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Aeolian and fluvial processes in dryland regions: the need for integrated studies

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ABSTRACT

Aeolian and fluvial processes play a fundamental role in dryland regions of the world and have important environmental and ecological consequences from local to global scales. Although both processes operate over similar spatial and temporal scales and are likely strongly coupled in many dryland systems, aeolian and fluvial processes have traditionally been studied separately, making it difficult to assess their relative importance in drylands, as well as their potential for synergistic interaction. Land degradation by accelerated wind and water erosion is a major problem throughout the world's drylands, and although recent studies suggest that these processes likely interact across broad spatial and temporal scales to amplify the transport of soil resources from and within drylands, many researchers and land managers continue to view them as separate and unrelated processes. Here, we illustrate how aeolian and fluvial sediment transport is coupled at multiple spatial and temporal scales and highlight the need for these interrelated processes to be studied from a more integrated perspective that crosses traditional disciplinary boundaries. Special attention is given to how the growing threat of climate change and land-use disturbance will influence linkages between aeolian and fluvial processes in the future. We also present emerging directions for interdisciplinary needs within the aeolian and fluvial research communities that call for better integration across a broad range of traditional disciplines such as ecology, biogeochemistry, agronomy, and soil conservation. This article is a US Government work and is in the public domain in the USA. Published in 2011 by John Wiley & Sons, Ltd.

KEY WORDS dust; land degradation; semiarid; soil erosion; wind; water

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INTRODUCTION

Aeolian and fluvial processes affect all major components of the Earth system and provide important biogeochemical linkages between the atmosphere, hydrosphere, biosphere, and pedosphere (Schlesinger *et al.*, 1990; Syvitski, 2003; Munson *et al.*, 2011a). The detachment, transport, and deposition of sediment by wind and water can have important environmental consequences, many of which may be detrimental and often irreversible. Land degradation by accelerated wind and water erosion is a major environmental problem worldwide (Bridges and Oldeman, 1999) and will likely remain so throughout the 21st century (Lal, 2001; Valentin *et al.*, 2005). Aeolian and fluvial processes have long been recognized as important drivers of land degradation and desertification (Pye, 1987; Schlesinger *et al.*, 1990; Belnap, 1995), especially in arid and semiarid regions where the synergistic effects of aeolian and fluvial transport may far exceed that of either type of process alone (Bullard and Livingstone, 2002). Drylands are particularly susceptible to wind and water erosion because vegetation cover is usually sparse, soil moisture is generally low, soils are often inherently weak due to low organic matter, and anthropogenic-related disturbance easily disrupts surface physical and biological crusting that can be slow to re-form (Belnap and Lange, 2003; Sivakumar, 2007).

Globally, soil degradation by wind and water erosion affects approximately 2 billion ha of land, of which 30% is agricultural land, 35% is rangeland and pasture, and the remaining is forest, woodland and shrubland (Oldeman *et al.*, 1991). Wind and water erosion are recognized as the major drivers of land degradation worldwide (Valentin *et al.*, 2005). Collectively, aeolian and fluvial processes erode approximately 75 billion Mg of soil annually (Pimentel *et al.*, 1995), with present erosion potential estimated to be about 0·38 mm year^{-1} for the globe (Yang *et al.*, 2003). Current global estimates of soil erosion are 20–100 greater than average rates of soil renewal (Cuff and Goudie, 2009). This is particularly true in drylands where it can take hundreds to thousands of years to form a few centimeters of top soil (Pillans, 1997). Dust sources experience

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decreased soil fertility (Neff *et al.*, 2005), whereas places where it is deposited are fertilized (Neff *et al.*, 2008). Much of the land area prone to soil degradation is located within drylands, which account for about 40% of the global land area and are inhabited by one third of the world's population (UNSO, 1997). When considering the various processes of land degradation in drylands, water erosion represents about 42% of the areas affected, wind erosion another 42%, chemical deterioration 10% and physical degradation of the soil structure 3·5% (UNEP, 1992). The total area of drylands susceptible to coupling of wind and water erosion is estimated to be 23·7 million km^2 or approximately 17·5% of the global land area (Williams and Balling, 1996; Bullard and McTainsh, 2003). Estimates of wind and water erosion in drylands are surprisingly similar in magnitude and spatial extent for all continents except Australia, where water is the primary driver of erosion, and Africa, where wind erosion dominates (UNEP, 1992).

