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Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world

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Abstract. Erosion by wind is one of the principal processes associated with land degradation in drylands and is a significant concern to land managers and policymakers globally. In the drylands of North America, millions of tons of soil are lost to wind erosion annually. Of the 60 million ha in the United States identified as most vulnerable to wind erosion (arid and dominated by fine sandy soils), 64% are managed by federal agencies (37 million ha). Here we review the drivers and consequences of wind erosion and dust emissions on drylands in the United States, with an emphasis on actionable responses available to policymakers and practitioners. We find that while dryland soils are often relatively stable when intact, disturbances including fire, domestic livestock grazing, and off-highway vehicles can increase horizontal eolian flux by an order of magnitude, in some cases as much as 40-fold. A growing body of literature documents the large-scale impacts of deposited dust changing the albedo of mountain snow cover and in some cases reducing regional water supplies by ~5%. Predicted future increases in aridity and extreme weather events, including drought, will likely increase wind erosion and consequent dust generation. Under a drier and more variable future climate, new and existing soil- and vegetation-disturbing practices may interact in synergistic ways, with dire consequences for environments and society that are unforeseen to many but fairly predictable given current scientific understanding. Conventional restoration and reclamation approaches, which often entail surface disturbance and rely on adequate moisture to prevent erosion, also carry considerable erosion risk especially under drought conditions. Innovative approaches to dryland restoration that minimize surface disturbance may accomplish restoration or reclamation goals while limiting wind erosion risk. Finally, multidisciplinary and multijurisdictional approaches and perspectives are necessary to understand the complex processes driving dust emissions and provide timely, context-specific information for mitigating the drivers and impacts of wind erosion and dust.

Key words: abatement; fugitive dust; land use; livestock; off-road vehicles; oil and gas; restoration; wind erosion.

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Introduction

Wind-driven erosion of topsoil and dust emissions in drylands threaten environmental, economic, and human health globally (Okin et al. 2011, ELD Initiative 2015, UNEP, WMO, and UNCCD 2016). Soil erosion by wind is one of the principal processes associated with land degradation in drylands (i.e., desertification), resulting in a loss of soil and plant productivity (Khalaf 1989, Schlesinger et al. 1990, Okin et al. 2001, 2006, Ravi 2011). Economic impacts of wind erosion and atmospheric dust include loss of agricultural productivity, damage to property and equipment, and reductions in snow pack and water supply (Painter et al. 2010, Joyce et al. 2013, Clow et al. 2016). Furthermore, atmospheric dust can reduce visibility, impact culturally important view sheds, increase traffic fatalities, and is implicated in a suite of respiratory ailments (Comrie 2005, Cook et al. 2005, Kavouras et al. 2009, Goudie 2014, Li et al. 2018). Ecological processes and human activities that exacerbate wind erosion and dust emissions have broad-scale implications for the functioning of global drylands and their residents, including those in the western United States.

In the United States, drylands (defined here as areas with an aridity index of ≤0.5; Schlaepfer 2017) are confined to western regions, and more than a third of these areas are managed as public lands (Fig. 1a–c). The Bureau of Land Management (BLM) is the largest manager of drylands in the United States (21%), followed by the US Forest Service (8%) and the Bureau of Indian Affairs (6%). Most US drylands are managed by state and private owners, and these areas tend to fall within the more productive (mesic) regions of the landscape, due to patterns in productivity and resulting colonization. Consequently, areas which are dry, dominated by erodible surface textures (Fig. 1d), and thus most susceptible to wind erosion (Fig. 1e), are disproportionately managed by federal agencies (~64%; Fig. 1f). These arid and semi-arid western rangelands, combined with cultivated drylands of the southwest and Great Plains, comprise the regions of the United States most susceptible to wind erosion and associated soil loss (Middleton and Thomas 1997).

A large proportion of US drylands have undergone some level of degradation caused by historical and current land use, fire, and increasing aridity (Millennium Ecosystem Assessment 2005, Pielke 2005, Neff et al. 2008, Balch et al. 2013, Sanderman et al. 2017, Sankey et al. 2017). Assessments of western rangelands by the USDA Natural Resource Conservation Service suggest that ~21% of the region has been degraded to some degree (Herrick et al. 2010). Although North America is responsible for only a small proportion of global dust emissions (~5.2%; Ravi 2011), local and regional atmospheric dust emissions in western US drylands are increasing (Reynolds et al. 2001, Brahney et al. 2013, Hand et al. 2017).

Managing wind erosion of surface soils and consequent dust generation in US drylands is challenging due to complex interactions among driving forces (e.g., economics and policy), pressures (e.g., weather, climate, fire, land use), and ecosystem states (e.g., topographic setting, vegetation, and soils), making effective mitigation responses difficult (Fig. 2). At the local scale, land use often modifies vegetation and soil properties such that wind erosion vulnerability is exacerbated (Fig. 3). Wind erosion and dust emissions have been shown to be linearly related (Gillette et al. 1997, Houser and Nickling 2001) but are important to differentiate, as they have different ecological and human impacts. We use the term *wind erosion* to describe more local-scale eolian processes, including the movement, deposition, and net loss of soil material. We use the term *dust* when referring to airborne particulate matter which are entrained into the atmosphere and transported across local, regional, and global scales.

The goal of this article is to provide a review of the drivers and consequences of wind erosion and dust emissions on drylands in the United States. Given that the vast majority of dry, western U.S. lands are highly sensitive to wind erosion and are managed by federal or state agencies (Fig. 1f), we focus here on wind erosion and dust originating from undeveloped drylands (e.g., non-cultivated and non-urban), including fugitive dust. We review the land use and climate pressures (direct drivers) of wind erosion, along with the potential impacts of wind erosion and dust on ecosystems, economics, and human health and well-being (Fig. 2). We conclude by discussing possible management responses, including approaches to mitigate wind erosion and restore wind-eroded areas, and highlight key knowledge gaps.

Mediating Ecosystem Properties

Wind erosion is mitigated by (1) factors that promote the cohesion of soil particles (i.e.,

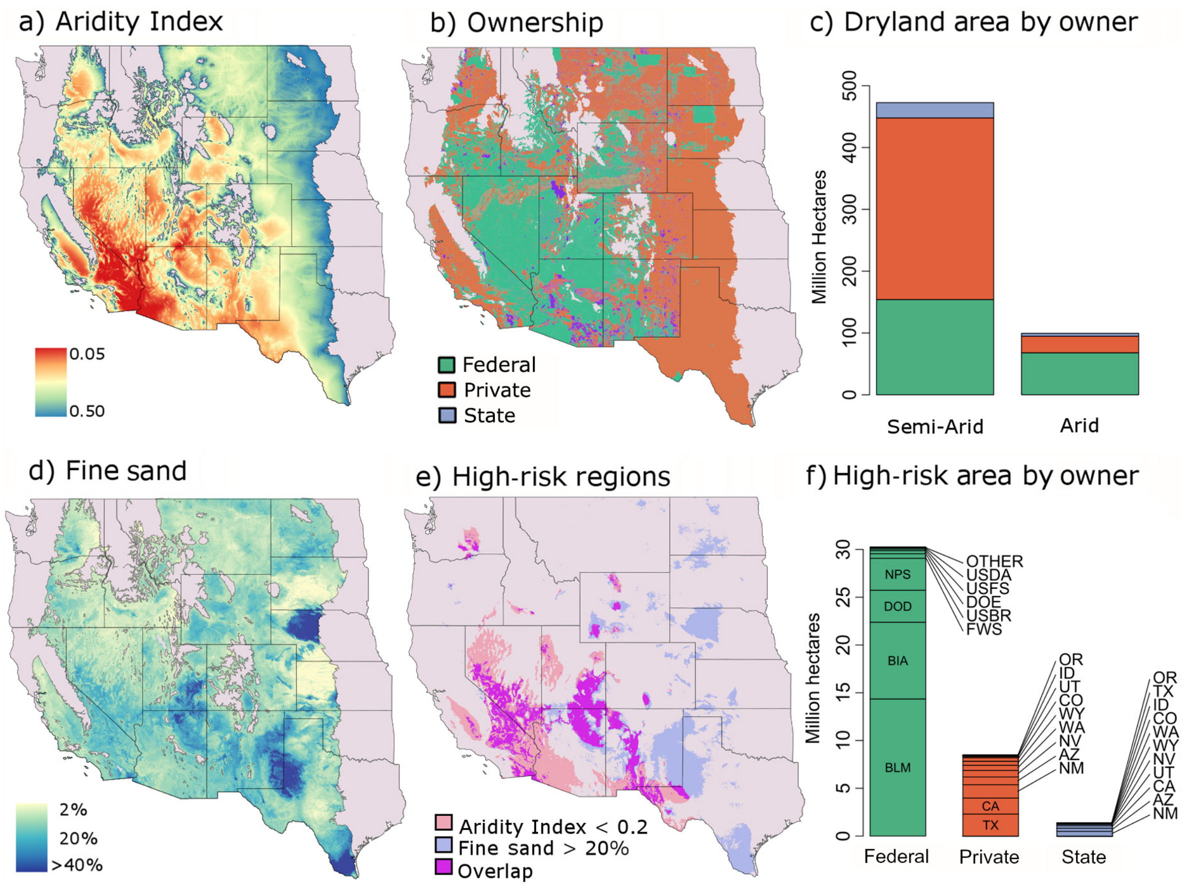

Fig. 1. Dust emission sensitivity and ownership in western US drylands. Aridity index (AI) calculated as total annual precipitation divided by potential evapotranspiration (PPT:PET) for regions with AI ≤ 0.5 (a). Dryland surface area according to ownership type (Federal, State, or Private) and aridity (semi-arid 0.5–0.2 and arid <0.2; b and c). Percent fine sand (particles 100–250 μm) content by mass of soil fines (<2 mm) in dryland surface soil (d). Regions to be considered as high risk for dust emissions based on prevalence of fine sands and aridity (e). Tabulated areal ownership of land in the highest risk category (fine sand >20% and AI < 0.2) by agency for federal land and state by private and state-owned land (f). Soils with higher percentages of fine sand have been shown to be more susceptible to eolian destabilization when a site is disturbed (Marticorena and Bergametti 1995, Okin et al. 2006, Belnap et al. 2007, Field et al. 2010). The fine sand map was created using a quantile regression forest with same predictor database as Ramcharan et al. (2018) by training with georeferenced samples in the U.S. National Cooperative Soil Survey soil characterization database. Details of the mapping and soil modeling are in Supporting information. BLM, Bureau of Land Management; BIA, Bureau of Indian Affairs; DOD, Department of Defense; NPS, National Park Service; FWS, Fish and Wildlife Service; USBR, US Bureau of Reclamation; DOE, Department of Energy; USFS, US Forest Service; USDA, US Department of Agriculture (exclusive of USFS).

