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Synthesis Paper

Effects of Changing Climate on the Hydrological Cycle in Cold Desert Ecosystems of the Great Basin and Columbia Plateau☆

Keirith A. Snyder [a,*], Louisa Evers [b], Jeanne C. Chambers [c], Jason Dunham [d], John B. Bradford [e], Michael E. Loik [f]

[a] US Department of Agriculture —Agricultural Research Service, Reno, NV 89512, USA
[b] Bureau of Land Management, Portland, OR 97204, USA
[c] US Forest Service, Rocky Mountain Research Station, Reno, NV 89512, USA
[d] US Geological Survey, Forest and Rangeland Ecosystem Science Center, Corvallis, OR 97331, USA
[e] US Geological Survey, Southwest Biological Science Center, Flagstaff, AZ 86011, USA
[f] Department of Environmental Studies, University of California, Santa Cruz, CA 95064, USA

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ABSTRACT

Climate change is already resulting in changes in cold desert ecosystems, lending urgency to the need to understand climate change effects and develop effective adaptation strategies. In this review, we synthesize information on changes in climate and hydrologic processes during the past century for the Great Basin and Columbia Plateau and discuss future projections for the 21st century. We develop midcentury projections of temperature and climate for the Great Basin and Columbia Plateau at timescales relevant to managers (2020 − 2050) and discuss concepts and strategies for adapting to the projected changes. For the instrumented record in the Great Basin and Columbia Plateau (1985 − 2011), a temperature increase of 0.7 − 1.4°C has been documented, but changes in precipitation have been relatively minor with no clear trends. Climate projections for 2020 − 2050 indicate that temperatures will continue to increase, especially in winter and during the night. Precipitation is more difficult to project, and estimates range from an 11% decrease to 25% increase depending on location. Recent records indicate that the Great Basin and Columbia Plateau are becoming more arid, a trend that is projected to continue. Droughts are likely to become more frequent and last longer, invasive annual grasses are likely to continue to expand, and the duration and severity of wildfire seasons are likely to increase. Climate projections can help in developing adaptive management strategies for actual or expected changes in climate. Strategies include reducing the risks of nonnative invasive plant spread and wildfires that result in undesirable transitions, planning for drought, and where necessary, facilitating the transition of populations, communities, and ecosystems to new climatic conditions. A proactive approach to planning for and adapting to climate change is needed, and publicly available Internet-based resources on climate data and planning strategies are available to help meet that need.

Introduction

Climate of the cold desert ecosystems of the Great Basin and Columbia Plateau (Fig. 1) is characterized by a combination of cold winters, hot and dry summers, and low and highly variable precipitation. In these regions, water is the primary resource limiting plant growth (DeLucia and Schlesinger, 1991; Donovan and Ehleringer, 1994). The geographically expansive regions of the Great Basin and Columbia Plateau span a wide range of elevations (generally 600 − 3 100 m) and therefore encompass large temperature and precipitation gradients. Variable climate conditions result in a host of different vegetation associations (Thompson et al., 2007), but the prevalence of various species of sagebrush (*Artemisia* spp.) is a common feature (Grayson, 2011). Most precipitation arrives in winter when temperatures limit plant and microbial physiological activity (Newman et al., 2006; Lauenroth and Bradford, 2009). The proportion of total precipitation delivered as snow is variable and averages approximately 75% across these regions (Klos et al., 2014) and roughly 20 − 40% in big sagebrush (*Artemisia tridentata*, Nutt.)−dominated ecosystems (Schlaepfer et al., 2012a). Water from snowmelt in the spring or rain that falls when temperatures are too cold for plant growth is typically stored deep within the soil profile. This deep soil moisture favors deeply rooted shrubs such as

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* Correspondence: Dr Keirith A. Snyder, USDA-ARS, 920 Valley Rd, Reno, NV 89512, USA. Tel.: +1 7775 784 6057; fax: +1 775784 1712.
E-mail address: keirith.snyder@ars.usda.gov (K.A. Snyder).

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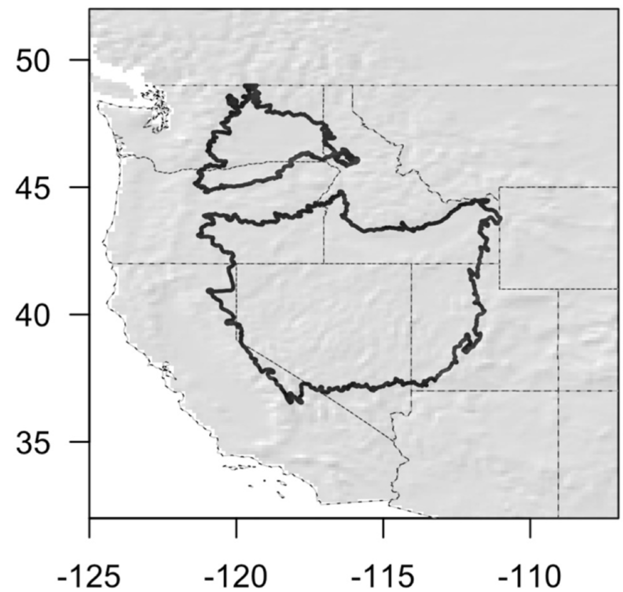

Figure 1. Map of the Columbia Plateau and Great Basin ecoregions in context of the western United States.

sagebrush (Schlaepfer et al., 2012a). The combination of soil temperature, soil moisture, soil texture, and soil depth determines which sagebrush species is dominant (Miller et al., 2011) and the composition of other plant species in cold desert ecosystems (West, 1983).

The earth's climate is changing globally due to increased emissions of greenhouse gases (carbon dioxide [CO_2] and other trace gases), which have altered the earth's energy balance and will continue to do so into the future (IPCC, 2013). The implications of these climatic changes for cold desert ecosystems depend on the interaction of temperature and precipitation, subsequent effects on the hydrologic cycle, and how they translate into responses of aquatic and terrestrial ecosystems. For vegetation communities, the outcomes will be largely determined by supply and demand for water, which will be affected by warming temperatures. The supply is driven by meteorological patterns that determine the spatial availability of soil water and timing of plant-available soil water (Loik et al., 2004). Soil water availability for plants is also affected by soil texture, rooting patterns, and plant community composition (Palmquist et al., 2016a). The atmospheric demand is a consequence of water vapor pressure and temperature; as air temperature warms, the atmosphere can hold more water. Drought may occur if supply of water is limited and atmospheric demand for water is greater due to increased temperatures. Drought severity is a measure of temperature, precipitation, and available water content relative to climatic norms for a given location (Lake, 2011). Droughts both reduce the supply of, and increase the demand for, water. For aquatic communities, consequences are determined by changes in output from seeps and springs, streamflow, and lake levels (Lake, 2011; Vose et al., 2016).

The highly variable topography in the Columbia Plateau and especially Great Basin could result in variable rates of change in a warming environment. For example, a study using gridded climate data examined the velocity of climate change, which is simply the amount of altitude or latitude that must be traveled to maintain a constant temperature, and found that flat terrains produce fast velocities while mountainous regions produce slow velocities (Loarie et al., 2009). Climate velocities are expected to drive responses in the Great Basin in particular as this region is characterized by well-defined basin and range topography with mountain ranges interspersed by relatively wide valley basins (Grayson, 2011). In order for plant species to survive, they must either have large thermal tolerances or be able to migrate to locations with suitable climates. Thus, mountain ranges could provide suitable habitat for species migration if species are able to disperse upslope, while species currently in wide, flat basins may be more at risk if they lack the necessary thermal tolerances (e.g., Warren et al., 2014). The highest elevations of the Great Basin ranges currently provide islands of habitat for a small number of species adapted to colder and moister conditions (Quinn and Harrison, 1988). Climate warming appears to be resulting in increased species richness on mountaintops worldwide, and the combination of higher temperatures and greater competition is increasing the vulnerability of the original inhabitants (Steinbauer et al., 2018).

Cold desert shrublands are already of considerable concern due to ongoing conversion to invasive annual grasslands (e.g., cheatgrass [*Bromus tectorum* L.]) at low to mid elevations and expansion of piñon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodlands at mid to higher elevations. The shift to annual grasslands is projected to increase as climate suitability for invasive annual grasses increases with climate change and the perpetuation of altered fire regimes (Bradley and Mustard, 2005; Balch et al., 2013; Boyte et al., 2016). Many woody species including sagebrush, piñon, and juniper are predicted to move northwards and upwards in elevation (Rehfeldt et al., 2006, 2012; Bradley, 2010; Schlaepfer et al., 2012a, 2012b; Homer et al., 2015; Still and Richardson, 2015).

Herein, we begin by reviewing existing literature on documented changes in climate and the hydrologic cycle that have occurred in the past century and synthesizing future projections for the 21st century. We focus specifically on the findings and interpretations for management of ecosystems in the Great Basin and Columbia Plateau. These regions have often been combined with the Colorado Plateau of the Intermountain West, Southern deserts, and the forests of the Pacific Northwest, but they are notably different from these other regions, which historically have been warmer, received much more precipitation as rainfall, or are more strongly influenced by summer monsoon rainfall. The Great Basin and Columbia Plateau are unique in that the majority of precipitation has historically been received in winter when cold temperatures limit plant transpiration and evaporation, thus largely decoupling precipitation inputs from potential evapotranspiration. To generate our own midcentury projections for Great Basin and Columbia Plateau at timescales relevant to managers (2020 − 2050), we use down-scaled Global Climate Change models (GCMs). We discuss consequences of these projected changes for drought, biological invasions, and wildfire in the Great Basin and Columbia Plateau.

Observed Climate Changes in Past Century

It is important to recognize that changes in precipitation and temperature during the past century have not occurred at a steady rate (Dalton, 2013; IPCC, 2013). As in many other areas, seasonal and annual variability in temperature and precipitation within the Great Basin and Columbia Plateau has increased (Dalton, 2013; Pendergrass et al., 2017; Swain et al., 2018). Naturally occurring atmospheric and oceanic cycles, such as the El Niño Southern Oscillation (ENSO), continue to influence the variability of precipitation and temperature (IPCC, 2013; Black et al., 2018). El Niño periods are typically warmer and drier in the northern and central Great Basin and warmer and wetter in the southern Great Basin. La Niña periods typically have the opposite effect in the region.

Air Temperature, Precipitation, Snowpack, and Streamflow

Time series and trends for air temperature, precipitation, snowpack, and streamflow from the published literature are available, but it is important to recognize that the time series presented are not always for the same number of years or time periods. Therefore, the interpretation of the means and trends can be affected by the timing and extent of the time series (Easterling and Wehner, 2009), particularly if the time series is short and influenced by the natural variability described earlier.

Nonetheless, this information is essential for understanding current trends and developing climate adaptation strategies.

