doi:10.2489/jswc.74.4.405

Climate change impacts on wind and water erosion on US rangelands

B.L. Edwards, N.P. Webb, D.P. Brown, E. Elias, D.E. Peck, F.B. Pierson, C.J. Williams, and J.E. Herrick

Abstract: Soil erosion by water and wind in US rangelands has serious implications for rangeland health and food security and poses significant hazards to human health and communities. Accordingly, understanding how future climate change may impact soil erosion is critical for developing appropriate management strategies that mitigate negative impacts to the extent practical and potentially build resilience. Here, we review potential impacts of climate change on controls of erosion in US rangelands and discuss potential erosion responses. Projected climate changes are expected to have regionally variable effects on important controls of erosion, especially vegetation cover; community composition; frequency, magnitude, and geographical range of fire disturbance; and high intensity, erosive weather events, all of which have the potential to increase rangeland vulnerability to erosion. We identify knowledge gaps relevant to these controls and discuss management considerations to address climate change impacts to soil erosion concerns for US rangelands. In order to improve resilience and the efficacy of climate change adaptation, we recommend that existing monitoring data be used to create assessments of vulnerability, that soil erosion should be explicitly included in management benchmarks and decision support tools, and that no-regrets management options be implemented in anticipation of future impacts.

Key words: climate change—rangeland—soil erosion—water erosion—wind erosion

Understanding the potential impacts of projected climate change on soil erosion in US rangelands is critical for developing forward-looking, sustainable land management practices for these high-value ecosystems. Rangelands cover approximately ~31% of total US land area (Havstad et al. 2009)—about 60% of western states (figure 1)—and provide a critical resource for food production in addition to other high-value ecosystem services (Mitchell 2000). Criteria for delineating rangelands vary depending on source (Lund 2007; Reeves and Mitchell 2011), but in general they can be defined as arid and semiarid systems with low primary production because of highly variable precipitation (Havstad et al. 2009; Briske et al. 2015). Rangelands are largely vegetated by grasses, forbs, and shrubs, but include diverse subenvironments distributed over the western United States, each with unique ecologies and management concerns (figure 1). Because they exist near physiological thresholds, rangelands are highly sensitive to climatic stressors; consequently, rangelands and the communities and industries they support are particularly vulnerable to climate change (Archer and Predick 2008).

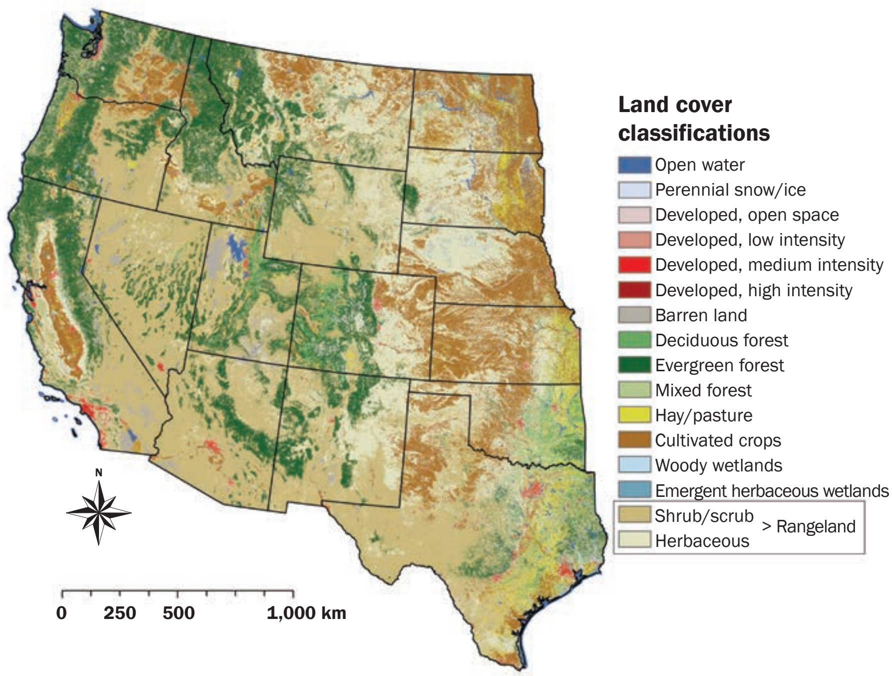
Predicting how rangelands will respond to climate change is difficult because of often large uncertainties in climate projections (Wuebbles et al. 2017), spatial variability in responses across vegetation communities and soil types (Webb et al. 2012; Briske et al. 2015), and ecogeomorphic feedbacks that may produce threshold-type responses (Archer and Predick 2008; Okin et al. 2018). Still, projected climate trends provide a useful framework for identifying potential impacts and highlighting knowledge gaps, research foci, and management considerations. Several reviews have discussed critical impacts of climate change on rangelands, including assessments for plant community responses (McKeon et al. 2009; Webb et al. 2012; Polley et al. 2013; Briske et al. 2015), ecosystem services (Palmquist et al. 2016; Boone et al. 2018), and livestock production systems (Howden et al. 2008; McKeon et al. 2009), as well as socioeconomic impacts and adaptation strategies (Thornton et al. 2009; Joyce et al. 2013; Webb et al. 2013). Fewer papers, however, (Nearing et al. 2005; Munson et al. 2011; Zhang et al. 2012; Pu and Ginoux 2017) have focused specifically on how climate change will impact key geomorphic processes such as soil erosion, and these are largely regional- or process-specific.

A significant portion of US rangelands are already vulnerable to soil erosion (Weltz et al. 2014). Soil erosion by water and wind is an important agent of land degradation that impacts nutrient availability, forage production and food security, and poses serious hazards to human health and communities. Conceptually, soil erosion on rangelands can be framed as a climate- and land management-driven balance between (1) largely biotic controls that resist sediment detachment and transport, e.g., vegetation, ground cover, and soil organic matter; and (2) abiotic processes that drive erosion, e.g., rainfall, overland flow, wind, and disturbance (Pierson et al. 2011; Turnbull et al. 2012; Williams et al. 2014b, 2016b). Rangelands are often sparsely vegetated, and the amount, type, and distribution of vegetation and ground cover strongly control infiltration, soil retention, and exposure of soils to potentially erosive rainfall and winds (Okin et al. 2006, 2018; Webb et al. 2014; Pierson and Williams 2016). Runoff, waterborne soil loss, and wind-driven sediment transport are typically low on well-vegetated sites. Cover reductions associated with land use- and/or climate-driven disturbances commonly result in amplified runoff and water erosion and greatly increase potential for aeolian transport and dust emission (Turnbull et al.

Brandon L. Edwards is a research assistant professor and **Nicholas P. Webb** is a research associate professor at the Jornada Experimental Range, New Mexico State University, Las Cruces, New Mexico. **David P. Brown** is director of the USDA Southern Plains Climate Hub in El Reno, Oklahoma. **Emile H. Elias** is director of the USDA Southwest Climate Hub in Las Cruces, New Mexico. **Dannele E. Peck** is director of the USDA Northern Plains Climate Hub in Fort Collins, Colorado. **Frederick B. Pierson** is research leader at the USDA Agricultural Research Service (ARS) Northwest Watershed Research Center in Boise, Idaho. **C. Jason Williams** is a research hydrologist at the USDA ARS Southwest Watershed Research Center in Tucson, Arizona. **Jeffrey E. Herrick** is a research soil scientist at the USDA ARS Jornada Experimental Range, Las Cruces, New Mexico.

Figure 1

Land cover classifications of the western United States based on the National Land Cover Database (2011). Rangeland, represented here as shrub/scrub and herbaceous land cover, represents 55.22% of the total land area of the western contiguous United States. Source: Homer et al. (2015).



2008; Pierson et al. 2011; Field et al. 2012; Turnbull et al. 2012; Williams et al. 2014b; Okin et al. 2018; Webb and Pierre 2018). In addition, disturbances such as wildfire and infrastructure development (e.g., for oil and gas extraction) can increase risks of runoff, flooding, and water and wind erosion events during recovery periods, which can be prolonged by drought (Sankey et al. 2009; Wagenbrenner et al. 2013; Miller et al. 2012; Pierson and Williams 2016). Further, plant community transitions that increase fire activity pose an even greater risk for long-term soil loss through frequent repeated burning (Pierson et al. 2011; Wilcox et al. 2012; Williams et al. 2014b, 2016c).

Predicting climate change impacts on rangeland soil erosion and identifying appropriate management strategies requires understanding the effects of climate on both resisting and driving controls. This paper provides a broad overview of the potential impacts of climate change on these controls for US rangelands. We then highlight potential water and wind erosion responses and identify key knowledge gaps regarding climate change-driven increases in erosion. Finally, we discuss current and future management considerations.

Climatic Setting and Observed and Projected Climate Changes

US rangelands include portions of the Great Plains, Intermountain West, Great Basin, and Desert Southwest. These regions are most commonly characterized by arid to semiarid climates, but precipitation and temperature vary across season, elevation, and geography. Climatic variations and extremes are common in these areas and can include multiyear droughts, large wildfires, floods, convective storms, and the passage of frontal systems that produce regional dust storms (Brazel and Nickling 1986; Herring et al. 2018).

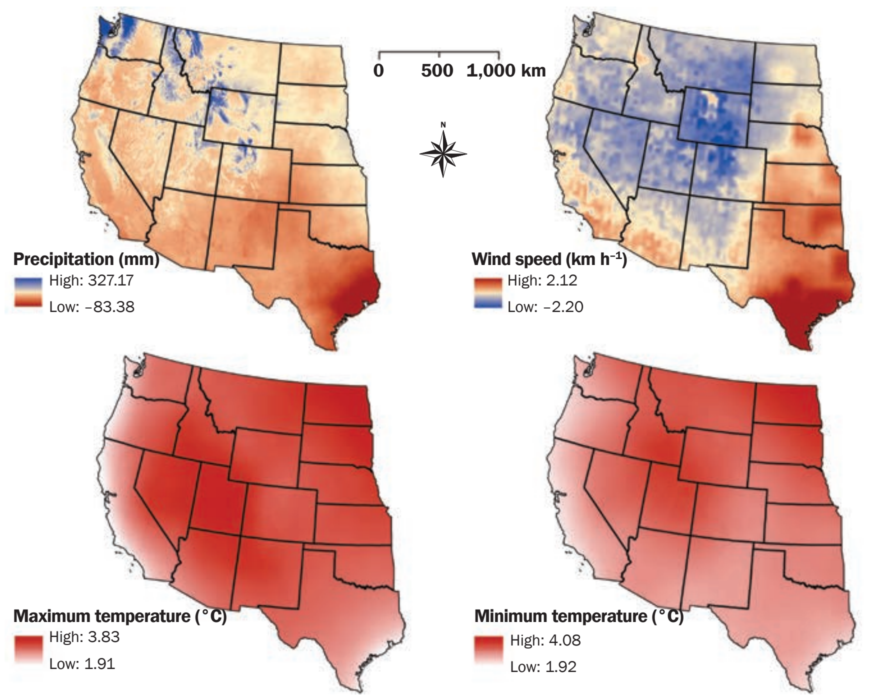
There is very high confidence that temperatures across most US rangelands have been warming over the past century, a trend that has intensified in recent decades (Vose et al. 2017). (Wuebbles et al. [2017] define "very high confidence" as strong evidence and high consensus among projections. "High confidence" is defined as having moderate evidence and medium consensus. "Medium confidence" is defined as having suggestive evidence but competing schools of thought. "Low confidence" is defined as having inconclusive evidence and disagreement among experts.) Indeed, some of the most pronounced increases in both winter and summer temperatures over the past 30 years have occurred over the western half of the country (Vose et al. 2017). A lengthening of the frost-free season by 7 to 17 d y^{-1} has also been observed (Hibbard et al. 2017). Output from the Coupled Model Intercomparison Project (CMIP5) suggests that mean temperatures across the West could increase by ~3.3°C (6°F) by the mid-21st century, and ~5°C (9°F) by late-21st century (figure 2) under the Representative Concentration Pathway 8.5 (RCP8.5) (Vose et al. 2017), which is consistent with observed increases in global carbon (C) emissions over the past 15 to 20 years (very high confidence) (Wuebbles et al. 2017). Under this scenario, widespread increases in temperature are projected across all seasons, especially summer and fall (figures 2 and 3). Such increases could affect soil erosion processes through impacts on evaporative stress and soil moisture deficit (medium confidence), growing season length (low confidence), and plant community structure (high confidence) (Blumenthal et al. 2016; Hibbard et al. 2017; Wehner et al. 2017).