presence of crusts, soil aggregates, and moisture; Fig. 3), (2) presence of large non-erodible objects in the soil matrix (i.e., rocks, embedded plant litter), and (3) surface roughness elements which create turbulence and reduce soil surface wind velocities (i.e., plant canopies, surface topography, large rocks; Musick and Gillette 1990, Lee 1991, Gillies et al. 2006, 2007, Field et al. 2010, Chappell and Webb 2016). The degree of protective sheltering by roughness elements depends on the size and orientation of gaps between vegetation patches, as well as vegetation

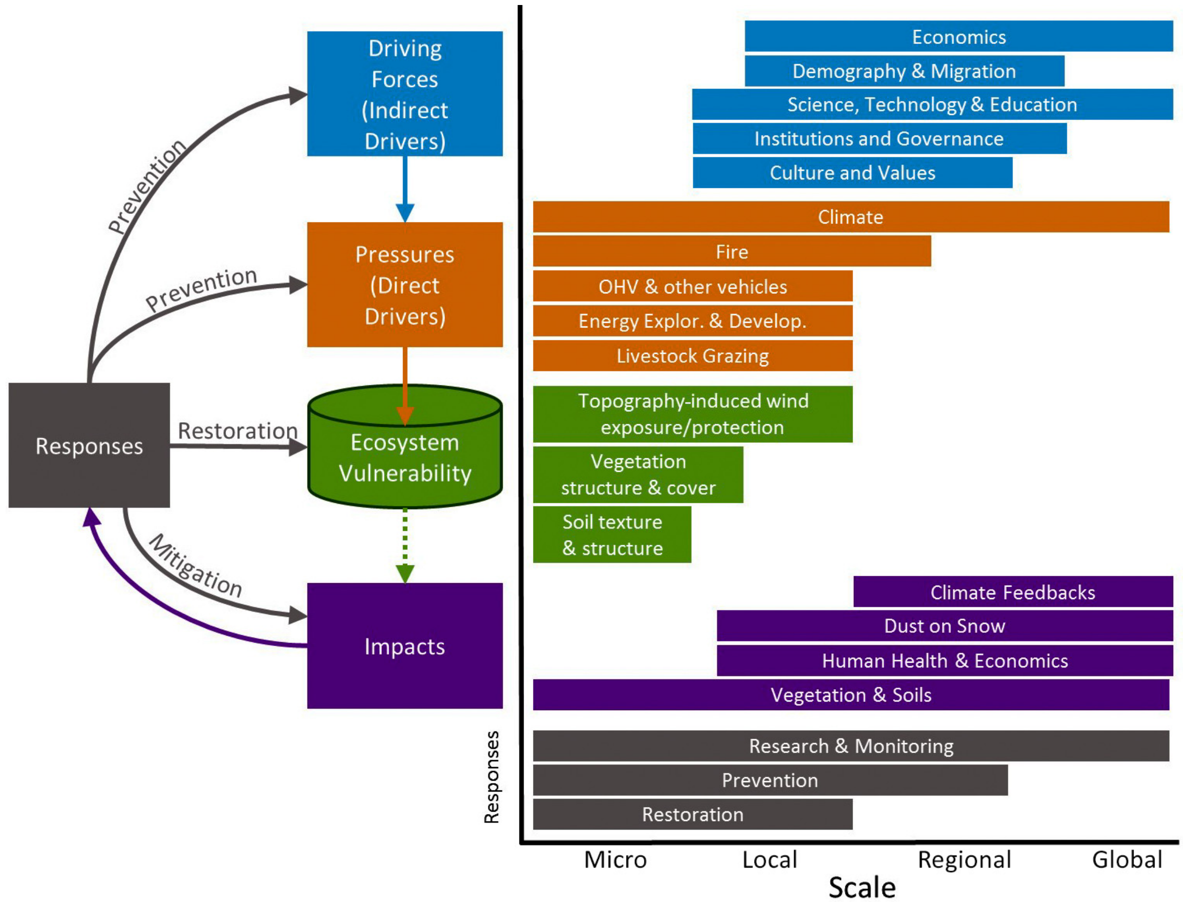

Fig. 2. A framework coupling human actions to impacts on dust production as well as providing a response framework for decision makers (left; adapted from European Environment Agency; Smeets and Weterings 1999) and examples of processes or properties within the framework classes and the scales over which they operate (right). In this conceptual model, driving forces operating at medium to broad scales affect pressures (direct drivers of dust) occurring at all scales. The dust impacts are then mediated by ecosystem properties that control ecosystem vulnerability to wind erosion and dust production (for a given set of direct drivers). Responses include prevention measures (e.g., new policy to affect driving forces or land management decisions that modify pressures), restoration of ecosystems (to reduce vulnerability), and mitigation (e.g., keeping at risk populations inside on bad air days). See Appendix S2 for a summary of key literature on drivers, impacts, and tools and strategies.

height and porosity (Okin et al. 2006, Li et al. 2007, Mayaud et al. 2016). In general, larger gaps and lower statured vegetation will result in higher wind speeds at the soil surface and, thus, greater potential erosion of surface soils, although intermediate densities of objects can create scouring turbulences, as with certain shrublands (Gillette et al. 1996, King et al. 2006). Horizontal sediment flux has been found to be higher in shrublands (large canopy gaps) than in grasslands (low connectivity of unvegetated patches but also low stature) and forests (high stature and low connectivity) by one and two orders of magnitude, respectively (Breshears et al. 2003). As such, conversion of grasslands or forests into shrublands could dramatically increase sediment production (Bergametti and Gillette 2010).

Due to the importance of plants in reducing erosion, plant species life history (i.e., annual

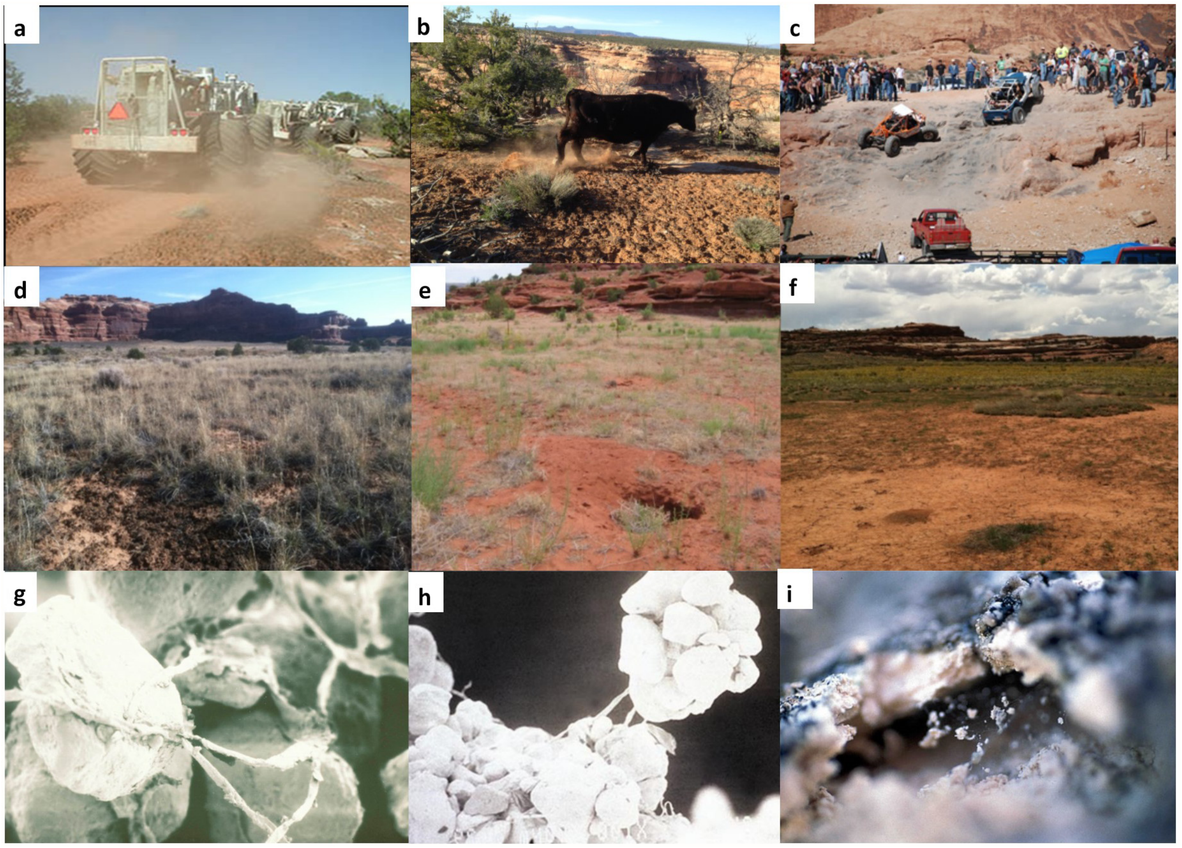

Fig. 3. Examples of pressures (direct drivers) of dust production (a–c) and ecosystem state variables mitigate or exacerbate wind erosion (d–i). Energy exploration (a), domestic livestock trampling (b), and off-highway vehicles (c). Example ecosystem conditions with differing dust vulnerability: intact perennial grass and biological soil crusts (d), perennial cover with loss of stabilizing biological soil crusts (e), and loss of both perennial vegetation and biological soil crusts (f). Close-up photographs demonstrating the role cyanobacteria in biological soils crusts play in aggregating sands and increasing wind resistance in deserts: polysaccharide sheaths holding individual sand grains (g) and soil aggregates (h), and biological soil crusts resisting erosion at high wind speeds within a wind tunnel (i).