Temperatures are increasing across the Great Basin and Columbia Plateau both annually and in all seasons (Kunkel et al., 2013a, 2013b; USGCRP, 2017). Between 1895 and 2011, temperatures increased by an estimated 0.7°C − 1.4°C (1.2°F − 2.5°F), with a greater increase in the southern than the northern Great Basin (Kunkel et al., 2013a, 2013b). Temperatures increased more at night than during the day and more in winter than in summer (Mote et al., 2005; Abatzoglou and Kolden, 2013; Kunkel et al., 2013a, 2013b; Tang and Arnone, 2013; USGCRP, 2017). These temperature changes have led to fewer cold snaps and more heatwaves, fewer frosty days and nights, less snow, and earlier snowmelt (Mote et al., 2005; Kunkel et al., 2013a, 2013b; Tang and Arnone, 2013; USGCRP, 2017). Although precipitation has increased in some areas over the past century (Wagner, 2003), the changes have been minor with no consistent spatial trends (Kunkel et al., 2013a, 2013b). Small increases in precipitation have occurred in parts of the Great Basin (Wagner, 2003; Abatzoglou et al., 2014; USGCRP, 2017), but the increases in evapotranspiration due to higher temperatures more than offset these small observed increases in precipitation in the overall water budget (Cook et al., 2004; Dai, 2013; Jeong et al., 2014; Finch et al., 2016). Dai (2013) using the Palmer Drought Severity Index from the period 1900 − 2000 demonstrated a trend of increasing aridity in the western United States.

Snowpack has declined in the western United States, including the Great Basin and Columbia Plateau, during the past 61 yr (Knowles, 2015; Mote et al., 2005, 2018). Snowpack is measured as snow-water equivalent (SWE), which is the vertical column of liquid water contained within the snowpack. Mote et al. (2018) evaluated observed trends 1 April SWE for the period from 1955 to 2016 and showed declines in SWE of ≤70% in northern Nevada and eastern Oregon, which were notably some of the largest negative trends in the western United States. These changes in SWE appeared to be largely driven by increasing temperature for the interior west and not changes in total precipitation (Mote et al., 2018). Peak SWE shifted 15 d earlier from 1982 to 2007 at weather stations that contribute to the Great Salt Lake Basin (Bedford and Douglass, 2008). The combination of these changes in temperature and precipitation mean that the Great Basin and Columbia Plateau are effectively becoming warmer and drier during summer (Cook et al., 2004; Palmquist et al., 2016b). There is, however, heterogeneity in snowpack accumulation and subsequent melting in the western United States. An analysis of Snow Telemetry stations (SNOTEL) in the western United States found that part of this variation can be explained by differences in relative humidity caused by cloudiness (Harpold and Brooks, 2018).

Early and midwinter snow loss episodes due to warm temperatures occur more frequently in more humid areas, such as the Pacific Northwest (Oregon, Washington, and Idaho), than in less humid areas and these episodes are increasing in frequency. In spring, warming temperatures mean an earlier start to snowmelt across the cold desert, but there are important differences in melt rates. In less humid climates with frequent, clear skies at night, such as the interior Great Basin and Southwest, there is greater outgoing long wave radiation and cooling at night, which, in combination with lower sun angles earlier in the year, results in a slower melt rate. In contrast, more humid areas with frequent cloudy skies, such as eastern Oregon and the Columbia Plateau, experience a faster melt rate due to the trapping of long wave radiation by water vapor at night and warmer nighttime temperatures. These differences in the frequency of winter snow loss episodes and in spring snowmelt rates mean that more humid areas face increased risks of winter flooding and reduced snowpack in spring, while less humid areas face increased snow water loss from sublimation in winter and evapotranspiration in spring. Both scenarios lead to less available water later in the year (Harpold and Brooks, 2018).

In addition to declines in snowpack SWE and changes in the persistence and melt rates of snowpack, the fraction of wintertime (November − March) precipitation that falls as snow versus rain (i.e., snow fraction ratio) is declining (Safeeq et al., 2016) in the western United States. This means less precipitation falls as snow and more as rain. The current range in snow fraction is between 20% and 70% in the Great Basin with small areas of 100%. The Columbia Plateau is similar but with more of the total area in the 10 − 30% range for the snow fraction (Safeeq et al., 2016). There was an overall downward trend in snow fraction of 1.9% per decade from 1916 to 2003 across most of the Great Basin (Safeeq et al., 2016). Decreases in snow fractions may have a variety of potential outcomes depending on temperature and timing of precipitation. Rain that falls on snow, such as during the large atmospheric river events observed in 2017 (Gershunov et al., 2017), can rapidly melt snow and cause flashy watershed responses and flooding in lower elevations, thus reducing the water available to recharge soil moisture at mid to high elevations. This sometimes leads to major erosional events in downstream areas (Rieman et al., 2001). Shifts from snow to rain when soils are frozen could also lead to flashier hydrologic responses and less recharge of deep soil water storage. Shifts from snow to rain when temperatures are cold enough to limit water losses from plant transpiration, but the infiltration capacity of soils is not exceeded (e.g. soils are not frozen), may have minimal impact on deep soil water storage or increase deep soil water storage in the spring (Palmquist et al., 2016b). However, if rainfall replaces snow and temperatures are increased enough to thaw soils and stimulate plant growth and physiological activity earlier in the year, this will result in less deep soil water recharge and potential changes in plant community composition (Huxman et al., 2005).

Mountain snowpack and snowmelt − derived water supply are a critical resource in the western United States for agriculture, industry, and urban uses. Streamflow integrates precipitation and temperature patterns over large drainage areas. Even without changes in precipitation amount and intensity, temperature increases alone can shift the timing of streamflow to earlier in the winter and spring, leading to lower flows during hot summer months when demand for water is high (Barnett et al., 2005). Across the western United States, widespread trends toward snowmelt and peak streamflows occurring 1 − 4 wk earlier have been documented from 1948 to 2002 (Stewart et al., 2005). These timing trends are strongest for the Pacific Northwest and Sierra Nevada, where peak flows have shifted 10 − 30 d earlier. Also, April to July flows are decreasing in the Sierra Nevada and eastern Oregon (Stewart et al., 2005). In terms of mean annual runoff, few locations show significant trends in median or mean flows (Westerling et al., 2006; Barnett et al., 2008), but there are consistent, significant decreases in streamflow in the lowest quartile of water years for the Pacific Northwest, which includes the Columbia Plateau and northern Great Basin. The driest 25% of years are exhibiting progressively lower streamflow for a majority of gaging stations in the Pacific Northwest and the change is substantial, ranging between −29% and −50% (Luce and Holden, 2009). Although low-elevation precipitation gages have not shown declines in precipitation since 1950, there is substantial evidence that declines in streamflow are due to reductions in precipitation at higher elevations, where far fewer measurement stations exist (Luce et al., 2013). Previous hypotheses attributed the decrease in streamflow in dry years to increased temperature, due to the lack of high-elevation precipitation data. However, Luce et al. (2013) found that the amount of observed temperature change was insufficient to explain the entire magnitude of the decrease and that changes in streamflow were likely attributable to decreases in lower-troposphere westerlies during the winter. This reduction in westerlies effectively blocks orographic lifting and thereby reduces winter precipitation at higher elevations. This decline in westerlies exceeded the range of variation explained by ENSO and points to other effects of a changing climate.

A few locations have increased mean annual streamflow. For example, annual streamflow in the Humboldt River, Nevada and Boise River, Idaho increased 16% and 12%, respectively, and peak annual flows occurred 10 − 15 d earlier during the past century (Wagner, 2003; Luce and Holden, 2009). In contrast, streamflow data from the Donner *und* Blitzen River located in Oregon show no clear change in mean annual discharge through time, but interannual variability has apparently increased, with potential impacts to native fish and wildlife species (Schultz et al., 2017), as well as water availability for irrigation. In 2015, > 75% of the potentially occupied stream network in the Willow-Whitehorse watershed in Oregon was unsuitable for trout due to warming or drying of stream channels (Schultz et al., 2017). Another study using data from the Pacific Northwest, Nevada, and California found that over the past 60 yr there was increased synchrony between stream temperature maxima and stream flow minima, suggesting that multiple stressors are affecting aquatic species (Arismendi et al., 2013). Reynolds Creek Experimental Watershed is an intensively instrumented watershed in southern Idaho representative of these cold deserts. Examination of 45 yr of data from high, mid-, and low elevation found increased temperatures, reduced snow fractions, and decreased SWE. No changes in annual streamflow have been observed, but earlier runoff at all elevations is occurring (Nayak et al., 2010). The high elevation had the greatest shifts in temperature and streamflow timing, while mid- and low elevations had greater decreases in snow fractions and SWE (Nayak et al., 2010).

Climate Projections for 21st Century

Abundant evidence exists for a warming climate in the past century, and climate science is providing critical information on what the future may hold (Folland et al., 2001; Kunkel et al., 2013a, 2013b; USGCRP, 2017). Climate scientists use Global Circulation Models (GCMs) to explore potential changes in temperature and precipitation (climate projections) using future scenarios of likely greenhouse gas concentrations in the atmosphere along with information on the earth's atmosphere, land surfaces and oceans (Flato et al., 2013). Climate is a long-term statistical representation of weather fluctuations, providing metrics of typical conditions against which short-term temperature and/or precipitation conditions can be compared (Flato et al., 2013). Climate scientists work continuously to improve GCMs, but uncertainties still remain about future greenhouse gas concentrations. These uncertainties arise in part from assumptions about human behavior (e.g., greenhouse gas emissions from burning of fossil fuels, population growth, economic activity) and just how the atmosphere, land surface, and oceans interact (IPCC, 2014). The magnitude and rate of change in temperature or precipitation differ from one GCM to another, and this variation among GCMs provides perspective on the uncertainty in long-term climate trajectories (Flato et al., 2013; USGCRP, 2017). As a whole, GCMs project continued temperature increases and additional changes in precipitation throughout the remainder of the century for the Great Basin and Columbia Plateau (Kunkel et al., 2013a, 2013b; Chambers et al., 2017; USGCRP, 2017).

2020 −2050 Climate Projections

To produce specific climate projections for the Great Basin and Columbia Plateau, we analyzed near-future conditions (2020 − 2050) based on downscaled output from 11 GCMs and two representative concentration pathways (RCPs), which characterize two scenarios of increasing greenhouse gas emissions. We used RCP4.5, which assumes emissions peak around 2040 then decline, and RCP8.5, where emissions continue to rise throughout the 21st century, representing a "business as usual" trajectory. We examined climate projections within the following EPA level III ecoregions: Central Basin and Range, Northern Basin and Range, Snake River Plain, and Columbia Plateau (see Fig. 1). Mapped results of these projections (Figs. 2 and 4) show the average conditions for 1980 − 2010 and 2020 − 2050 with the colors indicating how the area differs from the average for the entire region. These maps provide a spatial perspective on the geographical patterns of current and projected future climate and can help resource managers examine locations of potential interest. Additional details on the data sources and analysis methods for these climate projections can be found in Chambers et al. (2017).

