Rangeland *FAQ* Series

Science and Solutions for the Range

Fact Sheet 2 | uidaho.edu/range | August 2020

Rinker Rock Creek Ranch in spring.

How is Climate Change Impacting the Working Rangelands of the Pacific Northwest?

Rangelands provide habitat for wildlife, forage for livestock, and places to recreate. They are dynamic and ever-changing lands influenced by interacting climate, animal, and human forces. Living and working on rangelands is full of environmental as well as economic variation from year to year and across decades.

In recent decades, changes in climate patterns have impacted water resources, vegetation, and fire size and frequency. These changes are impacting not only the ecological function of rangelands, but also the lives of people who live, work, and recreate there. This creates concerns over how forage production, invasive species, wildland fire, and water availability might change in the future.

While climate change challenges ranching and land management in new ways, certain rangeland management practices may help slow climate change by storing and sequestering carbon, while other practices can help rangelands become more resistant and resilient to change.

The topic of climate change and its effects on rangelands is complicated and full of uncertainty. We hope the questions addressed in this document will add clarity to how climate change is influencing challenges on rangelands in the Pacific Northwest (PNW).

KEY POINTS

- There is higher year-to-year variation in the timing and amount of forage, as well as longer growing seasons. Warmer and drier summers, along with an expected increase in drought, create the potential for decreased forage amounts in water-limited places. Warming temperatures and fire will continue to favor annual grasses over perennials. Management implications from these changes include elevated heat stress in livestock, changes to turn-out dates, rotations, stocking rates and adaptive management planning.
- Water resources are changing. More precipitation is falling as rain than snow, spring snowpack is less than historical averages, the timing of when water moves out of watersheds is happening earlier in the year, and minimum streamflows have been observed to be lower.
- Fire season continues to lengthen, large fires are happening more frequently, and the area burned is increasing in the PNW. With increased area impacted by wildfire, sagebrush communities are being further pushed toward annual grass domination. Both fire and annual grasses can impact yearly grazing plans, grazing permits, stocking rates, and changes in management due to restoration and prevention.
- Rangelands store large amounts of carbon and keeping this carbon in the ground is critical to slowing global climate change. Converting degraded rangelands and croplands back to productive native rangelands with healthy perennial grasses has the potential to sequester atmospheric carbon. Managers should aim to keep rangelands productive, limit conversion to other land use types and look for opportunities to restore degraded rangelands back to their potential.

Contact: Karen Launchbaugh, Rangeland Center
Director 208.885.4393 | range@uidaho.edu

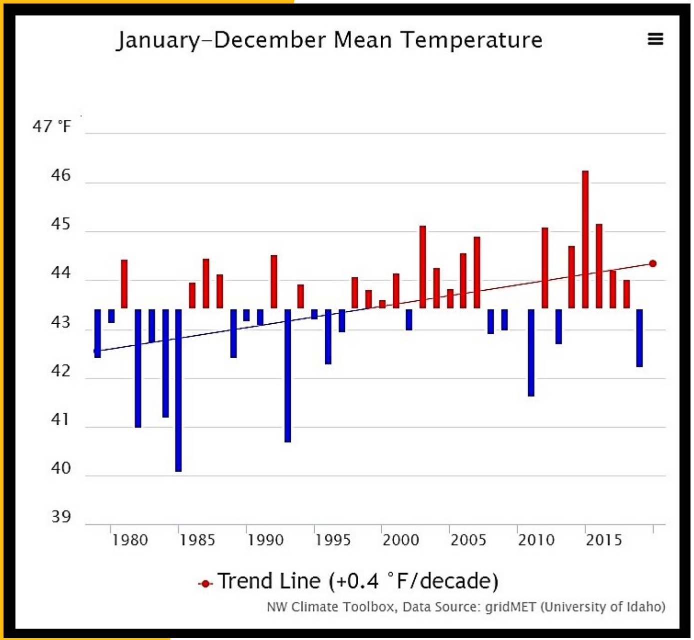
University of Idaho
Rangeland Center

How has the Pacific Northwest's climate changed?

Since the early 1900s, the average temperature across the intermountain west region of the Pacific Northwest increased by 1 to 3° F[1], causing more winter precipitation to fall as rain instead of snow[2]. Though precipitation trends across the northwest vary by location and time period, the strongest trend observed is an increase in spring precipitation[3].

