Frontiers in Ecology and the Environment

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Front Ecol Environ 2009; doi:10.1890/090050

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Wind erosion and associated dust emissions play a fundamental role in many ecological processes and provide important biogeochemical connectivity at scales from individual plants up to the entire globe. Yet, most ecological studies do not explicitly consider dust-driven processes, perhaps because most relevant research on aeolian (wind-driven) processes has been presented in a geosciences rather than an ecological context. To bridge this disciplinary gap, we provide a general overview of the ecological importance of dust, examine complex interactions between wind erosion and ecosystem dynamics from the scale of plants and surrounding space to regional and global scales, and highlight specific examples of how disturbance affects these interactions and their consequences. It is likely that changes in climate and intensification of land use will lead to increased dust production from many drylands. To address these issues, environmental scientists, land managers, and policy makers need to consider wind erosion and dust emission more explicitly in resource management decisions.

***Front Ecol Environ* 2009; doi:10.1890/090050**

For many scientists, the only dust they think about is the thin film of material that accumulates on their computer monitor on a regular basis. However, dust has enormous relevance to a wide range of ecological processes and environmental management challenges. Dust is fine particulate material that is removed from the land surface by wind erosion and is small enough to be suspended in the atmosphere (Bagnold 1941; Toy *et al.* 2002). Dust emissions vary with climate, as shown by paleo-studies (eg Clark *et al.* 2002), and also with land use. Perhaps the most notable example of how ecologically important dust can be is the Dust Bowl era of the 1930s in the American Great Plains, which is considered by many experts to be one of the most severe environmental catastrophes in the history of the US (eg Peters *et al.* 2007). The widespread cultivation of marginally arable lands, in conjunction with a severe regional-scale drought during the 1930s, caused substantial increases in wind-erosion rates, resulting in the degradation of roughly 90 million ha of land (Utz *et al.* 1938) and the loss of nearly 800 million metric tons of topsoil in 1935 alone (Johnson 1947; Hansen and Libecap 2004). This large-scale amplification of wind erosion was the result of small fields becoming more erosive and interconnected (Hansen and Libecap 2004), thereby triggering a threshold response (Peters *et al.* 2007). The devastating effects of the Dust Bowl were felt nationally and resulted in the formation of the Soil Conservation Service in 1935. However, the important ecological lessons of the Dust Bowl have faded with time, and most ecological studies do not explicitly consider the impact of dust flux and wind erosion. Ironically, the former Soil Conservation Service – now the Natural Resources Conservation Service – has shifted most of its focus to water erosion, and has largely abandoned the problem of wind-caused erosion (Field *et al.* in press).

In a nutshell:

- Ecologists and other environmental scientists often overlook the importance of dust and wind-driven processes, yet these processes exert a fundamental influence on biogeochemical and ecological systems
- The importance of these processes crosses scales from individual plants up to global levels
- Because changes in climate and intensification of land use are expected to result in increased dust production, ecologists, land managers, and policy makers need to more explicitly consider and manage dust emission

Environmental scientists are increasingly recognizing dust as both a major environmental driver and a source of uncertainty for climate models (Tanaka and Chiba 2006; Neff *et al.* 2008). Wind erosion and dust emission can cause substantial impacts, not only to human health (eg through respiratory problems), but also to basic ecosystem processes, at scales ranging from individual plants or even smaller (Figure 1a) up through local and regional scales (Figure 1b, c) to a global scale (Figure 1d), representing biogeochemical connectivity across continents (Peters *et al.* 2007; Okin *et al.* 2009).

Here, we provide a primer on the importance of aeolian (wind-driven) processes associated with wind erosion, as