The projected increase in mean annual temperature, averaged across GCMs, from 1980 - 2010 to 2020 - 2050 is ~1.6°C for RCP4.5 and ~1.9°C for RCP8.5 (see Fig. 2). The magnitude of the temperature increase varies by ± 0.5°C across the ecoregions examined, with somewhat greater increases in the northern areas under both RCPs (see Fig. 2). Increases in mean July maximum temperatures are expected to be slightly greater (~2.0°C for RCP4.5 and ~2.5°C for RCP 8.5) than increases in mean January minimum temperature (~1.8°C for RCP4.5 and ~2.0°C for RCP8.5), averaged across all GCMs (Fig. 3). However, the projected increases in January temperature are more geographically variable across the ecoregions examined, as well as more variable among GCMs, indicating higher uncertainty in changes to winter low temperatures than summer high temperatures (see Fig. 3). Precipitation estimates are generally more uncertain than temperature. While the change in mean annual precipitation from 1980 - 2010 - 2020 to 2050, averaged across GCMs, suggests an increase of ~6 − 8%, the GCMs range from a ~12% decrease to a 25% increase (Fig. 4). The ecological impacts of a potential increase in precipitation need to be balanced against the concurrent increases in atmospheric demand for moisture associated with rising temperatures (see Fig. 2; Palmquist et al., 2016b). Furthermore, the annual coefficient of variation in precipitation is generally high in dryland regions (Reynolds et al., 2007), so even with increased precipitation, there will be many dry years. In addition, Pendergrass et al. (2017) found that precipitation variability will likely increase at time scales ranging from daily to decadally, although less so in summer. This kind of change in precipitation is within the range of modeled snow scenarios for 2099 generated by the Coupled Model Inter-comparison Projects for the southwestern Great Basin (CMIP3 and CMIP5; Maurer et al., 2007; Loik et al., 2015). Even with a 25% increase, mean annual precipitation is not projected to increase > 400 mm for the region as a whole (see Fig. 4A). Changes in precipitation, while still ranging from negative to positive when grouped by season, show the projected increase to be more likely in winter and summer seasons, with less projected change in fall and spring (Fig. 5). While the largest increases in precipitation are projected for the southern part of the ecoregions examined, most of the area within these ecoregions is expected to experience minimal change in precipitation (< 4%).

Projections from the Literature

Projected increases in temperature are expected to cause a dramatic increase (64%) in the area of the Great Basin and Columbia Plateau that has a rain-dominated winter precipitation regime by the mid-21st century (Klos et al., 2014). Across the western United States, a 60% reduction in snowpack (i.e., precipitation as snow) is projected to occur within the next 30 yr (Fyfe et al., 2017). In response to these changes, the area dominated by seasonally persistent snowpack will likely continue to shrink and the area dominated by transient snow events will likely grow, resulting in reduced snow-to-rain ratios (Safeeq et al., 2016). At elevations of 2 000 to 2 500 m a 15% reduction in snow fraction is projected by 2040 in the Great Basin and Pacific Northwest (Safeeq et al., 2016). For comparison, Mote et al. (2018) found that an average reduction of 21% in 1 April SWE (equivalent to 36 km^3 of water) has already occurred in the western United States. This loss of SWE exceeds the water storage capacity of Lake Mead, the West's largest reservoir (32 km^3 of water). The change from snow to rain in conjunction with higher temperatures is likely to accelerate current trends and decrease the depth of soil water recharge, produce earlier starts of the growing season, and shorten the duration of soil water availability, resulting in hotter summers with longer periods of dry-soil conditions (Palmquist et al., 2016a, 2016b; Gergel et al., 2017).

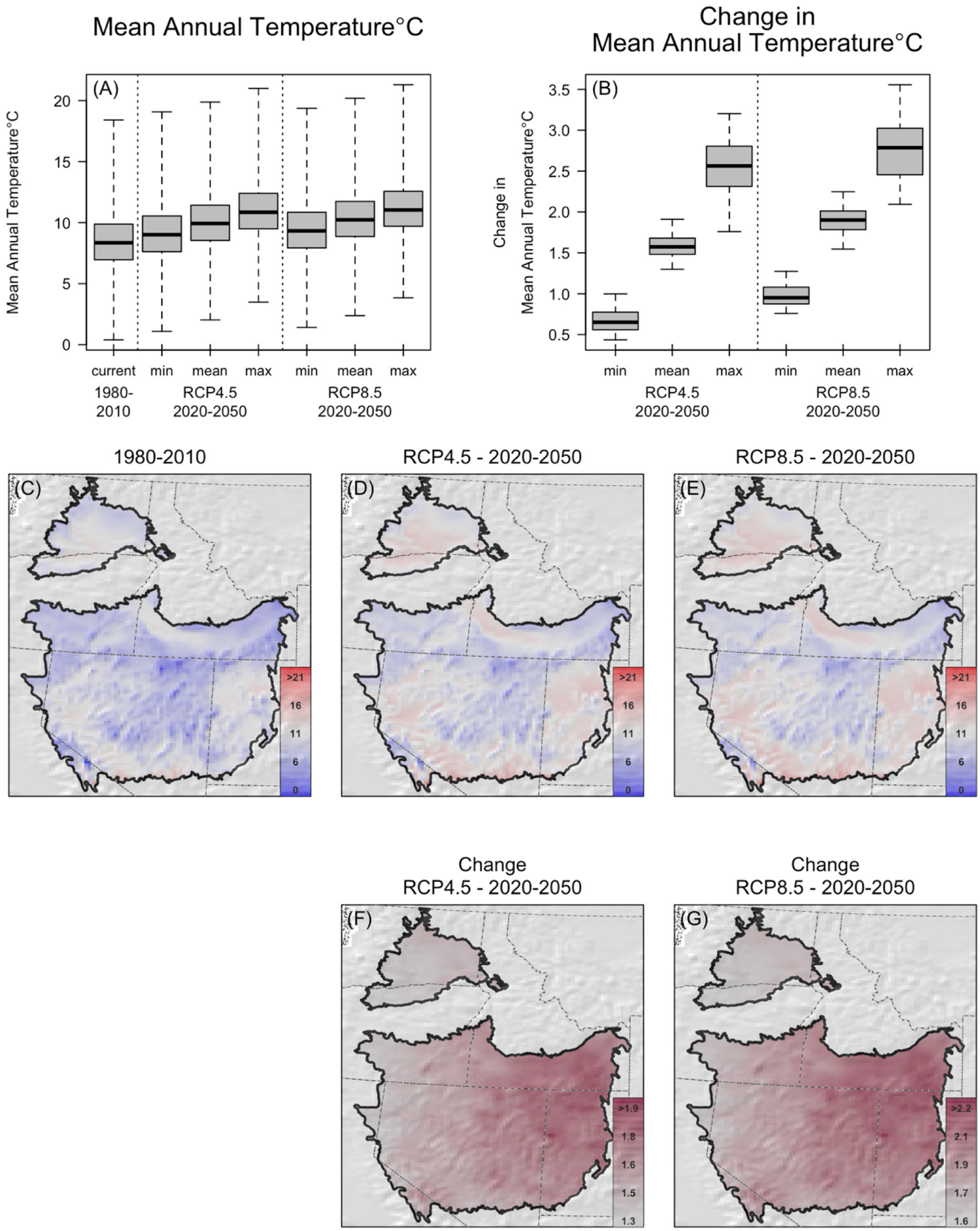

Figure 2. Climate change projections for mean annual temperature within the Central Basin and Range, Northern Basin and Range, Snake River Plain, and the Columbia Plateau ecoregions. **A**, Boxplots of mean annual temperature under historical (1980 — 2010) and future (minimum, mean, and maximum values for 2020 — 2050 from 11 GCMs under two RCPs). **B,** Boxplots of change in mean annual temperature between 1980 and 2010 and 2020 and 2050. Variability within boxes in **A** and **B** is variation among all 10 × 10 km grid cells within the ecoregions examined. Maps of mean annual temperature for 1980 — 2010 (**C**), 2020 — 2050 under RCP 4.5 (**D**), 2020 — 2050 under RCP8.5 (**E**), change from 1980 — 2010 to 2020 — 2050 under RCP4.5 (**F**), and change under RCP8.5 (**G**).

Projected changes in streamflow include increased winter streamflow, reduced and earlier spring peaks, and reduced summer and fall stream flows (Wagner, 2003; Barnett et al., 2005; Mote et al., 2018), as well as increased stream temperatures (Schultz et al., 2017). A projected midcentury 3°C change in temperature scenario using an integrated groundwater and surface water model for a watershed in the Great Basin produced earlier snowmelt and an earlier peak in streamflow and decreased streamflow during the summer and decreased

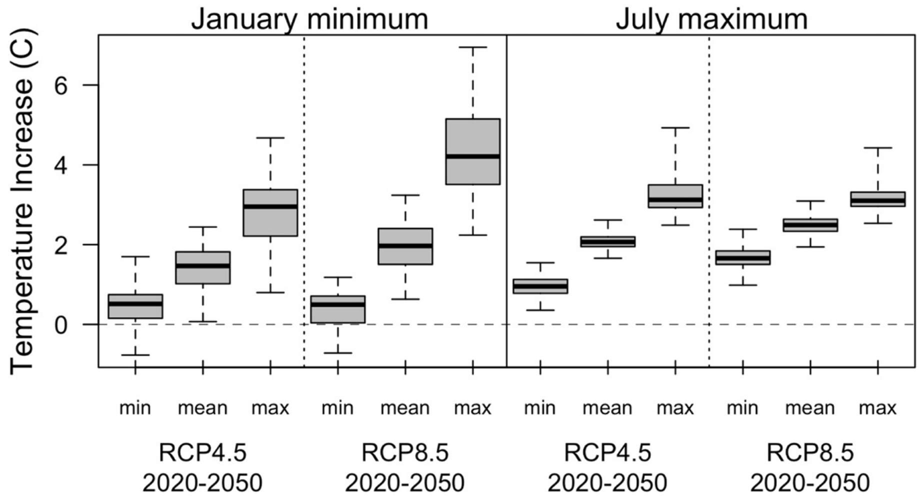

Figure 3. Projected change in mean January minimum and maximum July temperatures.

groundwater recharge (Carroll et al., 2017). There are few studies on the impacts of changes from snow to rain on ecological patterns and processes; the effects of changing snow to rain on Great Basin and Columbia Plateau organisms and ecosystem processes merit additional investigation.