versus perennial) is an important factor affecting soil surface vulnerability to wind erosion. Dust production in annual-dominated communities may be particularly linked to climate due to the high inter-annual variability in annual plant cover following fluctuations in soil moisture (Okin et al. 2011). Well-developed biological soil crusts ("biocrusts", i.e., communities of soil surface dwelling cyanobacteria, mosses, and lichens) can also stabilize soil surfaces even in the absence of plant cover as biocrust cover is not affected by short-term precipitation patterns (Fig. 3d; Munson et al. 2011). Although biocrusts are resistant to erosion by wind, even under very high wind speeds (Fig. 3i; Marticorena et al. 1997), they become susceptible to erosion by wind following disturbance of the soil surface (Belnap and Gillette 1997, 1998). Compressional disturbance such as the type produced by large ungulate grazers (Belnap et al. 2009) or off-highway vehicles (OHVs; Belnap et al. 2007) may produce this effect. The cyanobacterial filaments which predominate in biocrusts confer very high shear strength (Fig. 3g, h), but little compressional strength and thus are easily crushed (Belnap and Eldridge 2003).

Whereas wind erosion and dust emissions can be mitigated or exacerbated by local conditions and land use, certain climate, soil, and topographic settings are broadly recognized to be prone to dust production (Fig. 1e; Reheis and Kihl 1995, Gillette 1999, Prospero et al. 2002, Okin et al. 2011, Hahnenberger and Nicoll 2014). Erodible landscape settings tend to share key characteristics including (1) loose, dry, and finely granulated soil; (2) smooth soil surfaces with sparse or absent vegetation; and (3) a sufficiently large susceptible area. While such conditions naturally exist in dryland ecosystems west of the 100th meridian in the United States (Fig. 1; Lyles and Tatarko 1986), particularly lake beds or other fluvial settings which can be substantial dust sources (Reheis and Kihl 1995, Reheis 1997), high eolian fluxes observed in many areas result from current or historic human land use (Reheis et al. 2009).

Pressures

Soil surface-disturbing activities such as livestock grazing, off-highway vehicle use, wildland fire, and energy exploration and development increase wind erosion and dust production (Figs. 3, 4; Belnap and Gillette 1997, 1998, Belnap et al. 2007, Neff et al. 2008, Miller et al. 2012, Nauman et al. 2018). In the absence of surface disturbance or fire, many drylands of the western United States can be relatively stable and often produce minimal amounts of dust (Fig. 4; Field et al. 2010). For example, studies of lake sediments in the San Juan Mountains of southern Colorado suggest that dust input rates from upwind drylands prior to European settlement of the western United States during the 19th century were over five times lower than current rates (Neff et al. 2008). Changes to the frequency and/or intensity of fire regimes in western drylands over the previous century, due to a combination of land use, land management (including fire suppression), and species invasions, have been implicated in increased dust emissions (Vermeire et al. 2005, Whicker et al. 2006*a,b*, Miller et al. 2012, Dukes et al. 2018). Forecasted increases in aridity and decreases in soil moisture for drylands globally (Schlaepfer 2017) and for US drylands in particular (Cook et al. 2015, Ault et al. 2016) will likely amplify dust risks posed by these drivers (Achakulwisut et al. 2018).

Livestock Grazing

Grazing by domestic and native ungulates disrupts the soil surface (Fig. 3b), particularly physical and biological crusts, increasing soil erodibility, and the amount of loose sediment available for dust production (Belnap 2003). Following extensive western US settlement during the 19th century, dust-load increased ~500% above the late Holocene average due to a combination of drought and the expansion of livestock grazing in early 1800s (Neff et al. 2008). This interaction of land use, dry conditions, and dust still occurs today (Reynolds et al. 2001, Brahney et al. 2013) and will likely become increasingly important under future, drier conditions (Cook et al. 2015, Achakulwisut et al. 2018).

Grazing alters the cover, species composition, and structure of dryland plant and biological crust communities, although these impacts depend on the timing, intensity, as well as duration of grazing, and the evolutionary history and resilience of the plants and soils to herbivory and associated trampling (Mack and Thompson 1982, Fleischner 1994, Webb and Strong 2011, Aubault et al. 2015). In the short term, removal of plant biomass decreases plant height and cover, and trampling reduces the ability of biological and physical crusts to stabilize soil surfaces; these factors, in turn, decrease surface roughness and increase soil vulnerability to wind erosion (Belnap 2003, Hayes and Holl 2003). Over longer periods of grazing in drylands, selective herbivory and differing herbivory tolerances among plant species often lead to increased woody and exotic annual species cover, decreased perennial grass and biological crust cover and diversity, and increased connectivity of bare patches between perennial plants (Fleischner 1994, Cole et al. 1997, Harris et al. 2003, Hayes and Holl 2003, Duniway et al. 2018).

Climatic context mediates both short- and long-term impacts of grazing on vegetation and resulting wind erosion. In particular, relatively mesic and productive grasslands, such as the US Great Plains, tend to be resilient to (or even dependent on) large ungulate grazing (Mack and Thompson 1982), with little evidence of altered eolian processes in response to most grazing regimes (Follett et al. 2001, Field et al. 2011). By contrast, more arid regions show pronounced eolian responses to grazing due to loss of plant

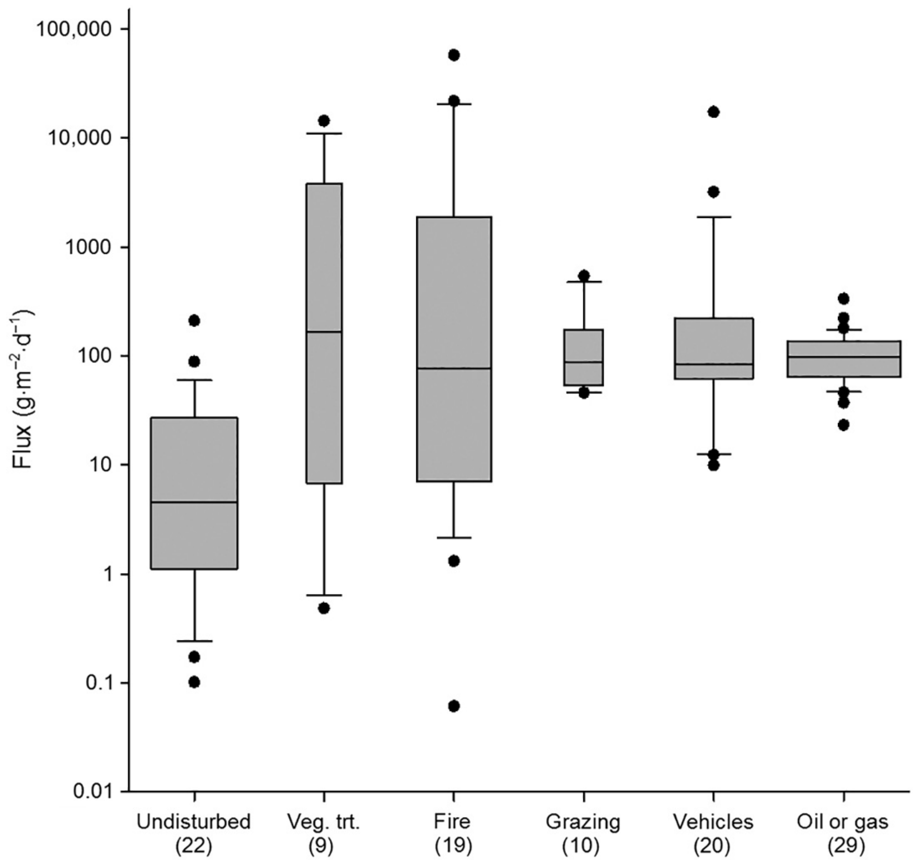

Fig. 4. Horizontal sediment mass flux from North American drylands organized into five disturbance settings: undisturbed ("control" plots in disturbance studies or sites receiving minimal or no disturbance), vegetation treatment (vegetation cutting, thinning, or removing), fire (prescribed, experimental, or wildfire), grazing (general or experimental livestock grazing), vehicles (off-highway or unpaved roads), and oil or gas (plugged and abandoned oil or natural gas pads). Data are plotted on a logarithmic scale, with median and interquartile ranges indicated by boxes, 5th and 95th quantile with whiskers, and outliers with dots. Parenthetical values after x-axis labels indicate number of values in each category. Data and sources are available in Appendix S3.

and biocrust cover, community shifts, and often synergistic interactions between the two processes (Neff et al. 2005, Belnap et al. 2009, Flagg et al. 2014). Sediment mass flux on the Colorado Plateau is generally 3–12 times higher with grazing depending on intensity and physical characteristics of the site (Fig. 4; Nauman et al. 2018). Climate conditions, in particular drought, may exacerbate the effect of grazing. For example, on the Colorado Plateau, currently grazed sites consistently produce 2.8 times more sediment than currently ungrazed sites during average and above-average precipitation years and up to a 50- to 100-fold increase in drought years (Belnap et al. 2009, Nauman et al. 2018).