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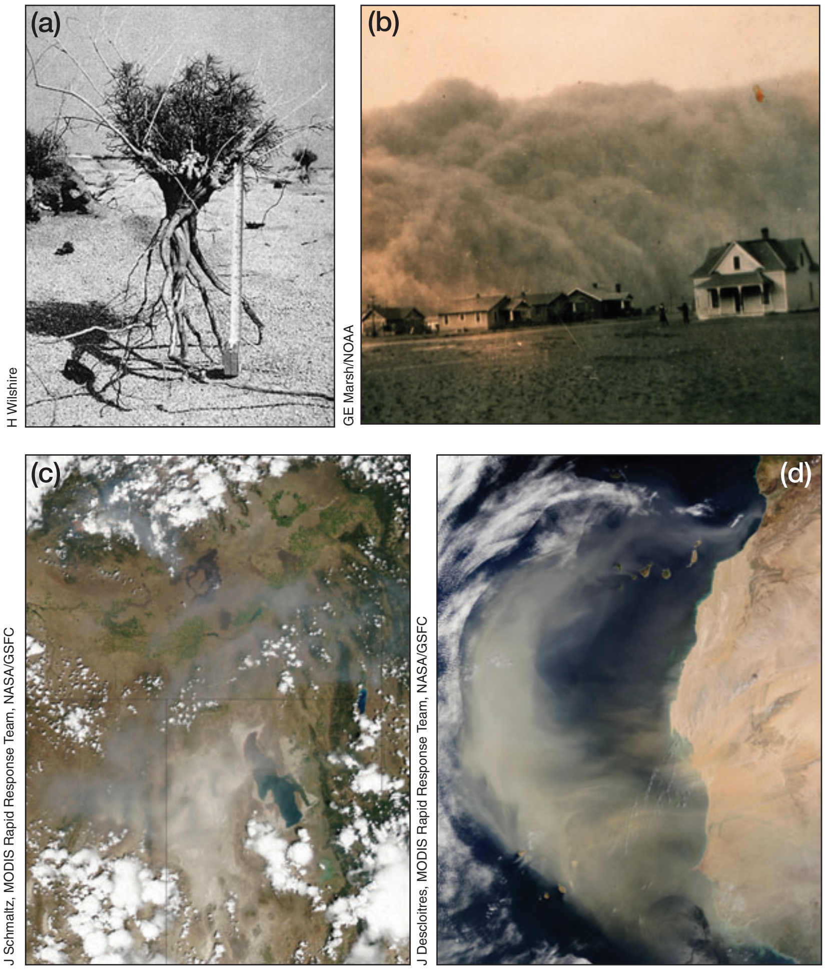

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Figure 1. *(a) Individual plant scale: shrub with exposed roots following the aftermath of a San Joaquin Valley dust storm in December 1977. (b) Local scale: dust storm approaching Stratford, Texas, April 18, 1935. (c) Regional scale: dust storm (tan pixels) on July 23, 2003, originating in the western part of Utah and blowing northeastward over Great Salt Lake. (d) Global scale: dust transport over the Atlantic Ocean, shown here off the west coast of northern Africa on March 2, 2003.*

well as an overview of their ecological relevance at scales from plant-interspace (the area between as well as beneath individual plants) to global, and associated aspects of biogeochemical connectivity. An underlying theme that plays out at many scales is that wind erosion has a highly non-linear response to disturbances that reduce ground cover below a critical threshold. We discuss how the effects of climate change (Seager *et al.* 2007) and land-use intensification (Okin *et al.* 2006) could amplify dust emissions from drylands and pose major environmental challenges for land managers and policy makers.

A wind erosion primer

Wind transports soil material through three mechanisms (Figure 2) that are roughly differentiated based on the soil particle diameter (these categories overlap): *surface creep* for soil particle diameters > 500 μm, *saltation* for diameters ranging from 20–500 μm, and *suspension* for diameters < 20 μm (Bagnold 1941; Toy *et al.* 2002; Goudie and Middleton 2006). All three processes redistribute soil and associated nutrients and organic material at different spatial scales (Field *et al.* in press). Wind-driven surface creep and saltating particles dominate the mass movement of soil on a local scale (less than several meters; Stout and Zobeck 1996). In contrast, suspended dust particles can be transported over long distances and can be moved at regional, continental, and even global scales (Chadwick *et al.* 1999; Prospero *et al.* 2001; Goudie and Middleton 2006). Most of the horizontal aeolian sediment transport occurs close to the soil surface, decreasing sharply with height (Shao *et al.* 1993). A small fraction of this flux can become suspended and thus be available for long-distance dust transport, as reflected in a vertical flux that is linearly related to horizontal flux (Gillette *et al.* 1997). Because soil nutrients (eg nitrogen, phosphorus) and organic matter are often associated with smaller soil particles, soil fertility in dust source areas becomes depleted while sink areas are concomitantly enriched (Li *et al.* 2007).