The most recent climate models have improved ability to model winter precipitation, but improvements in predictions of summer precipitation remain limited due to the inability of climate models to represent the mesoscale convective storms that dominate at that time of year (USGCRP, 2017). A number of studies indicate an increase in extreme precipitation events, more so in the northern part of the cold desert in winter due to a projected increase in the incidence of atmospheric rivers (e.g., Abatzoglou and Kolden, 2011; Collins et al., 2013; Huang and Ullrich, 2017; Kunkel et al., 2013a, 2013b; Prein et al., 2016; USGCRP, 2017). Warming temperatures will likely lead to more thunderstorms in summer (Prein et al., 2017) with individual cells that are smaller and produce more intense rainfall (Wasko et al., 2016). These increases in precipitation intensity could result in more runoff, increased flash flood risks to lives and property, and greater erosion where precipitation intensity exceeds soil infiltration rates (USGCRP, 2017). When atmospheric instability is coupled with low water vapor pressure during summer, "dry lightning" can occur in which little rain reaches the ground despite frequent cloud-to-ground discharges. Such events can increase risk of wildland fire ignition (Abatzoglou et al., 2016).

Consequences of Climate Change for Major Ecosystem Threats

Drought

Droughts are a shortage of precipitation that can influence the hydrologic cycle, which in turn influences agriculture and natural ecosystems (Van Loon et al., 2016; Vose et al., 2016). Crausbay et al. (2017) defined ecological drought "as a disturbance that pushes coupled human-natural systems beyond their adaptive capacity and triggers important socio-ecological feedbacks." They envisioned the effects of drought as proceeding in stages, from impacts only on ecological or human systems to transformational effects on both, with feedbacks possible between them. Many climate projections depict what appear to be incremental changes in temperature and precipitation, but rapid and dramatic shifts are also possible. For example, there are concerns about increasing prevalence of droughts in the west as climates warm (Dai, 2013; Diffenbaugh et al., 2015) and conditions become more variable (Black et al., 2018; Swain et al., 2018). The Great Basin is characterized by aridity, but the projected increases in temperature, which are relatively consistent among climate models, will likely create longer, hotter summers with more lengthy droughts.

Biological Invasions

Invasive species are widely distributed across the Great Basin and Columbia Plateau. Among these species, invasive annual grasses and the development of invasive annual grass/fire cycles are a primary concern (Chambers et al., 2009, 2014). The climatic regime of the Great Basin and Columbia Plateau is ideally suited to the life histories and ecophysiological traits of invasive annual grasses. The most widespread species, cheatgrass *(Bromus tectorum),* is a winter annual that germinates in fall through spring when native perennials are largely dormant. It has the capacity to grow rapidly, produce large numbers of seeds, and complete its life cycle before the summer dry period (James et al., 2011). Cheatgrass establishment and growth is limited by low soil water availability in winter and spring at lower elevations (Meyer et al., 2001) and low temperatures and deep snow at high elevations (Griffith and Loik, 2010; Bykova and Sage, 2012; Zelikova et al., 2013). Consequently, in cold desert ecosystems cheatgrass tends to be most abundant at lower to midelevations and rare to nonexistent at higher elevations with cool and especially cold soils (Chambers et al., 2007, 2014; Leger et al., 2009). Increases in temperature coupled with high phenotypic plasticity and genetic variation (Hufft and Zelikova, 2016) may be resulting in progressive increases in cheatgrass cover at higher elevations (Concilio and Loik, 2013). Another invasive annual grass, red brome *(Bromus rubens)* currently occurs at low levels of abundance at lower elevations on warmer and drier soils across much of the Great Basin (Salo, 2005). In a warming climate, cheatgrass may expand into higher elevations and contract at lower elevations, where conditions become too hot and dry (Bradley et al., 2016). However, red brome may spread into those areas where cheatgrass declines (Bradley et al., 2016).

Numerous studies have shown that the seasonality of precipitiation affects germination, establishment, and growth of cheatgrass (see review in Bradley et al., 2016). Decreases in summer precipitation or prolonged summer droughts across the Intermountain West could enable increases in cheatgrass in areas that currently have higher summer preciptiation and little to no cheatgrass (Bradley et al., 2016). Also, in a future climate with warmer and wetter conditions in the northern Great Basin, an overall increase in cheatgrass cover of 14% could occur by 2050, with the greatest increases occurring at elevations between 1 750 and 2 000 m (Boyte et al., 2016). In this scenario, October, April, and May precipitation would likely have the largest effects on cheatgrass cover (Boyte et al., 2016). Less is known about the climate suitability of other invasive annual grasses, such as medusahead *(Taeniatherum*

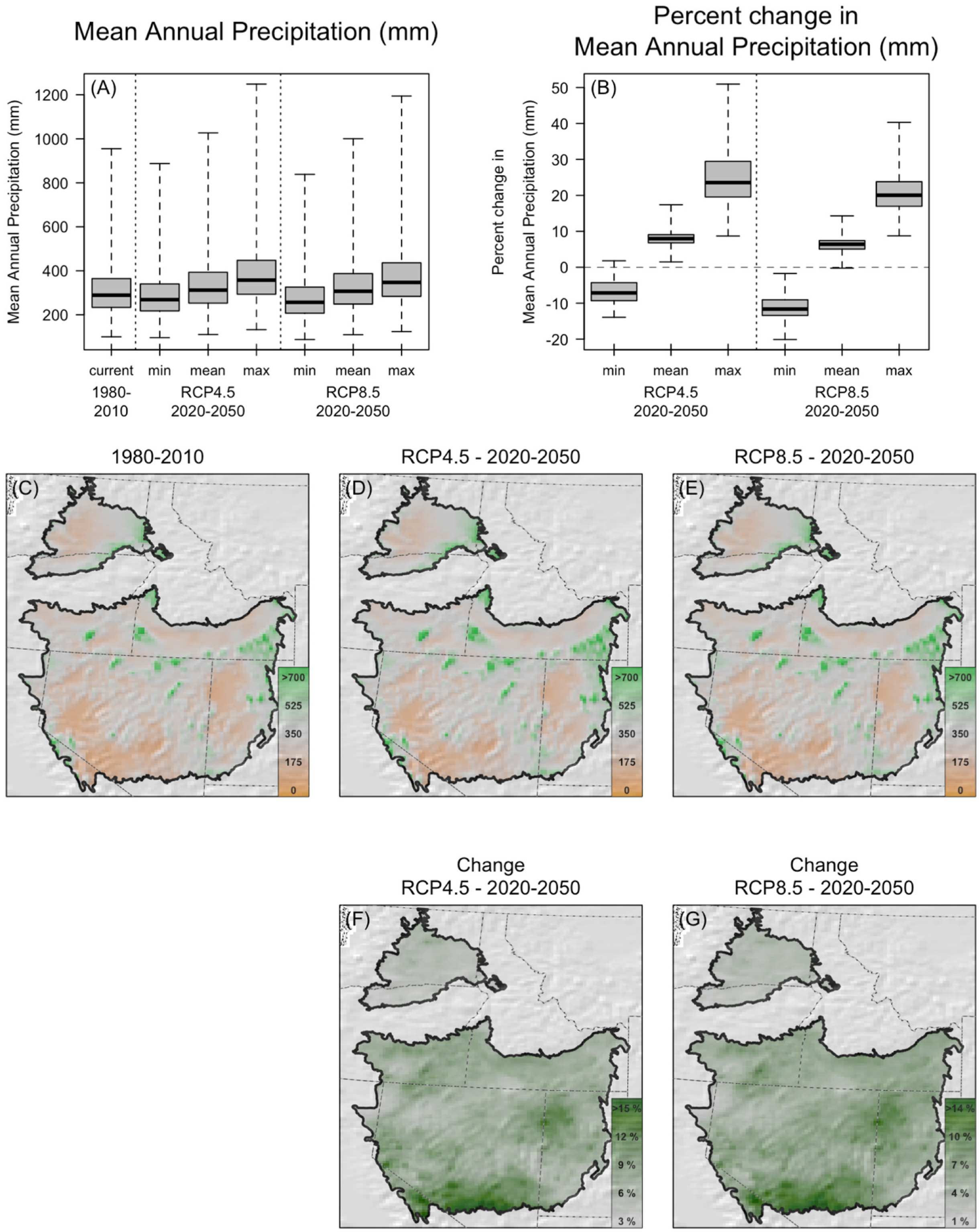

Figure 4. Climate change projections for mean annual precipitation within the Central Basin and Range, Northern Basin and Range, Snake River Plain and the Columbia Plateau ecoregions. **A,** Boxplots of mean annual precipitation under historical (1980—2010) and future (minimum, mean, and maximum values for 2020—2050 from 11 GCMs under two RCPs). **B,** Boxplots of change in mean annual precipitation between 1980—2010 and 2020—2050. Variability within boxes in **A** and **B** is variation among all 10 × 10 km grid cells within the ecoregions examined. Maps of mean annual precipitation for 1980—2010 (**C**), 2020—2050 under RCP 4.5 (**D**), 2020—2050 under RCP8.5 (**E**), change from 1980—2010 to 2020—2050 under RCP4.5 (**F**), and change under RCP8.5 (**G**).

caput-medusae) and ventenata *(Ventenata dubia)*, but these species are expanding in the Great Basin and are likely being affected by climate warming (Northam and Callihan, 1994; Davies and Johnson, 2008). Careful monitoring of changes in the distributions and abundances of invasive annual grasses and other invasive species, along with continued evaluations of the relationships among these changes and future climate, will be necessary to adapt invasive species management strategies as the climate warms.

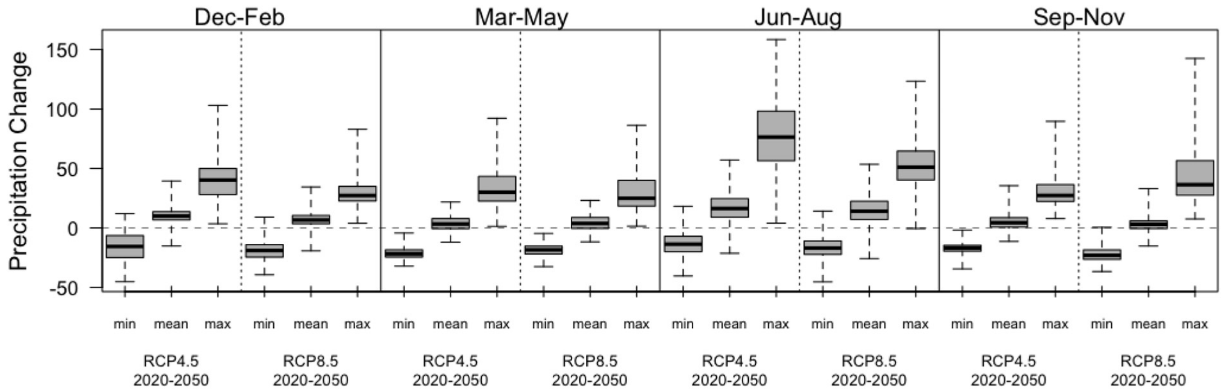

Figure 5. Seasonal projections for changes in precipitation.

