LA-UR- 09-00032

Approved for public release;
distribution is unlimited.

Title: The Ecology of Dust: Local- to Global-Scale Perspectives

Author(s): Jason P. Field, Jayne Belnap, David D. Breshears, Jason C. Neff, Gregory S. Okin, Jeffrey J. Whicker, Thomas H. Painter, Sujith Ravi, Marith C. Reheis, Richard L. Reynolds

Intended for: Frontiers in Ecology

Los Alamos
NATIONAL LABORATORY
EST. 1943

The ecology of dust: local- to global-scale perspectives

Jason P. Field, Jayne Belnap, David D. Breshears, Jason C. Neff, Gregory S. Okin,
Jeffrey J. Whicker, Thomas H. Painter, Sujith Ravi, Marith C. Reheis, and Richard L. Reynolds

For submission as a Review to *Frontiers in Ecology and the Environment*
Draft Dec 19, 2008
(draft author order – currently by organizing group, section leads, and supporting authors)
3500 word limit; 50 references

Abstract: Emission and redistribution of dust due to wind erosion in drylands drives major biogeochemical dynamics and provides important aeolian environmental connectivity at scales from individual plants up to the global scale. Yet, perhaps because most relevant research on aeolian processes has been presented in a geosciences rather than ecological context, most ecological studies do not explicitly consider dust-driven processes. 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 plant-interspace scale to regional and global scales, and highlight specific examples of how disturbance affects these interactions and their consequences. Changes in climate and intensification of land use will both likely lead to increased dust production. To address these challenges, environmental scientists, land managers and policy makers need to more explicitly consider dust in resource management decisions.

In a nutshell:

- Ecologists and other environmental scientists often overlook the importance of dust and aeolian processes, yet these processes are of fundamental biogeochemical and ecological significance.
- The importance of aeolian processes crosses scales from individual plants up to the globe.
- 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.

Introduction

Ecologists' first thought about dust may be the thin film of material that accumulates on their computer monitor on a regular basis. But dust actually has enormous relevance to a wide variety of ecological dynamics and applied issues, even though many ecologists often do not think about dust explicitly. Dust is fine particulate material that is small enough to be suspended in the air, and is the material transported through wind erosion (Bagnold 1941, Griffin *et al.* 2001, Toy *et al.* 2002). Perhaps the most notable example of how ecologically important dust can be is the Dust Bowl era during the 1930s in the American Great Plains (Figure 1b), which is considered by many to be one of the most severe environmental catastrophes in the history of America (Worster 1979, 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 rates of wind erosion, 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 resulted from small-scale fields becoming more erosive and interconnected (Hansen and Libecap 2004), thereby triggering a threshold-like 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 fluxes. Ironically, the former Soil Conservation Service, now the Natural Resources Conservation Service, has shifted the vast majority of its focus to water erosion, mostly abandoning the topic of wind erosion.

In contrast to the ecological community, geoscientists 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 on basic ecosystem processes at scales ranging from individual plants or smaller (Figure 1a) up through local and regional scales (Figure 1b, c) to a global scale (Figure 1d), providing biogeochemical connectivity across continents (Peters *et al.* 2007).

Here we provide ecologists and environmental scientists with a needed primer on the importance of aeolian processes associated with wind erosion and dust emission, as well as an overview of ecologically-relevant aeolian processes from the scales of individual plants up through global 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 the key role of disturbance and how changes in climate (Seager *et al.* 2007) and increased land use intensification (Okin *et al.* 2006) pose challenges for improving our understanding of dust and how to manage it.

A wind erosion primer

Wind transports soil material through three mechanisms (Figure 2) that are roughly differentiated based on the soil particle diameter: *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). All three processes redistribute soil and associated nutrients and organic material throughout an ecosystem at different spatial scales. Wind-driven surface creep and saltating particles dominate the mass movement of soil on a local scale (< several m) (Stout and Zobeck 1996). In contrast, suspended dust particles are available for long-distance transport and can move at regional, continental, and global scales (Griffin *et al.* 2001). Most of the wind erosion activity occurs as a horizontal flux close to the soil surface, decreasing exponentially with height (Bagnold 1941, Breshears et al. 2003). A small fraction of this flux, the dust fraction, can become suspended and be available for long-distance dust transport, as reflected in a vertical flux that can be correlated with horizontal flux (Whicker *et al.* 2006). Because soil nutrients (e.g., nitrogen, phosphorus) and organic matter are often associated with smaller soil particles, soil fertility in dust source areas is depleted and sink areas are concomitantly enriched (Van Pelt and Zobeck 2007, McGowan and Ledgard 2005).

Soil erosion rates at a specific location are influenced by a variety of factors. (Fryrear 1985, Zobeck *et al.* 2003). Local topography drives microscale wind gradients (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 velocity" wind speed at which particles of a given size under a given set of field conditions begin to detach from the soil surface (Zobeck *et al.* 2003). Atmospheric relative humidity controls soil moisture at the soil surface, especially during rainless periods (Ravi *et al.* 2004) because soil moisture in these particles is typically at equilibrium with atmospheric moisture. This is significant because soil moisture influences the interparticle forces that control the threshold wind speed, resulting in a clear, but complex, relationship between atmospheric relative humidity, particle size, and soil erodibility (Ravi *et al.* 2006a). These complex relationships need to be considered with regard to their relative role in affecting aeolian processes at scales from the individual plant up through regional and global.

Plant-interspace scale

At the plant-interspace scale, aeolian transport is a major abiotic transport mechanism for moving material both within and out of environments with discontinuous cover. The erosivity of the surface, and thus the potential impacts of aeolian processes at the plant-interspace scale, depends on both the ability of the soil surface to resist erosion and the ability of the wind to reach that 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, Belnap 2003, Okin *et al.* 2006). Silt and clay particles bind together when wetted, forming soil aggregates that often form a physical crust. Unless disturbed, these soils have an inherently higher resistance to erosion than soils dominated by coarser sand particles. Rocks, plant litter, and biological soil crusts all prevent soils from being exposed to the erosive force of wind. Biological soil crusts, composed of cyanobacteria, lichens, and moss, also stabilize soils by excreting mucilaginous material that bind soil surface particles together, increasing soil aggregate size, and thus increasing resistance to the shearing forces of wind (Belnap and Gardner 1993, Belnap 1995).