Though increased precipitation is generally considered a benefit on rangelands, these slight increases in spring precipitation occurred alongside higher spring temperatures, resulting in increasing aridity or dryness of the region[4], particularly since the 1980s[3]. These more arid conditions have led to a greater loss of water from plants and from the land surface, resulting in less available soil moisture during the growing season[3–5].

The warmer temperatures being experienced on Pacific Northwest rangelands lengthened the growing season by about four days per decade between 1975-2010[6], or by about two weeks across the last 40 years[3]. Warmer temperatures are also lengthening the frost-free season[3]. Multiple studies have predicted earlier and longer growing seasons across the northwest, leading to an earlier green-up and greater early season forage production by the end of the century[7,8].



NW Climate Toolbox, Data Source: gridMET (University of Idaho)

Figure 1. Mean annual temperatures from 1979 to 2019 across the inland pacific northwest. Figure sources: Hegewisch, K.C and Abatzoglou, J. T., 'Historical Climate Tracker' web tool. NW Climate Toolbox (https://climatetoolbox.org/) accessed on 04/18/2020. Data Source gridMet (University of Idaho)

How has climate change impacted rangeland vegetation?

Rangeland managers and ranchers are accustomed to rapidly changing weather conditions and variation in precipitation and temperature from year to year. However, climate change raises specific concerns about potential losses in forage production, higher year-to-year variability in forage amount, increases in annual grasses, and changes in the abundance of sagebrush on Pacific Northwest rangelands.

Upland forage production

It is difficult to assess current impacts of climate change on forage production because there are very few long-standing datasets on plant biomass and production[9]. A longer growing season does provide a longer period for plant growth and production. But warmer and drier summers can reduce available moisture for plant growth and increase the amount of water needed by plants during the growing season, setting the stage for lower forage being produced on the range. Increasing aridity can also reduce forage quality later in the season by bringing on earlier senescence and dormancy[10].

Models predict forage productivity to increase across the northern portion of North American grasslands by the end of the century due to increased growing season length[8,9,11]. While the growing season is expected to lengthen across the Pacific Northwest, soil water availability later in the growing season is expected to decrease due to increased temperatures. This has the potential to limit forage quality and productivity during these times of year[10,11]. Most climate projections predict hotter temperatures, so it is likely that droughts will last longer[5], and the forage season will start earlier in the spring and end earlier in the summer[12]. The earlier snowmelt will also impact water resources during summer months[12]. Also, it is expected that the year-to-year variation in available forage will increase[7].

Invasive Annual Grasses

Climate change will likely change the current geographic distributions of annual invasive grasses. Warmer winters and increased fire frequency will benefit annual exotic grasses such as cheatgrass, medusahead, and red brome, which have expanded in mid to low-elevation shrublands and woodlands in the last 50 years[1]. In general, warmer temperatures are creating earlier and longer growing seasons which tend to favor annual grasses. Cheatgrass will benefit from warmer summers and decreased precipitation due to reduced competition from native plants and the increased likelihood of fires[13]. Sites with sparse perennial grass cover are most susceptible to invasion by these annual grasses. In a changing climate, annual invasive grass species are likely to become more abundant at higher elevations[1,14].

Invasive annual grasses also benefit from disturbances such as wildfire. Increased temperatures and lower humidity during spring and summer create conditions advantageous for wildland fire[15]. This increased fire frequency and area burned benefit annual grasses that can invade areas where perennial plants are set back by intense and/or frequent fire. Annual invasive grasses are linked in a positive feedback loop with wildfire across the sagebrush steppe rangelands, meaning with more fire comes more annual grasses, and more annual grasses promotes more wildfires[5].

While many projections forecast cheatgrass range expansion in the northern latitudes and higher elevations, at lower latitudes (southern Nevada and Utah) cheatgrass is expected to contract where drier winters are projected (below 37 degrees latitude)[15] due to limited moisture and subsequent plant establishment and growth[16]. Unfortunately, the contraction of cheatgrass in its southern range may benefit another annual grass, red brome, which can tolerate drier conditions[16].