Wildfire

The link between increases in air temperature and greater fire size, longer fire seasons, and the duration of extreme fire weather is well established for forested ecosystems (e.g., Westerling et al., 2014). The Great Basin is experiencing similar changes in temperature, and most likely fire seasons and fire weather. Dennison et al. (2014) did not find a statistically significant change in the number of large fires per year, annual burned area, and 90th percentile large fire size between 1984 and 2014 for the Snake River Plain/Columbia Plateau and Basin and Range ecoregions but did find a trend toward increasing annual area burned and 90th percentile fire size. Also, Balch et al. (2013) found that more fires started in cheatgrass-dominated areas than in other vegetation types in the cold desert and that cheatgrass was associated with increased fire frequency and size. A recent analysis of fire patterns in piñon and juniper land cover types in the semiarid western United States indicates that the fire season started earlier and ended later over the 30-yr study period from 1984 to 2014 in the Basin and Range ecoregions (Board et al., 2018).

The cold desert is warm and dry enough to allow large fires every summer but does not always have enough fuel to burn (fuel-limited), whereas forests have enough fuel every summer but may not be warm or dry enough (energy-limited) to burn (Littell et al., 2009; Abatzoglou and Kolden, 2013; Westerling et al., 2014). Warmer and drier areas dominated by sagebrush and bunchgrasses often require ≥ 1 yr with above-normal precipitation to create enough fuel for large wildfires (Crimmins and Comrie, 2004; Littell et al., 2009; Westerling et al., 2014). Pilliod et al. (2017) used a 26-yr dataset for the northern Great Basin to model the effects of weather, fine fuels, and fire in the Great Basin. They found that above-average annual precipitation in the 3 yr before a fire was influential in explaining increased cheatgrass cover, particularly if ≥ 2 yr were wet. Non-native forbs and native herbaceous cover also increased in wet years, but only if the 2 prior yr were dry. Increased winter precipitation in the prior 2 yr and the previous summer resulted in increased litter accumulation. Interestingly, the area burned in a given year was largely determined by the cover of non-native forbs and native grasses, not the current year's cover of cheatgrass. The cheatgrass cover affected fire through its effect on litter accumulation in prior years. These findings illustrate that multiyear weather patterns need to be considered to improve the modeling of annual fire risk (Pilliod et al., 2017). Nonnative invasive annual grasses can promote fire by altering the fuel bed (Brooks et al., 2004; Brooks, 2008), and fire appears to promote further cheatgrass invasion by altering resource availability of both water and nitrogen (Chambers et al., 2007; Rau et al., 2014; Roundy et al., 2014). Expansive portions of the sagebrush ecosystem are now dominated by cheatgrass, and cheatgrass-dominated landscapes have burned two to four times as frequently as native Great Basin vegetation types since 1980 (Balch et al., 2013). These trends are likely to increase with continued increases in air temperature and further increases in invasive annual grasses that are more successful in warmer and drier climates and after disturbance (Haubensak et al., 2009).

Management Strategies

Land managers will need to consider a number of adaptive management strategies in the face of climate change. Adaptation is the process of adjusting to actual or expected changes in climate; adaptation seeks to moderate or avoid harm or to exploit beneficial opportunities (IPCC, 2014). Adaptation can be *incremental,* where the objective is to maintain the integrity of a system or process at a given scale or location. However, as the climate warms, ecosystems may not persist in their current locations. Thus, adaptation can also be *transformational,* where actions focus on changing the fundamental attributes of a system in response to climate and its effects (IPCC, 2014).

Managing natural resources within the context of climate adaptation requires the flexibility to modify management actions as environmental conditions change. A conceptual approach for addressing adaptation in use by USFWS (2010) and USFS (2011) focuses on climate resistance, resilience, and response strategies (Millar et al., 2007). *Resistance strategies* aim to increase the capacity of ecosystems to maintain their fundamental structure, processes, and functioning in the face of climate-related stressors such as drought, wildfire, insects, and disease in the short term. *Resilience strategies* seek to minimize the severity of climate change impacts by reducing vulnerability and increasing the capacity of ecosystem elements to adapt to climate change and its effects. *Response strategies* seek to facilitate large-scale ecological transitions in response to changing environmental conditions. A given strategy may fall into one of these categories or more than one category.

Managers can use climate change projections to determine the most appropriate climate adaptation strategies. If continued changes in climate are expected (i.e., increases in temperature and shifts in precipitation timing and amount) and the associated effects are relatively small within the next decade or two, current management practices can be adapted to maintain resistance while also building resilience. In some cases, this may consist of simply doing more of the same. Actions that sustain fundamental ecological conditions and processes and reduce non-climate stressors, such as managing livestock and wild horse and burro populations to maintain soil and hydrologic functioning, streambank and floodplain stability, and the capacity of native plant species to effectively compete with invasive plants, also help build resilience to changing climate into the system. Examples of other ongoing actions that are also adaptive to climate change are reducing fuel loads and fuel continuity; suppressing wildfires under more severe burning conditions, particularly in fuel beds either dominated by invasive annual grasses or at high risk of invasion; strategic placement of fuel breaks; limiting human activities that aid the spread of invasive plants; using Early Detection and Rapid Response strategies to prevent the spread of invasive plants; and reducing conifer expansion (Millar et al., 2007; Chambers et al., 2014, 2017; Maestas et al., 2016; USDI, 2016). Formal drought management plans, especially integrated plans that cover both base properties and leased pastures or allotments, can identify actions that reduce stress on native and desired plants, sustain fundamental ecological processes, maintain or enhance key structural or functional plant groups, and better manage stream flows and water temperatures to support native fish and other aquatic organisms during drought (Derner and Augustine, 2016; McEvoy et al., 2018).

If we expect changes in climate and the interactions of those changes with other threats to be large (e.g., rapid warming events, uncertainty of snowpack, extreme drought) in the next few decades, then more proactive strategies to facilitate plant and human community adjustments and species persistence may be warranted. In this case, continuing to do more of the same may not result in desired outcomes. Managers may consider changing what they do (change the activity), where they do it (change the location), or both (transformational). If plant phenological changes play out as expected (Reynolds et al., 1999; Wolkovich and Cleland, 2014; Tang et al., 2015), then the timing of certain management actions may be more effective if they also change. Beyond suppressing wildfires and constructing fuel breaks, managers may need to use prescribed fire to create fuel mosaics, thereby altering potential fire effects and promoting successional processes. Measures adopted during drought periods may need to become standard practice, such as changing grazing seasons, changing the type of animal grazed, altering the number of animals grazed to account for permanent changes in ecosystem productivity, and greater emphasis on targeted grazing to manage invasive plants and fine fuel loadings (Reeves et al., 2014; Svejcar et al., 2014; Finch et al., 2016; Holthuijzen and Veblen, 2016; Palmquist et al., 2016b). Managers will need to include bet-hedging strategies, such as including genetically diverse seeds and other plant materials from across a greater geographic range that considers both the current climate and the near-future climate (next 20 − 30 yr); favoring existing genotypes that are better adapted to future conditions; and increasing the diversity of nursery stock to provide those species and genotypes more likely to succeed (Millar et al., 2007; Bucharova, 2017; Chambers et al., in press). The timing of actions such as prescribed burning and seeding may need to shift to improve success rates and avoid unintended consequences. Assisted migration of species not typically found in an area, species that have no pathway to migrate on their own, such as fish and highly specialized plants, or of species with dispersal rates slower than climate velocity, may be needed to maintain general ecological functions or preserve desired species or genotypes (Millar et al., 2007; Loarie et al., 2009; Pilliod et al., 2015). These types of transformational actions involve social and economic considerations, as well as ecological considerations, and will require consensus building (Kates et al., 2012; Crausbay et al., 2017).

One concern in practicing climate adaptation is the uncertainty involved in translating climate information into on-the-ground responses. This uncertainty is driven by assumptions in the climate models, downscaling procedures, and emissions scenarios; how we expect changes in climate to influence ecological characteristics of local systems (e.g., soil moisture, stream flows, and probability of wildfire); how these influence ecological processes; and how different species will respond. Nonetheless, climate change projections provide a valuable tool to identify 1) places on the landscape where current desired objectives are unlikely to be attained in the future; 2) places where projected climate changes are unlikely to have significant effects (climate refugia); and 3) places where we can effectively employ climate adaptation measures to realize desired outcomes (Chambers et al., in press; Millar et al., 2007, 2012). Since the uncertainty in climate projections increases with the length of the projection, managers should search for strategies that are robust to several possibilities (Millar et al., 2007, 2012; Palmquist et al., 2016b). Monitoring provides critical information on changes in species and ecosystems resulting from climate change, allowing managers to take advantage of opportunities to facilitate transitions to systems that

Table 1
Internet resources for land managers.

Historical climate data
- Western Regional Climate Center (https://wrcc.dri.edu)—data from the National Weather Service cooperative stations and links to a number of drought-monitoring sites such as the Drought Monitor, Great Basin Weather and Climate Dashboard, near real-time stream data, and the National Drought and Mitigation Center.
- Climate Data Online (https://www.ncdc.noaa.gov/cdo-web/)—observation data from weather stations.
- WestMap (https://cefa.dri.edu/Westmap/)—monthly temperature and precipitation data by state, county, hydrologic unit, or user-selected pixels or polygons. Data are modeled using PRISM (Parameter-elevation Relationships on Independent Slopes Model).

Drought information
- National Integrated Drought Information System (https://www.drought.gov/drought/what-nidis)—different drought indicators and drought outlooks and forecasts including soil moisture, vegetation condition, agricultural impacts, and water supply. Also includes links to drought planning tools.
- Westwide Drought Tracker (https://wrcc.dri.edu/wwdt/current.php?folder=spi3&region=ww)—Maps of drought status using different indices such as Palmer Drought Indices, Standardized Precipitation Index, snow water equivalent, and soil moisture. Maps are available by the continental US or by regions and on different time scales.