The type, cover, and arrangement of vegetation is 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 is 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, and the height of the vegetation, which controls the size of the protected area downwind of individual plants (Breshears *et al.* 2009, Okin 2008). Thus, the amount of horizontal flux that occurs depends on the structure of the ecosystem and the degree of plant connectivity that exists (Okin *et al.* 2008; Figure 3).

Areas immediately downwind of vegetation (within 5-10 times the height of the plant) are relatively protected from the erosive force of the wind by the plant. In contrast, 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. Because saltating material carries most of the mass and momentum transport, it can have significant physical effects on existing vegetation including burial, pedestaling, cambial abrasion, and leaf stripping. This has been shown to lead to reduced plant growth and mortality, and to contribute to rapid changes in ecosystem structure (i.e., initiating a rapid change from a grassland to a shrubland) (Okin *et al.* 2006).

Finer particles moved by wind contain most of the cation-exchange capacity, water-holding capacity, and fertility of the soil. Some of these finer particles are trapped by local vegetation (Raupach *et al.* 2001), and, combined with a similar mechanism for water erosion, give rise to fertile islands found throughout dryland regions (Schlesinger *et al.* 1990). However, many of these finer soil particles are lost from the system (Gillette 1974), resulting in local depletion of soil fertility and water-holding capacity (Okin *et al.* 2006, Li *et al.* 2007, Li *et al.* 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, is striking due to the heavy reliance of germinant on soil resources and water in the uppermost soil layers. In addition to ecological effects, dust can endanger human health by obscuring visibility on highways, causing respiratory disease if inhaled, and carrying pathogens such as Valley Fever.

Many of the factors that drive wind erosion are, of course, greatly affected by soil surface disturbances. Grazing by cattle crushes biological and physical soil crusts and decreases vegetative cover (Nash *et al.* 2004, Belnap 2003), thereby increasing wind erosion (e.g., Neff *et al.* 2008). Off-road vehicles are also notable in impacting plant-interspace surface characteristics, particularly biological and physical soil crusts, and crushing vegetation (Belnap and Gillette 1997, Figure 4), as is military training (Breshears et al. 2009). Fire can dramatically increase wind erosion (Whicker et al. 2002, Breshears et al. 2009), although it occurs at a smaller spatial scale than grazing and recreational use. Burning vegetation (even by typical rangeland fires) releases different levels of organic compounds which induce different levels of water repellency in the soil, depending on several factors such as vegetation type, soil properties, fire intensity and duration (Debano 2000). By affecting the strength of interparticle wet-bonding forces (by increasing the soil-water contact angle), fire-induced water repellency enhances soil erodibility by causing a drop in threshold friction velocity, thereby increasing post-fire erosion (Whicker *et al.* 2002, Ravi *et al.* 2006b, 2007).

Thus there are important feedbacks between the vegetation and aeolian flux in deserts (Figure 5). Aeolian flux controls the redistribution of sediment and loss of dust and dust-borne nutrients, thus affecting the vegetation demographic processes and distribution. The amount and distribution of vegetation, in turn, affects the degree and spatial pattern of aeolian flux. This feedback can occur in most environments, including those with relatively high vegetation cover. The existence of this feedback, furthermore, is responsible for cascading land-degradation phenomena caused by local or regional disturbance events (Peter *et al.* 2007). At the same time, dust emitted by desert regions, particularly those that have experienced significant disturbance, can have critical consequences for downwind ecosystems.

Regional to global-scale consequences

The regional and global transport of dust plays many roles in the global earth system. Dust plays an important, yet uncertain, role in climate at both regional and global scales. At regional scales, through dust effects on atmospheric radiative balance and condensation nuclei, dust may influence climate variability through effects on surface temperatures and precipitation patterns (Held *et al.* 2005, Yoshioka *et al.* 2007). Dust deposited on mountain snowpack can have an indirect effect on climate by decreasing the albedo of snow-covered surfaces. Decreased albedo can trigger earlier and faster snowmelt (Painter *et al.* 2007; Figure 6), which potentially means smaller late-season water supplies in areas where seasonal water scarcity can be problematic. .

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 timescales, thus accelerating the uptake of atmospheric CO_2 (e.g., Jickells *et al.* 2005). Coral reef die-off in the Caribbean has been attributed to inputs of Saharan dust (Schinn xxxx).At the regional scale, there have been a number of 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 an important nutrient source. For example, the transport of Saharan dust to Amazon basin has played an important role in offsetting the losses of bedrock derived nutrients to leaching (Koren *et al.* 2006). Similarly studies in Hawaii suggest that dust is responsible for supplying essential plant elements supply to heavily weathered soils (Chadwick et al. 1999). There is mounting evidence that dust transport and deposition is important to temperate ecosystems as well. Transport of nitrogen, phosphorus and other nutrients by dust can be substantial (Okin *et al.* 2004, Neff et al. 2008) and the subsequent deposition of these nutrient 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). These diverse studies illustrates that dust is likely an important and underappreciated component of contemporary biogeochemical cycles.

The potential importance of dust to global biogeochemical cycles raises a number of questions about the magnitude, distribution and variation in dust fluxes across the earth. There have been numerous attempts to quantify the distribution of dust sources around the globe with consensus 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 dryland regions with large interannual variation in dust fluxes controlled primarily by climate (Prospero others). Although dust emissions from large deserts appear to be closely coupled to climate variation, dust emissions from some smaller deserts appear to be more heavily influenced by human land use change. In the semi-arid regions of China, there is much evidence that wind erosion of soils is influenced by grazing activities (e.g., Liu *et al.* 2007) and in South and North America ice and sediment core records suggest that human activity has increased dust deposition over the past 100-200 years. In the western U.S., lake sediment records from the San

Juan Mountains of Colorado suggest 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; Figure 7). 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 (Chavez, pers. comm.) In South America, human land use of semi-arid regions for grazing also appear to have increased dust deposition rates in the 20th century relative to the 19th century (Neff et al., 2008). The human role in dust emission and deposition may be limited at the global scale but at the 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 potential large, but poorly understood, perturbations to local, regional, and global hydrologic and biogeochemical cycling.