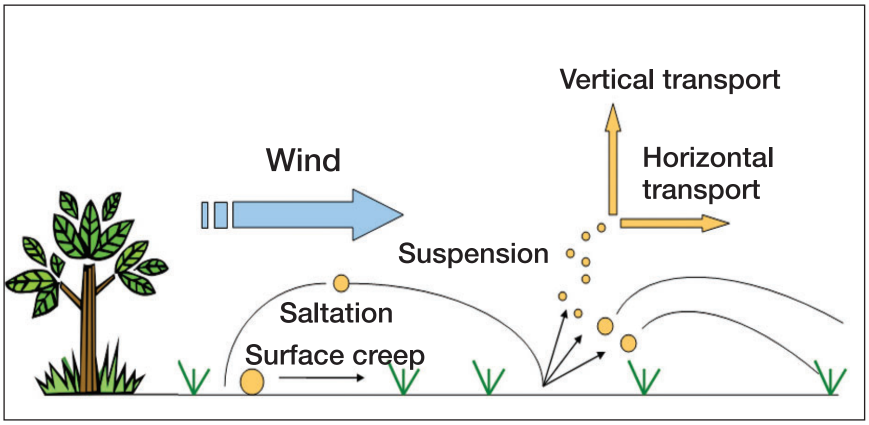

Figure 2. *How wind erosion works. Saltation occurs when the shear velocity of the wind exceeds the threshold shear velocity of the soil; suspension of dust-size particles occurs when saltating particles sand-blast the soil surface, overcoming the strong interparticle forces between fine particles.*

Wind erosion rates and dust emissions at a specific location are influenced by various factors, such as microscale wind gradients and atmospheric relative humidity (Toy *et al.* 2002). Wind speed is related to the amount of energy available to move sediment, and much aeolian research focuses on the "threshold friction velocity" wind speed at which particles of a given size under a given set of field conditions begin to detach from the soil surface (Gillette *et al.* 1980). Atmospheric relative humidity controls soil moisture at the soil surface, especially in arid and semiarid regions during rainless periods (Ravi *et al.* 2004), because soil moisture in particles at the soil surface is typically at equilibrium with atmospheric moisture. This is important, because soil moisture influences the interparticle forces that, in turn, influence the threshold velocity, resulting in a clear, but complex relationship between atmospheric relative humidity, particle size, and soil erodibility (Ravi *et al.* 2004). Wind erosion may be interactive with water erosion, although few studies have specifically addressed this issue (Field *et al.* in press). Collectively, these complex relationships need to be considered in terms of their relative role in affecting aeolian processes at all scales.

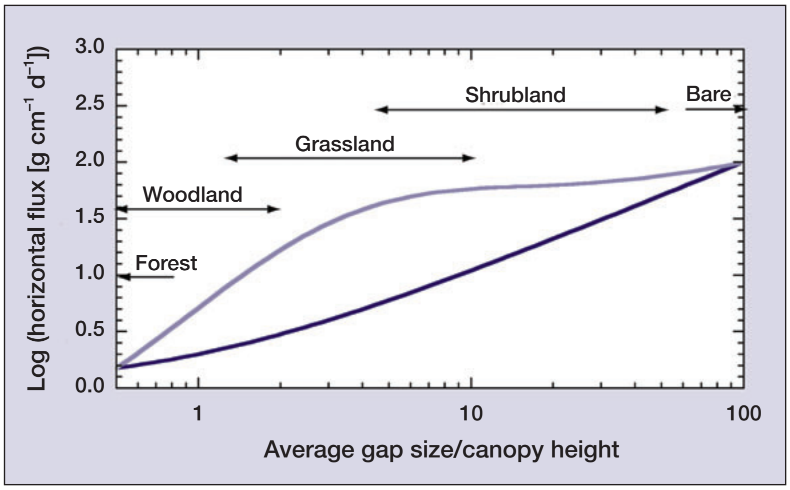

Figure 3. *Horizontal aeolian sediment flux as a function of the ratio of average unvegetated gap size to plant height. The black line indicates how flux would vary in the presence of an undisturbed herbaceous layer for each ecosystem; the gray line indicates how flux might vary in the presence of a disturbance that removed most of the herbaceous layer. Flux rates are calculated for realistic wind conditions in south-central New Mexico. Flux rates are calculated for a wind shear velocity of 100 cm* s^{-1}*, and a sandy loam soil with a threshold shear velocity of 24 cm* s^{-1} *is assumed. Woodland applies to lands that have a mix of small-stature trees and open spaces. Adapted from Okin (2008) and Breshears* et al. *(2009).*

