Questions (https://www.cakex.org/sites/default/files/documents/McCarthy%202010%20Climate%20Change%20Vulnerability%20Assessment%20CC%20VA%20Lessons%20Learned_2010_0.pdf)	2010	Southern Rockies and Colorado Plateau	-
Vulnerability Assessment and Strategies for the Sheldon National Wildlife Refuge and Hart Mountain National Antelope Refuge Complex (https://www.fws.gov/refuges/whm/pdfs/SheldonHartNWR_RVA_Report.pdf)	2011	Great Basin	Sagebrush; sage-grouse
Gunnison Basin Climate Change Vulnerability Assessment (http://www.cnhp.colostate.edu/download/documents/2011/Gunnison-CC-Vulnerability-Assessment_and_Appendices-FULL_REPORT-Jan_9_2012.pdf)	2011	Southern Rockies and Colorado Plateau	Sagebrush; Gunnison sage-grouse

Table L1.1. A selection of climate vulnerability assessments and adaptation strategies relevant to the sagebrush (*Artemisia* spp.) biome.—Continued

[-, unspecified]

Title	Year	Geography	Relevant targets
Anticipating Climate Change in Montana's Sagebrush-Steppe and Yellowstone River Systems (https://www.cakex.org/case-studies/anticipating-climate-change-montanas-sagebrush-steppe-and-yellowstone-river-systems)	2012	Badlands and Prairies	Sagebrush steppe
Final Memorandum II-3-C—Northwestern Plains Rapid Ecoregional Assessment (https://landscape.blm.gov/REA_General_Docs/NWP-REA_II-3-C_MainText_App%20A_Final.pdf)	2012	Badlands and Prairies	Shrubland
Vulnerability of Riparian Ecosystems to Elevated CO_2 and Climate Change in Arid and Semiarid Western North America (https://onlinelibrary.wiley.com/doi/full/10.1111/j.1365-2486.2011.02588.x)	2012	Badlands and Prairies, Great Basin, Northern Rockies, Southern Rockies and Colorado Plateau	Riparian
National Fish, Wildlife and Plants Climate Adaptation Strategy (https://toolkit.climate.gov/tool/national-fish-wildlife-and-plants-climate-adaptation-strategy)	2012	Badlands and Prairies, Great Basin, Northern Rockies, Southern Rockies and Colorado Plateau	All lands
A Climate Change Vulnerability Assessment of California's At-Risk Birds (https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0029507)	2012	Great Basin	Sage-grouse, birds
Final Memorandum II-3-C—Middle Rockies Rapid Ecoregional Assessment (https://landscape.blm.gov/REA_General_Docs/MIR_REA-II-3-C_MainReport_andAppxAandB.pdf)	2012	Northern Rockies	Shrubland, steppe, and savanna
Colorado Plateau Rapid Ecoregional Assessment (https://landscape.blm.gov/REA_General_Docs/COP_Final_Report_Body.pdf)	2012	Southern Rockies and Colorado Plateau	Sagebrush
Central Basin and Range Rapid Ecoregional Assessment—Final Report (https://landscape.blm.gov/REA_General_Docs/CBR_1_ReportBody.pdf)	2013	Great Basin	Semidesert shrub and steppe, species
Ecological Assessment Report—Northern Great Basin Rapid Ecoregional Assessment (https://landscape.blm.gov/REA_General_Docs/NGB_REA_Main_Report_and_App_A1.pdf)	2013	Great Basin	Sagebrush, species
Integrating Climate and Biological Data into Land Management Decision Models to Assess Species and Habitat Vulnerability—A Collaboration for Greater Sage-Grouse and their Habitats Final Report (https://www.sciencebase.gov/catalog/item/5761d9c4e4b04f417c2d30f4)	2014	Badlands and Prairies	Sage-grouse
Sierra Nevada Ecosystem Vulnerability Assessment Briefing—Sagebrush (http://ecoadapt.org/data/documents/SierraNevada_Sagebrush_VABriefing_23Oct2014.pdf)	2014	Great Basin	Sagebrush
Assessing the Future Vulnerability of Wyoming's Terrestrial Wildlife Species and Habitats (https://www.nature.org/media/wyoming/wyoming-wildlife-vulnerability-assessment-June-2014.pdf)	2014	Northern Rockies	Sagebrush
Climate, Land Management and Future Wildlife Habitat in the Pacific Northwest (https://cascprojects.org/#/project/4f8c64d2e4b0546c0c397b46/5006e784e4b0abf7ce733f4d)	2015	Great Basin	Sage-grouse
Northwest Regional Climate Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies (https://www.cakex.org/sites/default/files/documents/Northwest%20Vulnerability%20Assessment%20Final.pdf)	2015	Great Basin	Rangelands
Assessing the Vulnerability of Vegetation to Future Climate in the North Central U.S. (https://cascprojects.org/#/project/4f83509de4b0e84f60868124/504a01afe4b02b6b9f7bd940)	2016	Badlands and Prairies, Great Basin, Northern Rockies, Southern Rockies, and Colorado Plateau	Vegetation