The future: implications and projections

The future will bring many environmental changes to dryland areas that 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 (Christensen et al. 2007) in concert with a range of future precipitation possibilities for drylands, with most regions likely to experience a small decrease in precipitation. . By 2050, increased temperature alone is expected to cause the average soil moisture conditions in the southwest U.S. to be lower than soil moisture levels during the mega-droughts of this century, including the Dust Bowl years (Pulwarty et al. 2005). Because precipitation also is projected to decline over much of this region and drought years are frequent, soil moisture levels will likely be even lower than during these mega-drought periods. Such declines in soil moisture will result in a reduction of the protective cover of plants, slower recovery from disturbance, and an increase in dust emissions from exposed soil. Lower soil moisture also will mean drier fuels that burn more readily--wildfires in western U.S. are projected increase by 500% (ref)--which will also increase soils exposed to erosion and thus increase dust emissions (Whicker et al. 2006).

Worldwide, human use of dryland regions, which comprise almost 41% of the terrestrial land surface, is increasing dramatically. Currently, over 2 billion people use drylands for habitation and food (Millennium Assessment 2000), and much of the global population increase is occurring in these water-limited landscapes. For example, human populations in southern Arizona and California are expected to increase from 25 million to 38 million in 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 increasing dust emissions from the disturbed surfaces. Off-road recreation use 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 20 miles per daythis specific activity alone in this relatively small region generates up to 6 billion pounds 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 is also of concern. All of these activities will result in the loss of vegetation and soil surface protectors (e.g., scraping away vegetation for solar farms and oil pads), increased off-road vehicle traffic, pipelines, transmission lines, and greatly increased traffic on current and newly established dirt roads. The demand for water is also ever-increasing in these regions, resulting in water diversions or the pumping of water from shallow lakes, often drying them completely (e.g., Lake Aibi in China, Aral Sea in Uzbekistan, Owens Lake in U.S.), while. . pumping water from shallow aquifers can lead to the death of surface vegetation. These activities can leave vast expanses of soils highly vulnerable to wind erosion.

The conversion of perennial plant communities to ones dominated by annuals is also increasing globally, mostly as a result of fire, abandonment of agricultural fields, over-grazing, 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 carry fire in dry years that follow, leaving post-fire soils exposed 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 (Figure 8). For instance, the direct impacts to vegetation and associated with off-road vehicle use and dusting of nearby plants will both result in decreased plant biomass and cover. 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 effect occurs on landscapes where perennial plants have been replaced by annual plants. During drought years when few or no annual plants germinate or survive, barren soils are highly vulnerable to wind erosion. When these surfaces are then disturbed by livestock or vehicles, an exponential increase in soil loss can be observed when compared to an annual-dominated but untrampled landscape (Belnap et al. in press).

In summary, as temperatures increase and more dryland areas are trampled, cleared of vegetation, plowed, and/or converted to from perennial to annual plants, greater dust emissions, including more frequent and larger dust storms, can be expected from dryland regions. This will result in degraded soils and plants at the dust source, as well as human and ecosystem health issues during transport and at deposition points (e.g. Whicker et al. 2006). 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 (Breshears et al. 2009, Peters et al. 2008). 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 dust production to the fullest extent possible.

References

Bagnold RA. 1941. The physics of blown sand and desert dunes. London, UK: Chapman and Hall Ltd.

Belnap J. 2003. The world at your feet: desert biological soil crusts. *Front Ecol Environ* **1:** 181-89.

Belnap J. 1995. Surface disturbances: their role in accelerating desertification. *Environ Monit Assess* **37:** 39-57.

Belnap J and Gardner JS. 1993. Soil microstructure in soils of the Colorado Plateau: the role of the cyanobacterium. *Microcoleus vaginatus*. *Great Basin Nat* **53:** 40-47.

Belnap J and Gillette DA. 1997. Disturbance of biological soil crusts: impacts on potential wind erodibility of sandy desert soils in southeastern Utah. *Land Degrad Dev* **8:** 355-62.

Breshears DD, Whicker JJ, Johansen MP, and Pinder III JE. 2003. Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystems: quantifying dominance of horizontal wind-drive transport. *Earth Surf Proc Land* **28**: 1189-1209.

Breshears DD, Whicker JJ, Zou CB et al. 2009. A conceptual framework for dryland aeolian sediment transport along the grassland-forest continuum: effect of woody plant canopy cover and disturbance. *Geomorphology* In Press.

Chadwick OA, Derry LA, Vitousek PM, et al. 1999. Changing sources of nutrients during four million years of ecosystem development. *Nature* **397:** 491-97.

D'Antonio CM and Vitousek PM. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23: 63-87.

DeBano LF. 2000. The role of fire and soil heating on water repellence in wildland environments: a review. *J Hydrol* **231:** 195-206.

Dyck RIJ and Stukel JJ. 1976. Fugitive dust emissions from trucks on unpaved roads. Environmental Science and Technology 10:1046-1048.

Forman RTT, Sperling D, Bissonette JA, et al. 2003. Road Ecology: Science and Solutions. Washington, DC, Island Press.

Fryrear DW, 1985. Soil cover and wind erosion. *T Am Soc Ag Eng* **28:** 781-84.

Gillette DA. 1974. On the production of soil wind erosion aerosols having the potential for long range transport. *Journal des Recherches Atmospheriques* **8:** 735-44.

Gillette DA, Adams J, Endo A, et al. 1980. Threshold velocities for input of soil particles into the air by desert soils. *J Geogr Res* 85: 5621-30.

Griffin DW, Kellogg CA, and Shinn E. 2001. Dust in the wind: long range transport of dust in the atmosphere and its implications for global public and ecosystem health. *Global Change Human Health* **2:** 20-33.