■ Plant-interspace scale

At the plant-interspace scale, which includes the area between as well as beneath individual plants, aeolian transport is a major abiotic mechanism for moving material both within and out of environments with discontinuous cover. The erosivity of the soil surface, and thus the potential impacts of aeolian processes at the plant-interspace scale, depend on both the ability of the soil surface to resist erosion and the ability of the wind to reach the soil surface. Erosion resistance is determined by the strength of the soil and the presence of surface protectors, such as rocks, plant litter, and physical and biological soil crusts (Gillette *et al.* 1980; Okin *et al.* 2006). Rocks and plant litter too large to be moved by wind offer the greatest soil protection. Physical soil crusts – created by the binding together of silt and clay particles when wetted and then dried – protect soils, except when crusts are subjected to disturbance. Unless disturbed, these soils have an inherently higher resistance to erosion than soils dominated by coarser sand particles. Biological soil crusts, composed of cyanobacteria, lichens, and moss, stabilize soils by excreting mucilaginous material that binds soil surface particles together, thereby increasing soil aggregate size and increasing soil resistance to the shearing forces of wind (Belnap and Gillette 1997).

The type, cover, and arrangement of vegetation have the strongest influence on the ability of the wind to reach the soil surface. The patchy and dynamic nature of vegetation in dryland regions results in aeolian transport being highly heterogeneous in both space and time. The amount of material that is moved depends on the size of unvegetated gaps upon which the wind can act (generally excluding rocky or gravelly areas, referred to as desert pavement, and areas covered by physical or biological soil crust) and the height and density of the vegetation, which controls the size of the protected area downwind of individual plants (Breshears *et al.* 2009). Although surface characteristics are important, the amount of horizontal flux depends largely on the structure of the ecosystem and the degree of connectivity between unvegetated gaps (Okin *et al.* 2009; Figure 3). Unvegetated areas immediately downwind of vegetation (within 5–10 times the height of an individual plant) are relatively protected from the erosive force of the wind by the plant. In contrast, unvegetated areas further downwind from a plant do not experience the same degree of protection from erosion (Okin 2008). This disparity leads to heterogeneous erosion and the net movement of soil and litter from unvegetated gaps, and concentration of these resources beneath plant canopies. Saltation-sized particles are concentrated in protected areas beneath plant canopies, giving rise to coppice dunes in extreme circumstances, such as windy environments that have sparse vegetation cover and easily erodible soil. Because saltating material carries most of the mass and momentum, it can have considerable physical effects on existing vegetation, including burial, exposure of belowground plant tissue (pedastaling), abrasion of plant tissue, and leaf stripping. This has been shown to indirectly lead to reduced plant growth and mortality, and to contribute to rapid changes in ecosystem structure (ie initiating a rapid change from grassland to shrubland; Okin *et al.* 2006).