Off-highway Vehicle and Other Vehicle Use

Unpaved road networks and OHV use can also increase dust emissions from western US drylands (Figs. 3a, c, 4; Forman 2003, Ouren et al. 2007, Duniway and Herrick 2011). Unpaved roads, either established by use or engineered, generally involve removal of all vegetation and compaction of soils, resulting in large, connected reaches of exposed soil subject to wind erosion (Wilshire 1983, Brooks and Lair 2005). Horizontal eolian fluxes have been shown to be generally sevenfold to eightfold greater, but as much as 43 times greater, adjacent to unpaved roads than in comparable non-road areas (Fig. 4), with dust emissions from unpaved road traffic increasing linearly with vehicle weight and speed (Gillies et al. 2005, Goossens and Buck 2009*a*, Kuhns et al. 2010). Dust emissions from OHV recreation areas can be substantial (Goossens and Buck 2009*b*); for example, sediment mass flux is on average 61 times higher in OHV areas, with one of the higher horizontal sediment flux values measured using comparable methods (17,141 $g \cdot m^{-2} \cdot d^{-1}$) in an area open to cross-country travel near Hanksville, UT (Fig. 4). Additionally, excessive foot traffic has been shown to increase sediment production threefold to eightfold and estimated soil erosion rates up to 28-fold (based on military training activities; Whitecotton et al. 2000, Belnap et al. 2007). Notably, while the number of domestic livestock on western public lands is relatively stable or decreasing (Copeland et al. 2017), the size of unpaved road networks and amount of OHV traffic is increasing dramatically due to both energy development and recreational use (Watts et al. 2007, Leu et al. 2008, Allred et al. 2015). Unpaved road networks may therefore be increasingly important sources of dust emissions now and in the future.

Energy Exploration and Development

Energy exploration and development, both traditional and alternative, has expanded rapidly in recent decades in US drylands (e.g., Fig. 3a). Approximately 3 million ha of land was cleared for oil and gas development (roads, pads, pipelines) between 2000 and 2012 in a study area that spans the central United States through central provinces of Canada (Allred et al. 2015). Over a similar time period on the Colorado Plateau, the cumulative number of oil or gas wells nearly exponentially increased (Copeland et al. 2017). This rapid rise in oil and gas activity was spurred in large part by new technologies (hydraulic fracturing ["fracking"] and directional drilling) which have also resulted in the development of larger pads. In the Piceance Basin of northwestern Colorado, Martinez and Preston (2018) documented a ~4-fold increase in area disturbed by energy development between 2001 and 2016. This increase was driven by the doubling of the number of pads as well as a ~3.5-fold increase in average pad size (from a mean of 0.34 ha for pre-2001 pads to 1.2 ha for pads developed in 2012–2016; Martinez and Preston 2018).

Oil or gas wells are often in a production phase for many years and, when production slows or stops, are capped and reclaimed (termed "plugged and abandoned"). However, recovery of plugged and abandoned oil or gas pads in drylands of the western United States is slow and marked by varying success. In a study of abandoned well pads on the Colorado Plateau, approximately half of the well pads analyzed (1866 total) had more exposed surface bare ground than 75% of neighboring reference areas (based on a remote sensing and with 9–17 yr postabandonment; Nauman et al. 2017). Similarly, time-series remote sensing work in the same region suggests only about one-third of the 388 pads analyzed had at least 50% recovery of vegetative cover after 5 yr (Waller et al. 2018).

Research on how soils and vegetation mediate vulnerability to wind erosion (Figs. 2, 3; Okin 2008, Field et al. 2010) suggests that areas with extensive energy exploration and development are likely significant dust sources due to (1) the large amount of area from which vegetation is removed and soils are disturbed (Allred et al. 2015, Martinez and Preston 2018), (2) the long duration of production, and (3) extended periods of time before reclamation successfully stabilizes plugged and abandoned pads (Nauman et al. 2017, Waller et al. 2018). Trends in oil and gas development, coupled with low rates of reclamation success, suggest a potential role of these activities in regional wind erosion and increases in atmospheric dust, particularly in dry and erodible soils of the southwestern United States (Fig. 1e). For example, a monitoring network of passive aspirated dust traps (Big Springs Number Eight samplers; Nauman et al. 2018) shows some of the greatest horizontal eolian flux occurring adjacent to roads that provide access to active oil or gas wells, likely due to both the preponderance of heavy vehicles, high vehicle speeds, and amount of traffic in these areas (Gillies et al. 2005). Preliminary data shown in Fig. 4 suggest oil and gas pads that have been abandoned for many years to several decades still have 10-fold greater horizontal eolian flux than undisturbed lands. However, literature comparing wind erosion rates on and off oil and gas pads and/or evaluating the cumulative contribution of energy development to regional dust is generally lacking, indicating a clear research need.

Fire

Although more episodic than grazing and recreational use in the western United States (Field et al. 2010), fire can nonetheless increase regional wind erosion substantially (Fig. 4; Whicker et al. 2002, Vermeire et al. 2005, Breshears et al. 2009, Field et al. 2011, Miller et al. 2012, Dukes et al. 2018). In the short term, fire increases the susceptibility of soils to erosion by removing vegetation and biocrust cover (Ravi 2011). Depending on the type of vegetation present (DeBano 2000), fire may also alter the physical and chemical properties of soils, disrupting inter-particle wet-bonding forces and ultimately decreasing the threshold friction velocity of soils, thereby increasing susceptibility to wind erosion (Whicker et al. 2002, Ravi et al. 2007, 2009, Field et al. 2010, Miller et al. 2012).

As with other land-use disturbances, the longevity of post-fire effects on wind erosion and dust emission rates depends on various factors including intensity, duration, timing, and, importantly, climatic context (Vermeire et al. 2005, Field et al. 2010). For example, in a cold desert shrub steppe, Sankey et al. (2009) found that sediment transport initially increased post-fire, then quickly dropped to levels only slightly higher than unburned areas following the first spring green-up. By contrast, increased erosion has been shown to persist up to 5–10 yr post-fire in warmer, sandier regions (Wasson and Nanninga 1986, Wiggs et al. 1994).

Climate

Increasing aridity has exacerbated dusty conditions in the western United States (Hand et al. 2017) and will likely continue to do so throughout the 21st century with projected climate change (Seager 2007, Munson et al. 2011, Achakulwisut et al. 2018). Aridity influences dust emissions through three mechanisms. First, lower soil moisture contents associated with aridity reduce cohesion and aggregate formation among soil particles, thereby increasing soil erodibility (Chepil 1956, Shao 2001). Second, because vegetation productivity and composition in drylands is primarily limited by water availability (Noy-Meir 1973), reductions in soil water availability, such as during drought, will reduce vegetative cover and increase the size of gaps between plants, thereby increasing the amount of soil exposed to wind (Okin 2008, Munson et al. 2011). These effects are especially apparent in areas dominated by annual plants, such as *Bromus tectorum*, as annuals tend to be sparse or absent during droughts. Third, the recovery of physical and biological crusts is slowed, thus leaving disturbed soils vulnerable to erosion longer. The synergistic interplay between drying of surface soils and reductions in protective covers is the likely mechanism behind observed increases in sediment fluxes locally (Urban et al. 2009, Flagg et al. 2014) and regional dust emissions (Reynolds et al. 2001, Achakulwisut et al. 2017, Hand et al. 2017) and globally (Mahowald 2010, UNEP, WMO, and UNCCD 2016).

Dust emissions are also influenced by global weather phenomena as manifestations of regional climatic patterns, including the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO; Achakulwisut et al. 2017). In an analysis of 2002–2015 satellite-based dust observations, inter-annual variation of dust in the southwestern United States can be explained by three factors: (1) regional winter and spring precipitation and temperature anomalies, (2) winter and spring soil moisture, and (3) strength of trans-Pacific Asian dust transport in March (Achakulwisut et al. 2017). These results suggest regional hydro-climatic variability in the preceding winter and/or concurrent spring can predict springtime activity of fine dust (<2.5 μm). For example, when both ENSO and PDO are in negative phases during winter/early spring, southwestern US drylands experience drought, which will likely increase springtime fine dust levels (Achakulwisut et al. 2018). Indeed, fine dust particles at monitoring sites across the southwest respond together to broad climate drivers, with the strongest predictors of fine dust being climate over the previous two months (seasonal r^2 ranging from 0.36 to 0.71) (Achakulwisut et al. 2018).

Impacts

Dust transport is distinct from other modes of soil erosion because it can occur across a wide range of scales, from tens of meters to thousands of kilometers (McTainsh and Strong 2007), with the impacts also ranging from local to global

(Fig. 2). For example, dust from drylands can stimulate flushes of oceanic productivity and can be an important nutrient input to terrestrial ecosystems (Chadwick et al. 1999, Koren et al. 2006, Reynolds et al. 2006, Mahowald 2010). Here, we briefly review the impacts of dust with a focus on ecosystem services and human well-being in drylands of the western United States (Fig. 1).