Hansen ZK and Libecap GD. 2004. Small farms, externalities, and the Dust Bowl of the 1930s. *J Polit Econ* **112:** 665-94.

Held IM, Delworth TL, Lu J, et al. 2005. Simulation of Sahel drought in the 20th and 21st centuries. *P Natl Acad Sci USA* **102:** 17891-96.

Jickells TD, An ZS, Andersen KK, et al. 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* **308:** 67-71.

Johnson V. 1947. Heaven's tableland: the Dust Bowl story. New York, NY: Farrar, Straus.

Koren I, Kaufman YJ, Washington R, et al. 2006. The Bodele depression: a single spot in the Sahara the provides most of the mineral dust to the Amazon forest. Environ Res Lett. **1:** 014005, doi:10.1088/1748-9326/1/1/014005.

Li J, Okin GS, Hartman LJ, and Epstein HE. 2007. Quantitative assessment of wind erosion and soil nutrient loss in desert grasslands of southern New Mexico, USA. *Biogeochemistry* **85:** 317-32.

Li J, Okin GS, Alvarez LJ, and Epstein HE. 2008. Effects of wind erosion on the spatial heterogeneity of soil nutrients in a desert grassland of southern New Mexico. *Biogeochemistry* In Press.

Liu LY, Li XY, Shi PJ, et al. 2007. Wind erodibility of major soils in the farming-pastoral ecotone of China. *J Arid Environ* **68:** 611-23.

McGowan H. and Ledgard N. 2005. Enhanced dust deposition by trees recently established on degraded rangeland. *J R Soc New Zealand* **35:** 269-77.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Desertification Synthesis. World Resources Institute, Washington, DC.

Nash MS, Jackson E, and Whitford WG. 2004. Effects of intense, short-duration grazing on microtopography in a Chihuahuan Desert grassland. *J Arid Environ* **56**: 383-93.

Neff JC, Ballantyne AP, Famer GL, et al. 2008. Increasing eolian dust deposition in the western United States linked to human activity. *Nature - Geosciences* doi:10.1038/ngeo133

Okin GS. 2008. A new model for wind erosion in the presence of vegetation. *J Geophys Res-Earth Surf* **113:** F02S10.

Okin GS, Mahowald N, Chadwick OA, et al. 2004. Impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems. *Global Biogeochemical Cycles* **18:** GB2005, doi:10.1029/2003GB002145.

Okin GS, Herrick JE, Gillette DA. 2006. Multiscale controls on and consequences of aeolian processes in landscape change in arid and semiarid environments. *J Arid Environ* **65:** 253-75.

Okin GS, Parsons AJ, Wainwright J, et al. 2008. Do changes in connectivity explain desertification? *BioScience* In press.

Painter TH, Barrett AP, Landry CC, et al. 2007. Impact of disturbed desert soils on duration of mountain snowcover. *Geophys Res Lett* **34:** L12502, 10.1029/2007GL030208.

Peters DPC, Sala OE, Allen CD, et al 2007. Cascading events in linked ecological and socio-economic systems: predicting change in an uncertain world. *Front Ecol Environ* **5:** 221-24.

Pulwarty R, Jacobs K, and Dole R. 2005. The hardest working river: Drought and critical water problems in the Colorado River Basin, in D. Wilhite, ed. Drought and Water Crises: Science, Technology and Management. CRC Press, Boca Raton, Florica, p. 249-285.

Raupach MR, Woods N, Dorr G, et al. 2001. The entrapment of particles by windbreaks. *Atmos Environ* **35:** 3373-83.

Ravi S, D'Odorico P, Over TM, and Zobeck TM. 2004. On the effect of air humidity on soil susceptibility to wind erosion: the case of air-dry soils. *Geophys Res Lett* **31:** Art. No. L09501.

Ravi S, Zobeck TM, Over TM et al. 2006a. On the effect of wet bonding forces in air-dry soils on threshold friction velocity of wind erosion. *Sedimentology*: 10.1111/j.1365-3091.2006.00775.x.

Ravi S, D'Odorico P, Herbert B, et al. 2006b. Enhancement of wind erosion by fire-induced water repellency, *Water Resour Res* **42:** W11422, doi: 10.1029/2006WR004895.

Ravi S, D'Odorico P, Zobeck TM, et al. 2007. Feedbacks between fires and wind erosion in heterogeneous arid lands. *J Geophys Res-Biogeosciences* **112:** G04007.

Reynolds R, Neff J, Reheis M, and Lamothe P. 2006. Atmospheric dust in modem soil on aeolian sandstone, Colorado Plateau (USA): variation with landscape position and contribution to potential plant nutrients. *Geoderma* **130:** 108-123.

Schlesinger WH, Reynolds JF, Cunningham GL et al. 1990. Biological feedbacks in global desertification. *Science* **247:** 1043-48.

Seager R, Ting MF, Held I, et al. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* **316:** 1181-84.

Stout JE and Zobeck TM. 1996. The Wolfforth field experiment: a wind erosion study. *Soil Science* **161:** 616-32.

Swanson, T. Turrentine, T. C. Winter. (2003). Road Ecology: Science and Solutions. Washington, DC, Island Press.

Tanaka TY and Chiba M. 2006. A numerical study of the contributions of dust source regions to the global dust budget. *Global Planetary Change* **52:** 88-104.

Toy TJ, Foster GR, and Renard KG. 2002. Soil erosion: processes, prediction, measurement and control. New York, NY: John Wiley & Sons.

Van Pelt RS and Zobeck TM. 2007. Chemical constituents of fugitive dust. *Environ Monit Assess* **130:** 3-16.

Whicker JJ, Breshears DD, Wasiolek PT, et al. 2002. Temporal and spatial variation of episodic wind erosion in unburned and burned semiarid shrubland. *J. Environ Qual* **31:** 599-612.

Whicker JJ, Pinder JE, and Breshears DD. 2006. Increased wind erosion from forest wildfire: implications for contaminant-related risks. *J Environ Quality*. 35: 468-78.