Planning resources
- Sagebrush Climate Console (http://climateconsole.org/sagebrush)—provides recent climate data and climate projections by county, ecoregion, or watershed; 30-day forecasts by climate division; and indicators for how sensitive the selected area is to changing climate to enhance vegetation management success.
- Great Basin Weather Applications for Rangeland Restoration (http://greatbasinweatherapplications.org/)—still in development, this site will provide tools to help managers select conditions intended to increase restoration success and control invasive annual grasses.
- National Drought Mitigation Center (http://drought.unl.edu/)—includes links to state drought plans, links to several drought indicators, and several guides for planning for drought, including one specific to ranches.
- Northwest Climate Toolbox (https://climatetoolbox.org/)—contains a number of tools for examining past and future climate, including seasonal forecast maps and graphs, projections for streamflow, and historical climate variability.
- Seedlot Selection Tool (https://seedlotselectiontool.org/sst/)—although designed for trees, if managers know the approximate location of the source of a seedlot, they can select the seed source location and find areas with similar climate where that seedlot is likely to do well. Manager can locate potential seed source areas by selecting the planting location and finding areas with similar climate.
- The Landscape Toolbox (http://www.LandscapeToolbox.org) is a coordinated system of tools and methods for implementing land health monitoring and integrating monitoring data into management decision making.
- Land Resources Planning Toolbox: http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/en/ The LRP Toolbox is a freely accessible online source for a range of stakeholders, directly or indirectly involved in land use planning. The Toolbox contains a comprehensive number of existing tools and approaches that are used to implement land resources planning.

Citizen science opportunities
- Community Cooperative Rain, Hail, and Snow network (https://www.cocorahs.org/) or CoCoRaHS. A volunteer network that collects precipitation information.
- Weather Underground (https://www.wunderground.com/)—Buy and install a commercially available weather station and register it with the Weather Underground. Many stations can link directly to the Weather Underground through an Internet hub.
- National Phenology Network (https://www.usanpn.org/)—This project provides opportunities for adults and children to track and report phenological events such as green-up, flowering, bird migration and so forth using Nature's Notebook

are both better adapted in the long term and continue to provide desired ecosystem services (Millar et al., 2007). Monitoring at the edges of species ranges is particularly important for detecting range shifts in both native and invasive species and to determine when including plant materials from neighboring climate types is essential. Monitoring changes in snowpack cover and duration at the lower end can identify areas where additional measures may be needed to better retain what snow falls, leverage topographic features that retain soil moisture longer, and reduce other stressors that can result in ecosystem changes (Bainbridge, 2012; Loik et al., 2015; Finch et al., 2016).

Climate change is likely to produce surprises in how ecosystems respond. New plant communities are likely to arise, abrupt changes in ecological processes may occur (Millar et al., 2007), and disruptions in human economies are probable (Craine et al., 2010; Evans et al., 2010; Crausbay et al., 2017). We suggest that any process that considers or includes climate adaptation is beneficial and more likely to reduce ecological and economic disruptions. The projections that conditions will continue to get warmer and drier in the cold deserts have high certainty, and we can use that information to plan for the future.

Where to Find Information

Fortunately, there are a growing number of resources available to managers to apply for the purpose of climate adaptation. Table 1 provides a list of various resources available to managers to understand recent weather and climate patterns, track drought, and assist in planning strategies. These resources include where to find information about the historical and current climate and seasonal weather conditions, resources for climate change-related planning, and how to provide information that scientists can use to refine climate and climate impacts models, as well as detect where and at what rate changes in climate and phenology are occurring. The generally sparse populations and lack of large towns and cities mean that climate and climate-related impact information for much of the Great Basin and Columbia Plateau are lacking. As a result, climate change projections and downscaling that use historical weather and climate information have a built-in bias or lack of specificity for this area. Participating in citizen science projects that will increase this sort of information for the Great Basin and Columbia Plateau should eventually result in improved projections and estimates of impacts.

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References

Abatzoglou, J.T., Kolden, C.A., 2011. Climate change in western US deserts: potential for increased wildfire and invasive annual grasses. Rangeland Ecology & Management 64, 471–478.

Abatzoglou, J.T., Kolden, C.A., 2013. Relationships between climate and macroscale area burned in the western United States. International Journal of Wildlife Fire 22, 1003.

Abatzoglou, J.T., Rupp, D.E., Mote, P.W., 2014. Seasonal climate variability and change in the Pacific Northwest of the United States. Journal of Climatology 27, 2125–2142.

Abatzoglou, J.T., Kolden, C.A., Balch, J.K., Bradley, B.A., 2016. Controls on interannual variability in lightning-caused fire activity in the western US. Environmental Research Letters 11, 045005.

Arismendi, I., Safeeq, M., Johnson, S.L., Dunham, J.B., Haggerty, R., 2013. Increasing synchrony of high temperature and low flow in western North American streams: double trouble for coldwater biota? Hydrobiologia 712, 61–70.

Bainbridge, D.A., 2012. A guide for desert and dryland restoration: new hope for arid lands. Island Press, Washington, D. C., USA 416 p.

Balch, J.K., Bradley, B.A., D'Antonio, C.M., Gómez-Dans, J., 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). Global Change Biology 19, 173–183.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303.

Barnett, T.P., Pierce, D.W., Hidalgo, H.G., Bonfils, C., Santer, B.D., Das, T., Bala, G., Wood, A.W., Nozawa, T., Mirin, A.A., 2008. Human-induced changes in the hydrology of the western United States. Science 319, 1080–1083 80-.

Bedford, D., Douglass, A., 2008. Changing properties of snowpack in the Great Salt Lake Basin, Western United States, from a 26-Year SNOTEL record. The Professional Geographer 60, 374–386.

Black, B.A., van der Sleen, P., Di Lorenzo, E., Griffin, D., Sydeman, W.J., Dunham, J.B., Rykaczewski, R.R., García-Reyes, M., Safeeq, M., Arismendi, I., 2018. Rising synchrony controls western North American ecosystems. Global Changes in Biology 24, 2305–2314.

Board, D.I., Chambers, J.C., Miller, R.M., Weisberg, P.J., 2018. Fire patterns in piñon and juniper land cover types in the semiarid western US from 1984 through 2013. General Technical Report. RMRS-GTR-372. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA.

Boyte, S.P., Wylie, B.K., Major, D.J., 2016. Cheatgrass Percent Cover Change: Comparing Recent Estimates to Climate Change—Driven Predictions in the Northern Great Basin. Rangeland Ecology & Management 69, 265–279.

Bradley, B.A., 2010. Assessing ecosystem threats from global and regional change: hierarchical modeling of risk to sagebrush ecosystems from climate change, land use and invasive species in Nevada, USA. Ecography (Cop.) 33, 198–208.

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

Bradley, B.A., Curtis, C.A., Chambers, J.C., 2016. Bromus response to climate and projected changes with climate change. In: Germino, M., Chambers, J., Brown, C. (Eds.), Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US. Springer Series on Environmental, Springer, Berlin/Heidelberger, Germany, pp. 257–274.

Brooks, M.L., 2008. Plant invasions and fire regimes. In: Zouhar, K., Smith, J.K., Sutherland, S., Brooks, M.L. (Eds.), Wildland fire in ecosystems: fire and nonnative invasive plants. General Technical Report. RMRS-GTR-42 vol. 6. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA, pp. 33–45.

Brooks, M.L., D'Antonio, C.M., Richardson, D.M., Grace, J.B., Keeley, J.E., DiTomaso, J.M., Hobbs, R.J., Pellant, M., Pyke, D., 2004. Effects of invasive alien plants on fire regimes. Bioscience 54, 677–688.

Bucharova, A., 2017. Assisted migration within species range ignores biotic interactions and lacks evidence. Restoration Ecology 25, 14–18.

Bykova, O., Sage, R.F., 2012. Winter cold tolerance and the geographic range separation of *Bromus tectorum* and *Bromus rubens,* two severe invasive species in North America. Global Changes in Biology 18, 3654–3663.

Carroll, R.W., Huntington, J.L., Snyder, K.A., Niswonger, R.G., Morton, C., Stringham, T.K., 2017. Evaluating mountain meadow groundwater response to pinyon-juniper and temperature in a Great Basin watershed. Ecohydrology 10, e1792.

Chambers, J.C., Roundy, B.A., Blank, R.R., Meyer, S.E., Whittaker, A., 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum?* Ecology Monographs 77, 117–145.

Chambers, J.C., Leger, E., Goergen, E., 2009. Cold desert fire and invasive species management: resources, strategies, tactics, and response. Rangelands 31, 14–20.

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., 2014. Resilience to stress and disturbance, and resistance to *Bromus tectorum* L. invasion in cold desert shrublands of western North America. Ecosystems 17, 360–375.

Chambers, 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, Jessica R., Hanser, S.E., Havlina, J.C.B., 2017. 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 1. Science Basis and Applications. RMRS-GTR-360. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA, Accessed date: 3 May 2018 Available at: https://www.treesearch.fs.fed.us/pubs/53983.

Chambers, J. C., Evers, L., Joyce, L. 2018(in press). Climate adaption and mitigation. *In:* Science Framework for Conservation and Restoration of the Sagebrush Biome: Linking the Department of the Interior Secretarial Order 3336 to Long-Term Strategic Conservation Actions. Part 2. Science Basis and Applications. RMRS-GTR-XXX. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Collins, M., Knutti, R., Arblaster, J., Defresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski Jr., W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., Wehner, M., 2013. Long-term climate change: projections, commitments and irreversibility. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignore, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY, USA, pp. 1029–1136.

Concilio, A.L., Loik, M.E., 2013. Elevated nitrogen effects on *Bromus tectorum* dominance and native plant diversity in an arid montane ecosystem. Applied Vegetation Science 16, 598–609.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004. Long-term aridity changes in the western United States. Science 306, 1015–1018.

Craine, J.M., Elmore, A.J., Olson, K.C., Tolleson, D., 2010. Climate change and cattle nutritional stress. Global Changes in Biology 16, 2901–2911.

Crausbay, S.D., Ramirez, A.R., Carter, S.L., Cross, M.S., Hall, K.R., Bathke, D.J., Betancourt, J.L., Colt, S., Cravens, A.E., Dalton, M.S., 2017. Defining ecological drought for the 21st century. Bulletin of the American Meteorological Society 98, 2543–2550.

Crimmins, M.A., Comrie, A.C., 2004. Interactions between antecedent climate and wildfire variability across south-eastern Arizona. International Journal of Wildlife Fire 13, 455–466.