Sagebrush

Climate change is threatening sagebrush steppe habitat with different forces depending on the landscape. Across much of the sagebrush steppe, in places that are drier and typically lower in elevation, cheatgrass and other exotic annual grasses are invading and promoting frequent fires, while at higher elevations, pinyon pine and juniper are encroaching on sagebrush communities and competing for available resources. Warming trends mean that sagebrush is being pushed from warmer-lower elevation sites to cooler sites that are typically higher in elevation[17]. Sagebrush distribution is also expected to contract in the southern portion of its current range and expand its range slightly in the northern latitudes[18].

How has climate change impacted watershed and stream conditions?

While total amount of precipitation falling in a year has not changed much in the face of climate change, the timing of when that precipitation falls during the year and what form (rain instead of snow) is changing. With increasing temperatures we are experiencing less snow[1], and a reduced spring snowpack[19,20]. While these changes result in higher precipitation and soil moisture in the spring, we are experiencing decreasing summer precipitation[3].

Changing temperatures and precipitation patterns are affecting watershed-level characteristics. For example, in Idaho streams without dams, water is moving out from watersheds one to two weeks earlier than in the 1950s[22]. Across the Pacific Northwest, basins are experiencing lower annual minimum streamflow[22], affecting water available for livestock, irrigation and wildlife. Stream temperatures in the region have increased about 1.8°F in the last 20-40 years; this is particularly evident in the summer and early fall when high temperatures can significantly impact habitat for fish and amphibians[23]. Earlier spring snowmelt and peak stream flow may also change the nature and function of riparian systems[10,24], and may result in shifts in plant composition from grasses to forbs[25].

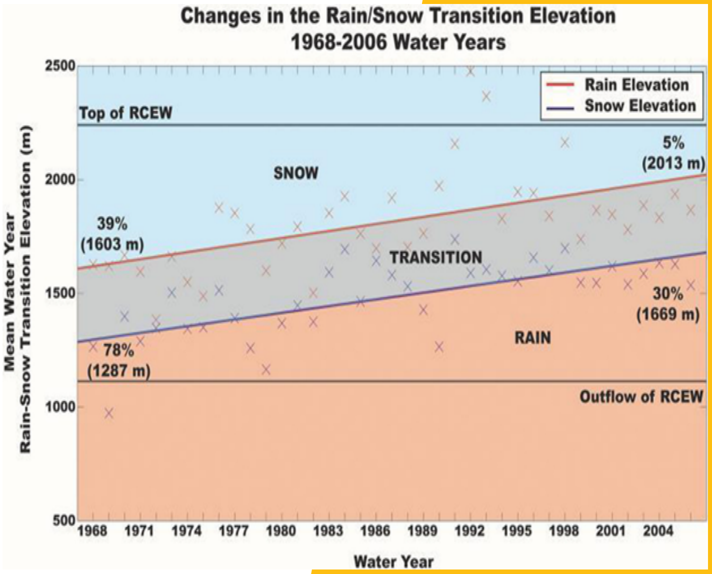


Figure 2. The impact of increasing air temperatures on rain and snow transition elevations and water resources at the Reynolds Creek Experimental Watershed (RCEW). The area dominated by winter snowpack in this watershed is shrinking (from 39% in 1968 to 5% in 2013) due to increasing temperatures causing more precipitation to fall as rain instead of snow. Also, the rain-snow transition elevation has risen by about 400 feet in the last 40 years. Used with permission from Seyfried, M. et al. Reynolds Creek Experimental Watershed and Critical Zone Observatory. Vadose Zo. J. 17, 180129 (2018).

How is climate change affecting wildland fires?

Across the Pacific Northwest, annual fire season length and area burned continue to increase[6]. In the Snake River plain and the Columbia plateau ecoregion, large fires are becoming more frequent[26]. The number, frequency, and size of wildfires is dictated by multiple variables: from climate, vegetation type, and fuel bed characteristics to natural and human ignitions[27].

Much of the increased fire frequency and area burned across the sagebrush steppe region has been attributed to annual grass invasion[28,29]. Annual grasses, such as cheatgrass, create a continuous fuel bed in places that historically had bunchgrasses and shrubs which had a more patchy and fuel limited landscape [27]. In these invaded places, the amount of accumulated litter from annual grasses, which is tied to increased precipitation in the prior year(s)[28], influences wildfire frequency and size[29].

How does climate change affect post-fire land restoration?

Rangeland systems pose difficulties for restoration post-fire because site conditions vary over space and time[30]. Selecting lands for restoration should be based on a decision framework that prioritizes lands of high conservation value which also have a high probability of responding well to treatment[27,31]. Key to this framework is the understanding of how land is resilient to disturbance and resistant to invasion by annual grasses.