Worster D. 1979. Dust Bowl: the southern plains in the 1930s. New York, NY: Oxford University Press.

Utz EJ, Kellogg CE, Reed EH, et al. 1938. The problem: the nation as a whole. In: Bennett HH and Lowdermilk WC (Eds). Soils and men. Yearbook of agriculture. Washington, DC: US Department of Agriculture.

Yoshioka M, Mahowald N, Conley A, et al. 2007. Impact of desert dust radiative forcing on Sahel precipitation: relative importance of dust compared to sea surface temperature variations, vegetation changes and greenhouse gas warming. *J Climate* **20:** DOI:10.1175/JCLI4056.1, 1445-67.

Zobeck TM, Sterk G, Funk R, et al. 2003. Measurement and data analysis methods for field-scale wind erosion studies and model validation. *Earth Surf Proc Land*, **28**: 1163-88.

Figures

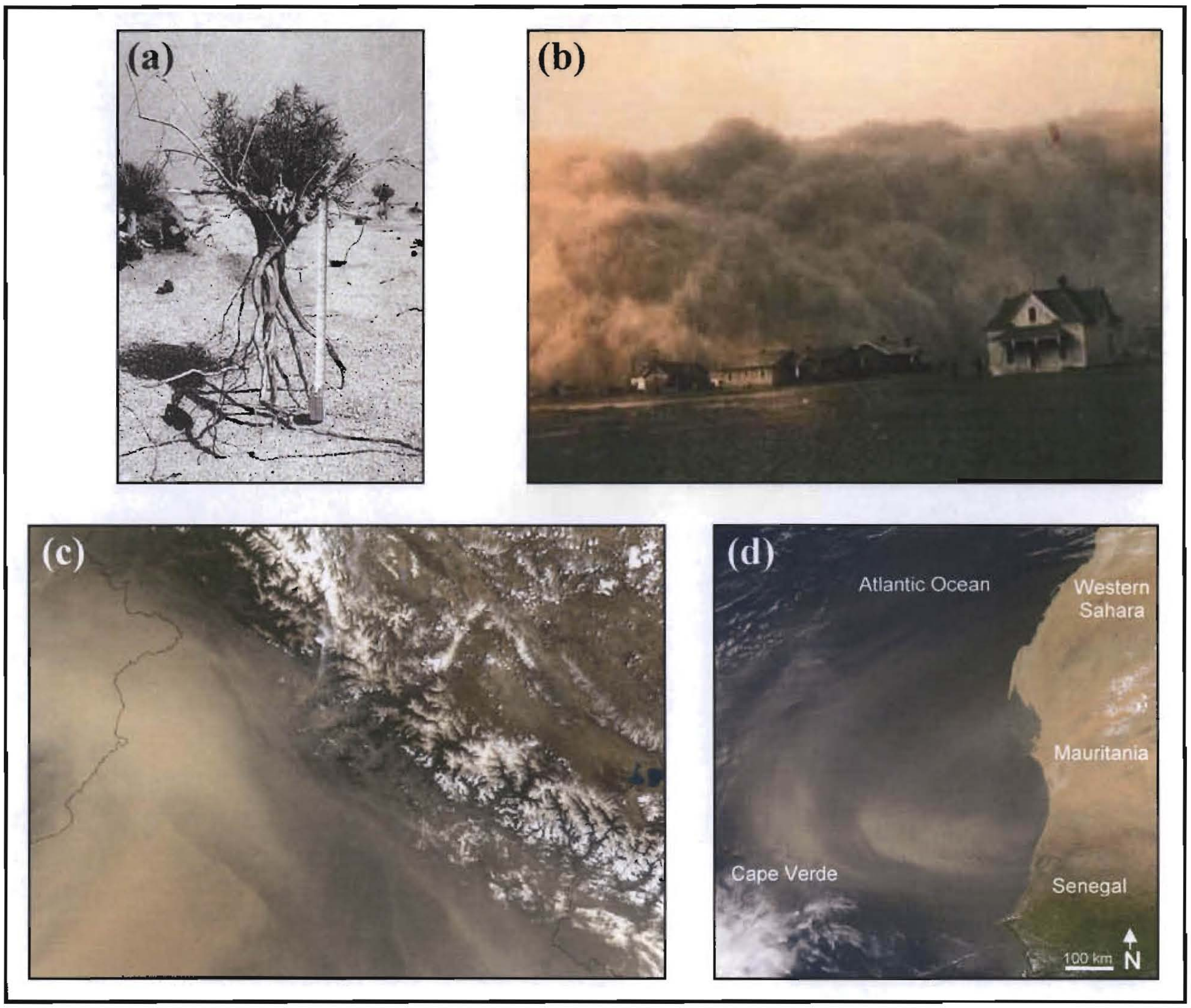


Figure 1. (a) plant-interspace scale: vegetation with exposed roots in Central Valley, CA, 1978; (b) Dust storm approaching Stratford, Texas, April 18 1935. [Image ID: theb1365, Historic C&GS Collection, Credit: NOAA George E. Marsh Album]; (c) local-scale dust storm (photo credit: Jayne?); (c) global-scale: dust transport across ocean off the west coast of northern Africa on September 29, 2008 [Moderate Resolution Imaging Spectroradiometer (MODIS)].