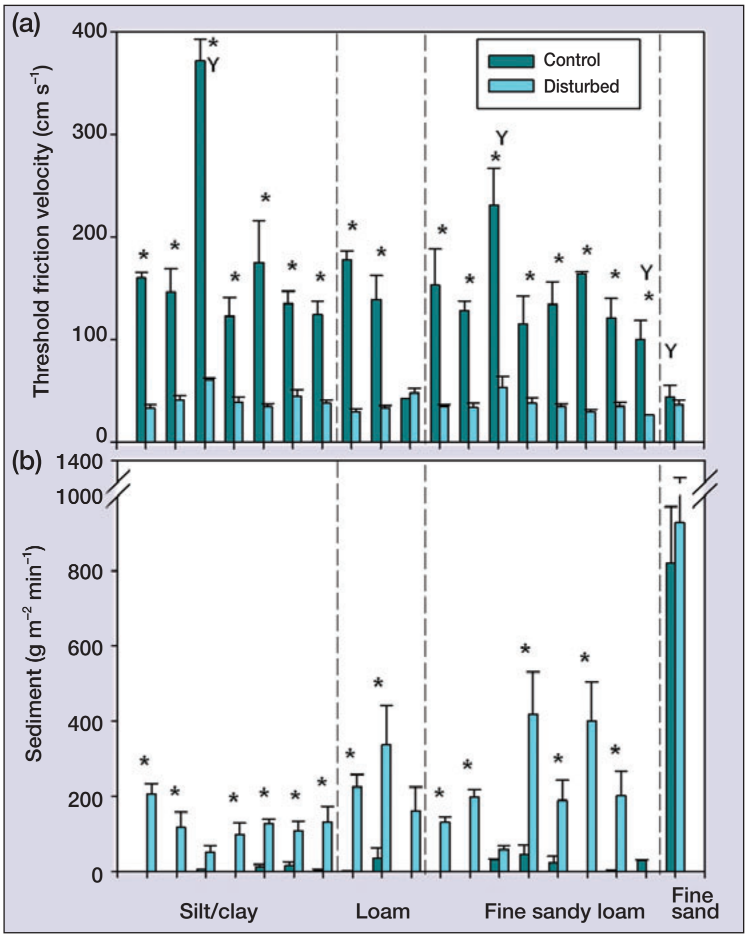

Figure 4. *Wind speeds at which sediment is detached from the soil surface (TFV). Thus, a higher value denotes greater soil stability. (b) The horizontal aeolian sediment flux; thus, a higher value denotes lower soil stability and greater sediment production. Error bars represent ± SE. * denotes statistical differences (P < 0.05). "Y" indicates that wind speeds generated by the tunnel were unable to disrupt the soil surface in the control soils; thus, reported values are conservative.*

Finer particles moved by wind – including silt- and clay-sized particles – contain most of the cation-exchange capacity, water-holding capacity, and fertility of the soil (Toy *et al.* 2002). Some of these finer particles are trapped by local vegetation (Raupach *et al.* 2001) and, combined with a similar mechanism for water erosion, contribute to the formation of fertile islands found throughout dryland regions (Schlesinger *et al.* 1990). In addition, fine particles and associated nutrients are added to soils by infiltration through gravelly surfaces (Reheis *et al.* 2009). However, many of these finer soil particles are eventually lost from the local system due to wind erosion (Gillette 1974), resulting in local depletion of soil fertility and water-holding capacity (Li *et al.* 2007, 2008). The relative depletion of fine particles at the surface may not have immediate impacts on existing vegetation, because the effect is concentrated above the root zone; the implications of this depletion for vegetation establishment, however, are striking, because of the heavy reliance of germinants on soil resources and water in the uppermost soil layers.

Many of the factors that drive wind erosion are, of course, greatly affected by soil surface disturbances. Grazing cattle crush biological and physical soil crusts and decrease vegetative cover (Nash *et al.* 2004), thereby increasing wind erosion (eg Neff *et al.* 2008). Offroad vehicles and military training activities also crush vegetation and impact plant-interspace surface characteristics, particularly biological and physical soil crusts (Belnap and Gillette 1997; Breshears *et al.* 2009; Figure 4). Fire can dramatically increase wind erosion (Whicker *et al.* 2002; Breshears *et al.* 2009), although fire may be less spatially extensive than grazing and recreational use. Burning vegetation (even by typical rangeland fires) releases different amounts of organic compounds, which, in turn, lead to different levels of water repellency in the soil, depending on various factors, such as vegetation type, soil properties, and fire intensity and duration (DeBano 2000). Fire-induced water repellency decreases the strength of interparticle wet-bonding forces by increasing the soil–water contact angle. This repellency enhances soil erodibility by causing a drop in threshold friction velocity, thereby increasing post-fire erosion (Whicker *et al.* 2002; Ravi *et al.* 2007).

There are important feedbacks between the vegetation and aeolian flux in deserts (Figure 5). Aeolian flux controls the redistribution of sediment and the loss of dust and dust-borne nutrients, thus affecting the amount and distribution of vegetation on the land surface. The amount and distribution of vegetation, in turn, affect the degree and spatial patterns of aeolian flux. This feedback can occur in most environments, including those with relatively high vegetation cover, and is responsible

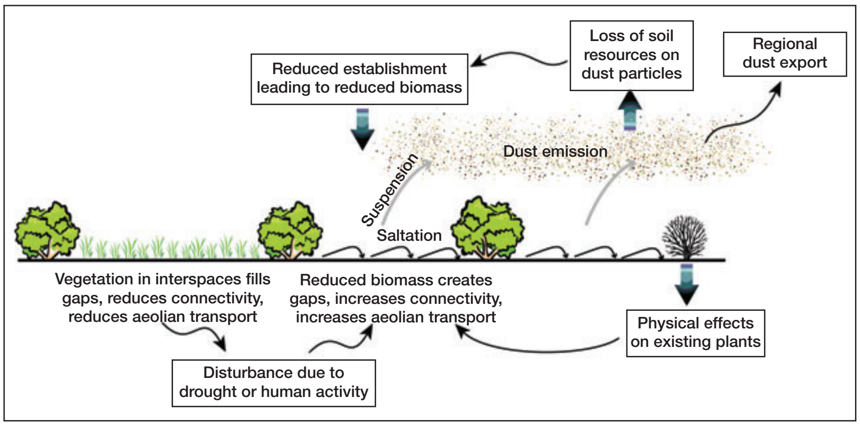

Figure 5. *Primary feedbacks between ecosystem function, wind erosion, and ecosystem structure.*

for cascading land-degradation phenomena caused by local or regional disturbance events (Peters *et al.* 2007). At the same time, dust emitted by desert regions, particularly those that have experienced substantial disturbance, can have critical consequences for downwind ecosystems.