DRIVERS FOR AEOLIAN AND FLUVIAL TRANSPORT

Water availability controls the degree to which fluvial or aeolian processes influence sediment transport (Kirkby, 1978). Aeolian processes dominate transport when water availability is low and decrease in importance as water availability increases, while fluvial processes become increasingly prominent as water availability in systems increases. Wind and water erosion are not highest at opposite extremes of the water availability gradient, since extremely dry environments may lack sediment availability and extremely wet environments have high vegetation cover, which limits the soil surface exposed to erosion (Schumm, 1965; Field *et al.*, 2009). Vegetation also increases surface roughness, which absorbs wind and water momentum and traps moving particles. Wind and water erosion have the greatest overlap and potential for amplified sediment transport in semiarid regions (Kirkby, 1978; Breshears *et al.*, 2003). Systems in these regions have an intermediate amount of water availability: high enough to make sediment available for erosion, but low enough to limit vegetation cover, which leaves a high proportion of the soil surface exposed to wind and water.

The sequence of events for both wind and water erosion is similar (Visser *et al.*, 2004). First, sediment is dislodged or detached when the shear stress of wind or water exceeds a threshold. The intensity of wind and water is controlled by complex regional circulation patterns, which vary from daily to millennial time scales. The threshold shear stress necessary for entrainment of sediment by wind or water depends on the size, shape, composition, organization, and cohesion among particles (Gillette, 1978). Soil cohesion is enhanced by crusts (dry) or seals (wet) that can increase the threshold shear stress necessary for the initiation of erosion, influence the amount of water infiltration and runoff, and affect the emergence of vegetation (Belnap and Lange, 2003; Singer and Shainberg, 2004). While crusts are generally thicker than seals, both can form as a result of physical (e.g. flooding), chemical (e.g. presence of exchangeable salts), or biological (e.g. cyanobacteria, lichen) activity. Once entrained, the transport of particles proceeds according to particle size: (1) creep (wind) or sliding/rolling (water) of the largest particles, during which particles generally stay in contact with the soil surface and travel relatively short distances (1 cm–1 m); (2) saltation of intermediate sized particles over intermediate distances (1 m–1 km); and (3) suspension of the smallest particles over long distances ($\gg$1 km; Bagnold, 1941; Allen, 1994). As water is more dense and viscous than air, there is less restriction on the size and magnitude of particles that can be moved (Livingstone and Warren, 1996). Once entrained, the moving particles can accelerate additional particle movement through sand blasting (wind) and splash (water). Wind or water keep particles entrained until fluid velocity decreases and gravitational force causes entrained particles to settle out according to size and weight, with the heavier/coarser particles deposited first.

Topography is a main driver for the direction of sediment transport by water but not necessarily for wind (Bullard and Livingstone, 2002). When precipitation exceeds the infiltration capacity of the soil, sediment carried by runoff moves downslope and is channelled through rills and gullies before reaching an outlet. The width and depth of the channel determines the rate of flow and the type of sediment transported. Although topography can influence the magnitude and direction of wind, sediment transport by wind is primarily controlled by pressure gradients caused by unequal heating of the Earth's surface. Because of the different properties of wind and water, sediment entrained in water moves in a horizontal direction oriented with slope, whereas material entrained in wind can move in both a horizontal and vertical direction oriented with the prevailing wind. In addition to being a driver of water and wind erosion, topography is also influenced by the two processes: aeolian activity enhances topographic relief and fluvial activity levels it (Langford, 1989).

COUPLED AEOLIAN AND FLUVIAL PROCESSES OCCUR AT DIFFERENT SPATIAL AND TEMPORAL SCALES

In contemporary dryland settings, sediment transported by one type of erosion can become the material available for transport by the other type of erosion, thereby amplifying the amount of soil lost or redistributed in the system. Aeolian and fluvial processes and their linkages vary in time and space. The evidence for aeolian–fluvial couplings is apparent both in features (structural elements; Figure 1a) and events (occurrences or processes that produce features; Figure 1b). At short time scales, water runoff creates rills, which can expand to form gullies and ephemeral streams at larger spatial scales. Similarly, wind events can produce ripples and dunes at small spatial scales. The same events can result in dust storms, during which fine-textured soil particles can be transported at a regional and global scale (Prospero and Lamb, 2003; Painter *et al.*, 2010). At an intermediate spatial scale, sand dunes or