Vegetation and Soils

At local scales, wind erosion of soils via creep, saltation, suspension, and loss of particles as dust can have profound effects on ecosystems (Field et al. 2010). Although plant cover, composition, and structure influence wind erosion and dust emission rates (Li et al. 2007, Okin 2008), wind erosion also shapes plant and biological crust communities via abrasion (Duniway et al. 2015) and burial by surface creep and saltating sands (Okin et al. 2001, Field et al. 2010, Pointing and Belnap 2014). Abrasion can reduce plant biomass, leaf area, and survival (Armbrust and Retta 2000), with seedlings being especially susceptible to sandblasting (Skidmore 1966). Physical damage to plants and biological soil crusts from eolian transport can lead to decreased plant size, productivity, and survivorship (McTainsh and Strong 2007, Ouren et al. 2007, Pointing and Belnap 2014). Additionally, loss of fine material from surface soils through winnowing can reduce the supply of many plant-essential nutrients including Na, P, K, and Mg (Neff et al. 2005, Li et al. 2007); such nutrient loss can have significant impacts on ecosystems given the already low fertility of many dryland soils (Reynolds et al. 2001, Okin et al. 2006, Li et al. 2007). Saltation-driven particle emission causes the depletion of mineral and organic fine particles that results in the coarsening of topsoils and reduction of soil organic matter. These changes in turn reduce soil fertility and soil water holding capacity, and may eventually lead to shifts in plant communities and opportunistic invasion of undesirable species (Lyles and Tatarko 1986, Belnap et al. 2009, Thomas and Redsteer 2016). Indeed, much of the nutrient concentrations currently found in Colorado Plateau soils have likely been deposited by past dust inputs, and the loss of this input via wind erosion today may profoundly affect ecosystem productivity (Reynolds et al. 2001).

Dust on Snow

Dryland dust emissions can affect downwind mountain ecosystems and regional water supplies. Soil erosion by spring winds in drylands with high amounts of exposed bare soil results in entrained dust that is deposited on downwind mountain snow cover (Fig. 5c; Painter et al. 2007, 2010, Li et al. 2013). Dust deposited on snow changes snow albedo and increases radiative forcing to result in earlier snow melt (Painter et al. 2018). This phenomenon is best quantified in the Rocky Mountains of southwest Colorado (Painter et al. 2007, 2010), but has also been documented in the Wasatch Mountains of Utah (Carling et al. 2012) and the Caucasus Mountains of West Asia (Kutuzov et al. 2013), among other regions.

A strong latitudinal gradient in mean snowpack Ca^{2+} concentrations (a proxy for dust deposition) suggests eastward dust movement from the southwestern United States to the Rocky Mountains (Clow et al. 2016). Dust deposition on snowpack increased by 81% from 1993 to 2014 in the southern Rocky Mountains, and during that same time period snowmelt timing became earlier by 7–18 d, likely due to the combination of decreased snowfall and increased dust deposition during spring (Clow et al. 2016). Other studies have documented dust on snow causing snowmelt to advance by up to 51 d in this region (Painter et al. 2007, Skiles et al. 2012).

These inputs of dust, and associated impacts on snow-cover duration and mountain soil fertility and chemistry, can have large effects on western US alpine ecosystems (Painter et al. 2007, Steltzer et al. 2009, Rhoades et al. 2010, Carling et al. 2012, Skiles et al. 2012). Dust inputs to these areas have been shown to increase snow-cover electrical conductivity, pH, and ion concentrations, with the changes to snow chemistry more pronounced at higher elevations above tree line (Rhoades et al. 2010, Carling et al. 2012). Dust falling on alpine environments has been shown to increase lake nutrient loads by as much as twofold to threefold, with large implications for the functioning of these remote aquatic systems, much of which is attributed to relatively recent human activity in adjoining drylands

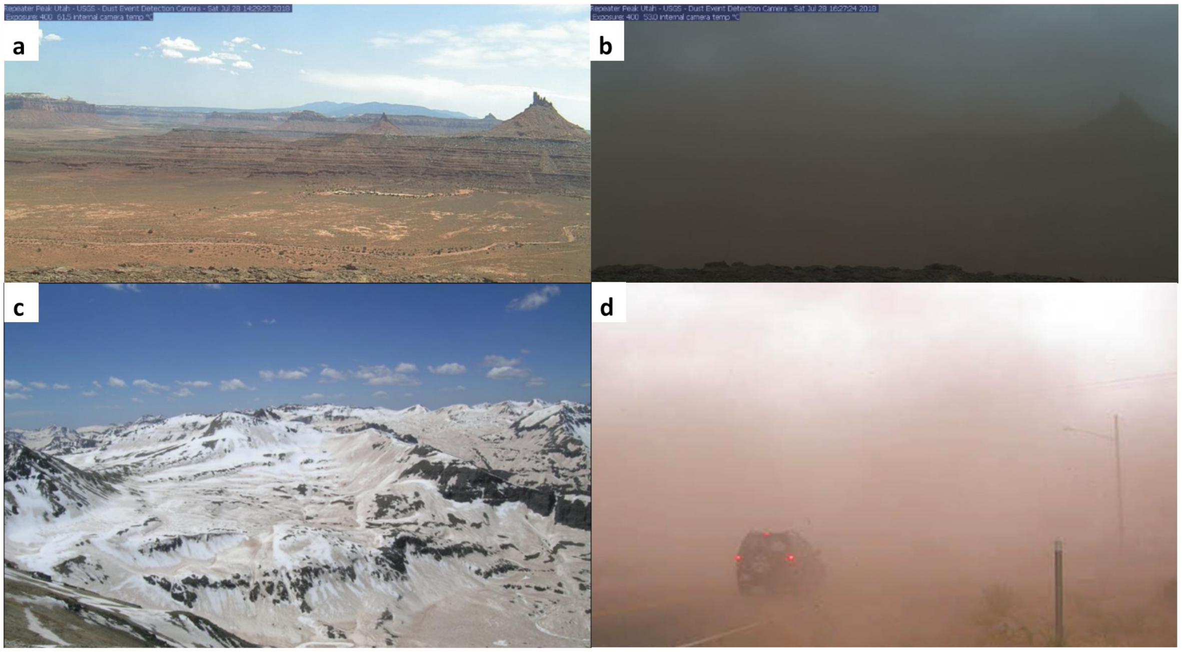

Fig. 5. Examples of dust impacts: dust storm impacting visibility near Canyonlands National Park, just prior (a) and after (b) dust event (28 July 2018); dust-on-snow event in the San Juan Mountains, Colorado (c); and low visibility on the highway near Moab, Utah (d).

(Lawrence et al. 2010, 2013, Brahney et al. 2014, 2015). This dust also has the potential to alter alpine soil texture and pedogenic processes in general (Rhoades et al. 2010). The change in timing of snow melt can alter alpine plant phenology in unexpected ways. For example, in an experimental manipulation of dust on snow in the southern Rockies, Steltzer et al. (2009) found that by decoupling snowmelt from seasonal patterns of warming, dust-induced early snowmelt may increase the frequency of years in which phenology is delayed after snowmelt.

At the regional scale, a very important consequence of dust deposition on snow is the reduction in regional water supplies (Painter et al. 2010, Skiles et al. 2015). The magnitude of this phenomenon was first documented in the San Juan Mountains of southwestern Colorado in the winter and spring of 2003 through 2006 (Painter et al. 2007, 2010). Modeled impact of dust on snow albedo, snow cover, and runoff from the Upper Colorado River Basin from 1916 to 2003 suggests that peak runoff occurred on average three weeks earlier under heavier dust loading and that increased evapotranspiration can decrease annual runoff by >1 billion cubic meters, or ~5% of the annual average (Painter et al. 2010). Water supplies in the Colorado River Basin are over-allocated in most years, and with climate change, these supplies are expected to be insufficient to meet growing human demands, independent of the impacts of dust (Udall and Overpeck 2017). With over 40 million municipal water consumers and 5.5 million hectares of irrigated agriculture depending on the Colorado River (USDI-BOR 2017), additional dust-mediated reductions in flow will likely have large socio-economic consequences.

Climate Feedbacks

The role of atmospheric dust in global and regional climate regulation has been recognized for some time (Schepanski 2018). Dust in the atmosphere can affect global temperatures through attenuation of sunlight by scattering and/or absorbing incoming solar radiation (Miller and Tegen 1998, Heinold et al. 2008, Kok et al. 2017). Dust may also indirectly alter the radiation budget by serving as cloud condensation nuclei that may prolong cloud lifespans, change clouds' light scattering abilities, and increase or decrease rainfall (Shine and Forster 1999, Stevens and Feingold 2009) and has been shown to be one of the most important ice condensation nuclei in the atmosphere (Cziczo and Froyd 2014). Dust may be the only atmospheric aerosol that has the potential to change atmospheric temperatures on a similar order of magnitude as CO_2 (Cubasch et al. 2001).

Along with increasing temperatures and dust production (Achakulwisut et al. 2017, Nauman et al. 2018), climate and dust share synergistic feedbacks (Mahowald 2010). For example, dust produced during 1930s Dust Bowl conditions may have intensified and spatially extended the drought (Cook et al. 2008). Climate change is intrinsically coupled with land degradation: Changes in climate at local to global levels drive land degradation by, for example, increasing drought frequency and/or intensity, leading to vegetation and soil loss (ELD Initiative 2015, UNEP, WMO, and UNCCD 2016). Losses in vegetation and biocrust cover, vegetation biomass, and soil protection can in turn decrease the land's ability to store carbon, thus exacerbating atmospheric CO_2 levels. Model results by Mahowald (2010) suggest that changes in regional climate from dust inputs are of the same order of magnitude as from changes due to other forcings (i.e., atmospheric CO_2) from the 1950s to the 1980s, especially for precipitation. Such dust-drought feedback could lead to unforeseen changes in drylands globally and in the southwestern United States.