■ Regional- to global-scale consequences

The regional and global transport of dust plays many fundamental roles in the Earth system. Dust has an important, yet relatively poorly quantified, influence on climate at both regional and global scales. At regional scales, dust can have a substantial effect on the atmospheric radiative balance and the concentration of condensation nuclei, both of which can influence climate variability via effects on surface temperatures and precipitation patterns (Yoshioka *et al.* 2007). Dust deposited on mountain snowpack can have an indirect effect on climate through the snow–albedo feedback (Painter *et al.* 2007; Steltzer *et al.* 2009; Figure 6). Dust decreases snow albedo, removing snow cover earlier and revealing a markedly darker land surface that absorbs solar radiation and reradiates in the infrared to the atmosphere. The triggering of earlier and faster snowmelt by dust can potentially result in less total and less late-season water supplies in areas where seasonal water scarcity occurs.

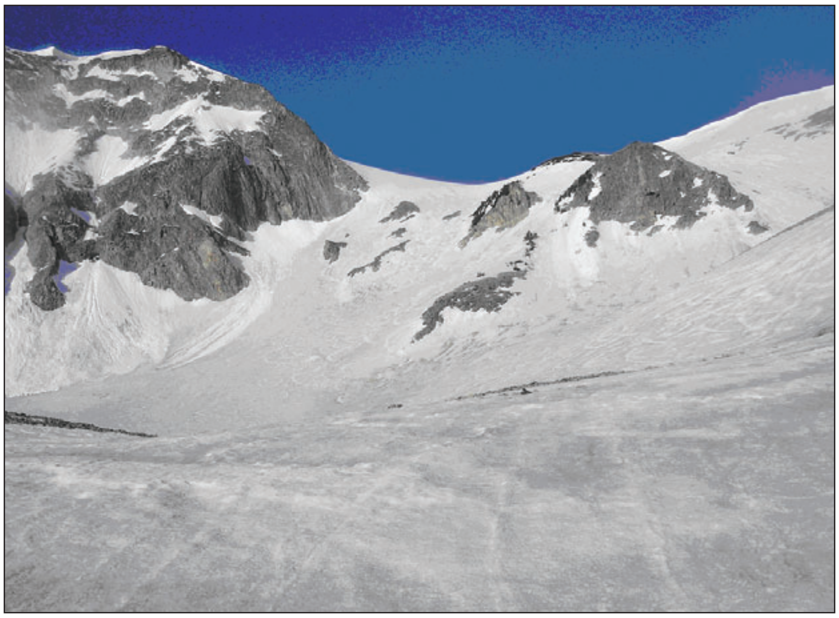

Figure 6. *Dust-laden snow on Mount Sopris, Colorado, May 2007.*

In addition to its effects on climate, dust plays an important role in the control of regional and global biogeochemical cycles and dispersal of pathogens. At the global scale, nutrient additions by dust may have stimulated the productivity of oceanic plankton over glacial time scales, thus accelerating the uptake of atmospheric CO_2 (eg Jickells *et al.* 2005). At the regional scale, there have been several studies examining the impact of dust deposition on terrestrial and aquatic nutrient cycling. In tropical ecosystems with a long legacy of chemical weathering and depletion of soil base cations and phosphorus, dust has been suggested as a major nutrient source. For example, the transport of Saharan dust to the Amazon basin has played an important role in offsetting the losses of bedrock-derived nutrients to leaching (Koren *et al.* 2006). Similar studies in Hawai‘i suggest that dust is responsible for supplying essential plant elements to heavily weathered soils (Chadwick *et al.* 1999). There is mounting evidence that dust transport and deposition are important to temperate ecosystems as well. Transport of nitrogen, phosphorus, and other nutrients by dust can be substantial (Neff *et al.* 2008), and the subsequent deposition of these nutrients may influence both terrestrial and aquatic ecosystems. In stable soil surfaces on the Colorado Plateau, dust accumulation in soils has increased the stocks of all macro- and micronutrients, especially phosphorus and magnesium (Reynolds *et al.* 2006). Long-term dust accumulation can lead to the development of loess soils (unstratified wind-blown silt deposits) in some regions, such as the American Midwest, providing for fertile agriculture (Pye 1987). These diverse studies illustrate that dust is an important and underappreciated component of contemporary biogeochemical cycles.