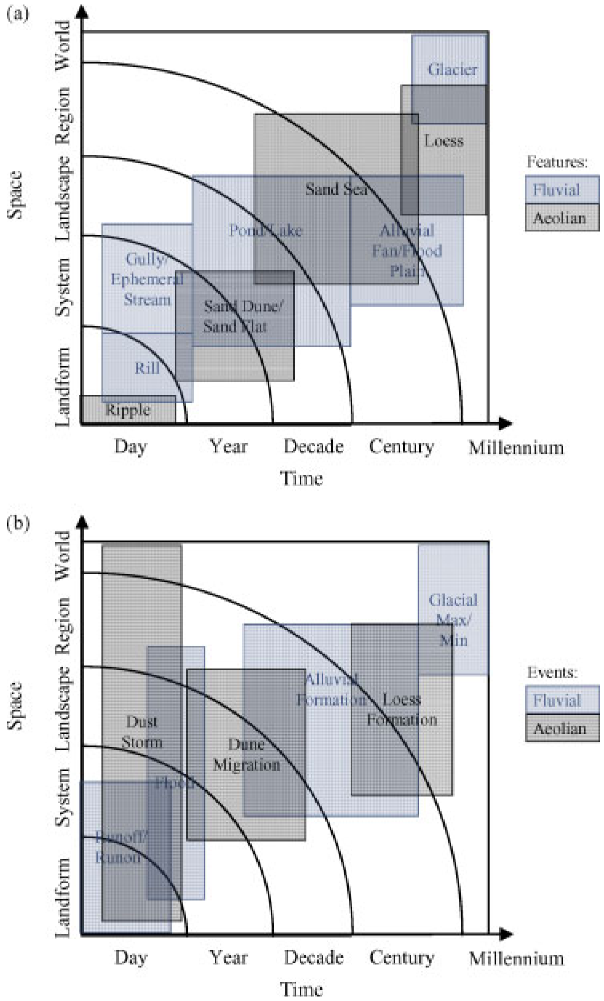

Figure 1. Spatial and temporal scales of aeolian and fluvial features (a) and events (b). Potential fluvial–aeolian interactions are shown where the two processes overlap.

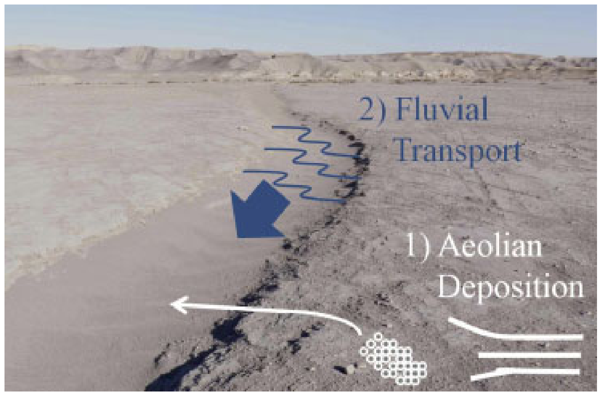

Figure 2. Fluvial–aeolian interaction at Factory Butte, UT (USA). Aeolian material was deposited into the channel over a period of weeks and emptied completely with one monsoonal rain event the day after the photo was taken. Photo credit: Matthew van Scoyoc, USGS.

sheets bordering water-filled channels can be incised to form extensive networks, where water carries sediment downslope (Langford, 1989). Water from these channels may collect and form inter-dune ponds and lakes, or an entire sand sea may become flooded due to a rising water table, which further deflates aeolian deposited features. Fluvial deflation of aeolian landforms commonly occurs after heavy storm events or during snowmelt from adjacent mountains.