Observed changes in annual precipitation have been more varied across US rangelands, with drying in much of the Southwest and Intermountain West and wetter conditions across much of the Great Plains (medium confidence) (Easterling et al. 2017). Patterns are even more heterogeneous at seasonal time scales, with drying in the Southwest observed during spring and summer and drying in the Northwest and Intermountain West observed during winter (see Easterling et al. [2017] for detailed maps). It should be noted that projections for annual precipitation by the mid-21st century under RCP8.5 are more uncertain than those for temperature but suggest significant drying in the Southern Plains and Southwest and slight increases in precipitation over portions of the Northern Plains and Northwest (figure 2) (Greene and Seager 2016). Midcentury projections under RCP8.5 for seasonal precipitation suggest that much of the Southwest will have drier winters and springs but wetter summers; much of the Southern Plains will have drier springs and summers with drying across all seasons in southeast Texas; the Northern Plains will have wetter springs and drier summers; and the Northwest, while more spatially variable than other regions, will have generally wetter winters with some drying in fall and spring (figure 3) (Swain and Hayhoe 2015). Other observed trends that are projected to continue through midcentury include increased frequency and intensity of heavy rainfall events (figure 4; high confidence) and a higher proportion of precipitation falling as rain instead of snow (high confidence) (Easterling et al. 2017). Climate change is also thought to be affecting the frequency, intensity, and location of extreme events that may impact erosion, such as large fires (medium confidence), severe thunderstorms (low confidence), and severe winter storms (low confidence) (Kossin et al. 2017; Wehner et al. 2017).

Surface wind speeds, beyond those during severe thunderstorms, were not addressed in detail by Wuebbles et al. (2017). However, Vautard et al. (2010) report that surface winds have declined across the northern midlatitudes over the past 30 years, a "stilling" of 10% in the United States. Large-scale circulations explain a portion of these changes, but so too may increased surface roughness due to land use change and land cover change (Vautard et al. 2010; Cowie et al. 2013). Patterns of seasonal wind speed projections for the midcentury are consistent with these evaluations (figure 3). Much uncertainty remains, however, about the complex physical connections between climate change, wind speed, and other extreme weather events (Seneviratne et al. 2012). What is certain is that wind and water erosion responses to climate change will be variable across US rangelands. Figure 4 summarizes key observed and midcentury climate change projections that may be particularly impactful for future trends in erosion.

Figure 2

Projected change in midcentury (2040 to 2069) mean annual maximum and minimum temperature, precipitation, and wind speed as compared with historical (1971 to 2000) simulated daily data. Projections are based on the multimodel mean of 20 Coupled Model Intercomparison Project 5 (CMIP5) models with representative concentration pathway (RCP) 8.5 downscaled using the multivariate adaptive constructed analogs (MACA) statistical method. Sources: Abatzoglou and Brown (2012) and Taylor et al. (2012).



Potential Impacts of Climate Change on Controls of Erosion

The potential for climate change to impact soil erosion from rangelands depends on its broad-scale effects on resisting and driving controls that define site susceptibility and vulnerability to erosion. At the site level, surface conditions that comprise resisting controls dictate susceptibility of the ground surface to erosion. Overall vulnerability to erosion is a function of surface susceptibility and exposure to driving forces, i.e., wind and water erosivity (figure 5) (Pierson et al. 2011; Williams et al. 2014b, 2016b).

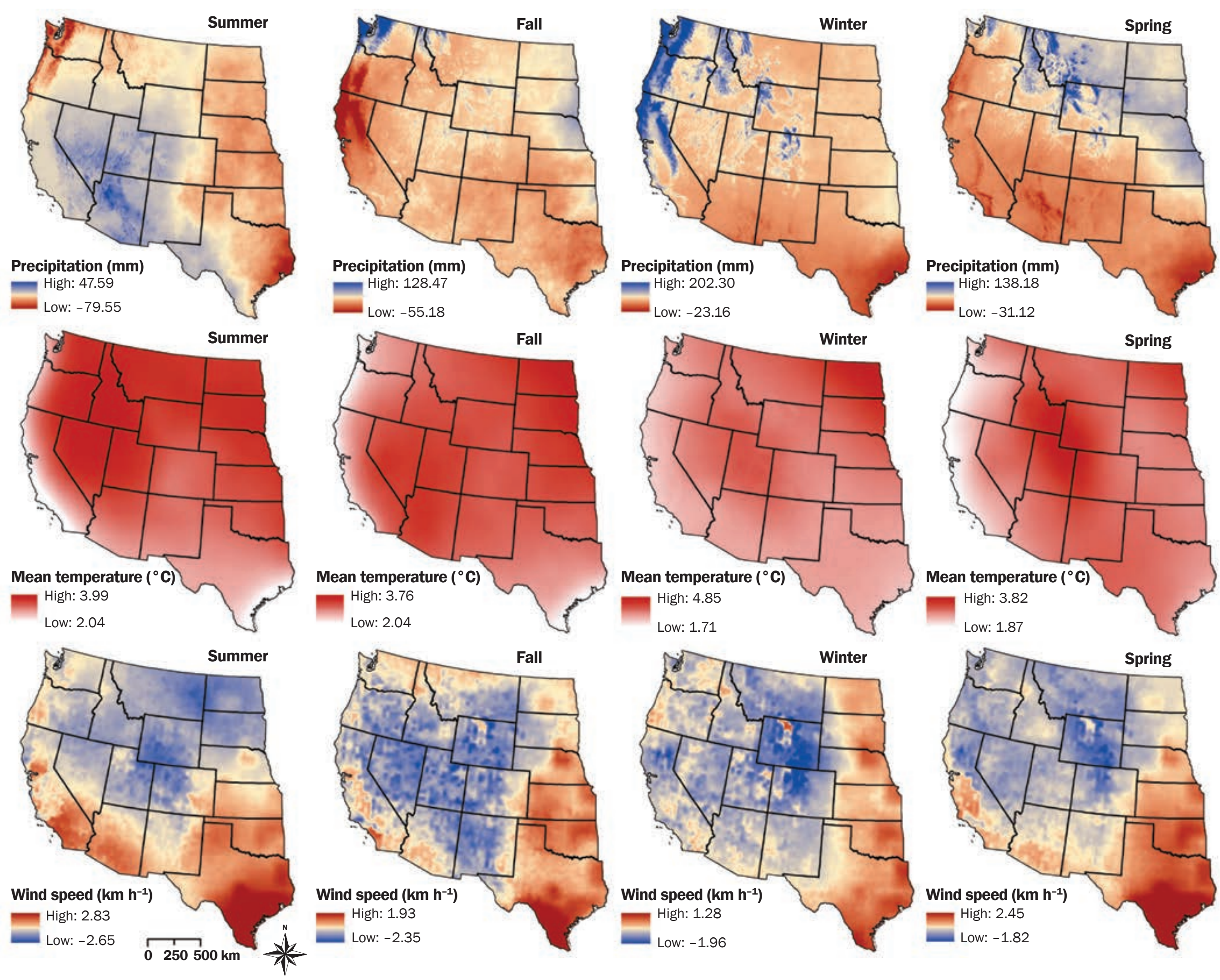
Surface susceptibility is defined by the amount, type, and distribution of vegetation and ground cover (biotic structure), inherent soil properties (e.g., bulk density, erodibility, texture, and water repellency), surface roughness (e.g., vegetation height and spacing), and topography/slope steepness (Wolfe and Nickling 1993; Webb and Strong 2011; Williams et al. 2014b). Spatial heterogeneity in surface susceptibility and precipitation across a site create heterogeneous infiltration, runoff, and water erosion patterns that dictate losses or retention of water and sediment resources (Wilcox et al. 2003; Ludwig et al. 2005; Puigdefábregas 2005; Pierson and Williams 2016). Sparsely vegetated or bare soil locations (source areas) exhibit high evaporative losses and low soil water storage (Huxman et al. 2005; Newman et al. 2010), promote runoff (Pierson et al. 2010; Turnbull et al. 2010; Williams et al. 2014b), and facilitate transfer of water and soil resources to areas with ample surface protection (sink areas) (Reid et al. 1999; Wilcox et al. 2003; Ludwig et al. 2005; Field et al. 2012; Pierson and Williams 2016). Vegetation, litter, and ground cover dampen the erosive energy of rainfall and overland flow and delay and reduce runoff and erosion by trapping water input, stabilizing sediment, and promoting infiltration (Webb et al. 2014; Pierson and Williams 2016). These same factors reduce wind erosion by sheltering soil from the wind and attenuating shear stress imparted to the surface by the wind field (Wolfe and Nickling 1993). However, while fractional cover of vegetation, rocks, and litter is of primary importance to susceptibility to water erosion, wind erosion is a lateral process. Thus, lateral cover of plants (and other nonerodible elements), their structure, height, and spatial distribution on the landscape control surface aerodynamics (Chappell et al. 2018).

Accumulation of soil water and nutrients in sink areas stimulates belowground biological activity, plant growth, and reproduction that further sustain the vegetative community and the overall source-sink structure (Schlesinger et al. 1990, 1996; Ludwig et al. 1997; Wilcox et al. 2003; Belnap et al. 2005; Ludwig et al. 2005; Turnbull et al. 2012). Water and wind-driven sediment transport may also be complementary, with water-driven transport of soil and nutrients into eroded intercanopy gaps increasing the availability of sediment and nutrients for entrainment and transport by wind (Bullard and McTainsh 2003; Okin et al. 2006).

Journal of Soil and Water Conservation 74(4):405-418 www.swcs.org

Figure 3

Projected seasonal change in midcentury (2040 to 2069) temperature, precipitation, and wind speed as compared with historical (1950 to 2005) simulated daily data. Projections are based on the multimodel mean of 20 Coupled Model Intercomparison Project 5 (CMIP5) models representative concentration pathway 8.5 downscaled using the multivariate adaptive constructed analogs (MACA) statistical method. Sources: Abatzoglou and Brown (2012) and Taylor et al. (2012).



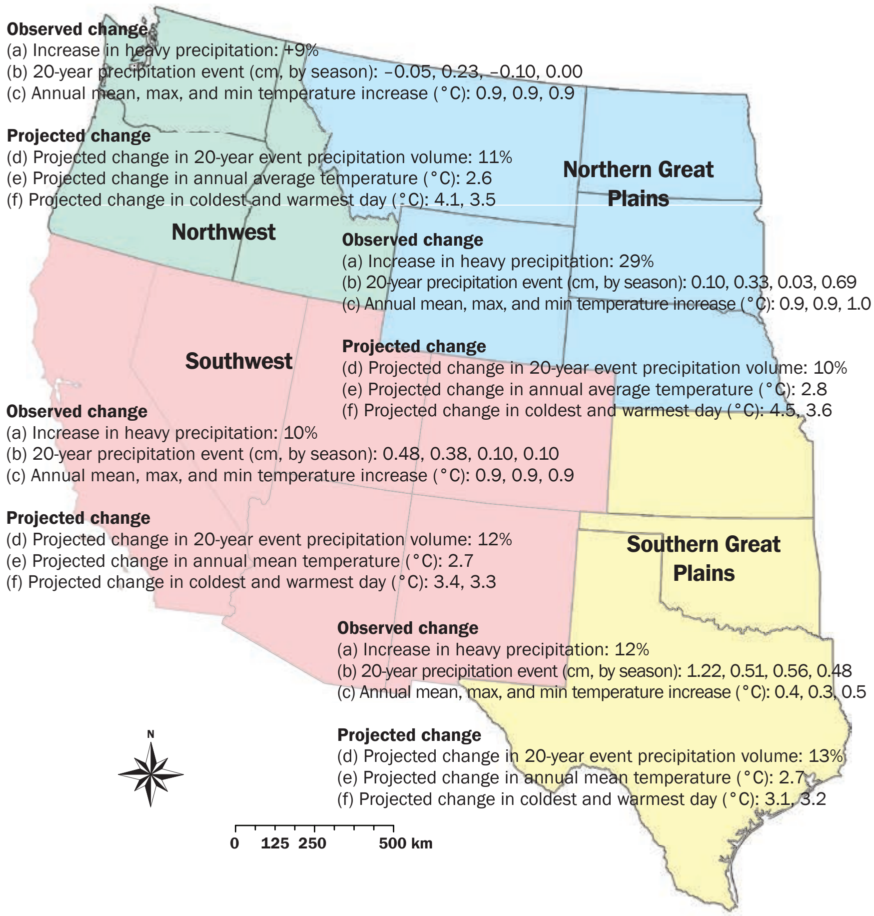
On well-vegetated and stable hillslopes, a feedback exists where vegetation and ground cover trap water and soil resources and promote soil properties that facilitate infiltration. Soil resource accumulation stimulates biological productivity that further sustains vegetation and ground cover, low surface susceptibility, and long-term ecological resilience. In the absence of disturbance, vulnerability to erosion and overall ecological resilience are therefore a function of the key characteristics that define an ecological site: (1) climate, (2) soil attributes, (3) plant community dynamics, and (4) landscape position (Williams et al. 2016b; Galloza et al. 2018). Alteration of vegetation structure through plant community shifts, fire, or other disturbances can increase the susceptibility of the ground surface to runoff and sediment transport, particularly under intense rainfall or wind events (figure 5) (Davenport et al. 1998; Turnbull et al. 2008; Bergametti and Gillette 2010; Pierson et al. 2011; Wilcox et al. 2012; Webb et al. 2014; Williams et al. 2014b, 2014a).