When selecting restoration actions, key considerations are soil moisture, air temperature, and historical and current ecological plant communities. For example, knowing the perennial grass cover before disturbance helps managers understand the invasion risk after a disturbance because a site with less than 20% perennial grass cover is more likely to be invaded by annual grasses compared to sites with greater than 20% perennial grass cover[32].

The influence of recent weather conditions and how these conditions impact plant species and objectives in restoration work is also important. With climate change and the associated increases in year-to-year temperature and precipitation variability, as well as extreme events, it is becoming increasingly important for restoration efforts to take an iterative adaptive approach with the expectation that multiple years of action may be required[33].

While restoring native biodiversity across disturbed sites is a well-intentioned goal, the abundance of perennial grass has been shown to be more effective at preventing invasion from annual grasses than more plant diversity[14,34]. Therefore, seeding and restoration efforts focused on re-establishing dominant perennial grasses may be the most effective route to limit annual grass invasion[34]. Warmer and drier sites invaded by exotic annuals are more challenging to restore than are wetter, cooler sites[30]. For example, restoration outcomes using broadcast seeding and drill seeding in warm, dry sites often have lower success than in cooler, wetter sites[30]. New seed technologies such as seed coatings, seed pellets with multiple seeds, and genetic selection of desired traits show promise to improve restoration success[30]. Restoration success increases when the seeds used come from areas that match the climate (especially minimum temperatures) of the restoration site[35].

Given the difficulties associated with restoration in the sagebrush steppe, applying management actions that boost resilience prior to the occurrence of disturbance should also be considered. For example, wildfire suppression and prevention in targeted high-value and resilient areas is another management step that can be taken to diminish the impact of fire on this landscape[36]. Other examples include revegetation of native perennial species in degraded or cheatgrass-invaded areas[37] .

Can rangelands store carbon from the atmosphere?

There is great interest in the potential of managed rangelands to capture greenhouse gases and sequester carbon[38]. Whether rangelands capture more carbon than they emit depends on precipitation, management, soils, and site potential. The process through which rangelands sequester carbon begins with leaves in above-ground biomass capturing carbon through photosynthesis and then storing that carbon in stems, branches, and roots in the soil (Figure 3).

The amount captured varies annually based on precipitation, and it varies from site to site based on soils and site potential. Carbon is also emitted from above-ground and below-ground parts of plants through both respiration and decomposition. In years with average or above-average precipitation, western rangelands tend to capture slightly more carbon than they emit on an annual basis (i.e. a sequestration rate of around 0.55 tons of CO_2/acre/year), but in drought years this can be zero or even negative (a net emission of carbon)[39,40].

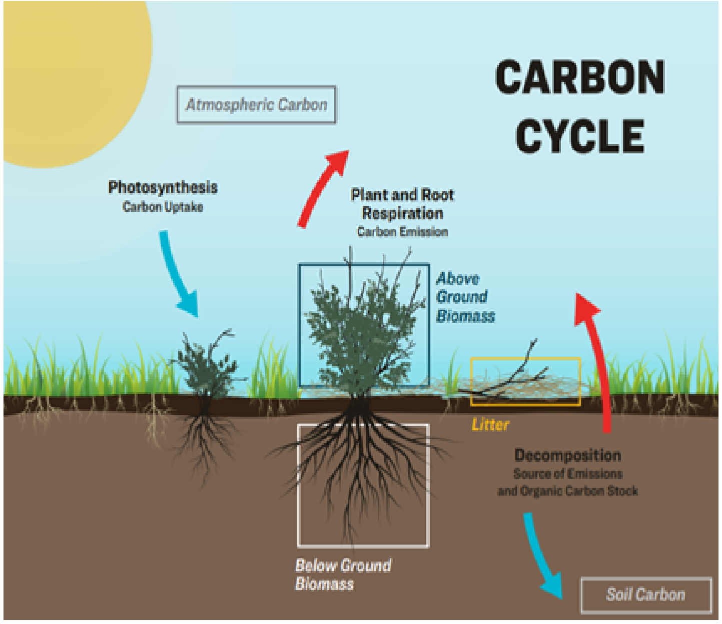


Figure 3. The carbon cycle. Blue arrows denote carbon (CO_2) being taken up by plants or stored in the soil. Red arrows denote when carbon is released through respiration or decay.