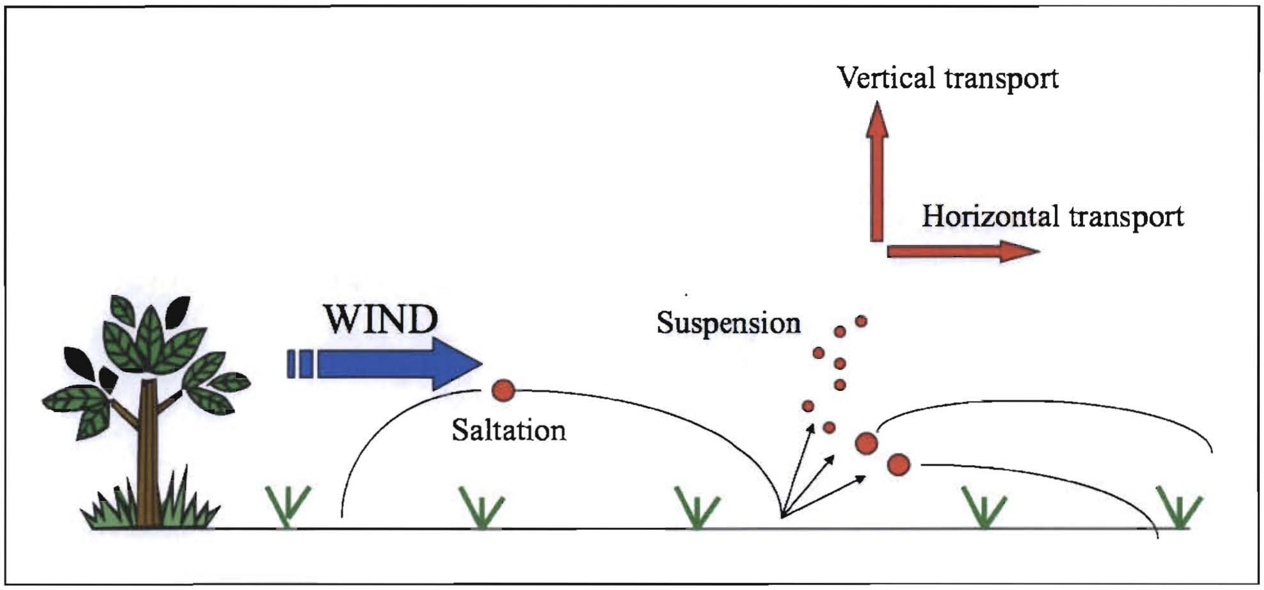


Figure 2. How wind erosion works.

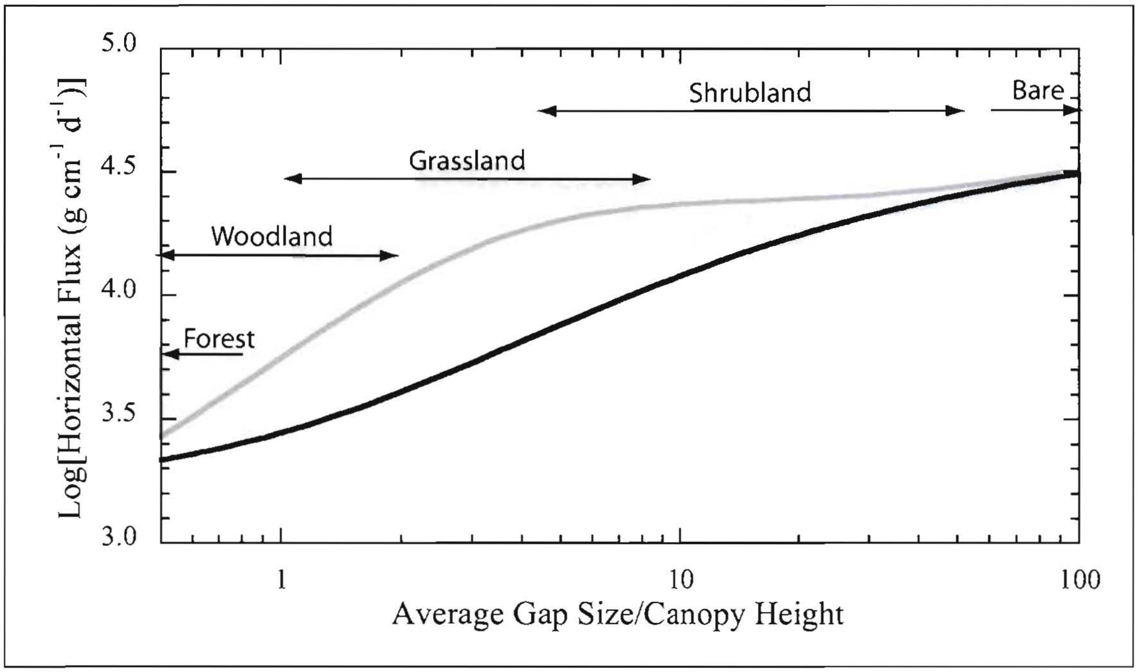
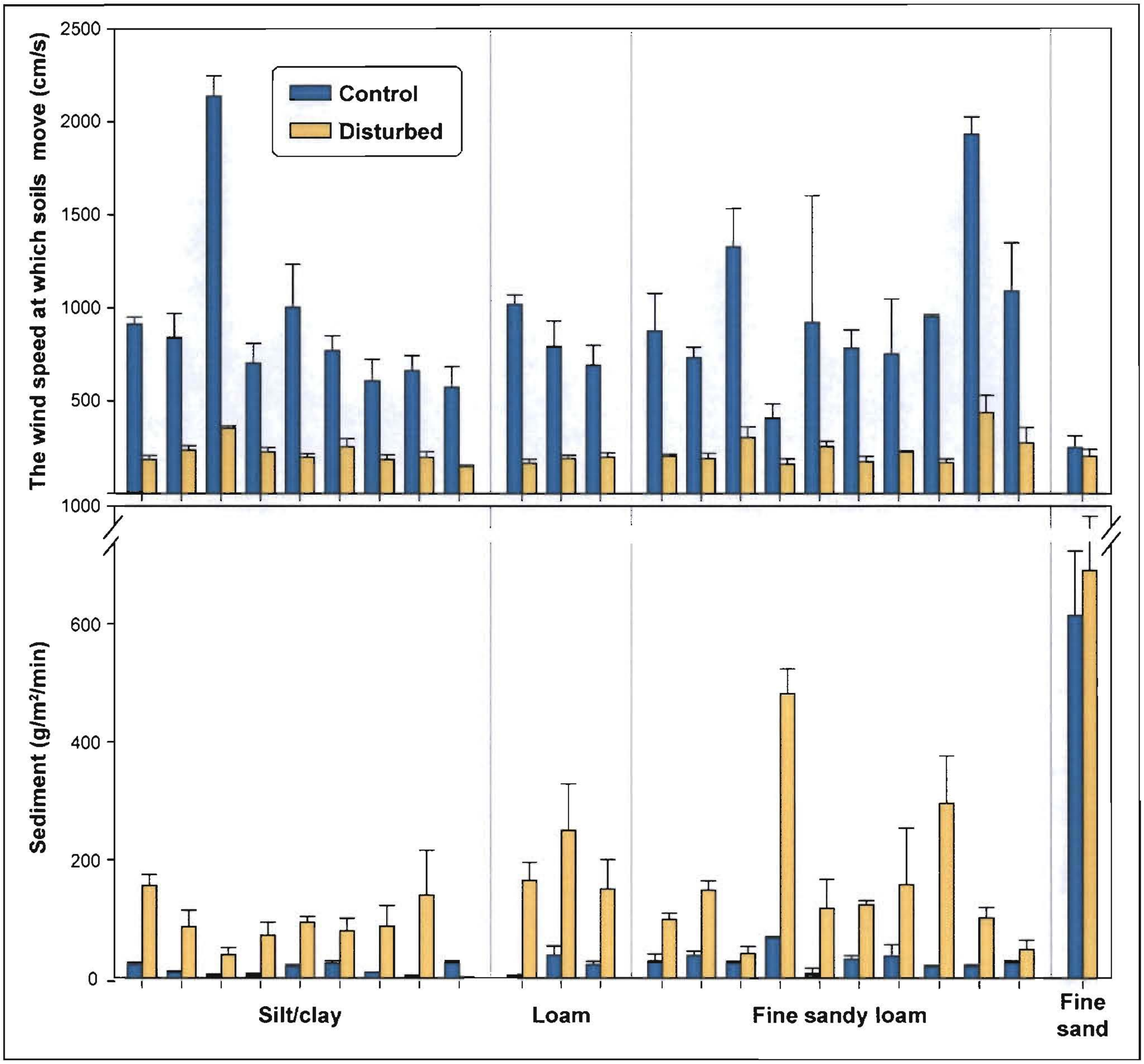