Dai, A.G., 2013. Increasing drought under global warming in observations and models. Nature Climate Change 3, 52–58.
Dalton, M.M., 2013. Climate change in the Northwest: implications for our landscapes, waters, and communities. Island Press, Washington, DC, USA.
Davies, K.W., Johnson, D.D., 2008. Managing medusahead in the Intermountain West is at a critical threshold. Rangelands 30, 13–15.
DeLucia, E.H., Schlesinger, W.H., 1991. Resource-use efficiency and drought tolerance in adjacent Great Basin and sierran plants. Ecology 72, 51–58.
Dennison, P.E., Brewer, S.C., Arnold, J.D., Moritz, M.A., 2014. Large wildfire trends in the western United States, 1984-2011. Geophysical Research Letters 41, 2928–2933.
Derner, J.D., Augustine, D.J., 2016. Adaptive management for drought on rangelands. Rangelands 38, 211–215.
Diffenbaugh, N.S., Swain, D.L., Touma, D., 2015. Anthropogenic warming has increased drought risk in California. Proceedings of the National Academy of Sciences of the United States of America 112, 3931–3936.
Donovan, L.A., Ehleringer, J.R., 1994. Water-stress and use of summer precipitation in a Great-Basin shrub community. Ecology 8, 289–297.
Easterling, D.R., Wehner, M.F., 2009. Is the climate warming or cooling? Geophysical Research Letters 36.
Evans, G.R., Washington-Allen, R.A., Child, R.D., Mitchell, J.E., Bobowski, B.R., Loper, R.V., Allen-Diaz, B.H., Thompson, D.W., Welling, G.R., Reuwsaat, T.B., 2010. Criterion III: maintenance of rangeland productive capacity. In: Mitchell, J.E. (Ed.), Criteria and indicators of sustainable rangeland management. University of Wyoming Extension, Laramie, WY, USA, pp. 139–170 Publication No. SM-56.
Finch, D.M., Pendleton, R.L., Reeves, M.C., Ott, J.E., Kilkenny, F.F., Butler, J.L., Ott, J.P., Pinto, J.R., Ford, J.R., Runyon, J.B., Rumble, M.A., Kitchen, S.G., 2016. Chapter 8. Rangeland drought: effects, restoration, and adaptation. In: Vose, J.M., Clark, J.S., Luce, C.H., Patel-Weynand, T. (Eds.), Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis. General Technical Report. WO-93b. US Department of Agriculture, Forest Service, Washington, DC, USA, pp. 155–194.
Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., Rummukainen, M., 2013. Evaluation of climate models. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Chapter 9. Cambridge University Press, New York, NY, USA, pp. 741–866.
Folland, C.K., et al., 2001. In: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Observed climate variability and change. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, United Kingdom, pp. 99–181.
Fyfe, J.C., Derksen, C., Mudryk, L., Flato, G.M., Santer, B.D., Swart, N.C., Molotch, N.P., Zhang, X.B., Wan, H., Arora, V.K., Scinocca, J., Jiao, Y.J., 2017. Large near-term projected snowpack loss over the western United States. Nature Community 8. https://doi.org/10.1038/ncomms14996, Accessed date: 5 March 2018 Available at:.
Gergel, D.R., Nijssen, B., Abatzoglou, J.T., Lettenmaier, D.P., Stumbaugh, M.R., 2017. Effects of climate change on snowpack and fire potential in the western USA. Climate Change 141, 287–299.
Gershunov, A., Shulgina, T., Ralph, F.M., Lavers, D.A., Rutz, J.J., 2017. Assessing the climate-scale variability of atmospheric rivers affecting western North America. Geophysical Research Letters 44, 7900–7908.
Grayson, D., 2011. The Great Basin: a natural prehistory. University of California Press, Berkeley, CA, USA 418 p.
Griffith, A.B., Loik, M.E., 2010. Effects of climate and snow depth on *Bromus tectorum* population dynamics at high elevation. Oecologia 164, 821–832.
Harpold, A.A., Brooks, P.D., 2018. Humidity determines snowpack ablation under a warming climate. Proceedings of the National Academy of Sciences of the United States of America 115, 1215–1220.
Haubensak, K., D'Antonio, C., Wixon, D., 2009. Effects of fire and environmental variables on plant structure and composition in grazed salt desert shrublands of the Great Basin (USA). Journal of Arid Environments 73, 643–650.
Holthuijzen, M.F., Veblen, K.E., 2016. Grazing effects on precipitation-driven associations between sagebrush and perennial grasses. Western North American Naturalist 76, 313–325.
Homer, C.G., Xian, G., Aldridge, C.L., Meyer, D.K., Loveland, T.R., O'Donnell, M.S., 2015. Forecasting sagebrush ecosystem components and greater sage-grouse habitat for 2050: learning from past climate patterns and Landsat imagery to predict the future. Ecology Indicators 55, 131–145.
Huang, X., Ullrich, P.A., 2017. The changing character of twenty-first-century precipitation over the western United States in the variable-resolution CESM. Journal of Climatology 30, 7555–7575.
Hufft, R.A., Zelikova, T.J., 2016. Ecological genetics, local adaptation, and phenotypic plasticity in *Bromus tectorum* in the context of changing climate. In: Germino, M.J., Chambers, J.C., Brown, C.S. (Eds.), Exotic brome-grasses in arid and semiarid ecosystems of the western U.S.Springer, New York, NY, USA, pp. 133–154
Huxman, T.E., Wilcox, B.P., Breshears, D.D., Scott, R.L., Snyder, K.A., Small, E.E., Hultine, K., Pockman, W.T., Jackson, R.B., 2005. Ecohydrological implications of woody plant encroachment. Ecology 86, 308–319.
IPCC, 2013. Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignore, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate change 2013, the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY, USA, pp. 3–29.
IPCC, 2014. Climate change 2014: impacts, adaptation, and vulnerability. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandea, P.R., White, L.I. (Eds.), Part B: regional aspects. Contribution of Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY, USA 688 p.
James, J.J., Drenovsky, R.E., Monaco, T.A., Rinella, M.J., 2011. Managing soil nitrogen to restore annual grass-infested plant communities: effective strategy or incomplete framework? Ecology Applications 21, 490–502.
Jeong II, D., Sushama, L., Khaliq, M.N., 2014. The role of temperature in drought projections over North America. Climate Change 127, 289–303.
Kates, R.W., Travis, W.R., Wilbanks, T.J., 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. Proceedings of the National Academy of Sciences of the United States of America 109, 7156–7161.
Klos, P.Z., Link, T.E., Abatzoglou, J.T., 2014. Extent of the rain-snow transition zone in the western US under historic and projected climate. Geophysical Research Letters 41, 4560–4568.
Knowles, N., 2015. Trends in snow cover and related quantities at weather stations in the conterminous United States. Journal of Climatology 28, 7518–7528.
Kunkel, K.E., Stevens, L.E., Stevens, S.E., Sun, L., Janssen, E., Wuebbles, D., Redmond, K.T., Dobson, J.G., 2013a. Regional climate trends and scenarios for the U.S. national climate assessment. Part 5. Climate of the Southwest U.S. NOAA Technical Report NESDIS 142 — 145, Washington, DC, USA, 79 p
Kunkel, K.E., Stevens, L.E., Stevens, S.E., Sun, L., Janssen, E., Wuebbles, D., Redmond, K.T., Dobson, J.G., 2013b. Regional climate trends and scenarios for the U.S. National Climate Assessment. Part 6. Climate of the Northwest U.S. NOAA Technical Report NESDIS 142 — 146, Washington, DC, USA, 83 p
Lake, P.S., 2011. Drought and aquatic ecosystems: effects and responses. John Wiley & Sons, Hoboken, NJ, USA 400 p.
Lauenroth, W.K., Bradford, J.B., 2009. Ecohydrology of dry regions of the United States: precipitation pulses and intraseasonal drought. Ecohydrology 2, 173–181.
Leger, E.A., Espeland, E.K., Merrill, K.R., Meyer, S.E., 2009. Genetic variation and local adaptation at a cheatgrass *(Bromus tectorum)* invasion edge in western Nevada. Molecular Ecology 18, 4366–4379.
Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L., 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecology Applications 19, 1003–1021.
Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., Ackerly, D.D., 2009. The velocity of climate change. Nature 462, 1052.
Loik, M.E., Breshears, D.D., Lauenroth, W.K., Belnap, J., 2004. A multi-scale perspective of water pulses in dryland ecosystems: climatology and ecohydrology of the western USA. Oecologia 141, 269–281.
Loik, M.E., Griffith, A.B., Alpert, H., Wade, C.E., Martinson, S.J., 2015. Impact of intra-versus inter-annual snow depth variation on water relations and photosynthesis for two Great Basin Desert shrubs. Oecologia 178, 403–414.
Luce, C.H., Holden, Z.A., 2009. Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. Geophysical Research Letters 36 (16). https://doi.org/10.1029/2009GL039407.
Luce, C.H., Abatzoglou, J.T., Holden, Z.A., 2013. The missing mountain water: slower westerlies decrease orographic enhancement in the Pacific Northwest USA. Science 342, 1360–1364.
Maestas, J., Pellant, M., Okeson, L., Tilley, D., Havlina, D., Craycroft, T., Brazee, B., Williams, M., Messmer, D., 2016. Fuel breaks to reduce large wildfire impacts in sagebrush ecosystems. Plant Materials Technical Note No. 66. USDA Natural Resources Conservation Service, Boise, ID, USA, Boise, ID, USA.
Maurer, E.P., Brekke, L., Pruitt, T., Duffy, P.B., 2007. Fine-resolution climate projections enhance regional climate change impact studies. Eos Transactions of the American Geophysical Union 88, 504.
McEvoy, J., Bathke, D.J., Burkardt, N., Cravens, A.E., Haigh, T., Hall, K.R., Hayes, M.J., Jedd, T., Podĕbradská, M., Wickham, E., 2018. Ecological drought: accounting for the non-human impacts of water shortage in the Upper Missouri Headwaters Basin, Montana, USA. Resources 7, 14.
Meyer S. E., Garvin S. C., and Beckstead J. 2001. Factors mediating cheatgrass invasion of intact salt desert shrubland. *In:* McArthur D. E., and Fairbanks D. J. [comps]. Shrubland Ecosystem Genetics and Biodiversity: Proceedings. Proc RMRS-P-21. Ogden, UT, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 224 — 232.
Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Application 17, 2145–2151.
Millar, C.I., Skog, K.E., McKinley, D.C., Birdsey, R.A., Swanston, C.W., Hines, S.J., Woodall, C.W., Reinhardt, E.D., Peterson, D.L., Vose, J.M., 2012. Adaptation and mitigation. In: Vose, J.M., Peterson, D.L., Patel-Weynand, T. (Eds.), Effects of climate variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. General Technical Report PNW-GTR-870. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA, pp. 125–192.
Miller, R.F., Knick, S.T., Pyke, D.A., Meinke, C.W., Hanser, S.E., Wisdom, M.J., Hild, A.L., 2011. Characteristics of sagebrush habitats and limitations to long-term conservation. Great sage-grouse ecological conservation and landscape species and its habitats. Studies in Avian Biology 38, 145–184.
Mote, P.W., Hamlet, A.F., Clark, M.P., Lettenmaier, D.P., 2005. Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86, 39.
Mote, P.W., Li, S., Lettenmaier, D.P., Xiao, M., Engel, R., 2018. Dramatic declines in snowpack in the western US. NPJ Climate Atmospheric Science 1, 2.
Nayak, A., Marks, D., Chandler, D.G., Seyfried, M., 2010. Long-term snow, climate, and streamflow trends at the Reynolds Creek experimental watershed, Owyhee Mountains, Idaho, United States. Water Resources Research 46.