Between 80-90% of the carbon stored on rangelands is in the soil stored as organic matter and roots (about 63 tons of CO_2/acre), with lesser amounts of carbon in living and dead plant materials above the ground (<1 ton of CO_2/acre)[40,41]. Most of this carbon is stable over long periods of time (barring disturbances such as tilling), leaving only a small portion likely to increase or decrease through changes in precipitation or management[42].

Improving soil health and forage production of degraded rangelands can increase their ability to sequester more carbon[38]. For example, rangelands that transition to cheatgrass may store less soil carbon than healthy sage steppe ecosystems[41]. Furthermore, cheatgrass-dominated rangelands are likely to experience more frequent wildfires which can reduce the amount of soil carbon even more by depleting above-ground biomass and litter[43,44].

What we do know is that some of the largest sequestration potentials occur through converting cropland and degraded rangeland back to productive rangeland[38,45]. It is also important to minimize the conversion of intact rangeland to other land uses such as cropland, housing, industry, and energy production. This retains large amounts of carbon in the ground which would otherwise be released into the atmosphere[42]. Converting healthy rangelands to another use can result in losses of over 50% of the carbon stored in the soils[42].

Whether grazing increases carbon sequestration rates and thus total carbon storage in rangelands is uncertain[46], due largely to differences in climate, soil, vegetation, grazing management approaches, and the methods used to assess soil carbon[45,47]. Several studies show a slight increase, but others show a slight decrease, and still others show no difference between grazed and ungrazed sites[42]. Hampering our understanding is the lack of studies in sagebrush steppe ecosystems that address how grazing and how different grazing methods affect soil organic matter. The few that are available show little difference between soil carbon amounts in grazed (with low stocking rates) compared to un-grazed areas[46]. There is also a need to understand the co-benefits of grazing livestock, as targeted grazing to reduce herbaceous fuels which could otherwise be consumed in a wildfire is becoming a more common practice.

What are future projections of temperature and precipitation across the Pacific Northwest?

The Pacific Northwest climate is projected to become warmer and drier during summer with reduced snowpack in winter. Warming is projected to increase by 3 to 11º F (1.8 to 6.1º C) with summer experiencing the largest increases by the end of the century[48]. Extreme heat events, days when the temperature is over 100º F, are projected to increase, while cold extremes will decrease[49].

Projections of annual precipitation over time vary between climate models and are associated with significant uncertainties. The strongest consistency in precipitation models is that summer precipitation is projected to decrease as much as 30% by 2100[48]. Winter precipitation is expected to increase slightly when averaging over multiple climate models[48], and the variability and extremity of precipitation events is also likely to increase[50].

These projected changes in temperature and precipitation are expected to affect growing conditions. The frost-free period and growing-degree days are expected to increase[51]. Warming is expected to decrease soil water availability, most pronounced during late summer, and induce earlier snow melt and reduced stream flow[22]. A reduction in stream base flows in summer, due to decreases in snowpack, earlier melting, as well as a reduction in summer precipitation, will impact riparian systems and the ability to store water above ground in shallow aquifers[52].

For More Information:

- Climate change and vegetation resources

Climate: Variability and Change in the Past and Future. In: Change in the Northwest: Implications for Our Landscapes, Waters, and Communities. (Island Press, 2013). Mote, P. W., Abatzoglou, J. T. & Kunkel, K. E.

Climate Change and North American Rangelands: Trends, Projections, and Implications. Polley, H. W. et al. Rangel. Ecol. Manag. 66, 493–511 (2013).

Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. Bradley, B. A. Glob. Chang. Biol. 15, 196–208 (2009).

The response of big sagebrush (*Artemisia tridentata*) to interannual climate variation changes across its range. Kleinhesselink, A. R. & Adler, P. B. Ecology 99, 1139–1149 (2018).

Declining annual streamflow distributions in the Pacific Northwest United States. Luce, C. H. & Holden, Z. a., 1948-2006. Geophys. Res. Lett. 36, 2–7 (2009).

Wildfire, climate, and invasive grass interactions negatively impact an indicator species by reshaping sagebrush ecosystems. Coates, P. S. et al. Proc. Natl. Acad. Sci. 113, 12745–12750 (2016).