The importance of dust to global biogeochemical cycles raises several questions about the magnitude, distribution, and variation in dust fluxes across the Earth; this has led to numerous attempts to quantify the contributions of dust sources around the globe. Dust from land disturbed by humans or extreme climatic events, such as drought, may constitute a substantial fraction – perhaps one-third to one-half – of the total atmospheric dust loading (Tegen and Fung 1995). Model assessments indicate that global fluxes are dominated by the large deserts of North Africa, Asia, and the Middle East (Tanaka and Chiba 2006). This global emission flux appears to be dominated by non-arable, hyperarid regions, with large interannual variation in dust fluxes controlled primarily by climate (Figure 7).

Dust emissions from some less arid drylands appear to be more heavily influenced by human land use. In the semiarid regions of China, for instance, there is evidence that wind erosion of soils is influenced by grazing activities (eg Liu *et al.* 2007), and in South and North America, ice and sediment core records reveal that human activity has increased dust deposition over the past 100–200 years. In the western US, lake sediment records from the San Juan Mountains of Colorado show that dust loading reached a peak of ~ 500% of background (late Holocene) deposition circa 1900, when settlement and widespread livestock grazing dramatically increased (Neff *et al.* 2008). Abandoned cotton fields in Texas and Arizona and military training grounds in Texas and California consistently produce large regional dust storms that can be seen on satellite imagery

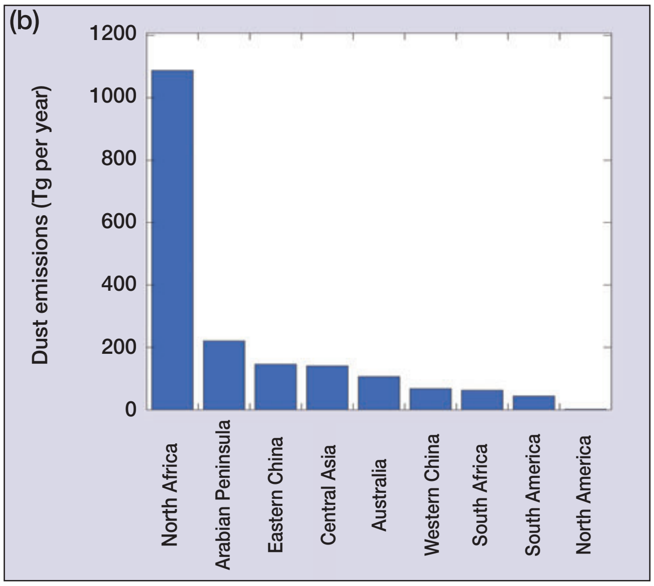

Figure 7. *Map showing global distribution of (a) drylands and (b) their respective dust emissions by region. Tg = teragram. Modified from Tanaka and Chiba (2006).*

(eg Prospero *et al.* 2002). In South America, human land use of semiarid regions for grazing also appears to have increased dust deposition rates in the 20th century, relative to those of the 19th century (McConnel *et al.* 2007). The human role in dust emission and deposition may be limited at the global scale, but at local to regional scales, dust appears to be mostly a byproduct of human land-use decisions. In this way, humans may be indirectly responsible for potentially large, but poorly understood, perturbations to local, regional, and global hydrologic and biogeochemical cycling.

■ Projections and implications

The future will bring many environmental changes to dryland areas; these will act independently and synergistically to affect dust fluxes at the local, regional, and global scales. Projected climate changes include a global increase in temperatures (Seager *et al.* 2007) in concert with a range of future precipitation possibilities for drylands. This could include green-up in some areas, but most regions are more likely to experience a small decrease in precipitation. By 2050, increased temperature alone is expected to decrease average soil moisture conditions in the southwestern US (Seager *et al.* 2007) to levels below those experienced during the most severe droughts of this century, including the Dust Bowl years (Pulwarty *et al.* 2005). Such declines in soil moisture will probably result in a reduction in the protective vegetative cover, a slower recovery from disturbance, and an increase in dust emission from exposed soil. Lower soil moisture will also mean drier fuels that burn more readily – wildfires in the western US are projected to increase substantially in both frequency and intensity (Ryan *et al.* 2008), which will also increase exposed soils and the hydrophobicity of those soils, thus amplifying dust emissions (Whicker *et al.* 2002; Ravi *et al.* 2007).