Human Health and Economic Well-Being

Suspended particles entrained in the atmosphere as dust diminish air quality, negatively affecting human health, visibility, and economic systems in drylands globally (UNEP, WMO, and UNCCD 2016). Atmospheric dust has been linked to numerous respiratory and cardiovascular disorders and irritants, including coccidiomycosis, silicosis, airborne pathogens, allergens, and chemical/radiological contaminants (Crooks et al. 2016). Coccidiomycosis, or Valley Fever, is one such condition relevant to western drylands. Coccidiomycosis is a potentially fatal infection caused by inhalation of airborne spores of *Coccidioides immitis*, a soil dwelling fungus found in the southwestern United States. The association between increased periods of dust and increases in Coccidiomycosis exposure rates and outbreaks suggests a potential causal relation between wind erosion and infection (Comrie 2005, Goudie 2014, Gorris et al. 2018).

Evaluation of atmospheric dust in national parks in the Four-Corners region suggests residents of the southwest US experience much higher exposure rates than would be indicated by the standard PM2.5 and PM2.5–10 size fraction measurements (Neff et al. 2013). This work corroborates other surveys of dust on snow, dust deposited on the Canary Islands, and in many other places that total suspended particles (not just PM10) should be considered when monitoring atmospheric dust (Reynolds et al. 2016). Increases in regional dust forecast with increasing aridity in the southwest are expected to further impact human health, including increasing rates of Coccidiomycosis and up to a 300% increase in hospital admissions for cardiovascular and respiratory illness (adults ≥65 yr old based on RCP8.5 emission scenarios; Achakulwisut et al. 2018). Further, dry or ephemeral lakes, common in the Great Basin and Mojave Deserts, produce very fine dust that contain elevated levels of potentially toxic inorganic constituents (Goldstein et al. 2017).

Visibility in the southwest United States has decreased in recent decades, likely due to increased regional dust emissions (Kavouras et al. 2009, Hand et al. 2014). The importance of visibility ("viewsheds") for tourism and associated economic activity is an increasingly important consideration for regional land management (Fig. 5a, b; Schulze et al. 1983, USDI-BLM 2016). Other important human health and economic concerns related to dust include traffic fatalities caused by low visibility (Fig. 5d); damage to buildings, machines, and infrastructure; and reduced agricultural production (Ashley et al. 2015, UNEP, WMO, and UNCCD 2016, Middleton 2017, Li et al. 2018).

Responses

With a warmer, drier, and more variable future climate predicted for much of the southwestern

United States, including more extreme droughts (Seager 2007, Cook et al. 2015, Ault et al. 2016), it is imperative to minimize the risk of wind erosion and dust generation. The atmospheric residence time for particulate dust (PM10) can range from seconds to weeks (Lei and Wang 2014, Reynolds et al. 2016), suggesting that effective control of dust sources can have rapid impacts on atmospheric pollution levels. A comprehensive dust-management strategy should therefore include a combination of (1) eliminating or reducing the intensity or extent of land-use activities that produce dust; (2) implementing restoration or reclamation strategies that promote ecosystem resilience to wind erosion; (3) accounting for landscape heterogeneity for both planning potential dust-producing land uses and targeting restoration/reclamation actions to maximize dust abatement; and (4) encouraging research and monitoring to further understand the interaction of eolian processes, pressures, and ecosystems.

Prevention

Many culturally and economically important uses of western landscapes contribute to regional dust ("Pressures", Fig. 2). However, increasing land-use pressures and aridification combined (Copeland et al. 2017) may have unforeseen, synergistic consequences—even from land uses not increasing in intensity or extent (e.g., grazing by ungulates; Beschta et al. 2013).

For domestic livestock on western public lands, current management and permitting focuses on the "carrying capacity" concept (Sayre 2017), which may lack the necessary flexibility for adaptation to increasing climate variability. Historically, some of the most detrimental impacts to dryland ecosystems have resulted from improper land use during droughts. For example, overgrazing during the droughts of the 1930s and 1950s in the Chihuahuan Desert have been correlated with persistent grass loss and increased shrub dominance, despite subsequent reduction or elimination of grazing (Herbel et al. 1972, Browning et al. 2012). Similar grazing-induced ecosystem changes on the Colorado Plateau are documented during the same period (Godfrey 2008, Denis 2012, Duniway et al. 2018).

There are two broad types of strategies that can be used to minimize livestock-induced dust emissions. First, timely information on eolian processes and risk of wind erosion, such as those provided by wind erosion models or monitoring networks, should be used to trigger pro-active management intervention. Currently, wind erosion or dust-related destocking events are often done reactively (e.g., after a human health-related impact such as traffic fatalities). Such proactive management could limit the wind erosion-related damage due to grazing during times of drought, particularly during the spring (Neff et al. 2005, Reheis and Urban 2011, Flagg et al. 2014). Additionally, these data could be used to manage herds to avoid dust emission hotspots (Gillette 1999), such as where sandy soils that are prone to saltation occur adjacent to fine soils prone to suspension (Nauman et al. 2018). Second, structural changes to livestock management may be needed to effectively mitigate dust emissions. This could include greater flexibility in herd management, changing stocking rates or timing of use based on new understanding of climate change vulnerability (Polley et al. 2013, Hoover et al. 2015), or new spatial data on the distribution of high-erosion risk soils or ecological states (Figs. 1, 2d; Poitras et al. 2018, Ramcharan et al. 2018). Finally, new livestock breeds or species and modified or new economic structures may be ultimately required (in part driven by changes to driving forces, Fig. 2; Joyce et al. 2013, Anderson et al. 2015).

Mitigation of dust emissions from unpaved roads, energy exploration and development, and recreational off-road driving presents a set of challenges and opportunities that differ distinctly from those related to livestock grazing (Duniway and Herrick 2011). Whereas the permitting and regulation process for livestock on federal lands has been well established for decades (Sayre 2017), management of energy exploration and development activities, recreation off-highway vehicle use, transportation infrastructure, and other related activities is governed by a relatively new and evolving set of policies by various management and regulatory agencies. Therefore, new technologies or management goals have the potential to be more readily adopted and, therefore, to reduce effectively potential dust emissions from these activities.

As dust from roads is correlated with vehicle speed, traffic can be slowed by employing dips, curves, or more infrequent grading schedules. Application of gravel and other dust suppressants to unpaved roads have also been shown to be effective (Edvardsson 2009), with magnesium chloride application reducing fugitive dust up to fourfold (compared to untreated roads; Sanders et al. 2015), although these often encourage high-speed travel. Use of oversized, low-pressure, and smooth (aka "balloon") tires on energy exploration heavy machinery appears to reduce damage to shrubs and biocrusts (M. C. Duniway, *personal observation*; conventional energy exploration shown in Fig. 3a). Similarly, directional drilling for oil and gas resources provides greater flexibility in the location of drilling pads, as well as the ability to reduce the number of pads and decrease the length of road networks by locating multiple wells on a single, large pad (Martinez and Preston 2018).

Such flexibility in the siting of oil and gas pads can facilitate application of new insights that are being gleaned through remote sensing analyses of reclamation practices regionally by targeting development to soil and vegetation settings where reclamation success is more likely (Nauman et al. 2017). Research from the Mojave Desert suggests sandy soils tend to be more supply-limited when it comes to releasing dust-sized particles compared to silty soils (Goossens and Buck 2009*a*). In support of this, Nauman et al. (2018) observed sustained levels of extremely high horizontal flux at a silty soil recreational area in southcentral Utah. Although there is no observational evidence demonstrating a density-dependent association between the area disturbed by OHVs, unpaved road networks, or energy development infrastructure and wind-driven sediment flux, research in other settings (Gillette and Pitchford 2004, Li et al. 2007, Rachal et al. 2015) as well as observation of landscape-scale connectivity impacts on horizontal flux (Gillette et al. 1996, Miller et al. 2012) suggests that larger connected areas of disturbed ground devoid of vegetation such as found at modern oil and gas well drill sites (Martinez and Preston 2018) and at OHV areas open to cross-country travel may result in very large dust fluxes (Fig. 4). These data suggest that minimizing the extent of connected areas of loose, erodible soils is an important mitigation measure in areas affected by OHVs, oil and gas development, and other broad disturbances. More research is needed to understand how varying spatial patterns and density of road networks might influence dust emissions.

Finally, avoidance is likely the most cost-effective approach to limit creation of new dust sources in many instances (Munson et al. 2011). Spatially explicit information on management practice options, risks, and potential outcomes (Herrick et al. 2006, Bestelmeyer et al. 2016) can be used to avoid land uses that remove vegetation and disturb soil surfaces in the most sensitive areas, particularly when coupled with wind exposure maps (National Renewable Energy Lab 2012).

Restoration/Reclamation

Active management interventions aimed at modifying soils and vegetation to promote a more desirable ecosystem state or condition (hereafter, restoration; Fig. 6) have a long history, but mixed success, in western drylands (Bestelmeyer et al. 2015, Duniway et al. 2015, Nauman et al. 2017, Copeland et al. 2018). Western dryland restoration activities typically include emergency stabilization activities after wildfire, range improvement and fuels management actions, and reseeding of highly disturbed lands.