Funding provided by: USDA Northwest Climate Hub Northwest Climate Hub Grant (FS agreement number 17-JV-11261944-073)

Written by Vincent Jansen and Eric Winford. Edited by Lindsay Lodis, Karen Launchbaugh, and Joan Jones. We thank our stakeholder advisory committee for providing the questions and for insightful feedback.

The Rangeland Center is bridging the gap between science and land management by engaging stakeholders to develop solution-based research that has valuable and real-world implications for Idaho rangelands. Learn more at www.uidaho.edu/range.

University of Idaho
Rangeland Center

For More Information:

- Restoration resources

A Field Guide for Selecting the Most Appropriate Treatment in Sagebrush and Piñon-Juniper Ecosystems in the Great Basin. https://www.fs.fed.us/rm/pubs/rmrs_gtr322.pdf

Restoration Handbook for Sagebrush Steppe Ecosystems with Emphasis on Greater Sage-Grouse Habitat— Part 1, 2, 3. Site Level Restoration Decisions. https://pubs.er.usgs.gov/publication/cir1416,
https://pubs.er.usgs.gov/publication/cir1418,
https://pubs.usgs.gov/circ/1426/cir1426.pdf

Operationalizing resilience and resistance concepts to address invasive grass-fire cycles https://www.fs.fed.us/rm/pubs_journals/2019/rmrs_2019_chambers_j001.pdf

- Rangelands and carbon resources

Sanderson, J. S. et al. Cattle, conservation, and carbon in the western Great Plains. J. Soil Water Conserv. 75, 5–12 (2020).

Carbon fluxes on North American rangelands. Svejcar, T. et al. Rangel. Ecol. Manag. 61, 465–474 (2008).

- Webpages, maps and tools

Northwest Climate Hub:
https://www.climatehubs.usda.gov/hubs/northwest

US Drought Monitor: Current Drought Map:
https://www.climatehubs.usda.gov/index.php/hubs/northwest/drought-map

http://climateconsole.org/sagebrush

https://climatetoolbox.org/

http://climateengine.org/

https://www.usgs.gov/media/videos/sagebrush-ecosystems-a-changing-climate-and-adaptive-management

Literature Cited

To find more information on specific research, you can match the number behind the sentence to the list below. To find the original research document,use Google Scholar to search the title of the work, click “All versions” to find an open access version.

1.Chambers, J. C. & Pellant, M. Climate Change Impacts on Northwestern and Intermountain United States Rangelands. Rangelands 30, 29–33 (2008).
2.Safeeq, M. et al. Influence of winter season climate variability on snow–precipitation ratio in the western United States. Int. J. Climatol. 36, 3175–3190 (2016).
3.Abatzoglou, J. T., Rupp, D. E. & Mote, P. W. Seasonal Climate Variability and Change in the Pacific Northwest of the United States. Am. Meteorolgical Soc. 27, 2125–2143 (2014).
4.Dai, A. Increasing drought under global warming in observations and models. Nat. Clim. Chang. 3, 52–58 (2013).
5.Snyder, K. A. et al. Effects of Changing Climate on the Hydrological Cycle in Cold Desert Ecosystems of the Great Basin and Columbia Plateau. Rangel. Ecol. Manag. 72, 1–12 (2019).
6.Klos, Z., J .Abatzoglou, J. Blades, M. Clark, M. Dodd, T. Hall, A. Haruch, P. Higuera, J. Holbrook, V. Jansen, K. Kemp, A. Lamar, A. Lankford, T. Link, T. Magney, A. Meddens, L. Mitchell, B. Moore, P. Morgan, B. Newingham, R. Niemeyer, B. Soderquist, A. S, C. W. Indicators of Climate Change in Idaho : An Assessment Framework for Coupling Biophysical Change and Social Perception. Weather Clim. Soc. 7, 238–254 (2015).
7. Reeves, M. C., Bagne, K. E. & Tanaka, J. Potential Climate Change Impacts on Four Biophysical Indicators of Cattle Production from Western US Rangelands. Rangel. Ecol. Manag. 70, 529–539 (2017).
8. Hufkens, K. et al. Productivity of North American grasslands is increased under future climate scenarios despite rising aridity. Nat. Clim. Chang. 6, 710–714 (2016).
9. Reeves, M. C., Moreno, A. L., Bagne, K. E. & Running, S. W. Estimating climate change effects on net primary production of rangelands in the United States. Clim. Chang. 429–442 (2014). doi:10.1007/s10584-014-1235-8
10. Polley, H. W. et al. Climate Change and North American Rangelands: Trends, Projections, and Implications. Rangel. Ecol. Manag. 66, 493–511 (2013).
11. Polley, H. W., Bailey, D. W., Nowak, R. S., & Stafford-Smith, M. (2017). Ecological consequences of climate change on rangelands. In Briske, D. D (Ed.), Rangeland systems: Processes, management and challenges (pp. 229–260). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-46709-2
12. Neibergs, J. S., Hudson, T. D., Kruger, C. E. & Hamel-Rieken, K. Estimating climate change effects on grazing management and beef cattle production in the Pacific Northwest. Clim. Change 146, 5–17 (2018).
13. Bradley, B. A. Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. Glob. Chang. Biol. 15, 196–208 (2009). 181, 543–557 (2016).
14. Bansal, S. & Sheley, R. L. Annual grass invasion in sagebrush steppe: the relative importance of climate, soil properties and biotic interactions. Oecologia 181, 543–557 (2016).