Whether climate change will have broad-scale negative impacts on soil erosion in US rangelands depends on (1) the degree to which it regionally alters controls of erosion that increase site susceptibility through altered disturbance regimes and plant community dynamics, and (2) how much it increases overall vulnerability by altering trends in both surface susceptibility and driving forces, such as the amount, timing, and erosive energy of precipitation and wind. The following sections summarize the potential impacts of climate change on the dominant controls of erosion in rangelands.

Vegetation Response to Projected Climate Change. Projected changes in atmospheric carbon dioxide (CO_2) concentration, temperature, and precipitation will likely have significant impacts on vegetation production, cover, and community structure in US rangelands (Polley et al. 2013; Briske et al. 2015). Rangeland net primary production depends primarily on amount and timing of precip-

Figure 4

Regional observed and projected changes in temperature and precipitation. (a) Observed change in heavy precipitation (amount of precipitation that exceeds 99th percentile; 1958 to 2016). (b) Observed change in the daily 20-year precipitation event (cm; seasonal maximum precipitation totals: 1948 to 2015). (c) Observed regional increase in annual mean temperature, 1986 to 2016 to 1901 to 1960. (d) Projected percentage increase in daily 20-year precipitation event for mid-century scenario (RCP8.5). (e) Projected change in annual average temperature. (f) Projected temperature change for coldest and warmest day. Source: Wuebbles et al. (2017).



itation (Polley et al. 2013), while warming and increasing CO_2 concentrations contribute primarily to plant water use efficiency, evaporative demand, and growing season length (Polley et al. 2013; Briske et al. 2015). Vegetation community structure depends on competition for limited water resources and nutrients (Gherardi and Sala 2015), but also on abiotic feedbacks associated with wind and water redistribution of soil, soil nutrients, and C, as well as land use and management (Hibbard et al. 2017).

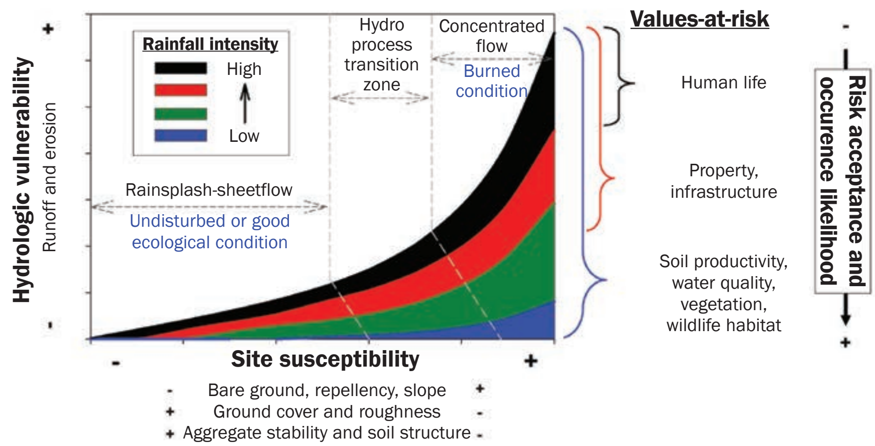
Increased CO_2 concentrations promote growth and allow for more efficient water use by plants, which has the potential to offset the effects of warming to some degree (Polley et al. 2013). However, these benefits will likely be limited by water availability in the Southern Plains and Southwest. Polley et al. (2013) and Briske et al. (2015) suggest that coupled warming and drying trends in the Southwest and Southern Plains will reduce overall net primary productivity and could favor shifts in community composition to more woody species in the Southern Plains and Southwest. In contrast, increased CO_2 and warming coupled with wetter conditions in the Northern Plains will likely lead to increased productivity but may favor invasive C3 herbaceous species. Both agree that predicting vegetation response in the Northwest—where overall precipitation amounts are projected to be relatively stable with a seasonal shift to wetter winters and drier summers—is more uncertain, but that warmer, drier summers should reduce late summer productivity and wetter, warmer winters could favor invasive annual grasses, particularly cheatgrass (*Bromus tectorum* L.), which has serious implications for increased fire activity (Balch et al. 2013; Pilliod et al. 2017).

Field studies have shown that increased interannual variability in precipitation decreases overall ecosystem productivity and that this effect becomes more pronounced over time (Sala et al. 2012; Gherardi and Sala 2015). Moreover, Gherardi and Sala (2015) demonstrated that shrub productivity in southwestern deserts increases in response to increased precipitation variability while grass productivity decreases, which suggests that prolonged periods of increased variability in precipitation could promote community transitions from grass-dominated to shrub-dominated landscapes. Shrub encroachment, once initiated, is often self-sustaining. High infiltration rates, deeper soil water storage, and entrapment of nutrient rich soils underneath or adjacent to shrub canopies create favorable conditions for shrub growth, often at the expense of herbaceous species (Schlesinger et al. 1990; Parsons et al. 1992; Bhark and Small 2003; Okin et al. 2009; Turnbull et al. 2010; Field et al. 2012). Overall, community transitions might occur, which favor erodibility and increase site susceptibility. Such transitions should be closely monitored for their effects on soil erosion.

Wind Erosivity. Mean wind speeds are projected to be lower for much of the western United States, except for the Southern Plains and portions of the Northern Plains regions (figure 2), but these projections are highly uncertain (Vautard et al. 2010). Regardless, this small reduction in potential erosivity will likely be offset in many locations by vegetation responses to climate change. Wind erosivity depends on how the wind field interacts with exposed soil at the surface, which is controlled by vegetation cover and structure (Mayaud and Webb 2017). Vegetation both extracts momentum from the wind and provides shelter zones in which wind speeds at the surface are reduced depending on plant density and size (Wolfe and Nickling 1993). Thus, trends in vegetation that promote sparseness or transition from dense-cover grasses to shrubs with exposed gaps can effectively increase wind erosivity (Munson et al. 2011; Okin et al. 2018). Further, while mean wind speeds are projected to be lower for most of the West, large-scale wind erosion and dust emission

Figure 5

Conceptual model of hydrologic vulnerability and risk. Hydrologic vulnerability (measured as runoff and erosion response, *y*-axis) is a function of site susceptibility (*x*-axis) and rainfall intensity (indicated by colors). Vulnerability dictates resources at risk. Concentrated flow processes dominate the postfire environment where site susceptibility is high (e.g., high bare ground, water-repellent soils) or rainfall is of moderate to high intensity. Rainsplash processes prevail where susceptibility is low (well-aggregated soils, land surface well protected by litter cover). Rainsplash, sheetflow, and concentrated flow processes all contribute to the runoff/erosion response where site susceptibility is indicative of disturbed conditions (reduced ground cover and aggregate stability, poor soil structure). The overall hydrologic response is amplified with increasing slope steepness. Sources: modified from Pierson et al. (2011) and Williams et al. (2014a).



events are largely driven by frontal passages over much of the region. Drier winters and springs in the Southern Plains and Southwest may leave many sites more vulnerable to these erosive events by reducing early season production and affecting green-up timing, and increased fire activity in the Northwest could lead to more exposed surface area during recovery periods.

In addition to synoptic scale frontal wind patterns, local convective winds are also important drivers of wind erosion in US rangelands. Local dust events are often coupled with convective storms (Brazel and Nickling 1986; Novlan et al. 2007), which can account for a significant portion of dust activity/hazards. In general, climate models predict an increase in extreme thunderstorm events (Kossin et al. 2017), but confidence in these projections is low. Thus, relating increases in convective storm frequency and magnitude to increased potential for wind erosion is highly uncertain and remains a difficult challenge to aeolian researchers.

Soil Crusting. Another significant control for aeolian processes in rangelands is physical and biological soil crusting, which significantly increases transport thresholds (Gillette et al. 1982; Belnap and Gillette 1998). Few papers have focused specifically on projected climate change implications for soil crusts in the context of soil erosion (Ferrenberg et al. 2015), and this remains a significant knowledge gap in our understanding of how climate change will impact aeolian processes in US rangelands. However, some relationships are relatively well understood. Both types of crust reduce wind erosion and have variable effects on water erosion. Climate change is likely to affect the proportion of the soil surface covered by different types of crusts at any time through one or more of the following processes: reduced rainfall frequency reduces opportunities for physical crust reformation following physical disturbance, but increased intensity generates stronger crusts that may be more persistent. Warming and changes to rainfall timing and intensity may negatively affect biological crusts (Belnap and Eldridge 2003) at a level similar to physical disturbance (Ferrenberg et al. 2015). While crusts can withstand limited soil mobility (Langston and McKenna Neuman 2005; Kidron and Zohar 2014), even small increases in aeolian activity because of reductions in extent, duration, or strength of soil crusts could potentially lead to further instability and increased susceptibility to wind erosion.

Rainfall Erosivity. Climate change models consistently project an increase in the frequency and intensity of high intensity rainfall events for the western United States (figure 4) (Easterling et al. 2017), and thus erosivity (Nearing 2001; Zhang et al. 2012; Biasutti and Seager 2015; Nearing et al. 2017). Rainfall erosivity is defined as the capability of rainfall to cause soil loss by water and is a function of the energy of rainfall and rainfall intensity (Nearing et al. 2017). However, Nearing et al. (2017) point out that kinetic energy of rainfall is not a direct driver of erosion in cases where runoff (transport) is limited, rather water erosion rates are generally highest where overland flow occurs and that rainfall energy is effectively a surrogate for discharge or runoff generation. Runoff rates are generally greatest where surface conditions are bare (high susceptibility) and, under these conditions, are exacerbated with increasing rainfall intensity—high vulnerability (figure 5) (Pierson et al. 2011; Williams et al. 2014b; Pierson and Williams 2016).

Magnitude of erosion under these conditions is dependent on the connectivity of runoff; the amount of sediment available for transport; and the amount, energy, and transport capacity of overland flow (Pierson et al. 2011; Al-Hamdan et al. 2012, 2013, 2015; Williams et al. 2016a). Well-connected, bare conditions and high sediment availability are most common following short-term disturbances such as wildfire, but also occur with declines in vegetation and cover over time because of poor land use practices, drought, and woody plant encroachment (Pierson et al. 2007, 2010; Turnbull et al. 2008, 2012; Al-Hamdan et al. 2012; Williams et al. 2014a, 2016b, 2016a). Given these relationships, climate change impacts on erosivity are likely compounding in their effect on erosion through concomitant changes in plant community dynamics and disturbance regimes such as fire, drought, and desertification. As such, increases in rainfall erosivity may have the greatest impact through exacerbating the effects of fire, desertification, and poor land use practices on runoff generation and soil loss by water (Zhang et al. 2012). It is also worth noting that during extreme weather events, the effect of high winds on rain (wind-driven rain) has the potential to significantly increase rainfall erosivity for a given precipitation intensity (Marzen et al. 2017). Given the projected increase in extreme weather events, this impact should not be ignored in research and modeling efforts.

Impacts on Disturbance. The frequency of large fires, annual area burned, and drought-induced tree die-off have increased across the western US rangeland-dry forest continuum in recent decades and are expected to increase further with projected climate change (Breshears et al. 2005, 2009; Westerling et al. 2006; Keane et al. 2008; Morgan et al. 2008; Flannigan et al. 2009; Littell et al. 2009; Spracklen et al. 2009; Abatzoglou and Kolden 2011; Miller et al. 2011; Balch et al. 2013; Williams et al. 2014b). Much of the interior western United States now exists in a state in which rangeland and woodland wildfires stimulated by annual grasses and dense woody fuels have a greater likelihood of progressing upslope into dry forests, where wildfire activity is also increasing (Keane et al. 2008; Nelson and Pierce 2010; Balch et al. 2013).