A review of land management treatments on BLM lands across the southwestern United States from 1940 to 2000 found that the proportion of projects that have restoration-oriented objectives has increased relative to those with extractive objectives (e.g., planting forage for livestock; Copeland et al. 2018). This trend suggests an opportunity to both prioritize soil conservation and dust mitigation as project goals and test and improve methodologies going forward. However, the same study found an increase in the proportion of treatments occurring in lower-elevation, warmer, and drier desert scrub regions relative to cooler, wetter regions. Greater amounts of land treatments in low elevation deserts are of concern from a dust-risk perspective, given that restoration is generally more challenging in hotter, drier areas (Bainbridge 2012) and that the potential for dust generation is greater in more arid settings (Fig. 1e; Lu and

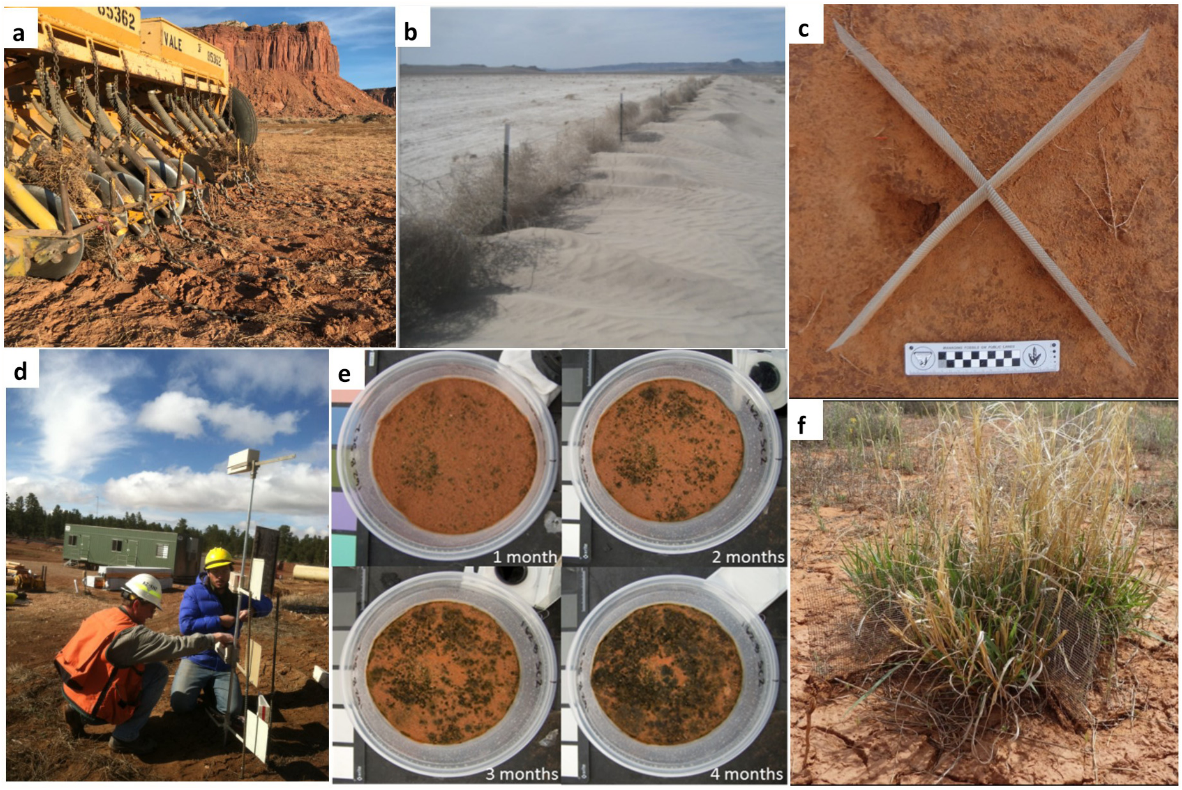

Fig. 6. Reclamation strategies influence dust emission. Soil surface-disturbing activities such as rangeland drill seeding may increase dust emissions (rangeland drill, a); use of physical barriers to control horizontal dust fluxes (cross-fencing used following the Miflord Flat Fire [Miller et al. 2012]) b); connectivity modifiers (c); using passive dust traps to monitor dust emissions from uranium mines near the Grand Canyon, Arizona (d), examples of lab-grown biological soil crusts that can be used for restoration, and successful perennial grass restoration using connectivity modifiers (Fick et al. 2016; f).

Shao 2001, UNEP, WMO, and UNCCD 2016). Other work suggests restoration species currently recommended by experts are not likely to perform well under future climates (Butterfield et al. 2017), further posing risk of increased dust generation if seeding or planting projects fail (e.g., Miller et al. 2012). Here, we review available strategies for restoration suitable for dust mitigation, or, for treatments that do not have dust mitigation as a primary objective, restoration activities that would provide the auxiliary benefit of minimizing the risk of dust generation ("Restoration" arrow in Fig. 2).

Traditional restoration techniques applied to western drylands often combine seeding with soil surface disturbance to improve seed-soil contact and seed burial (e.g., harrowing, chaining, or drill seeding; Figs. 4, 6a; Government Accountability Office 2006). The soil-disturbing nature of these treatments imparts inherent dust-production risk in more arid regions, as seeded species are unlikely to germinate in dry years, leaving large areas of exposed, disturbed soils. Work monitoring horizontal eolian sediment flux following the Milford Flat Fire found the highest flux levels in areas that were burned and received a reclamation treatment (21.0–44,010.7 $g \cdot m^{-2} \cdot d^{-1}$), relative to both untreated (16.3 to 1251.0 $g \cdot m^{-2} \cdot d^{-1}$) and unburned/untreated (35.2–555.3 $g \cdot m^{-2} \cdot d^{-1}$) areas (treatments were primarily aerial seeding followed by chaining or mechanical seeding through use of a rangeland drill; Miller et al. 2012). In a comparison of different fuels reduction methods in a two-needle piñon (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*) woodland in southeastern Utah, Gillan et al. (2016) found that near-surface horizontal eolian sediment flux increased 33-fold in a pile-and-burn and 131-fold in a broadcast burn treatment. Interestingly, the studies reported by Miller et al. (2012) and Gillan et al. (2016) were both done during an extreme drought period in the southwest United States (2008 to 2010). Grantz et al. (1998) examined the effectiveness of surface-disturbing furrowing and direct seeding of native shrubs and a bunch grass on a 1000-ha site near Antelope Valley, Mojave Desert, CA, with the goal of reducing immediate and long-term dust emissions. They found that the treatments reduced dust emissions, but only in an anomalous year with above average and late rainfall. They hypothesized that in "normal years," minimal disturbance protocols like broadcasting seed onto untilled surfaces would be as effective as disturbing protocols, and less costly (Grantz et al. 1998), even though seeds broadcast on the soil surface are more susceptible to granivory (Fick et al. 2016). Indeed, precipitation in western US drylands is unreliable year to year, increasingly so with climate change, indicating that management strategies in these regions need to address and limit risk under dry conditions (Grantz et al. 1998, Miller et al. 2012, Duniway et al. 2015, Gillan et al. 2016).

The growing recognition that soil stability is a prerequisite for successful revegetation in drylands has prompted experimentation with restoration techniques that specifically attempt to stabilize soil while also restoring native plant cover. Installing physical barriers such as straw checkerboards (Li et al. 2006), slash-piles (Visser et al. 2004), jute netting, or distributed small physical structures (Rachal et al. 2015, Fick et al. 2016) both impede the movement of sediment and wind across the soil surface and provide microsites with reduced abiotic stress for seedlings (Fig. 6a, c, f). Other techniques focus on directly improving soil surface cohesion via amendments of soil stabilizers (e.g., polyacrylamide, psyllium), biocrust inoculum, or both, to stabilize soils and promote plant recovery (Fig. 6e; Davidson et al. 2002, Maestre et al. 2006). Disrupting the surface stability of large areas using mechanical means may not be viable where dust production is a high risk, despite reduction of some surface disturbance using technological improvements for large-scale rangeland seeding (e.g., "no-till" seeding; Ott et al. 2016). The reduced risk may be worth the cost even when accounting for labor-intensive restoration methods. The relative expense of these dust-reducing treatments highlights the importance of determining where (and when) restoration treatments will be most effective.

Research, Monitoring, and Modeling

One of the most devastating and well-known extreme wind erosion events in the United States, the 1930s Dust Bowl on the Great Plains, was caused primarily by a combination of improper agricultural land use and drought (Egan 2006). In response to this environmental, social, and economic catastrophe, several government programs were developed that effectively promoted soil conservation and curbed wind erosion. The most effective of these involved research and education on best practices for managing farmland, providing financial support to the neediest farmers to help with erosion control, buying and converting large swaths of erodible land to grasslands, and encouraging the formation of local conservation districts (Lee and Gill 2015). Important lessons from the efforts and successes of the Dust Bowl should be considered when confronting dust in the western United States today, although many of the specific programs that achieved success in restoring lands following the Dust Bowl are less relevant to today's western drylands (e.g., the majority of western lands most susceptible to wind erosion are not privately owned; Fig. 1f).

Research and monitoring are needed to understand dust emission risks in the context of evolving land use and a changing climate. Whereas controlled experiments often provide the strongest statistical inference, a great deal can be learned from post-restoration monitoring and other related survey work. For example, five years of post-restoration treatment monitoring following the Milford Flat Fire in western Utah revealed important new insights on the interaction of landscape connectivity, drought, and abrasion by saltating sand particles in generating huge amounts of dust and limiting restoration success (Miller et al. 2012, Duniway et al. 2015).