15. Abatzoglou, J. T. & Kolden, C. a. Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. Rangel. Ecol. Manag. 64, 471–478 (2011).
16. Bradley, B. A., Curtis, C. A. & Chambers, J. C. Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US. in Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US 257–274 (2016). doi:10.1007/978-3-319-24930-8
17. Kleinhesselink, A. R. & Adler, P. B. The response of big sagebrush (*Artemisia tridentata*) to interannual climate variation changes across its range. Ecology 99, 1139–1149 (2018).
18. Still, S. M. & Richardson, B. A. Projections of Contemporary and Future Climate Niche for Wyoming Big Sagebrush (*Artemisia tridentata subsp. wyomingensis)*: A Guide for Restoration . Nat. Areas J. 35, 30–43 (2015).
19. Holden, Z. A. et al. Decreasing fire season precipitation increased recent western US forest wildfire activity. Proc. Natl. Acad. Sci. 115, E8349–E8357 (2018).
20. Mote, P. W., Li, S., Lettenmaier, D. P., Xiao, M. & Engel, R. Dramatic declines in snowpack in the western US. npj Clim. Atmos. Sci. 1, (2018).
21. Seyfried, M. et al. Reynolds Creek Experimental Watershed and Critical Zone Observatory. Vadose Zo. J. 17, 180129 (2018).
22. Luce, C. H. & Holden, Z. a. Declining annual streamflow distributions in the Pacific Northwest United States, 1948-2006. Geophys. Res. Lett. 36, 2–7 (2009).
23. Isaak, D. J. et al. Global Warming of Salmon and Trout Rivers in the Northwestern U.S.: Road to Ruin or Path Through Purgatory? Trans. Am. Fish. Soc. 147, 566–587 (2018).
24. Carroll, R. W. H. et al. Evaluating mountain meadow groundwater response to Pinyon-Juniper and temperature in a great basin watershed. Ecohydrology 10, 1–18 (2017).
25. Browning, D. M., Snyder, K. A. & Herrick, J. E. Plant Phenology: Taking the Pulse of Rangelands. Rangelands 41, 129–134 (2019).
26. Dennison, P. E., Brewer, S. D., Arnold, J. D. & Moritz, M. A. Large wildfire trends in the western United States, 1984–2011. Geophys. Res. Lett. 41, 2928–2933 (2014).
27. Chambers, J. C. et al. Operationalizing Resilience and Resistance Concepts to Address Invasive Grass-Fire Cycles. Front. Ecol. Evol. 7, (2019).
28. Pilliod, D. S., Welty, J. L. & Arkle, R. S. Refining the cheatgrass – fire cycle in the Great Basin : Precipitation timing and fine fuel composition predict wildfire trends. 8126–8151 (2017). doi:10.1002/ece3.3414
29. Balch, J. K. ., Bradley, B. A., D'Antonio, Carla, M. & Gomez-Dans, J. Introduced annual grass increases regional fire activity across the arid western USA (1980 – 2009). Glob. Chang. Biol. 19, 173–183 (2013).
30. Svejcar, T., Boyd, C., Davies, K., Hamerlynck, E. & Svejcar, L. Challenges and limitations to native species restoration in the Great Basin, USA. Plant Ecol. 218, 81–94 (2017).
31. Pyke, D. A. et al. Restoration Handbook for Sagebrush Steppe Ecosystems with Emphasis on Greater Sage-Grouse Habitat— Part 1. Concepts for Understanding and Applying Restoration U.S. Geological Survey Circular 1416. Circ. 1426, USGS, Dep. Inter. 44 (2015).
32. Chambers, J. C. et al. Resilience and Resistance of Sagebrush Ecosystems: Implications for State and Transition Models and Management Treatments. Rangel. Ecol. Manag. 67, 440–454 (2014).