Over intermediate time scales, sand flats and dunes can migrate, encroaching on downwind drainage areas during dry periods. Aeolian sediment can be blown across the soil surface and deposited directly into channels, where it is stored until a large precipitation event causes water to carry the sediment down the channel (Figure 2). This interaction can occur over a time frame of weeks to years, depending on the amount of aeolian sediment available for movement and the timing and intensity of subsequent rainfall events. This linkage between aeolian and fluvial processes has been observed by multiple researchers, yet we could find no quantitative measures of sediment moved by this interaction. Fluvial formations (e.g. alluvial fans, flood plains) are the result of sediment accrual over time from heavy precipitation events and flooding. Aeolian transport of fluvial deposition in arid and semiarid regions frequently occurs in the rain shadow of mountain ranges. Increased precipitation at high elevation can lead to runoff, which results in erosion and flow of debris to low elevation areas. Water in arid and semiarid regions is often limited in space and time due to high evapotranspiration and transmission losses, which makes fluvial deposition episodic and constrained to the outlets of drainages (Bullard and Livingstone, 2002). Dry conditions, coupled with wind events that follow the accretion of fluvial sediment, often result in aeolian output of the deposited material.

In the Mojave Desert (USA), several aeolian–fluvial transport corridors have been described (Lancaster, 1989; Brown *et al.*, 1990; Reynolds *et al.*, 2007). One of the best documented examples is from the Mojave River, in southeastern California, which terminates as an alluvial fan delta and connects to a series of dry lake beds or playas. Stratigraphic observations, as well as luminescence and radiocarbon dating, give quantitative estimates of past sediment transport and suggest several periods marked by alluvial and aeolian formations (Brown *et al.*, 1990). Although sediment supply reached peaks when pluvial periods in the Late Pleistocene filled lakebeds, contemporary climate continues to influence sediment supply and transport. Heavy winter precipitation is the primary cause of fluvial sediment transport. Sediment entrainment occurs at the headwaters of the Mojave River in the San Bernardino Mountains and sediment is transported downstream to an alluvial delta (Figure 3). Drying out of sediment and dominant westerly winds initiate aeolian transport of lacustrine and fan sediments, which feed downwind dune and sand ramp formations, and lead to large dust storms, which are currently being monitored by the USGS and collaborators (Urban *et al.*, 2009; Figure 4).

As illustrated in the Mojave Desert example, shifts between dry periods of primarily aeolian and wet periods of primarily alluvial activity occur at intermediate to long time scales as a result of climatic variability. The magnitude

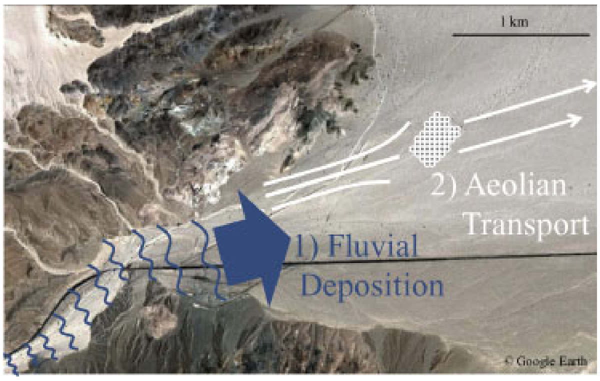

Figure 3. Fluvial–aeolian interaction at Mojave River delta in southeastern CA (USA). Fluvial deposition from adjacent mountains provides material for aeolian transport during high winds.

Figure 4. Southeast view of the north end of Soda (dry) Lake (northeast of the Mojave River delta) during a clear day on 15 November 2010 (a) and dusty day on 30 January 2011(b). The camera used to collect these photos is part of a study to monitor dust emissions in the Mojave Desert and Colorado Plateau, USA (http://gec.cr.usgs.gov/info/sw/clim-met). Photo credit: Frank Urban (USGS) and Rob Fulton (CSU-Fullerton).

of wind and precipitation vary by season, but drought can occur at annual to decadal time scales. Prospero *et al.* (2003) have documented long-range transport of wind-borne dust, largely in response to drought conditions caused by the North Atlantic Oscillation. In contrast, wet periods suppress dust emission and increase the likelihood of episodic flooding. At the longest time scales, periods of glacial and inter-glacial activity mark major transitions between aeolian and fluvial activity, respectively (Petit *et al.*, 1990). Many loess formations worldwide have been formed by aeolian deposited silt as sediment from glaciers is exposed from melt and desiccation. Loess formations may also result from variations in the expansion and contraction of deserts, as on the Loess Plateau in China.