Invasion by and expansion of annual cheatgrass is the primary cause of increased fire frequency and annual area burned on sagebrush rangelands throughout much of the western United States (Keane et al. 2008; Miller et al. 2011; Balch et al. 2013). Cheatgrass escalates wildfire activity on rangelands by increasing the horizontal continuity of fuels and the likelihood of ignition (Brooks et al. 2004; Link et al. 2006). Burning of cheatgrass infested sites favors cheatgrass dominance and perpetuates a recurring grass-fire cycle (Knapp 1996; Brooks et al. 2004; Davies et al. 2012; Balch et al. 2013). Abatzoglou and Kolden (2011) suggest both cheatgrass invasibility and the length of the fire season in the Great Basin will be enhanced by a warmer climate and an increase in wet winters. Across the interior west, cheatgrass is moving upslope (Keeley and McGinnis 2007; McGlone et al. 2009; Griffith and Loik 2010; Bromberg et al. 2011), potentially setting up occurrence of the cheatgrass-fire cycle at higher elevations and in woodlands and dry forests. At mid-elevations, pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) expansion into sagebrush (*Artemisia* spp.) communities and infill on existing woodlands have increased woody fuel loading and increased risk of severe wildfires (Keane et al. 2008; Romme et al. 2009).

In recent decades, warming winter and spring air temperatures at mid-elevations of the western United States have yielded decreased snowpacks (Mote et al. 2005; Regonda et al. 2005; Knowles et al. 2006; Trenberth et al. 2007; Bonfils et al. 2008; Nayak et al. 2010), earlier spring snowmelt and streamflow (McCabe and Clark 2005; Regonda et al. 2005; Stewart et al. 2005; Pederson et al. 2011), and drier fuel conditions (Westerling et al. 2006). These trends have extended fire seasons and increased fire frequency and area burned in western forests (Pierce et al. 2004; Westerling et al. 2006; Morgan et al. 2008; Pierce and Meyer 2008; Littell et al. 2009). In the southwestern United States, recent landscape- to regional-scale die-offs of pinyon and juniper have been attributed to periods of drought and limited soil water availability, plant water stress, bark beetle infestations, and reduced tree regeneration (Allen 2007; Allen and Breshears 1998; Breshears et al. 2005, 2009; Clifford et al. 2013; Gaylord et al. 2013; Redmond et al. 2013, 2015). Projections of climate and plant community transitions are highly variable, but most forecast warming and drought, increased dry-season cyclonic storms, longer fire seasons, and greater wildfire activity across the rangeland-dry forest continuum of the western United States (Flannigan et al. 2000, 2009; Whitlock et al. 2003; Gedalof et al. 2005; Running 2006; Bradley et al. 2009; Spracklen et al. 2009; Littell et al. 2010; Abatzoglou and Kolden 2011; Balch et al. 2013; Williams et al. 2014b). These broad-scale disturbances potentially increase susceptibility of rangelands to erosion across landscape to regional scales (Williams et al. 2014b).

Potential Trends and Implications of Soil Erosion

Increased aeolian sediment transport and dust emission have several implications for rangeland plant communities and ecogeomorphology and pose a serious hazard to human health. Soil loss and redistribution affects overall soil health, biogeochemical cycles, and land potential. Because many rangelands exist near ecological thresholds, even relatively small perturbations may degrade sites beyond their ability to recover (Archer and Predick 2008). Further, increased dust emissions could have significant implications for air quality and human health, while episodic hazards such as dust storms also pose immediate threats to human life.

Limited studies have attempted to quantify effects of climate change on wind erosion in US rangelands (Munson et al. 2011; Pu and Ginoux 2017). In general, lower projected wind speeds over much of the western United States (figure 2) will likely be offset by changes to vegetation controls, e.g., increases in intercanopy gaps. Further, more frequent fires and shorter fire return intervals could lead to increased erosion from disturbed sites. Longer-term stresses and response to climatic change such as increased moisture deficits, decreased productivity, and grass-shrub transitions also have the potential to significantly increase site susceptibility to aeolian processes. These effects could potentially be exacerbated by future reductions in soil crusting. Indeed, dust emission rates have increased significantly over the past two decades (Hand et al. 2016), despite wind stilling over much of the area. Given the potential impacts of climate change on US rangelands, overall dust emission could continue to increase over both short- and long-term time scales despite the predicted decrease in overall wind speed over much of the western United States. Plot-scale research has explored the interactions between vegetation change and aeolian processes in US rangelands, but the impact of ecosystem changes for current and future regional dust emissions has not been established over large areas. It is incumbent on the rangeland research and management communities to monitor responses to these stresses across relevant thresholds of aeolian activity, as well as how these changes promote dust emission frequency and magnitude.

Projected climate changes and vegetation community response suggest increased landscape vulnerability to soil erosion by water over much of US rangelands, with the most pronounced impacts likely related to drought and increased disturbance. Knowledge regarding drought impacts on erosion in US rangelands comes primarily from studies in the Southwest, which suggest that community transitions that result in a reduction of herbaceous cover and favor connected, bare intercanopy spaces can lead to increased runoff and erosion (Wilcox et al. 1996; Allen and Breshears 1998). These results suggest that, overall, prolonged vegetation reductions associated with drought may cause increases in erosion through increased surface susceptibility. In general, amplified runoff and associated erosion are likely during high water input, erosive events at sites where cover is decreased by any disturbance (Pierson et al. 2011; Williams et al. 2014b). Indeed, there is ample evidence from the Southwest that documents increased soil erosion following coarsening of plant community structure via grassland-shrubland conversion—e.g., desertification (Schlesinger et al. 1990; Turnbull et al. 2008, 2012)—associated with a combination of factors including land use and climate (Buffington and Herbel 1965; Grover and Musick 1990; Bahre and Shelton 1993; Archer et al. 1995; Van Auken 2000, 2009). Coarsening of plant community structure increases fine-scale erosion by rainsplash and sheetflow (Abrahams et al. 1995; Parsons et al. 1996a). In turn, runoff generated in bare interspaces promotes concentrated flow and amplifies downslope sediment transport (Luk et al. 1993; Parsons et al. 1996b; Wainwright et al. 2000; Turnbull et al. 2010). Water and soil losses inhibit herbaceous productivity and further propagate bare ground connectivity (Bhark and Small 2003). In general, both wind and water erosion increase with increasing bare ground over broad scales, potentially degrading sites beyond conservation and restoration thresholds (Turnbull et al. 2012). Similar responses have been reported for coarsening of plant community structure following shrubland-to-woodland conversions driven by land use, climate, and reduced fire activity in the northwestern United States (Pierson et al. 2007, 2010, 2013; Williams et al. 2014a, 2016b, 2016c, 2016a). In contrast, recent studies of streamflow following drought-induced pinyon, juniper, and lodgepole pine (*Pinus contorta* Douglas) die-off in the Southwest have reported either decreases to little change in streamflow over short timescales (Guardiola-Claramonte et al. 2011; Biederman et al. 2015). In both studies, the authors suggest that decreases in streamflow were associated with increased water use by enhanced herbaceous cover following tree die-off. Thus, the limited research to date on drought-specific impacts on water erosion from US rangelands hinders accurate prediction of drought impacts on erosion with climate change, and this should be a research focus moving forward.

Disturbance by wildfires increases susceptibility and vulnerability to erosion at plot to watershed scales and increases hazards to values-at-risk such as natural resources, property, infrastructure, and human life (figure 5) (Calkin et al. 2007; Robichaud et al. 2010; Pierson et al. 2011; Williams et al. 2014b; Pierson and Williams 2016). Much of what is currently known about fire impacts on erosion comes from plot- to hillslope-scale artificial rainfall experiments and anecdotal reports of debris flows and mudslides (Pierson et al. 2002, 2011; Williams et al. 2014b; Pierson and Williams 2016). Increasing wildfire activity associated with climate change poses significant environmental, social, and economic consequences associated with erosion events (Pierson et al. 2011; Wilcox et al. 2012; Williams et al. 2014b). More frequent and larger fires increase the likelihood and potential magnitude of both onsite and offsite impacts to values-at-risk (figure 5). More frequent surface exposure due to repeated burning will likely increase both water and wind erosion during commonly occurring storms in addition to increasing the probability susceptible soil surfaces will be exposed when less frequent, high intensity events—which climate projections indicate are likely to increase (Kossin et al. 2017)—occur. Loss of biologically important surface soils during more frequent high intensity events may be particularly critical for rangelands where soil formation takes decades (Allen et al. 2011; Sankey et al. 2012). This may be especially problematic where large fires are followed by drought years with minimal plant recruitment that prolongs susceptibility.

Waterborne sediment pulses transported into channels during postfire erosion events and subsequently flushed into streams (Cannon et al. 2001; Meyer and Pierce 2003; Pierce et al. 2004) may negatively impact water resources, fisheries, and channel geomorphology (Minshall et al. 2001; Pierce et al. 2011). Further, several studies have linked large debris flow events in dry forests of the Interior West to warm climatic conditions (Medieval Warm Period, 1,050 to 750 years ago) and periods of extensive fires (Meyer and Pierce 2003; Pierce et al. 2004; Pierce and Meyer 2008). Fire-induced debris flows can transport tremendous volumes of sediment and debris into main stem rivers (Cannon et al. 2001; Meyer et al. 2001; Pierce et al. 2011), and the literature suggests that these events may become more common under continued increases in wildfire activity and high intensity, erosive rainfall events on extensively burned landscapes (Williams et al. 2014b).

Current knowledge is strong regarding fire impacts on surficial processes across plot to small watershed scales, but research is still needed to relate varying surface susceptibility to runoff and erosion responses for burned versus unburned conditions and to better represent hydrologic and erosion recovery in quantitative hydrology and erosion models under changing precipitation regimes (Pierson et al. 2011; Moody et al. 2013; Williams et al. 2014b; Pierson and Williams 2016). Likewise, current ability to accurately model and predict postfire hydrologic and associated erosion responses over large spatial scales and complex topography remains limited, particularly under potentially changing precipitation regimes and erosivity and for flood, debris flow, and mud-slide responses. More work is also needed to assess the impacts of fire on aeolian transport rates and dust emission events (Dukes et al. 2018). Advancements in these key areas are important in the development of postfire decision support tools for assessing and predicting erosion responses under a changing climate.

Discussion

Managing the impacts of climate change on wind and water erosion will be critical for the long-term sustainability of US rangelands (Webb et al. 2017). Our review of potential climate change impacts on erosion drivers, and the likely responses, brings us to some important considerations for the management of current and future erosion as the basis for maintaining and improving soil health, water and air quality, and the ecosystem services that depend on them. Foremost are the following questions:

1. How can wind and water erosion and their responses to land use and management be effectively monitored across diverse rangeland ecosystems?
2. How can information about soil erosion be incorporated into management decisions?
3. What management actions are necessary to reduce the negative impacts of climate change while leveraging positive impacts?
4. What proportion of often limited management resources should be devoted to anticipating future climate change impacts versus addressing current impacts of invasive species, grazing-induced changes in the fire regime, and soil degradation?

Quantifying wind and water erosion rates and their responses to land use, land management, and land cover changes will be essential to develop management responses that are effective into the future. Currently, our understanding of regional wind erosion rates is limited and supported largely by coarse spatial resolution (e.g., >1°) model estimates of dust emission (Shao et al. 2011). Little is known about the current magnitude of wind erosion rates in US rangelands (Breshears et al. 2003; Nauman et al. 2018), with most available measurements of sediment transport rather than erosion, and with limited scope (Munson et al. 2011; Wagenbrenner et al. 2012; Webb et al. 2014). More is known about runoff and water erosion in US rangelands because of its longer research focus (Nearing et al. 2017). As measuring wind and water erosion rates over the large area of US rangelands is impractical, modeling approaches that can leverage data collected by existing monitoring programs—or remote sensing (Chappell et al. 2018)—provide the best opportunities for evaluating erosion rates and the process responses to land use and climate change. The Aeolian EROsion (AERO) model (Edwards et al. 2018) and Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al. 2011; Al-Hamdan et al. 2015) can be applied to standardized rangeland monitoring data—like those collected as part of the Bureau of Land Management's Assessment, Inventory and Monitoring (AIM) program (Toevs et al. 2011) and the USDA Natural Resources Conservation Service's National Resources Inventory (NRI) (Goebel 1998)—and provide the opportunity to assess rangeland wind and water erosion across plot to regional scales. As of December of 2017, AIM and NRI data have been collected at over 50,000 locations across the US rangelands to which AERO and RHEM can be applied, with support in model calibration and testing to establish uncertainties from networked observatory sites like the USDA's Long-Term Agroecosystem Research Network (Robertson et al. 2008) and associated National Wind Erosion Research Network (Webb et al. 2016).