Worldwide, human use of dryland regions, which comprise almost 41% of the terrestrial land surface, is increasing dramatically. Currently, over 2 billion people depend on drylands for habitation and food (MA 2005), and much of the global population growth is occurring in these water-limited landscapes (Reynolds *et al.* 2007). For example, human populations in southern Arizona and California are expected to grow from 25 million to 38 million over the next 11 years (Pulwarty *et al.* 2005). An increase in human settlement/use of these landscapes will be accompanied by a further loss in the protective covering of plants, plant litter, and physical and biological soil crusts, thereby amplifying dust emissions from the disturbed surfaces. Offroad recreational activity in southern California has risen from virtually zero in 1960 to almost 10 million user-days in 2006 (Bureau of Land Management RIMS database). If users drive 32 km per day, this specific activity alone, in this relatively small region, can generate as much as 2.7 metric tons of dust per year (Dyck and Stukel 1976; Forman *et al.* 2003). The now-exploding exploration and development of energy resources (including wind and solar) in dryland regions are also of concern. All of these activities will result in the loss of vegetation and soil surface protectors (eg scraping away vegetation for solar farms and oil pads), increased offroad vehicle traffic, pipelines, transmission lines, and greatly increased traffic on existing and newly established dirt roads. The demand for water is also ever-increasing in these regions – demands that result in water diversions or the pumping of water from shallow lakes, often drying them completely (eg Lake Aibi in China, Aral Sea in Uzbekistan, Owens Lake in US), or from shallow aquifers, which may lead to the death of vegetation (Elmore *et al.* 2008). These activities can leave vast expanses of soils highly vulnerable to wind erosion. An example of the influence of dust from dry-lake sediments on vegetation is provided by Blank *et al.* (1999), who found that dust from playas (dry or ephemeral lake beds), which are rich in nitrates and other nutrients, stimulated the invasion of a playa-margin, dune-mantled landscape by weeds (such as *Salsola paulsenii*).

The conversion of perennial plant communities to those dominated by annual plants is also increasing globally, mostly as a result of fire, abandonment of agricultural fields, overgrazing, and other soil surface-disturbing activities (D'Antonio and Vitousek 1992). In wet years, the annual cover is sufficient to stabilize soils and may even exceed the protection offered by the perennial community. However, in dry years, these annual grasses do not germinate, or die shortly after germination, leaving soils barren and vulnerable to erosion. Dominance by annual plants also accelerates fire cycles. In wet years, these grasses produce sufficient continuous fuels to promote fire in the dry years that follow, leaving post-fire soils vulnerable to erosion.

Dust responses can become synergistic with changes in climate and land use when one or more of the above factors coincide in time or space. For instance, offroad vehicle use leads to decreases in plant biomass and cover, as a result of direct impacts to vegetation and dusting of nearby plants (Sharifi *et al.* 1999). When these impacts occur during times of reduced soil moisture, the reduction in plant cover is even greater, allowing for increased erosion. Another synergistic series of effects can occur on landscapes where perennial plants have been replaced by annual plants. When these surfaces are then disturbed by livestock or vehicles, an exponential increase in soil loss can be observed, as compared to that in an annual-dominated but untrampled landscape (Belnap *et al.* in press).

In summary, greater dust emissions, including more frequent and larger dust storms, are likely to occur from dryland regions as temperatures increase and more dryland areas are trampled, cleared of vegetation, plowed, and/or converted from perennial to annual plants. These increasing emissions will result in degraded soils and plants at the dust source, as well as in impacts to human and ecosystem health during transport and at deposition points. Avoiding the potentially severe consequences of this future scenario will require a new approach to the management of dryland regions. We need to identify the chronic and acute sources of dust that have potentially large impacts at local, regional, and global scales (Peters *et al.* 2007). We also need to better understand how the timing, type, and intensity of different land uses affect dust production. The overarching challenge for ecologists and other environmental scientists, land managers, and policy makers will be to work together to manage vulnerable areas in ways that reduce excess dust production to the fullest extent possible (Okin *et al.* 2009).

Acknowledgements

We thank KA Ferguson, DJ Law, CJ Perry, and SL Phillips for comments on the manuscript. This work was supported by the US Department of Agriculture Cooperative State Research, Education, and Extension Service (CSREES 2005-38420-15809), the National Science Foundation (NSF DEB-0816162, DEB-0618210, DEB-0823205, EAR-072021), and the Global Change Program of the US Geological Survey.

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