DISTURBANCE AND EXTREME EVENTS

Erosion potential has increased by about 17% worldwide over the last century, primarily through the expansion of cropland, with anthropogenic activities now accounting for approximately 60% of all erosion (Yang *et al.*, 2003). Major dust storms have also become more frequent in many drylands as a result of increased human activity (Middleton *et al.*, 1986). About half of the global dust load is derived from disturbed soils affected by surface disturbances such as cultivation, livestock grazing and energy development, deforestation, and climate-induced vegetation shifts (Tegen and Fung, 1995; Painter *et al.*, 2010). Human activities have also led to accelerated rates of water erosion over much of the world; however, inputs of fluvial sediment to coastal and marine systems have been decreasing globally, also as a result of human activities such as reservoir construction (Syvitski, 2003). In comparison, inputs of aeolian sediment to mountains, coastal and marine systems have been increasing globally due to human activities and land-use intensification throughout much of the world's drylands (Tegen and Fung, 1995; Neff *et al.*, 2008).

Global rates of soil erosion and sediment transport are driven largely by the frequency and magnitude of extreme and episodic events (Coppus and Imeson, 2002; Washington *et al.*, 2003). Although the importance of extreme events has long been recognized, their high spatial and temporal variability often makes them difficult to study in practice. The majority of wind and water events that occur in arid and semiarid environments play only a minor role with respect to their total contribution to erosion rates over annual to decadal time scales (Knight *et al.*, 1995; Coppus and Imeson, 2002; McTainsh *et al.*, 2005). The magnitude and frequency of extreme wind and water events can have serious and often irreversible consequences for ecosystem stability and productivity if erosion rates exceed the rate of soil renewal. When considering extreme events, dust storms likely pose the greatest potential for off-site environmental impacts (Pimentel *et al.*, 1995) because wind events have the potential to rapidly transport millions of tonnes of sediment to depositional areas thousands of kilometres away from the source (Zhang, 2001; Prospero *et al.*, 2002). By contrast, most extreme rainfall events are typically generated by convective thunderstorms, which are usually more limited in spatial extent than wind events. Extreme erosion events can also occur in response to heavy rainfall associated with large frontal systems and cyclones; however, events like this do not always transport large amounts of sediment as might be expected because fluvial deposition is often substantial during large-scale rainfall events (Meade, 1996). In most systems, the amount of runoff and water erosion usually decreases with increasing spatial scale as a result of increased deposition over the land surface (Reid *et al.*, 1999; Lal, 2001).

Rates of soil loss from extreme events can be impressive. Some of the largest documented rates of soil loss anywhere in the world can be attributed to aeolian activity in dryland environments. In the western United States for example, a single wind event eroded more than 0·5 m of sediment from agricultural fields in California (Wilshire *et al.*, 1981) and up to 1 m of sediment during a 12-h period in northwest Texas (McCauley *et al.*, 1981). Dust storms of this severity have been estimated to contain as much as 350 million Mg of sediment, which is comparable in magnitude to the massive dust storms characteristic of the 1930s Dust Bowl (Lockeretz, 1978; Worster, 1979). In the case of water erosion, recent evidence from Australia, China, USA, and elsewhere suggests that gully erosion is the main source of fluvial sediment production and is largely confined to drainage headwaters (Valentin *et al.*, 2005; Wilkinson and McElroy, 2007). Episodic events of gully erosion and landsliding produce large influxes of fluvial sediment to stream channels, with immediate and often detrimental impacts on aquatic communities and river channel geomorphology (Miller *et al.*, 2003). Some of the largest documented rates of fluvial transport can be found in areas that have extreme rates of gully erosion and landsliding. For example, erosion rates in excess of 9600 Mg ha^{-1} $year^{-1}$ have been documented in parts of Southeast Asia where human activities such as deforestation and road construction have increased substantially in recent decades (Sidle *et al.*, 2011). These values are among the highest ever reported for extreme water events and are comparable to losing about 0·5 m of soil per year.

EMERGING RESEARCH DIRECTIONS FOR AEOLIAN–FLUVIAL LINKAGES

Dust transported at the regional scale is an exemplary example of the linkage between aeolian and fluvial processes. Dryland soil surfaces are relatively stable until disturbed, but once disturbed, can produce significantly elevated amounts of dust (Field *et al.*, 2010) that is often deposited on the snowpack of nearby mountains (Neff *et al.*, 2008; Painter *et al.*, 2010). Deposited dust decreases the albedo of the snow, increasing melt rates. During years of heavy dust deposition, the duration of snow cover in the southern Rocky Mountains can be shortened by several weeks (Painter *et al.*, 2010). Models suggest that the resultant evapotranspiration losses from the then exposed soils can reduce Colorado River flows by up to 5% annually. In addition, high flows can occur earlier and late season flows can be diminished, making water management difficult. Such large alterations in the hydrologic cycle would be expected to have significant effects on aquatic and upland ecosystems, although this has not been directly investigated.