Establishing model estimates of water erosion and wind-driven sediment transport from existing monitoring data will provide new opportunities to link erosion assessments to land classification systems and land resource hierarchies that are used to inform management (Salley et al. 2016). For example, incorporating model estimates of wind and water erosion from AIM and NRI data into ecological site descriptions (ESDs) (Caudle et al. 2013) and relating erosion rates to core indicators of rangeland condition (Herrick et al. 2017) and rangeland health (Pyke et al. 2005) could provide the necessary information for resource managers to identify tolerable erosion rates; establish benchmarks (e.g., in ground cover) for erosion control, which relate to water and air quality (e.g., 1977 Clean Air Act and National Ambient Air Quality Standards); and to consider erosion management and trade-offs alongside other resource concerns. Recent applications of ESDs and state-and-transition models to evaluate rangeland dust emission (Galloza et al. 2018) and water erosion (Williams et al. 2016b, 2016c) have shown the utility of integrating monitoring data with erosion models and conceptual models of ecosystem states and their dynamics (figure 6). Such systems approaches will be useful for understanding and managing the impacts of climate change on rangeland erosion and feedbacks of the processes to ecosystem health and production.

We contend that management actions and resources needed to address future climate change on soil erosion in rangelands are largely those necessary to address the current impacts of invasive species, fire, and soil degradation. Increasing the health and overall resilience of rangeland ecosystems will in many, if not most, cases reduce negative climate change impacts and improve the efficacy of climate adaptation while allowing positive impacts to be exploited (Webb et al. 2013). At a minimum, an increased focus on addressing or adapting to current threats—e.g., shrub invasion of Chihuahuan Desert ecosystems (Archer et al. 2017), changing grass-fire cycles and invasion of Great Basin sagebrush shrublands by cheatgrass (Balch et al. 2013), and slow ecological recovery of ecosystems affected by infrastructure development for oil and gas extraction (Nauman et al. 2017)—that are likely to be *exacerbated* by climate change and impact rangeland communities is justified (Dallimer and Stringer 2018). Planned rather than reactive management of rangeland soil erosion and the potential process responses to climate change is likely to have the greatest positive impact on the quality of rangeland soil, vegetation, air, and water resources over the long term (Briske et al. 2015). Participatory research to develop innovative range management systems that are inherently more flexible and suited to changing climatic and market conditions are also likely to build resilience to an increasingly unpredictable climate (Spiegal et al. 2018).

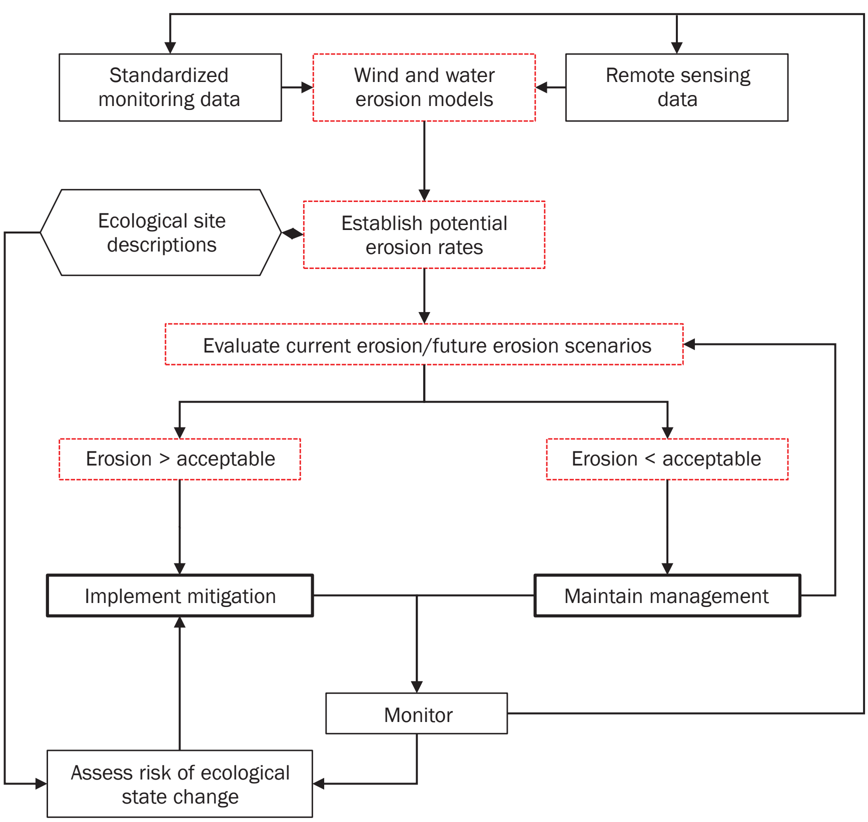
Finally, among the many climatic controls on erosion, our confidence in their midcentury projections vary dramatically. There is relatively high confidence in projections of rising temperatures, as well as more frequent and severe soil moisture deficits, wildfires, and heavy precipitation events. However, confidence is relatively low in projections of average precipitation (annual and seasonal), intense storms, and surface wind speeds. Changes in land use and land cover may be equally if not more important as climate change in determining future erosion rates (Ferrenberg et al. 2015) but may well be influenced by climatic changes. There is great uncertainty about how plant communities will respond to climate change and how the socioeconomic drivers of land use change will impact rangeland wind and water erosion. In the face of such uncertainty, explicitly considering the trade-offs for erosion impacts against other management objectives and implementing flexible, "no-regrets" management practices that achieve multiple objectives could have both immediate and long-term benefits for US rangelands.

Summary and Conclusions

Conservation of US rangeland resources into the future presents a substantial challenge to the management community. Soil erosion by wind and water is already a serious threat to US rangelands and may be accelerated by future climate change. Managing to limit soil erosion impacts today will be critical for adaptation, given that many of the challenges we currently face are expected to be exacerbated if current trajectories of emissions and climate change continue. Moreover, given our current understanding, more widespread erosion will only increase exposure and sensitivity of rangelands to climate impacts—reducing resilience to climatic stressors and pushing some rangelands past restoration and conservation thresholds—which reduces the adaptive capacity of land users. Our understanding of ecogeomorphic links between erosion processes and rangeland condition and trajectory is improving, but more research is needed to inform management efforts to build rangeland resilience. The following summarize our current understanding of the potential impacts of climate change on erosion in US rangelands and highlight important knowledge gaps and research needs:

- Projected trends toward reduced vegetation cover and shifts in vegetation communities from herbaceous to shrub-dominated landscapes resulting from warming and drying have the potential to significantly increase landscape susceptibility to water and wind

Figure 6
Generalized schema that includes accounting for current erosion in evaluating and managing rangeland soil planning for future climate changes.



soil erosion over much of the western United States.

- Potential increases in rainfall erosivity may have the greatest impact by exacerbating effects of fire, desertification, and poor land use practices on runoff and erosion.
- Increased disturbance from fire and exotic invasive grasses has the potential to significantly increase frequency and magnitude of erosive events over both short time scales commensurate with increased susceptibility during recovery periods and longer time scales associated with increased vulnerability to erosion because of more frequent, larger fires over an expanded range.
- Projected climate change could slow recovery times to fire and other disturbances, e.g., infrastructure development for oil and gas extraction, that are increasing in density across western rangelands and may impact soil erosion and dust emission.
- More work is needed to expand our ability to model postfire hydrologic and erosion response over large areas and complex topography.
- More research is needed to understand the impact of ecosystem changes, e.g., reductions in vegetation density, community shifts, and soil crusting, for current and future wind erosion and regional dust emission from US rangelands.
- More research is needed to improve understanding of drought-specific impacts on water erosion in US rangelands, which is currently limited.
- Existing, extensive plot-scale rangeland monitoring and remote sensing data should be leveraged in modeling frameworks to establish baseline assessments of current vulnerability of US rangelands to soil erosion and, where possible, used to assess potential changes to future vulnerability associated with rangeland responses to climate change.
- Soil erosion should be explicitly included in management benchmarks and decision support tools to better mitigate negative consequences of erosion and its impacts on water resources and air quality.
- Flexible, no-regrets management options should be implemented to combat current soil erosion impacts on US rangelands, which will improve rangeland resilience and the efficacy of future climate change adaptation.
- Finally, fundamental knowledge of erosion processes is critical to developing accurate models and appropriate management practices. As such, processed-based research to further our understanding of the underlying processes and refine models used to guide management is a continual need.

Acknowledgements

We would like to thank Paige Ramsey (GIS specialist at the USDA Southwest Climate Hub in Las Cruces, New Mexico) for her patient assistance with producing figures for this article.

Disclaimer

This work is a product of the USDA Agricultural Research Service. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the USDA, which is an equal opportunity provider and employer. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

References

Abatzoglou, J.T., and T.J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology 32:772-780.

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

Abrahams, A.D., A.J. Parsons, and J. Wainwright. 1995. Effects of vegetation change on interrill runoff and erosion, Walnut Gulch, southern Arizona. Geomorphology 13:37-48.

Al-Hamdan, O.Z., M. Hernandez, F.B. Pierson, M.A. Nearing, C.J. Williams, J.J. Stone, J. Boll, and M.A. Weltz. 2015. Rangeland hydrology and erosion model (RHEM) enhancements for applications on disturbed rangelands. Hydrological Processes 29:445-457.

Al-Hamdan, O.Z., F.B. Pierson, M.A. Nearing, C.J. Williams, J.J. Stone, P.R. Kormos, J. Boll, and M.A. Weltz. 2012. Concentrated flow erodibility for physically based erosion models: Temporal variability in disturbed and undisturbed rangelands. Water Resources Research 48:W07504.

Al-Hamdan, O.Z., F.B. Pierson, M.A. Nearing, C.J. Williams, J.J. Stone, P.R. Kormos, J. Boll, and M.A. Weltz. 2013.

Risk assessment of erosion from concentrated flow on rangelands using overland flow distribution and shear stress partitioning. Transactions of the ASABE 56:539-548.

Allen, C.D. 2007. Interactions across spatial scales among forest dieback, fire, and erosion in northern New Mexico landscapes. Ecosystems 10:797-808.

Allen, C.D., and D.D. Breshears. 1998. Drought-induced shift of a forest-woodland ecotone: Rapid landscape response to climate variation. Proceedings of the National Academy of Sciences of the United States of America 95:14839-14842.

Allen, E.B., R.J. Steers, and S.J. Dickens. 2011. Impacts of fire and invasive species on desert soil ecology. Rangeland Ecology and Management 64:450-462.

Archer, S.R., E.M. Andersen, K.I. Predick, S. Schwinning, R.J. Steidl, and S.R. Woods. 2017. Woody plant encroachment: Causes and consequences. *In* Rangeland Systems, ed. D.D. Briske, 25-84. Cham, Switzerland: Springer.

Archer, S.R., and K.I. Predick. 2008. Climate change and ecosystems of the southwestern United States. Rangelands 30:23-28.

Archer, S.R., D.S. Schimel, and E.A. Holland. 1995. Mechanisms of shrubland expansion: Land use, climate or CO_2? Climatic Change 29:91-99.

Bahre, C.J., and M.L. Shelton. 1993. Historic vegetation change, mesquite increases, and climate in southeastern Arizona. Journal of Biogeography 20:489-504.

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

Belnap, J., and D. Eldridge. 2003. Disturbance and recovery of biological soil crusts. *In* Biological Soil Crusts: Structure, Function and Management, eds. J. Belnap and O.L. Lange, 363-383. Berlin: Springer-Verlag.

Belnap, J., and D.A. Gillette. 1998. Vulnerability of desert biological soil crusts to wind erosion: The influences of crust development, soil texture, and disturbance. Journal of Arid Environments 39:133-142.

Belnap, J., J.R. Welter, N.B. Grimm, N. Barger, and J.A. Ludwig. 2005. Linkages between microbial and hydrologic processes in arid and semiarid watersheds. Ecology 86:298-307.

Bergametti, G., and D.A. Gillette. 2010. Aeolian sediment fluxes measured over various plant/soil complexes in the Chihuahuan desert. Journal of Geophysical Research 115:F03044.

Bhark, E.W., and E.E. Small. 2003. Association between plant canopies and the spatial patterns of infiltration in shrubland and grassland of the Chihuahuan desert, New Mexico. Ecosystems 6:185-196.

Biasutti, M., and R. Seager. 2015. Projected changes in US rainfall erosivity. Hydrology and Earth System Sciences 19:2945-2961.