Figure 3. Horizontal aeolian sediment flux as a function of the ratio of average unvegetated gap size to plant height (Adapted from Okin, 2008 and Breshears et al., 2008). The black line indicates how flux would vary in the presence of an undisturbed herbaceous layer for each ecosystem. The gray line 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.



2500
2000
1500
1000
500
1000
600
400
200
0
The wind speed at which soils move (cm/s)
Sediment (g/m²/min)
Control
Disturbed
Silt/clay
Loam
Fine sandy loam
Fine sand

Figure 4.

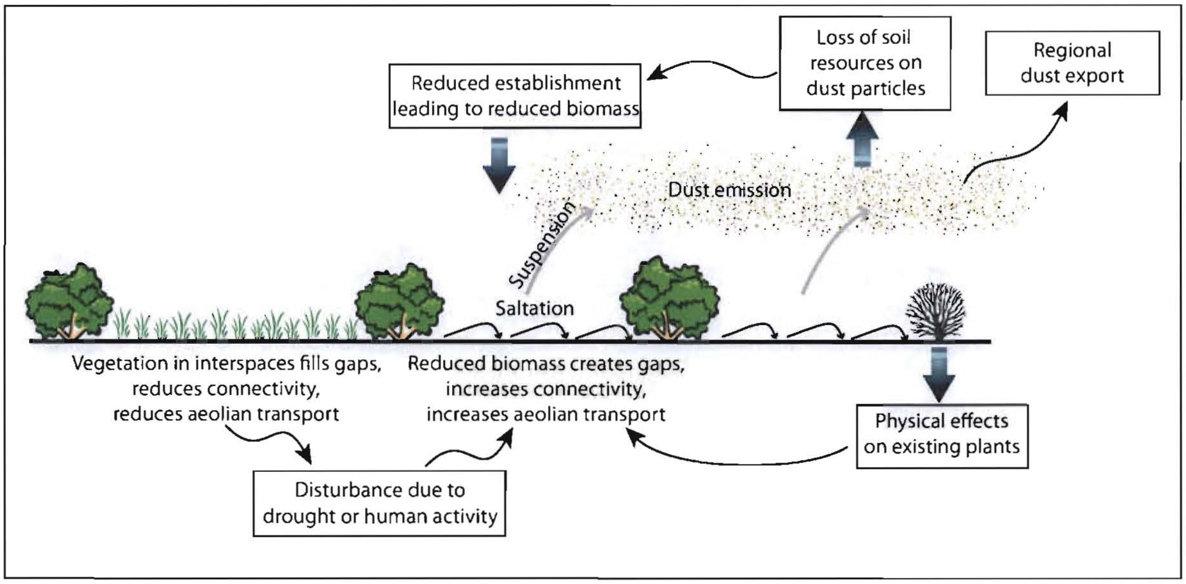


Figure 5. Primary feedbacks between ecosystem function, wind erosion, and ecosystem structure.