Post-fire restoration funding typically prioritizes soil stabilization and prevention of dominance by invasive plant species (e.g., Bureau of Land Management's [BLM] Emergency Stabilization and Rehabilitation program [ES&R]; USDI-BLM 2007). In general, funding for long-term monitoring is limited. Similarly, other restoration efforts focus on "acres treated" with less emphasis on planned controls and rigorous monitoring (though see examples in Coffman et al. 2014, Havrilla et al. 2017, among others). Management actions, such as post-fire emergency stabilization, range improvement, fuels reductions, and/or reclamation of oil and gas disturbances, offer the opportunity to test hypotheses about which restoration practices are most effective. New national-scale monitoring programs will likely produce data useful for modeling eolian processes and dust risk and allow a broader-scale understanding of restoration effectiveness and how this relates to wind erosion (Nusser and Goebel 1997, Munson et al. 2011, Toevs et al. 2011, Webb et al. 2014).

Wind erosion, dust, and eolian transport monitoring networks have proved invaluable in our understanding of regional air quality (Brahney et al. 2013, Neff et al. 2013, Hand et al. 2014, 2017) and how local-scale, land-use decisions are affecting eolian processes (Reynolds et al. 2001, Flagg et al. 2014, Nauman et al. 2018). The National Wind Erosion Research Network (NWERN; Webb 2016) is an important monitoring effort currently addressing information gaps for modeling eolian processes across land uses. Efforts like NWERN, coupled with appropriate vegetation and soil monitoring, should enable estimates of dust emissions resulting from soil and/or vegetation disturbances as well as modeled dust consequences of various management action alternatives.

An important application for wind erosion modeling is large-scale planning for new roads, trails, and energy development (e.g., USDI-BLM 2016). It is unclear how well these models reflect actual dust from roads in drylands of the southwest (but see Etyemezian et al. 2004), despite the application of established models to simulate dust from unpaved roads (e.g., EPA 2006). Passive horizontal eolian sediment traps are a relatively low-cost approach for monitoring wind erosion processes and fluxes at local scales (Fig. 6d), and such traps have been used successfully to understand the consequences of land use for decades (Fryrear 1986, Zobeck et al. 2003, Miller et al. 2012, Flagg et al. 2014, Nauman et al. 2018). Remotely sensed imagery available at high spatial and temporal resolution (Ginoux et al. 2012, Li et al. 2013, Chappell and Webb 2016, von Holdt et al. 2017) and new sensors (e.g., CALIPSO; Yu et al. 2015) will continue to better identify and quantify emissions to the atmosphere.

Extensive work has tracked the dryland origins of dust-on-snow events in western US mountain ranges. These include using mineral and isotopic signatures in the dust itself (Neff et al. 2008, Reynolds et al. 2010, Reynolds 2014), tracking of dust events using satellite imagery, backtracking of dust movement using regional circulation models (Painter et al. 2007, Carling et al. 2012, Li et al. 2013), and use of a network of dust-on-snow observatories (Skiles et al. 2015, Clow et al. 2016). This body of work, combined with other research documenting the degradation of western lands in response to land use and fire over the previous 150 yr (Pointing and Belnap 2014), strongly suggests that recent increases in dust deposition to regional mountains are due to a combination of changing land use, increased fire frequency, and increasing aridity in southwestern drylands (Fig. 1). However, the ability of these methods to identify provenance of dust cannot effectively pinpoint exact source locations or culpable land uses (see *Pressures*; Fig. 2; but see https://gec.cr.usgs.gov/dustdetection/ and von Holdt et al. 2017). At best, these studies use evidence from other studies to discuss the possible anthropogenic activities generating dust (Painter et al. 2007). Estimating the relative contribution of different land uses or pressures to the dust-on-snow phenomenon that can be used to target management or policy changes will require a multi-scale approach combining the above methods (dust-on-snow monitoring, isotopic analysis, back trajectory models, and remote sensing; Kavouras et al. 2009), monitoring and modeling of eolian fluxes in the dryland source areas, including using local-scale flux monitoring across different land-use settings (Nauman et al. 2018), and regional networks of atmospheric samplers (Neff et al. 2013).

Finally, best practices for minimizing dust risk and/or restoring degraded drylands should be tailored to specific ecosystem states (Fig. 2), and they thus vary with landscape, climate, vegetation, and soil setting (Field et al. 2010, Ravi 2011). Information delivery systems that incorporate landscape and climate context can address this need (Herrick et al. 2006, Bestelmeyer et al. 2016). In general, greater caution will be required in relatively dry and windy locations with fine sands (Fig. 1e). Such locations are highly prone to erosion and lie where restoration is generally challenging (i.e., Gillette et al. 1980, Webb and Strong 2011). To quantify risk of dust with varying climate scenarios across the landscape, improvement of site-specific models is needed which (1) account for biotic and abiotic factors and interactions and (2) characterize eolian flux variability at finer scales (<250-m spatial resolution; Lu and Shao 2001, Munson et al. 2011, Chappell and Webb 2016). Results of such models may trigger use of minimal soil-disturbing approaches (Fick et al. 2016), soil stabilizers (Belnap and Gillette 1998, Chiquoine et al. 2016, Antoninka et al. 2017), or both.

Based on our review of the available literature, we have identified the following high-priority areas of research to facilitate informed responses to wind erosion and dust emissions on US drylands:

1. *Improved measurements and modeling of the cumulative dust consequences of unpaved road networks and energy infrastructure*. Current relevant models are either focused on dust generated by vehicles (EPA 2006), the influence of vegetation (Okin 2008), or soil erodibility for idealized soils without crusting or the impacts of surface disturbances (Shao 2001, Webb and Strong 2011) with no model able to account for all factors together along with the spatial arrangement of disturbances. Furthermore, while the cumulative impacts of roads and associated traffic have been evaluated for several species and habitats (Forman 2003, Wheeler et al. 2005, Green et al. 2017), there is very little research on the implications of dust from dense road networks for wildlife behavior and habitat quality (though see Talley et al. 2006).
2. *Livestock management to minimize wind erosion.* Although much is known regarding mechanisms that link livestock impacts on western rangelands and the vulnerability of drylands to wind erosion, more work is needed to better understand the interactions between livestock management, ecosystems, and eolian processes. This research should focus on the development of tools and accessible information that allows livestock and rangeland managers to quickly assess wind erosion risks and provide options to limit risk.
3. *Provenance of dust-on-snow*. Better identification of the dominant geographic and land-use sources of the dust-on-snow phenomenon is needed to target effectively the reduction or prevention of dust production (altering both driving forces and pressures; Fig. 2) and restoration actions. The importance of water supplies in the Colorado River Basin (CRB) for regional water users and economies, the over-allocated condition of the CRB, combined with forecast reductions in water supplies due to climate change (Udall and Overpeck 2017) suggests mitigating dryland conditions producing dust that are deposited on regional snow cover will become top priority in the near future.
4. *Mitigating wind erosion and dust with restoration*. Restoration of degraded drylands is a critical management tool for reducing erosion of surface soils by wind and generation of dust. However, most broad-scale restoration approaches are aimed at restoring vegetation and entail some level of soil disturbance, without including dust reduction as a management goal. New approaches are needed that (1) are achievable at broad scales, (2) minimize risk of wind erosion, and (3) lead to success in reaching vegetation and soil objectives, particularly in more arid regions. Furthermore, analysis tools to facilitate comparisons of relative risk of wind erosion for various treatment scenarios can further aid managers and avoid unnecessary dust emission.

Summary and Outlooks

Erosion, dust emission, and recovery in drylands are governed by the interaction of aridity, vegetation, soil stability, and land use. Increasing temperatures and more variable precipitation, including extreme droughts, will likely increase risks associated with wind erosion and consequent generation of dust (Cook et al. 2008, Ravi 2011, Cook et al. 2015). Conventional restoration and reclamation approaches often entail surface disturbance and rely on adequate moisture to prevent erosion and therefore carry considerable erosion risk if wet conditions do not occur. New and existing land uses may have consequences under a drier, more variable future that may appear as "surprises" under previous climate regimes but are likely predictable given our current understanding of the interaction of regional warming and eolian processes.

Wind erosion and consequent dust emissions carry considerable risk for ecosystems and people at multiple scales (Fig. 2). Worldwide, billions of tons of desert dust are transported annually over distances ranging from hundreds of meters to thousands of kilometers (Ginoux et al. 2012, Pointing and Belnap 2014, UNEP, WMO, and UNCCD 2016). Given the wide range of scales over which dust movements and eolian processes operate, it is critical that dust-mitigation efforts also work at multiple scales and across land management units. As was learned in the Dust Bowl, cooperation and collaboration are needed to prevent wind erosion and promote restoration; dust emissions resulting from one land owner or permittee's failure will not be contained by administrative or ownership boundaries. Larger-scale planning efforts that span jurisdictions may therefore help avoid deleterious wind erosion impacts in the future (USDI-BLM 2007). Furthermore, work that fuses field monitoring, remote sensing, and modeling may provide early warning indicators that can prevent accelerated wind erosion.

Eolian dust production is a significant threat to western US drylands, and the urgency to address this threat will likely only increase in a hotter, drier future. The relatively stable and wind-resistant nature of many dryland soils when undisturbed (Fig. 4) suggests that many dryland settings have the potential to be highly resistant to wind erosion. Multidisciplinary and multi-jurisdictional approaches and perspectives to research, mitigation, and restoration are needed to advance our understanding of the complex processes driving dust emissions and mitigate impacts of wind erosion to these vulnerable regions through management strategies that minimize risk. Finally, prevention by reducing the areas of dust-producing land uses and the protection of intact areas, particularly in vulnerable ecosystem settings, remain the most assured strategy for conserving soil resources, air quality, and limiting the deleterious effects of wind erosion and atmospheric dust to ecosystems, humans, and the economy.

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