Biederman, J.A., A.J. Somor, A.A. Harpold, E.D. Gutmann, D.D. Breshears, P.A. Troch, D.J. Gochis, R.L. Scott, A.J.H. Meddens, and P.D. Brooks. 2015. Recent tree die-off has little effect on streamflow in contrast to expected increases from historical studies. Water Resources Research 51:9775-9789.

Blumenthal, D.M., J.A. Kray, W. Ortmans, L.H. Ziska, and E. Pendall. 2016. Cheatgrass is favored by warming but not CO_2 enrichment in a semi-arid grassland. Global Change Biology 22:3026-3038.

Bonfils, C., B.D. Santer, D.W. Pierce, H.G. Hidalgo, G. Bala, T. Das, T.P. Barnett, D.R. Cayan, C. Doutriaux, A.W. Wood, A. Mirin, and T. Nozawa. 2008. Detection and attribution of temperature changes in the mountainous western United States. Journal of Climate 21:6404-6424.

Boone, R.B., R.T. Conant, J. Sircely, P.K. Thornton, and M. Herrero. 2018. Climate change impacts on selected global rangeland ecosystem services. 2018. Global Change Biology 24:1382-1393.

Bradley, B.A. 2009. Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. Global Change Biology 15:196-208.

Brazel, A.J., and W.G. Nickling. 1986. The relationship of weather types to dust storm generation in Arizona (1965-1980). International Journal of Climatology 6:255-275.

Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, J.H. Kastens, M.L. Floyd, J. Belnap, J.J. Anderson, O.B. Myers, and C.W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences 102:15144-15148.

Breshears, D.D., O.B. Myers, C.W. Meyer, F.J. Barnes, C.B. Zou, C.D. Allen, N.G. McDowell, and W.T. Pockman. 2009. Tree die-off in response to global change-type drought: Mortality insights from a decade of plant water potential measurements. Frontiers in Ecology and the Environment 7:185-189.

Breshears, D.D., J.J. Whicker, M.P. Johansen, and J.E. Pinder. 2003. Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystems: Quantifying dominance of horizontal wind-driven transport. Earth Surface Processes and Landforms 28:1189-1209.

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

Bromberg, J.E., S. Kumar, C.S. Brown, and T.J. Stohlgren. 2011. Distributional changes and range predictions of downy brome (*Bromus tectorum*) in Rocky Mountain National Park. Invasive Plant Science and Management 4:173-182.

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

Buffington, L.C., and C.H. Herbel. 1965. Vegetational changes on a semidesert grassland range from 1858 to 1963. Ecological Monographs 35:140-164.

Bullard, J.E., and G.H. McTainsh. 2003. Aeolian-fluvial interactions in dryland environments: Examples, concepts and Australia case study. Progress in Physical Geography 27:471-501.

Calkin, D.E., K.D. Hyde, P.R. Robichaud, J.G. Jones, L.E. Ashmun, and D. Loeffler. 2007. Assessing post-fire values-at-risk with a new calculation tool. USDA Forest Service - General Technical Report RMRS-GTR:1-32.

Cannon, S.H., R.M. Kirkham, and M. Parise. 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. Geomorphology 39:171-188.

Caudle, D., J. DiBenedetto, M. Karl, K. Sanchez, and C. Talbot. 2013. Interagency ecological site handbook for rangelands. Washington, DC: USDA Bureau of Land Management, Forest Service, and Natural Resources Conservation Service.

Chappell, A., N.P. Webb, J.P. Guerschman, D.T. Thomas, G. Mata, R.N. Handcock, J.F. Leys, and H.J. Butler. 2018. Improving ground cover monitoring for wind erosion assessment using MODIS BRDF parameters. Remote Sensing of Environment 204:756-68.

Clifford, M.J., P.D. Royer, N.S. Cobb, D.D. Breshears, and P.L. Ford. 2013. Precipitation thresholds and drought-induced tree die-off: Insights from patterns of *Pinus edulis* mortality along an environmental stress gradient. New Phytologist 200:413-421.

Cowie, S.M., P. Knippertz, and J.H. Marsham. 2013. Are vegetation-related roughness changes the cause of the recent decrease in dust emission from the Sahel? Geophysical Research Letters 40:1868-1872.

Dallimer, M., and L.C. Stringer. 2018. Informing investments in land degradation neutrality efforts: A triage approach to decision making. Environmental Science and Policy 89:198-205.

Davenport, D.W., D.D. Breshears, B.P. Wilcox, and C.D. Allen. 1998. Viewpoint: Sustainability of pinon-juniper ecosystems - A unifying perspective of soil erosion thresholds. Journal of Range Management 51:231-240.

Davies, G.M., J.D. Bakker, E. Dettweiler-Robinson, P.W. Dunwiddie, S.A. Hall, J. Downs, and J. Evans. 2012. Trajectories of change in sagebrush steppe vegetation communities in relation to multiple wildfires. Ecological Applications 22:1562-1577.

Dukes, S., H.B. Gonzales, S. Ravi, D.E. Grandstaff, R.S. Van Pelt, J. Li, G. Wang, and J.B. Sankey. 2018. Quantifying postfire aeolian sediment transport using rare earth element tracers. Journal of Geophysical Research: Biogeosciences 123:288-299.

Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner. 2017. Precipitation changes in the United States. *In* Climate Science Special Report: Fourth National Climate Assessment, Volume I, eds. D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, 207-230. Washington, DC: US Global Change Research Program.

Edwards, B.L., N.P. Webb, and S.E. McCord. 2018. AERO: A wind erosion modeling framework with applications to monitoring data. Paper presented at the Southern US Dust Monitoring and Mitigation Symposium, Soil and Water Conservation Society Annual Meeting, Albuquerque, NM, USA, July 29-August 1, 2018. https://swclimatehub.info/dust-symposium-2018.

Ferrenberg, S., S.C. Reed, and J. Belnap. 2015. Climate change and physical disturbance cause similar community shifts in biological soil crusts. Proceedings of the National Academy of Sciences 119:12116-12121.

Field, J.P., D.D. Breshears, J.J. Whicker, and C.B. Zou. 2012. Sediment capture by vegetation patches: Implications for desertification and increased resource redistribution. Journal of Geophysical Research 117:G01033.

Flannigan, M.D., M.A. Krawchuk, W.J. De Groot, B.M. Wotton, and L.M. Gowman. 2009. Implications of changing climate for global wildland fire. International Journal of Wildland Fire 18:483-507.

Flannigan, M.D., B.J. Stocks, and B.M. Wotton. 2000. Climate change and forest fires. Science of the Total Environment 262:221-229.

Galloza, M.S., N.P. Webb, M.P. Bleiweiss, C. Winters, J.E. Herrick, and E. Ayers. 2018. Exploring dust emission responses to land cover change using an ecological land classification. Aeolian Research 32:141-153.

Gaylord, M.L., T.E. Kolb, W.T. Pockman, J.A. Plaut, E.A. Yepez, A.K. Macalady, R.E. Pangle, and N.G. Mcdowell. 2013. Drought predisposes piñon-juniper woodlands to insect attacks and mortality. New Phytologist 198:567-578.

Gedalof, Z., D.L. Peterson, and N.J. Mantua. 2005. Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. Ecological Applications 15:154-174.

Gherardi, L.A., and O.E. Sala. 2015. Enhanced precipitation variability decreases grass- and increases shrub-productivity. Proceedings of the National Academy of Sciences 112:12735-12740.

Gillette, D.A., J. Adams, D. Muhs, and R. Kihl. 1982. Threshold friction velocities and rupture moduli for crusted desert soils for the input of soil particles into the air. Journal of Geophysical Research 87:9003-9015.

Goebel, J.J. 1998. The National Resources Inventory and Its Role in US Agriculture. *In* Agricultural Statistics 2000, 181-192. Voorburg, The Netherlands: International Statistical Institute.

Greene, A.M., and R. Seager. 2016. Categorical representation of North American precipitation projections. Scientific Reports 6:23888.

Griffith, A.B., and M.E. Loik. 2010. Effects of climate and snow depth on *Bromus tectorum* population dynamics at high elevation. Oecologia 164:821-832.

Grover, H.D., and H.B. Musick. 1990. Shrubland encroachment in southern New Mexico, USA: An analysis of desertification processes in the American southwest. Climatic Change 17:305-330.

Guardiola-Claramonte, M., P.A. Troch, D.D. Breshears, T.E. Huxman, M.B. Switanek, M. Durcik, and N.S. Cobb. 2011. Decreased streamflow in semi-arid basins following drought-induced tree die-off: A counter-intuitive and indirect climate impact on hydrology. Journal of Hydrology 406:225-233.

Hand, J.L., W.H. White, K.A. Gebhart, N.P. Hyslop, T.E. Gill, and B.A. Schichtel. 2016. Earlier onset of the spring fine dust season in the southwestern United States. Geophysical Research Letters 43:4001-4009.

Havstad, K.M., D.C. Peters, B. Allen-Diaz, J. Bartolome, B.T. Betelmeyer, D. Briske, J. Brown, M. Brunsun, J.E. Herrick, L. Huntsinger, P. Johnson, L. Joyce, R. Pieper, A.J. Svejcar, and J. Yao. 2009. The western United Sates rangelands, a major resource. *In* Grassland: Quietness and Strength for a New American Agriculture, eds. W.F. Wedin, and S.L. Fales, 75-93. Madison, WI: American Society of Agronomy Inc., Crop Science Society of America Inc., and Soil Science Society of America Inc.

Herrick, J.E., J.W. Van Zee, S.E. McCord, E.M. Courtright, J.W. Karl, and L.M. Burkett. 2017. Monitoring Manual for Grassland, Shrubland, and Savanna Ecosystems, Volume 1: Core Methods, Second Edition. Las Cruces, NM: USDA Agricultural Research Service Jornada Experimental Range.

Herring, S.C., N. Christidis, A. Hoell, J.P. Kossin, C.J. Schreck III, P.A. Stott. 2018. Explaining extreme events of 2016 from a climate perspective. Bulletin of the American Meteorological Society 99:S1-S57.

Hibbard, K.A., F.M. Hoffman, D. Huntzinger, and T.O. West. 2017. Changes in land cover and terrestrial biogeochemistry. *In* Climate Science Special Report: Fourth National Climate Assessment, Volume I, eds. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, 277-302. Washington, DC: US Global Change Research Program.

Homer, C., J. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. Herold, J. Wickham, and K. Megown. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States–representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81:345-354.

Howden, S.M., S.J. Crimp, and C.J. Stokes. 2008. Climate change and Australian livestock systems: Impacts, research and policy issues. Australian Journal of Experimental Agriculture 48:780-788.

Huxman, T.E., B.P. Wilcox, D.D. Breshears, R.L. Scott, K.A. Snyder, E.E. Small, K. Hultine, W.T. Pockman, and R.B. Jackson. 2005. Ecohydrological implications of woody plant encroachment. Ecology 86:308-319.

Joyce, L.A., D.D. Briske, J.R. Brown, H.W. Polley, B.A. McCarl, and D.W. Bailey. 2013. Climate change and North American rangelands: Assessment of mitigation and adaptation strategies. Rangeland Ecology and Management 66:512-528.

Keane, R.E., J.K. Agee, P. Fulé, J.E. Keeley, C. Key, S.G. Kitchen, R. Miller, and L.A. Schulte. 2008. Ecological effects of large fires on US landscapes: Benefit or catastrophe? International Journal of Wildland Fire 17:696-712.

Keeley, J.E., and T.W. McGinnis. 2007. Impact of prescribed fire and other factors on cheatgrass persistence in a Sierra Nevada ponderosa pine forest. International Journal of Wildland Fire 16:96-106.

Kidron, G.J., and M. Zohar. 2014. Wind speed determines the transition from biocrust-stabilized to active dunes. Aeolian Research 15:261-267.

Knapp, P.A. 1996. Cheatgrass (*Bromus tectorum* L) dominance in the Great Basin Desert. History, persistence, and influences to human activities. Global Environmental Change 6:37-52.

Knowles, N., M.D. Dettinger, and D.R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate 19:4545-4559.

Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner. 2017. Extreme storms. *In* Climate Science Special Report: Fourth National Climate Assessment, Volume I, eds. D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, 257-276. Washington, DC: US Global Change Research Program.

Langston, G., and C. McKenna-Neuman. 2005. An experimental study on the susceptibility of crusted surfaces to wind erosion: A comparison of the strength properties of biotic and salt crusts. Geomorphology 72:40-53.

Link, S.O., C.W. Keeler, R.W. Hill, and E. Hagen. 2006. *Bromus tectorum* cover mapping and fire risk. International Journal of Wildland Fire 15:113-119.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western US ecoprovinces, 1916-2003. Ecological Applications 19:1003-1021.