More than sediment is moved in drylands by the combination of wind and water. Elements are attached to soil particles and thus areas experiencing soil loss via wind erosion also experience reduced soil fertility (Neff *et al.*, 2005, 2008). When these particles enter washes, the nutrients can either remain attached or be dissolved in the water. These elements then become vulnerable to wind erosion when either the sediment is deposited or the water evaporates. Because fine particles in the soil are moved more readily than larger soil particles, soil texture becomes coarser with both wind and water erosion, thus reducing water-holding capacity and soil surface stability (Lal, 2001; Neff *et al.*, 2005). Thus, the linkage between aeolian and fluvial processes affects the fertility of source areas (e.g. soils) and sinks (e.g. water bodies, alluvial deposits). This can reverberate upwards through the food chain, as plants growing in poorer soils have less nutrients in their tissues than plants growing on similar soils where wind erosion is minimized (Neff *et al.*, 2005) and thus provide forage of lower quality to livestock and wildlife.

As observed with sediment, plant litter can also be blown into nearby dry washes and streams, where it is removed by subsequent water flows (Belnap, personal observation). Through this mechanism, the coupling of aeolian and fluvial processes may be of major importance in carbon and nutrient cycling in dryland regions, although this has yet to be investigated. This may be of special concern in areas invaded by exotic annual grasses. The perennial vegetation that once dominated dryland regions grows slowly and generally has persistent leaves and stems. When leaves are dropped, many of the nutrients are first resorbed (Killingbeck and Whitford, 2001). In contrast, the nutrients extracted from the soil to build annual plant tissue are lost from the systems when these plants dry up and blow or wash away each year. This loss may further lower soil fertility.

EFFECTS OF PROJECTED GLOBAL CHANGES ON AEOLIAN AND FLUVIAL PROCESSES

There are many projected global changes, including changes in climate, land cover, and land use, which are likely to increase soil erosion and also intensify the linkage between the movement of materials by wind and water. Climate is projected to become hotter and drier in many drylands, particularly in the southwestern United States (IPCC, 2007; Seager *et al.*, 2007). The plant cover in dryland settings is expected to decrease as a result (Munson *et al.*, 2011b). This decrease will likely increase the vulnerability of soil surfaces to wind and water erosion, as well as increase overland flow. In an amplifying feedback, this will accelerate the loss of wind-blown or waterborne materials. Long-term observations and climate models also suggest more intense rainfall and wind events in the future (Easterling *et al.*, 1999; IPCC, 2007), which will increase the movement of materials from ecosystems.

Soil surface disturbance is intensifying in many dryland regions. The western United States is seeing greater urbanization, suburbanization, recreation and the development of mineral and energy resources. In developing countries, increasing populations are pushing people to utilize more marginal dryland regions. These activities all increase the amount of material available for movement by wind and water. In addition, disturbed soils are often invaded by exotic annual grasses. The spread of these grasses is rapidly increasing and their presence also results in greater wind and water erosion. Whereas wet years provide more extensive plant cover and reduce vulnerability to erosion, fuels loads are increased and fires often follow. As most native dryland vegetation is not adapted to fire (Esque and Schwalbe, 2002), these fires generally result in a dramatic loss of perennial native vegetation and an increase in exotic annual grasses. This results in increased exposure of soils to erosion both directly after fire and in drought years, when these plants do not germinate. Both these scenarios increase wind and water erosion, as well as the linkage between the two processes. Increased groundwater withdrawal can lower the water table such that plant roots can no longer obtain water from that source, leaving previously vegetated areas barren (Castelli *et al.*, 2000). Increased drought will also result in the drying of lakes, reservoirs, and small streams, leaving sediments available to wind erosion and then subsequent flushing by water during intense precipitation events.