Newman, B.D., Wilcox, B.P., Archer, S.R., Breshears, D.D., Dahm, C.N., Duffy, C.J., McDowell, N.G., Phillips, F.M., Scanlon, B.R., Vivoni, E.R., 2006. Ecohydrology of water-limited environments: a scientific vision. Water Resources Research 42. https://doi.org/10.1029/2005wr004141.

Northam, F.E., Callihan, R.H., 1994. New weedy grasses associated with downy brome. US Department of Agriculture and Forestry Service Intermountain Research Station. *General Technical Report* INT-313.

Palmquist, K.A., Schlaepfer, D.R., Bradford, J.B., Lauenroth, W.K., 2016a. Mid-latitude shrub steppe plant communities: climate change consequences for soil water resources. Ecology 97, 2342–2354.

Palmquist, K.A., Schlaepfer, D.R., Bradford, J.B., Lauenroth, W.K., 2016b. Spatial and ecological variation in dryland ecohydrological responses to climate change: implications for management. Ecosphere 7 (11), 1–20.

Pendergrass, A.G., Knutti, R., Lehner, F., Deser, C., Sanderson, B.M., 2017. Precipitation variability increases in a warmer climate. Scientific Report 7, 17966.

Pilliod, D.S., Arkle, R.S., Robertson, J.M., Murphy, M.A., Funk, W.C., 2015. Effects of changing climate on aquatic habitat and connectivity for remnant populations of a wide-ranging frog species in an arid landscape. Ecological Evolution 5, 3979–3994.

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. Ecological Evolution 7, 8126–8151.

Prein, A.F., Holland, G.J., Rasmussen, R.M., Clark, M.P., Tye, M.R., 2016. Running dry: the US Southwest's drift into a drier climate state. Geophysical Research Letters 43, 1272–1279.

Prein, A.F., Liu, C., Ikeda, K., Trier, S.B., Rasmussen, R.M., Holland, G.J., Clark, M.P., 2017. Increased rainfall volume from future convective storms in the US. Nature Climate Change 7, 880.

Quinn, J.F., Harrison, S.P., 1988. Effects of habitat fragmentation and isolation on species richness: evidence from biogeographic patterns. Oecologia 75, 132–140.

Rau, B.M., Chambers, J.C., Pyke, D.A., Roundy, B.A., Schupp, E.W., Doescher, P., Caldwell, T.G., 2014. Soil resources influence vegetation and response to fire and fire-surrogate treatments in sagebrush-steppe ecosystems. Rangeland Ecology & Management 67, 506–521.

Reeves, M.C., Moreno, A.L., Bagne, K.E., Running, S.W., 2014. Estimating climate change effects on net primary production of rangelands in the United States. Climate Change 126, 429–442.

Rehfeldt, G.E., Crookston, N.L., Warwell, M.V., Evans, J.S., 2006. Empirical analyses of plant-climate relationships for the western United States. International Journal of Plant Science 167, 1123–1150.

Rehfeldt, G.E., Crookston, N.L., Sáenz-Romero, C., Campbell, E.M., 2012. North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. Ecological Applications 22, 119–141.

Reynolds, J.F., Virginia, R.A., Kemp, P.R., De Soyza, A.G., Tremmel, D.C., 1999. Impact of drought on desert shrubs: effects of seasonality and degree of resource island development. Ecological Monograph 69, 69–106.

Reynolds, J.F., Smith, D.M.S., Lambin, E.F., Turner, B.L., Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernández, R.J., Herrick, J.E., 2007. Global desertification: building a science for dryland development. Science 316, 847–851.

Rieman, B., Peterson, J.T., Clayton, J., Howell, P., Thurow, R., Thompson, W., Lee, D., 2001. Evaluation of potential effects of federal land management alternatives on trends of salmonids and their habitats in the interior Columbia River basin. Forest Ecology and Management 153, 43–62.

Roundy, B.A., Young, K., Cline, N., Hulet, A., Miller, R.F., Tausch, R.J., Chambers, J.C., Rau, B., 2014. Piñon–juniper reduction increases soil water availability of the resource growth pool. Rangeland Ecology & Management 67, 495–505.

Safeeq, M., Shukla, S., Arismendi, I., Grant, G.E., Lewis, S.L., Nolin, A., 2016. Influence of winter season climate variability on snow-precipitation ratio in the western United States. International Journal of Climatology 36, 3175–3190.

Salo, L.F., 2005. Red brome (*Bromus rubens* subsp. *madritensis*) in North America: possible modes for early introductions, subsequent spread. Biological Invasions 7, 165–180.

Schlaepfer, D.R., Lauenroth, W.K., Bradford, J.B., 2012a. Effects of ecohydrological variables on current and future ranges, local suitability patterns, and model accuracy in big sagebrush. Ecography (Cop.) 35, 374–384.

Schlaepfer, D.R., Lauenroth, W.K., Bradford, J.B., 2012b. Ecohydrological niche of sagebrush ecosystems. Ecohydrology 5, 453–466.

Schultz, L.D., Heck, M.P., Hockman-Wert, D., Allai, T., Wenger, S., Cook, N.A., Dunham, J.B., 2017. Spatial and temporal variability in the effects of wildfire and drought on thermal habitat for a desert trout. Journal of Arid Environments 145, 60–68.

Steinbauer, M.J., Grytnes, J.-A., Jurasinski, G., Kulonen, A., Lenoir, J., Pauli, H., Rixen, C., Winkler, M., Bardy-Durchhalter, M., Barni, E., et al., 2018. Accelerated increase in plant species richness on mountain summits is linked to warming. Nature 556, 231–234.

Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2005. Changes toward earlier streamflow timing across western North America. The Journal of Climate 18, 1136–1155.

Still, S.M., Richardson, B.A., 2015. Projections of contemporary and future climate niche for Wyoming Big Sagebrush (*Artemisia tridentata* subsp. wyomingensis): a guide for restoration. Nature Areas Journal 35, 30–43.

Svejcar, T., Boyd, C., Davies, K., Madsen, M., Bates, J., Sheley, R., Marlow, C., Bohnert, D., Borman, M., Mata-Gonzàlez, R., 2014. Western land managers will need all available tools for adapting to climate change, including grazing: a critique of Beschta et al. Environmental Management 53, 1035–1038.

Swain, D.L., Langenbrunner, B., Neelin, J.D., Hall, A., 2018. Increasing precipitation volatility in twenty-first-century California. Nature Climate Change 8, 427–433.

Tang, G.P., Arnone, J.A., 2013. Trends in surface air temperature and temperature extremes in the Great Basin during the 20th century from ground-based observations. Journal of Geophysical Research 118, 3579–3589.

Tang, G., Arnone, J.A., Verburg, P.S.J., Jasoni, R.L., Sun, L., 2015. Trends and climatic sensitivities of vegetation phenology in semiarid and arid ecosystems in the US Great Basin during 1982-2011. Biogeosciences 12, 6985–6997.

Thompson, R.S., Anderson, K.H., Pelletier, R.T., Shafer, S.L., Bartlein, P.J., 2007. Atlas of relations between climatic parameters and distributions of important trees and shrubs in North America—Ecoregions of North America: *US Geological Survey Professional Paper* 1650–E.

United States Department of Interior, 2016. Safeguarding America's lands and waters from invasive species: a national framework for early detection and rapid response. USDI, Washington, DC, USA 55 p.

United States Fish and Wildlife Service, 2010. Rising to the urgent challenge: strategic plan for responding to accelerating climate change. Available at: https://www.fws.gov/home/climatechange/pdf/CCStrategicPlan.pdf, Accessed date: 20 September 2016.

United States Forest Service, 2011. National roadmap for responding to climate change. FS-957b. US Department of Agriculture, Forest Service, Washington, DC, USA 32 p.

United States Global Change Research Program, 2017. Climate science special report: fourth national climate assessment, volume I. US Global Change Research Program, Washington, DC, USA 470 p.

Van Loon, A.F., Gleeson, T., Clark, J., Van Dijk, A.I.J.M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A.J., Tallaksen, L.M., Uijlenhoet, R., 2016. Drought in the Anthropocene. Nature Geoscience 9, 89.

Vose, J.M., Miniat, C.F., Luce, C.H., Asbjornsen, H., Caldwell, P.V., Campbell, J.L., Grant, G.E., Isaak, D.J., Loheide, S.P., Sun, G., 2016. Ecohydrological implications of drought. Drought impacts US forest rangelands. A Comprehensive Scientific Synthesis. WO-GTR-93b. US Department of Agriculture Forest Service, Washington, DC, USA, pp. 231–251.

Wagner, F.H. (Ed.), 2003. Preparing for a changing climate—the potential consequences of climate variability and change. Rocky Mountain/Great Basin regional climate-change assessment teamfor the US Global Change Research Program. Utah State University, Logan, UT, USA 240 p.

Warren, D.R., Dunham, J.B., Hockman-Wert, D., 2014. Geographic variability in elevation and topographic constraints on the distribution of native and nonnative trout in the Great Basin. Transactions of American Fishing Society 143, 205–218.

Wasko, C., Sharma, A., Westra, S., 2016. Reduced spatial extent of extreme storms at higher temperatures. Geophysical Research Letters 43, 4026–4032.

West, N.E., 1983. Western intermountain sagebrush steppe. In: West, N.E. (Ed.), Temperate deserts and semi-deserts. Elsevier Publishing Company, Amsterdam, the Netherlands, pp. 351–374.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US Forest Wildfire Activity. Science 313, 940.

Westerling, A., Brown, T., Schoennagel, T., Swetnam, T., Turner, M., Veblen, T., 2014. Briefing: climate and wildfire in western U.S. forests. In: Sample, V.A., Bixler, R.P. (Eds.), Forest conservation and management in the Anthropocene: conference proceedings. Proceedings. RMRS-P-71. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA, pp. 81–102.

Wolkovich, E.M., Cleland, E.E., 2014. Phenological niches and the future of invaded ecosystems with climate change. AoB Plants 6. https://doi.org/10.1093/aobpla/plu013, Accessed date: 18 August 2017.

Zelikova, T.J., Hufbauer, R.A., Reed, S.C., Wertin, T., Fettig, C., Belnap, J., 2013. Eco-evolutionary responses of *Bromus tectorum* to climate change: implications for biological invasions. Ecology Evolution 3, 1374–1387.