Littell, J.S., E.E. Oneil, D. McKenzie, J.A. Hicke, J.A. Lutz, R.A. Norheim, and M.M. Elsner. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Climatic Change 1-30, doi: 10.1007/s10584-010-9858-x.

Ludwig, J., D. Tongway, D. Freudenberger, J. Noble, and K. Hodgkinson. 1997. Landscape ecology: Function and management - principles from Australia's rangelands. Collingwood, VIC, Australia: CSIRO.

Ludwig, J.A., B.P. Wilcox, D.D. Breshears, D.J. Tongway, and A.C. Imeson. 2005. Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. Ecology 86:288-297.

Luk, S.H., Q. Cai, and G.P. Wang. 1993. Effects of surface crusting and slope gradient on soil and water losses in the hilly loess region, North China. Catena 24:29-45.

Lund, H.G. 2007. Accounting for the world's rangelands. Rangelands 29:3-10.

Marzen, M., T. Iserloh, J.L.M.P. de Lima, W. Fister, and J.B. Ries. 2017. Impact of severe rain storms on soil erosion: Experimental evaluation of wind-driven rain and its implications for natural hazard management. Science of the Total Environment 590:502-513.

Mayaud, J.R., and N.P. Webb. 2017. Vegetation in drylands: Effects on wind flow and aeolian sediment transport. Land 6:64.

McCabe, G.J., and M.P. Clark. 2005. Trends and variability in snowmelt runoff in the western United States. Journal of Hydrometeorology 6:476-482.

McGlone, C.M., J.D. Springer, and W.W. Covington. 2009. Cheatgrass encroachment on a ponderosa pine forest ecological restoration project in Northern Arizona. Ecological Restoration 27:37-46.

McKeon, G.M., G.S. Stone, J.I. Syktus, J.O. Carter, N.R. Flood, D.G. Ahrens, D.N. Bruget, C.R. Chilcott, D.H. Cobon, R.A. Cowley, and S.J. Crimp. 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: A review of issues. The Rangeland Journal 31:1-29.

Meyer, G.A., and J.L. Pierce. 2003. Climatic controls on fire-induced sediment pulses in Yellowstone National Park and central Idaho: A long-term perspective. Forest Ecology and Management 178:89-104.

Meyer, G.A., J.L. Pierce, S.H. Wood, and A.J.T. Jull. 2001. Fire, storms, and erosional events in the Idaho batholith. Hydrological Processes 15:3025-3038.

Miller, M.E., M.A. Bowker, R.L. Reynolds, and H.L. Goldstein. 2012. Post-fire land treatments and wind erosion - Lessons from the Milford Flat Fire, UT, USA. Aeolian Research 16:29-44.

Miller, R.F., S.T. Knick, D.A. Pyke, C.W. Meinke, S.E. Hanser, M.J. Wisdom, and A.L. Hild. 2011. Characteristics of sagebrush habitats and limitations to long-term conservation. *In* Greater Sage-Grouse: Ecology and Conservation of a Landscape Species and Its Habitats, Studies in Avian Biology, Vol. 38, ed. S.T. Knick, J.W. Connelly, 145-184. Berkeley, CA: University of California Press.

Minshall, G.W., C.T. Robinson, D.E. Lawrence, D.A. Andrews, and J.T. Brock. 2001. Benthic macroinvertebrate assemblages in five central Idaho (USA) streams over a 10-year period following disturbance by wildfire. International Journal of Wildland Fire 10:201-213.

Mitchell, J.E. 2000. Rangeland Resource Trends in the United States: A technical Document Supporting the 2000 USDA Forest Service RPA Assessment. General Technical Report RMRS-GTR-68. Fort Collins, CO: USDA.

Moody, J.A., R.A. Shakesby, P.R. Robichaud, S.H. Cannon, and D.A. Martin. 2013. Current research issues related to post-wildfire runoff and erosion processes. Earth-Science Reviews 122:10-37.

Morgan, P., E.K. Heyerdahl, and C.E. Gibson. 2008. Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. Ecology 89:717-728.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86:39-49.

Munson, S.M., J. Belnap, and G.S. Okin. 2011. Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau. Proceedings of the National Academy of Sciences 108:3854-3959.

Nauman, T.W., M.C. Duniway, M.L. Villarreal, and T.B. Poitras. 2017. Disturbance automated reference toolset (DART): Assessing patterns in ecological recovery from energy development on the Colorado Plateau. Science of the Total Environment 584:476-488.

Nauman, T.W., M.C. Duniway, N.P. Webb, and J. Belnap. 2018. Elevated aeolian sediment transport on the Colorado Plateau, USA: the role of grazing, vehicle disturbance, and increasing aridity. Earth Surface Processes and Landforms. https://doi.org/10.1002/esp.4457.

Nayak, A., D. Marks, D.G. Chandler, and M. Seyfried. 2010. Long-term snow, climate, and streamflow trends at the Reynolds Creek Experimental Watershed, Owyhee Mountains, Idaho, United States. Water Resources Research 46:W06519.

Nearing, M.A. 2001. Potential changes in rainfall erosivity in the US with climate change during the 21st century. Journal of Soil and Water Conservation 56(3):229-232.

Nearing, M.A., V. Jetten, C. Baffaut, O. Cerdan, A. Couturier, M. Hernandez, Y. Le Bissonnais, M.H. Nichols, J.P. Nunes, C.S. Renschler, V. Souchère, and K. van Oost. 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61:131-154.

Nearing, M.A., H. Wei, J.J. Stone, F.B. Pierson, K.E. Spaeth, M.A. Weltz, D.C. Flanagan, and M. Hernandez. 2011. A rangeland hydrology and erosion model. Transactions of the ASABE 54:901-908.

Nearing, M.A., Y. Shui-qing, P. Borrelli, and V.O. Polyakov. 2017. Rainfall erosivity: An historical review. Catena 157:357-362.

Nelson, N.A., and J. Pierce. 2010. Late-Holocene relationships among fire, climate and vegetation in a forest-sagebrush ecotone of southwestern Idaho, USA. Holocene 20:1179-1194.

Newman, B.D., D.D. Breshears, and M.O. Gard. 2010. Evapotranspiration partitioning in a semiarid woodland: Ecohydrologic heterogeneity and connectivity of vegetation patches. Vadose Zone Journal 9:561-572.

Novlan, D.J., M. Hardiman, and T.E. Gill. 2007. A synoptic climatology of blowing dust events in El Paso, Texas from 1932–2005. *In* Preprints, 16th Conference on Applied Climatology. Boston, MA: American Meteorological Society.

Okin, G.S., D.A. Gillette, and J.E. Herrick. 2006. Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments. Journal of Arid Environments 65:253-275.

Okin, G.S., A.J. Parsons, J. Wainwright, J.E. Herrick, B.T. Bestelmeyer, D.C. Peters, and E.L. Fredrickson. 2009. Do changes in connectivity explain desertification? BioScience 59: 237-244.

Okin, G.S., O.E. Sala, E.R. Vivoni, J. Zhang, and A. Bhattachan. 2018. The interactive role of wind and water in functioning of drylands: What does the future hold? BioScience 68:670-677.

Palmquist, K.A., D.R. Schlaepfer, J.B. Bradford, and W.K. Lauenroth. 2016. Spatial and ecological variation in dryland ecohydrological responses to climate change: Implications for management. Ecosphere 7(11): e01590, doi: 10.1002/ecs2.1590.

Parsons, A.J., A.D. Abrahams, and J.R. Simanton. 1992. Microtopography and soil-surface materials on semi-arid piedmont hillslopes, southern Arizona. Journal of Arid Environments 22:107-115.

Parsons, A.J., A.D. Abrahams, and J. Wainwright. 1996a. Responses of interrill runoff and erosion rates to vegetation change in southern Arizona. Geomorphology 14:311-317.

Parsons, A.J., J. Wainwright, and A.D. Abrahams. 1996b. Runoff and erosion on semi-arid hillslopes. *In* Advances in Hillslope Processes, eds. M.G. Anderson and S.M. Brooks, 1061-1078. Chichester, UK: John Wiley and Sons.

Pederson, G.T., S.T. Gray, T. Ault, W. Marsh, D.B. Fagre, A.G. Bunn, C.A. Woodhouse, and L.J. Graumlich. 2011. Climatic controls on the snowmelt hydrology of the northern Rocky Mountains. Journal of Climate 24:1666-1687.

Pierce, J., and G. Meyer. 2008. Long-term fire history from alluvial fan sediments: The role of drought and climate variability, and implications for management of Rocky Mountain forests. International Journal of Wildland Fire 17:84-95.

Pierce, J.L., G.A. Meyer, and A.J.T. Jull. 2004. Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. Nature 432:87-90.

Pierce, J.L., G.A. Meyer, and T. Rittenour. 2011. The relation of Holocene fluvial terraces to changes in climate and sediment supply, South Fork Payette River, Idaho. Quaternary Science Reviews 30:628-645.

Pierson, F.B., J.D. Bates, T.J. Svejcar, and S.P. Hardegree. 2007. Runoff and erosion after cutting western juniper. Rangeland Ecology and Management 60:285-292.

Pierson, F.B., D.H. Carlson, and K.E. Spaeth. 2002. Impacts of wildfire on soil hydrological properties of steep sagebrush-steppe rangeland. International Journal of Wildland Fire 11:145-151.

Pierson, F.B., and C.J. Williams. 2016. Ecohydrologic impacts of rangeland fire on runoff and erosion: A literature Synthesis. General Technical Report RMRS-GTR 2016. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Pierson, F.B., C.J. Williams, S.P. Hardegree, P.E. Clark, P.R. Kormos, and O.Z. Al-Hamdan. 2013. Hydrologic and erosion responses of sagebrush steppe following juniper encroachment, wildfire, and tree cutting. Rangeland Ecology and Management 66:274-289.

Pierson, F.B., C.J. Williams, S.P. Hardegree, M.A. Weltz, J.J. Stone, and P.E. Clark. 2011. Fire, plant invasions, and erosion events on western rangelands. Rangeland Ecology and Management 64:439-449.

Pierson, F.B., C.J. Williams, P.R. Kormos, S.P. Hardegree, P.E. Clark, and B.M. Rau. 2010. Hydrologic vulnerability of sagebrush steppe following pinyon and juniper encroachment. Rangeland Ecology and Management 63:614-629.

Pilliod, D.S., J.L. Welty, and R.S. Arkle. 2017. Refining the cheatgrass-fire cycle in the Great Basin: Precipitation timing and fine fuel composition predict wildfire trends. Ecology and Evolution 7:9126-9151.

Polley, H.W., D.D. Briske, J.A. Morgan, K. Wolter, D.W. Bailey, and J.R. Brown. 2013. Climate change and North American rangelands: Trends, projections, and implications. Rangeland Ecology and Management 66:493-511.

Pu, B., and P. Ginoux. 2017. Projection of American dustiness in the late 21st century due to climate change. Scientific Reports 7:5553.

Puigdefabregas, J. 2005. The role of vegetation patterns in structuring runoff and sediment fluxes in drylands. Earth Surface Processes and Landforms 30:133-147.

Pyke, D., J.E. Herrick, P.L. Shaver, and M. Pellant. 2005. Rangeland health attributes and indicators for qualitative assessment. Journal of Range Management 55:584-597.

Redmond, M.D., N.S. Cobb, M.J. Clifford, and N.M. Barger. 2015. Woodland recovery following drought-induced tree mortality across an environmental stress gradient. Global Change Biology 21:3685-3695.

Redmond, M.D., N.S. Cobb, M.E. Miller, and N.M. Barger. 2013. Long-term effects of chaining treatments on vegetation structure in piñon–juniper woodlands of the Colorado Plateau. Forest Ecology and Management 305:120-128.

Reeves, M.C., and J.E. Mitchell. Extent of coterminous US rangelands: Quantifying implications of differing agency perspectives. Rangeland Ecology and Management 64:585-597.

Regonda, S.K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. Seasonal cycle shifts in hydroclimatology over the western United States. Journal of Climate 18:372-384.

Reid, K.D., B.P. Wilcox, D.D. Breshears, and L. MacDonald. 1999. Runoff and erosion in a pinon-juniper woodland: Influence of vegetation patches. Soil Science Society of America Journal 63:1869-1879.