Some current land management practices can exacerbate the problem of soil loss in dryland regions. For example, dryland cropping replaces perennial vegetation with annual crops, includes fallow rotations, and disturbs the surface soil, all of which can increase erosion potential. The production of nitrogen-fixing legumes such as alfalfa or crops requiring fertilization (e.g. cotton) often result in the propagation of annual weeds once the fields are abandoned, as the annual plants can out-compete the native perennials in resultant high-nitrogen environments. Thus, in drought years, annuals do not germinate or grow and these fields may experience high soil losses from wind and water erosion. Another common policy is the need to 'prove up' water rights by using the water for irrigation of crops for a short time period (in the Western USA ownership of water rights is dependent on using the water at regular intervals). Again, crops such as alfalfa are often cultivated for a limited number of growing seasons and, when field are left unused, annual weeds typically follow.

The combination of intensified land use and drier soils is expected to increase the severity, frequency and extent of soil erosion in drylands by both wind and water (Manabe and Wetherald, 1986; Gregory *et al.*, 1999). Many soil erosion models show that rill erosion is directly related to the amount of rainfall, but that wind erosion increases exponentially if wind speeds exceed a critical threshold. This suggests wind erosion is more sensitive to changes in climate than water erosion (Gregory *et al.*, 1999). Direct measurements of sediment transport in semiarid grasslands in southern Arizona following extreme wind and water events support model assumptions that aeolian transport might be more sensitive to changes in climate than fluvial transport (Field *et al.*, 2011). However, more direct observations of extreme erosion events are needed to better assess the potential consequences of projected climate change on the relative rates of wind and water erosion and transport.

TRADITIONAL PERSPECTIVES AND INTERDISCIPLINARY NEEDS

Most geologist, geophysicists, and soil scientists generally recognize the importance of wind and water erosion and their potential for interaction in arid and semiarid regions, yet traditional academic perspectives have caused many researchers to segregate into one of two disciplines; those focusing on aeolian process and those focusing on fluvial processes. For example, many scientists and resource managers that study land degradation processes in drylands contend that water erosion is the sole desertification process, whereas others believe that wind erosion is the only important process (Dregne, 2002). In general, there are more studies that focus on fluvial transport than aeolian transport, even in arid and hyperarid environments where aeolian processes likely dominate, and very few studies that explicitly consider both processes (Field *et al.*, 2009). Although the aeolian research community has been growing steadily since Bagnold's (1941) classic work on aeolian entrainment (Stout *et al.*, 2009), aeolian processes in general represent major, but understudied actors in the world's drylands (Goudie and Middleton, 1992). A large fraction of the aeolian literature focuses on wind erosion from croplands and agricultural practices (Stout *et al.*, 2009); however, global dust models suggest that the contribution of agricultural lands to global dust loads is relatively small, being less than 10% of the total (Tegen and Fung, 1995). More diversification of expertise and interdisciplinary discourse within the aeolian research community could go a long way in advancing our current understanding of the role of aeolian processes in the biosphere.

Several key challenges lie before the environmental and geosciences research communities to better understand the linkages between aeolian and fluvial systems. We need to develop a more integrated perspective of aeolian–fluvial dynamics that accounts for potential interactions and feedbacks between the two processes, using common units of measurement. More information about the relative and absolute magnitudes aeolian and fluvial transport needs to be obtained to facilitate decision making by scientists and land managers to develop more effective land management strategies. We need to address the large differences in scale that are normally (but not always) considered in studies in the same region. For instance, whereas a given hydrologic study may be done at a large watershed scale, an aeolian study in the same region may be done at the local scale. The study of how dust impacts snow melt rates and thus the hydrologic cycle is just beginning. We also have little understanding of how linkages between aeolian and fluvial processes affect aquatic and upland ecosystems. Aeolian and fluvial transport linkages also can have important consequences for global nutrient cycles, biogeochemical processes, oceanic productivity and land surface-atmosphere interaction (Goudie and Middleton, 1992; Meade, 1996; Jickells *et al.*, 2005). Both processes play a fundamental role throughout the world's drylands, and as a result have attracted the attention of researchers from diverse academic disciplines, such as ecologists, biogeochemists, agronomists and soil conservationists. Drylands are likely to play an even greater role in nutrient cycling and land surface-atmosphere feedbacks in the near future, as drylands are expected to increase in spatial extent, along with episodic wind and rainfall events and the long-range transport of soil resources (Schlesinger *et al.*, 1990).

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