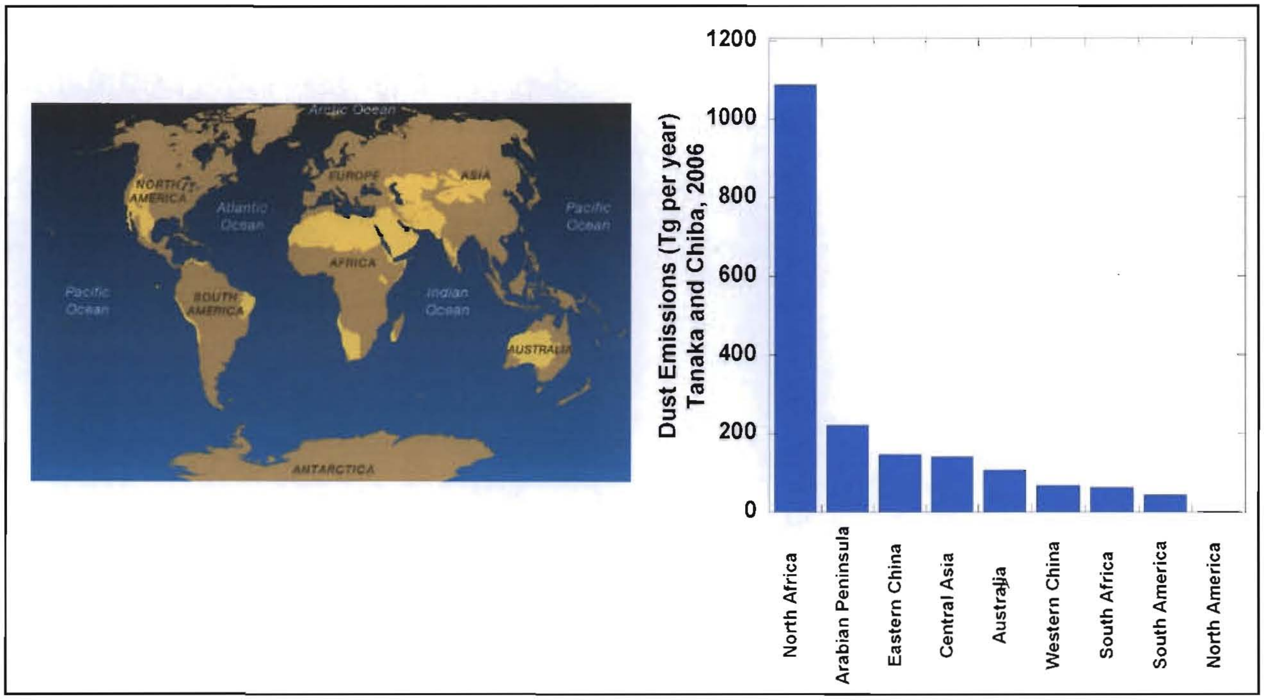


Figure 6. Global dust emission map/cartoon.

Figure 7. Photo of dusty snow (Painter will have better photo).

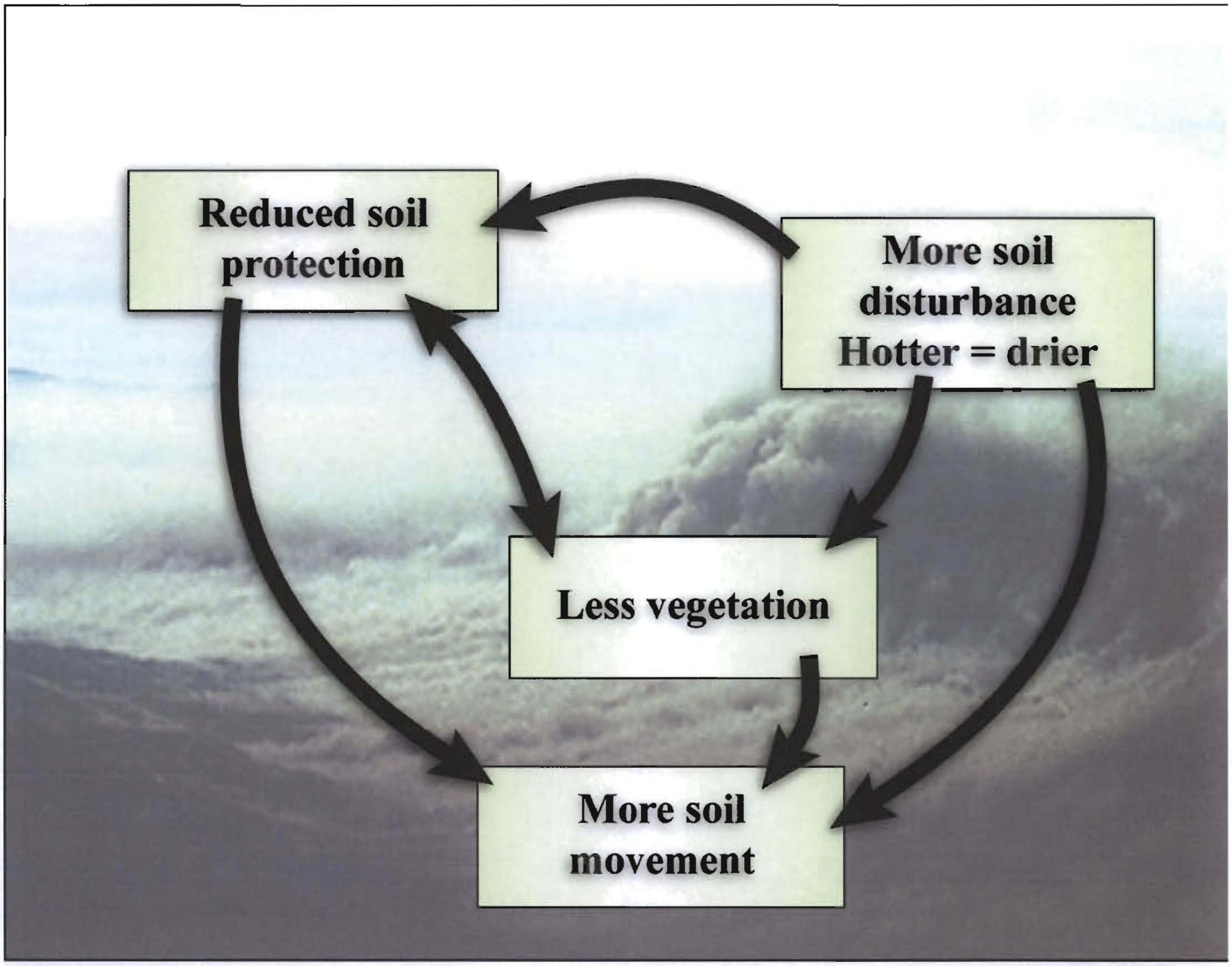

Reduced soil protection
More soil disturbance Hotter = drier
Less vegetation
More soil movement

Figure 8.