Robertson, G.P., V.G. Allen, G. Boody, E.R. Boose, N.G. Creamer, L.E. Drinkwater, J.R. Gosz, L. Lynch, J.L. Havlin, L.E. Jackson, S.T. Pickett, L. Pitelka, A. Randall, A.S. Reed, T.R. Seastedt, R.B. Waide, and D.H. Wall. 2008. Long-term agricultural research: A research, education, and extension imperative. Bioscience 58:640–645.

Robichaud, P.R., L.E. Ashmun, and B.D. Sims. 2010. Post-fire treatment effectiveness for hillslope stabilization. General Technical Report RMRS-GTR-240. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Romme, W.H., C.D. Allen, J.D. Bailey, W.L. Baker, B.T. Bestelmeyer, P.M. Brown, K.S. Eisenhart, M.L. Floyd, D.W. Huffman, B.F. Jacobs, R.F. Miller, E.H. Muldavin, T.W. Swetnam, R.J. Tausch, and P.J. Weisberg. 2009. Historical and modern disturbance regimes, stand structures, and landscape dynamics in pinon-juniper vegetation of the western United States. Rangeland Ecology and Management 62:203-222.

Running, S.W. 2006. Is global warming causing more, larger wildfires? Science 313:927-928.

Sala, O.E., L.A. Gherardi, L. Reichmann, E. Jobbágy, and D. Peters. 2012. Legacies of precipitation fluctuations on primary production: Theory and data synthesis. Philosophical Transactions of the Royal Society B 367:3135-3144.

Salley, S.W., C.H. Monger, and J.R. Brown. 2016. Completing the land resource hierarchy. Rangelands 36:313-317.

Sankey, J.B., M.J. Germino, and N.F. Glenn. 2009. Aeolian sediment transport following wildfire in sagebrush steppe. Journal of Arid Environments 73:912-919.

Sankey, J.B., M.J. Germino, T.T. Sankey, and A.N. Hoover. 2012. Fire effects on the spatial patterning of soil properties in sagebrush steppe, USA: A meta-analysis. International Journal of Wildland Fire 21:545-556.

Schlesinger, W.H., J.A. Raikes, A.E. Hartley, and A.F. Cross. 1996. On the spatial pattern of soil nutrients in desert ecosystems. Ecology 77:364-374.

Schlesinger, W.H., J.F. Reynolds, G.L. Cunningham, L.F. Huenneke, W.M. Jarrell, R.A. Virginia, and W.G. Whitford. 1990. Biological feedbacks in global desertification. Science 247:1043-1048.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang. 2012. Changes in climate extremes and their impacts on the natural physical environment. *In* Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, eds. C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, 109-231. Cambridge: Cambridge University Press.

Shao, Y., K.H. Wyrwoll, A. Chappell, J. Huang, Z. Lin, G.H. McTainsh, M. Mikami, T.Y. Tanaka, X. Wang, and S. Yoon. 2011. Dust cycle: An emerging core theme in Earth system science. Aeolian Research 2:181-204.

Spiegal, S., B.T. Bestelmeyer, D.W. Archer, D.J. Augustine, E.H. Boughton, R.K. Boughton, M.A. Cavigelli, P.E. Clark, J.D. Derner, E.W. Duncan, C.J. Hapeman, R.D. Harmel, P. Heilman, M.A. Holly, D.R. Huggins, K. King, P.J. Kleinman, M.A. Liebig, M.A. Locke, G.W. McCarty, N. Millar, S.B. Mirsky, T.B. Moorman, F.B. Pierson, J.R. Rigby, G.P. Robertson, J.L. Steiner, T.C. Strickland, H.M. Swain, B.J. Wienhold, J.D. Wulfhorst, M.A. Yost, and

C.L. Walthal. 2018. Evaluating strategies for sustainable intensification of US agriculture through the Long-Term Agroecosystem Research network. Environmental Research Letters 13:034031.

Spracklen, D.V., L.J. Mickley, J.A. Logan, R.C. Hudman, R. Yevich, M.D. Flannigan, and A.L. Westerling. 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. Journal of Geophysical Research D: Atmospheres 114.

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

Swain, S., and K. Hayhoe. 2015. CMIP5 projected changes in spring and summer drought and wet conditions over North America. Climate Dynamics 44:2737-2750.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl. 2012. An overview of CMIP5 and the experimental design. Bulletin of the American Meteorological Society 93:485-498.

Thornton, P.K., J. van de Steeg, A. Notenbaert, and M. Herrero. 2009. The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. Agricultural Systems 101:113–127.

Toevs, G.R., J.W. Karl, J.T. Taylor, C.S. Spurrier, M. Karl, M.R. Bobo, and J.E. Herrick. 2011. Consistent indicators and methods and a scalable sample design to meet assessment, inventory, and monitoring information needs across scales. Rangelands 33:14-20.

Trenberth, K.E., L. Smith, T. Qian, A. Dai, and J. Fasullo. 2007. Estimates of the global water budget and its annual cycle using observational and model Data. Journal of Hydrometeorology 8:758-769.

Turnbull, L., J. Wainwright, and R.E. Brazier. 2008. A conceptual framework for understanding semi-arid land degradation: Ecohydrological interactions across multiple-space and time scales. Ecohydrology 1:23-34.

Turnbull, L., J. Wainwright, and R.E. Brazier. 2010. Changes in hydrology and erosion over a transition from grassland to shrubland. Hydrological Processes 24:393-414.

Turnbull, L., B.P. Wilcox, J. Belnap, S. Ravi, P. D'Odorico, D. Childers, W. Gwenzi, G. Okin, J. Wainwright, K.K. Caylor, and T. Sankey. 2012. Understanding the role of ecohydrological feedbacks in ecosystem state change in drylands. Ecohydrology 5:174-183.

Van Auken, O.W. 2000. Shrub invasions of North American semiarid grasslands. Annual Review of Ecology and Systematics 31:197-215.

Van Auken, O.W. 2009. Causes and consequences of woody plant encroachment into western North American grasslands. Journal of Environmental Management 90:2931-2942.

Vautard, R., J. Cattiaux, P. Yiou, J.-N. Thepaut, and P. Ciais. 2010. Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. Nature Geoscience 3:756-761.

Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner. 2017. Temperature changes in the United States. *In* Climate Science Special Report: Fourth National Climate Assessment, Volume I, eds. D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, 185-206. Washington, DC: US Global Change Research Program.

Wagenbrenner, N.S., M.J. Germino, B.K. Lamb, P.R. Robichaud, and R.B. Foltz. 2012. Wind erosion from a sagebrush steppe burned by wildfire: Measurements of PM 10 and total horizontal sediment flux. Aeolian Research 10:25-36.

Wainwright, J., A.J. Parsons, and A.D. Abrahams. 2000. Plot-scale studies of vegetation, overland flow and erosion interactions: Case studies from Arizona and New Mexico. Hydrological Processes 14:2921-2943.

Webb, N.P., J.E. Herrick, and M.C. Duniway. 2014. Ecological site-based assessments of wind and water erosion: Informing accelerated soil erosion management in rangelands. Ecological Applications 24:1405-1420.

Webb, N.P., J.E. Herrick, J.W. Van Zee, E.M. Courtright, C.H. Hugenholtz, T.M. Zobeck, G.S. Okin, T.E. Barchyn, B.J. Billings, R. Boyd, and S.D. Clingan. 2016. The National Wind Erosion Research Network: Building a standardized long-term data resource for aeolian research, modeling and land management. Aeolian Research 22:23-36.

Webb, N.P., N.A. Marshall, L.C. Stringer, M.S. Reed, A. Chappell, and J.E. Herrick. 2017. Land degradation and climate change: Building climate resilience in agriculture. Frontiers in Ecology and the Environment 15:450-459.

Webb, N.P., and C. Pierre. 2018. Quantifying anthropogenic dust emissions. Earth's Future 6:286-295.

Webb, N.P., C.J. Stokes, and J.C. Scanlan. 2012. Interacting effects of vegetation, soils and management on the sensitivity of Australian savanna rangelands to climate change. Climatic Change 112:925-943.

Webb, N.P., C.J. Stokes, and N.A. Marshall. 2013. Integrating biophysical and socio-economic evaluations to improve the efficacy of adaptation assessments for agriculture. Global Environmental Change 23:1164-1177.

Webb, N.P., and C.L. Strong. 2011. Soil erodibility dynamics and its representation for wind erosion and dust emission models. Aeolian Research 3:165-179.

Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande. 2017. Droughts, floods, and wildfires. *In* Climate Science Special Report: Fourth National Climate Assessment, Volume I, eds. D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, 231-256. Washington, DC: US Global Change Research Program.

Weltz, M.A., L. Jolley, M. Hernandez, K.E. Spaeth, C. Rossi, C. Talbot, M. Nearing, J. Stone, D. Goodrich, F. Pierson, H. Wei, and C. Morris. 2014. Estimating conservation needs for rangelands using USDA National Resources Inventory Assessments. Transactions of the ASABE 57(6):1559-1570.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase Western US forest wildfire activity. Science 313:940-943.

Whitlock, C., S.L. Shafer, and J. Marlon. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. Forest Ecology and Management 178:5-21.

Wilcox, B.P., D.D. Breshears, and C.D. Allen. 2003. Ecohydrology of a resource-conserving semiarid woodland: Effects of scale and disturbance. Ecological Monographs 73:223-239.

Wilcox, B.P., J. Pitlick, C.D. Allen, and D.W. Davenport. 1996. Runoff and erosion from a rapidly eroding pinyon-juniper hillslope. *In* Advances in Hillslope Processes, Volume 1, eds. M.G. Anderson and S.M. Brooks, 61-77. New York: John Wiley and Sons, Ltd.

Wilcox, B.P., L. Turnbull, M.H. Young, C.J. Williams, S. Ravi, M.S. Seyfried, D.R. Bowling, R.L. Scott, M.J. Germino, T.G. Caldwell, and J. Wainwright. 2012. Invasion of shrublands by exotic grasses: Ecohydrological consequences in cold versus warm deserts. Ecohydrology 5:160-173.

Williams, C.J., F.B. Pierson, O.Z. Al-Hamdan, P.R. Kormos, S.P. Hardegree, and P.E. Clark. 2014a. Can wildfire serve as an ecohydrologic threshold-reversal mechanism on juniper-encroached shrublands. Ecohydrology 7:453-477.

Williams, C.J., F.B. Pierson, P.R. Robichaud, O.Z. Al-Hamdan, J. Boll, and E.K. Strand. 2016a. Structural and functional connectivity as a driver of hillslope erosion following disturbance. International Journal of Wildland Fire 25:306-321.

Williams, C.J., F.B. Pierson, P.R. Robichaud, and J. Boll. 2014b. Hydrologic and erosion responses to wildfire along the rangeland-xeric forest continuum in the western US: A review and model of hydrologic vulnerability. International Journal of Wildland Fire 23:155-172.

Williams, C.J., F.B. Pierson, K.E. Spaeth, J.R. Brown, O.Z. Al-Hamdan, M.A. Weltz, M.A. Nearing, J.E. Herrick, J. Boll, P.R. Robichaud, D.C. Goodrich, P. Heilman, D.P. Guertin, M. Hernandez, H. Wei, S.P. Hardegree, E.K. Strand, J.D. Bates, L.J. Metz, and M.H. Nichols. 2016b. Incorporating hydrologic data and ecohydrologic relationships into ecological site descriptions. Rangeland Ecology and Management 69:4-19.

Williams, C.J., F.B. Pierson, K.E. Spaeth, J.R. Brown, O.Z. Al-Hamdan, M.A. Weltz, M.A. Nearing, J.E. Herrick, J. Boll, P.R. Robichaud, D.C. Goodrich, P. Heilman, D.P. Guertin, M. Hernandez, H. Wei, V.O. Polyakov, G. Armendariz, S.K. Nouwakpo, S.P. Hardegree, P.E. Clark, E.K. Strand, J.D. Bates, L.J. Metz, and M.H. Nichols. 2016c. Application of ecological site information to transformative changes on Great Basin sagebrush rangelands. Rangelands 38:379-388.

Wolfe, S.A., and W.G. Nickling. 1993. The protective role of sparse vegetation in wind erosion. Progress in Physical Geography 17:50-68.

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, B.C. Dokken, B.C. Stewart, and T.K. Maycock. 2017. Climate Science Special Report: Fourth National Climate Assessment, Volume I. Washington, DC: US Global Change Research Program.

Zhang, Y., M. Hernandez, E. Anson, M.A. Nearing, H. Wei, J.J. Stone, and P. Heilman. 2012. Modeling climate change effects on runoff and soil erosion in southeastern Arizona rangelands and implications for mitigation with conservation practices. Journal of Soil and Water Conservation 67(5):390-405, doi:10.2489/jswc.67.5.390.