33 Hardegree, S. P. et al. Weather-Centric Rangeland Revegetation Planning. Rangel. Ecol. Manag. 71, 1–11 (2018).
34. Davies, K. W., Johnson, D. D. & Nafus, A. M. Restoration of Exotic Annual Grass-Invaded Rangelands: Importance of Seed Mix Composition. Invasive Plant Sci. Manag. 7, 247–256 (2014).
35. Germino, M. J., Moser, A. M. & Sands, A. R. Adaptive variation, including local adaptation, requires decades to become evident in common gardens. Ecol. Appl. 29, 1–7 (2019).
36. Coates, P. S. et al. Wildfire, climate, and invasive grass interactions negatively impact an indicator species by reshaping sagebrush ecosystems. Proc. Natl. Acad. Sci. 113, 12745–12750 (2016).
37. Chambers, J. C. et al. Resilience to stress and disturbance, and resistance to *Bromus tectorum* L. invasion in cold desert shrublands of western North America. Ecosystems 17, 360–375 (2014).
38. Henderson, B. B. et al. Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. Agric. Ecosyst. Environ. 207, 91–100 (2015).
39. Svejcar, T. et al. Carbon fluxes on North American rangelands. Rangel. Ecol. Manag. 61, 465–474 (2008).
40. Zhu, Z. [editor] & Reed, B. C. [editor]. USGS Professional Paper 192: Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of the Western United States. U. S. Geol. Surv. Prof. Pap. 192 (2012). doi:10.3133/pp1804
41. Rau, B. M. et al. Transition from sagebrush steppe to annual grass (*Bromus tectorum)*: Influence on belowground carbon and nitrogen. Rangel. Ecol. Manag. 64, 139–147 (2011).
42. Sanderson, J. S. et al. Cattle, conservation, and carbon in the western Great Plains. J. Soil Water Conserv. 75, 5–12 (2020).
43. Lal, R. Soil carbon management and climate change. Carbon Manag. 4, 439–462 (2013).
44. Davies, K. W., Vavra, M., Schultz, B. & Rimbey, N. Implications of Longer Term Rest from Grazing in the Sagebrush Steppe. J. Ragel. Appl. 1, 1–8 (2014).
45. Conant, R. T., Paustian, K. & Elliot, E. Grassland management and conversion into grassland- effects on Soil Carbon. Ecol. Appl. 11, 343–355 (2001).
46. Shrestha, G. & Stahl, P. D. Carbon accumulation and storage in semi-arid sagebrush steppe: Effects of long-term grazing exclusion. Agric. Ecosyst. Environ. 125, 173–181 (2008).
47. Derner, J. D., Augustine, D. J. & Frank, D. A. Does Grazing Matter for Soil Organic Carbon Sequestration in the Western North American Great Plains? Ecosystems (2018). doi:10.1007/s10021-018-0324-3
48. Mote, P. W. & Salathe, E. P. Future climate in the Pacific Northwest. Clim. Chang. 102, 29–50 (2010).
49. Mote, P. W., Abatzoglou, J. T. & Kunkel, K. E. Climate: Variability and Change in the Past and Future. In: Change in the Northwest: Implications for Our Landscapes, Waters, and Communities. (Island Press, 2013).
50. Pendergrass, A. G., Knutti, R., Lehner, F., Deser, C. & Sanderson, B. M. Precipitation variability increases in a warmer climate. Sci. Rep. 7, 1–9 (2017).
51. Kunkel, K. E. et al. Regional climate trends and scenarios for the U.S. National Climate Assessment. Part 6. Climate of the Northwest U.S. NOAA technical report (2013).
52. Luce, C. H. Effects of Climate Change on Snowpack, Glaciers, and Water Resources in the Northern Rockies. Adv. Glob. Chang. Res. 63, 25–36 (2018).