Table L1.1. A selection of climate vulnerability assessments and adaptation strategies relevant to the sagebrush (*Artemisia* spp.) biome.—Continued

[-, unspecified]

Title	Year	Geography	Relevant targets
Final Project Report—Assessing Climate Change Vulnerability and Adaptation in the Great Basin (https://www.sciencebase.gov/catalog/item/58d2e1cce4b0236b68f84fc0)	2016	Great Basin	-
Mid-Latitude Shrub-Steppe Plant Communities—Climate Change Consequences for Soil Water Resources (https://pubs.er.usgs.gov/publication/70171093)	2016	Great Basin, Northern Rockies; Southern Rockies and Colorado Plateau	Soil water
Changes to Watershed Vulnerability under Future Climates, Fire Regimes, and Population Pressures (https://cascprojects.org/#/project/4f8c64d2e4b0546c0c397b46/531dc54de4b04cb293ee7806)	2016	Great Basin; Northern Rockies, Southern Rockies, and Colorado Plateau	Water resources
Southern California Riparian Habitats—Climate Change Adaptation Actions Summary (https://www.cakex.org/sites/default/files/documents/EcoAdapt_SoCalAdaptationSummary_Riparian_FINAL_small.pdf)	2016	Southern California	Riparian
Upper Snake River Tribes Foundation Climate Change Vulnerability Assessment (https://uppersnakerivertribes.org/app/uploads/files/usrt-climate-assessment.pdf)	2017	Great Basin	Sagebrush, riparian, mule deer, and jackrabbits
Climate Change Vulnerability and Adaptation in South Central Oregon (http://adaptationpartners.org/scoap/docs/SCOAP_GTR_Final.pdf)	2017	Great Basin	Shrubland and grassland
Responding to Ecological Drought in the Intermountain Region (https://www.climatehubs.usda.gov/sites/default/files/r4-droughtfactsheet.pdf)	2017	Great Basin	Rangelands
Wyoming Basin Rapid Ecoregional Assessment (https://landscape.blm.gov/REA_General_Docs/WYB_Report.pdf)	2017	Northern Rockies	Sagebrush steppe, species
Potential Climate Change Impacts on Greater Sage-Grouse Connectivity in the U.S. Northern Rockies (https://www.sciencebase.gov/catalog/item/5867e0d4e4b0cd2dabe7c76a)	2017	Northern Rockies	Sage-grouse
Vulnerability Assessment of Ecological Systems and Species to Climate and Land Use Change within the North Central Climate Change Center and Partner Land Conservation Cooperatives Final Report (https://www.sciencebase.gov/catalog/item/58dd78eee4b02ff32c6859b2)	2017	Northern Rockies	Species
Vulnerability Assessment of Sagebrush Ecosystems: Four Corners and Upper Rio Grande Regions of the Southern Rockies Landscape Conservation Cooperative (https://lccnetwork.org/sites/default/files/Sagebrush%20Vulnerability%20Assessment%20SRLCC_Final.pdf)	2017	Southern Rockies and Colorado Plateau	Sagebrush
Vulnerability of Sagebrush Ecosystem to Climate Change within the Green River Basin (https://www.sciencebase.gov/catalog/item/55b7931de4b09a3b01b5fa0f)	2017	Southern Rockies and Colorado Plateau	Sagebrush
Climate Change and Rocky Mountain Ecosystems (https://www.springer.com/us/book/9783319569277#aboutBook)	2018	Northern Rockies	-
Vulnerability and Adaptation to Climate Change in the Northern Rocky Mountains (http://adaptationpartners.org/nrap/)	2018	Northern Rockies	-
Climate Change Vulnerability and Adaptation in the Intermountain Region—Part 1 (https://www.fs.fed.us/rm/pubs_series/rmrs/gtr/rmrs_gtr375_1.pdf)	2018	Northern Rockies, Great Basin	Sagebrush