Effects of enhanced wind erosion on surface soil texture and characteristics of windblown sediments

Junran Li,[1] Gregory S. Okin,[2] and Howard E. Epstein[3]

Received 25 November 2008; revised 28 January 2009; accepted 10 February 2009; published 10 April 2009.

[1] It is well documented that wind redistributes and transports soil resources in semiarid ecosystems. However, fewer studies have quantitatively linked wind erosion to detailed grain-size fractions and associated nutrient content in surface soil and windblown sediment. In this study, we examined (1) the effects of enhanced wind erosion on surface soil particle-size distribution and (2) carbon (C) and nitrogen (N) characteristics of windblown sediments in a typical desert grassland of southern New Mexico. Our results show that surface soil has become noticeably coarser over a 2-year period. In particular, content of soil particles in the category of 250–500 μm increased significantly, but soil particles in the fractions of 50–125 μm and <50 μm were significantly depleted. In addition to the enrichment of C and N in the windblown sediments, our results reveal that fine particles (e.g., $D < 50$ μm) were enriched to a much higher degree at height than C and N. Significantly, our results reveal that nearly 12% of total organic carbon (TOC) and 9% of total nitrogen (TN) were found in the particles with diameter <50 μm, which account for only 1–2% of the mass of windblown sediments. In this wind susceptible environment, our findings suggest that (1) significant soil texture change (e.g., the loss of soil fines) driven by wind erosion could happen rapidly and soil fine particles (e.g., silt and clay) may be depleted within a few years and (2) the loss of even a small fraction of fine particles may indicate a substantial depletion of soil C and N.

Citation: Li, J., G. S. Okin, and H. E. Epstein (2009), Effects of enhanced wind erosion on surface soil texture and characteristics of windblown sediments, *J. Geophys. Res.*, *114*, G02003, doi:10.1029/2008JG000903.

1. Introduction

[2] Wind erosion is a global phenomenon occurring in many arid, semiarid, and agricultural areas of North Africa, the Middle East, Central Asia, Australia, North America, and China [*D'Almeida*, 1986; *Goudie*, 1983; *Gillette and Hanson*, 1989; *Liu*, 1985]. In North America, the Chihuahuan Desert has been identified as one of the "hot spots" of dust production, with wind energy frequently reaching 100 W m^{-2} in the spring time and soil loss rates about 1400 g m^{-2} yr^{-1} for mesquite-vegetated sandy soils [*Gillette and Hanson*, 1989; *Peters*, 2002]. Several climate models suggest that future global warming may reduce soil moisture over large areas of semiarid grassland in North America [*Manabe and Wetherald*, 1986, 1987; *Seager at al.*, 2007], which may favor the dominance of woody plants over grasses in this area [*Smith et al.*, 2000]. A recent experimental study suggests that mesquite dominated shrubland had by far the largest wind erosion sand fluxes among several plant communities found in the northern Chihuahuan Desert [*Gillette and Pitchford*, 2004]. Most recently, models predict that the U.S. Southwest and northern Mexico will be most responsive to the strengthening greenhouse effect [*Kerr*, 2008]. The combined consequences of future climate change may, therefore, further increase wind erosion in these regions.

[3] Semiarid grasslands in the northern Chihuahuan Desert have decreased dramatically and undergone substantial invasion by woody plants within the past 150 years [*Gibbens et al.*, 2005]. Exact causes for shrub encroachment and grass deterioration remain a subject of debate; however, reasons such as climate variation and increased anthropogenic activities have been suggested [*Archer et al.*, 1995; *Scanlon et al.*, 2005; *Schlesinger et al.*, 1990; *Betancourt*, 1996]. Further encroachment of shrubs may localize soil fertility under their canopy, leading to the development of "fertile islands", which characterize desert habitats on all continents but are particularly well documented in the American Southwest [*Schlesinger et al.*, 1996; *Schlesinger and Pilmanis*, 1998; *Rynolds et al.*, 1999; *Li et al.*, 2007, 2008a].

[4] Until recently, the role of wind in the loss and redistribution of soil resources in arid and semiarid grasslands has been largely overlooked [*Coppinger et al.*, 1991; *Larney et al.*, 1998; *Okin and Gillette*, 2001]. Instead, a great deal of work on fertile islands in semiarid lands has focused on vegetation changes and the role of water in these changes [*Schlesinger et al.*, 2000; *Augustine and Frank*, 2001]. *Schlesinger et al.* [2000] suggest that water cannot, by

[1]Department of Biological and Environmental Engineering, Soil and Water Laboratory, Cornell University, Ithaca, New York, USA.
[2]Department of Geography, University of California, Los Angeles, California, USA.
[3]Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA.

0148-0227/09/2008JG000903

itself, account for the observed losses and patterns in soil resources and resulting vegetation changes in the Chihuahuan Desert. More recently, the studies by *Li et al.* [2007, 2008a] at the Jornada Experimental Range (JER) in southern New Mexico have shown that wind erosion plays important roles in the depletion and patterned redistribution of soil organic carbon (SOC) and a variety of soil nutrients.

[5] One of the direct consequences of wind erosion is the loss of soil and associated soil nutrients through saltation for particles >50 μm and vertical emission of finer particles. Saltation is responsible primarily for the redistribution of surface soil within the ecosystem and exerts influences on vegetation and soils at a local scale [*Larney et al.*, 1998; *Li et al.*, 2007; *Okin et al.*, 2006]. Emission of soil particles with diameters <50 μm has significant impacts on soil nutrient status of local soils as well as downwind ecosystems as far as thousands of kilometers [*Okin et al.*, 2004]. Although the transport capacity of wind is much less than that of water, water-based transport of soil nutrients and particulate matter is limited in many desert areas due to the closed basins and flat terrain. Wind erosion, on the other hand, can remove the fine, nutrient-rich particles from the soil's entire surface [*Larney et al.*, 1998; *Gillette and Pitchford*, 2004]. In a creosote (*Larrea tridentata*) dominated shrubland in southern New Mexico, *Breshears et al.* [2003] estimated that soil loss caused by wind erosion exceeded water erosion by 33 times.

[6] It is well documented that windblown sediment has higher nutrient concentrations than the surface materials of the parent soil [*Zobeck et al.*, 1989; *Leys and McTainsh*, 1994; *Li et al.*, 2007]. While many studies of wind erosion have focused on wind physics and soil resource redistribution [*Gillette and Chen*, 2001; *Okin and Gillette*, 2001; *Gillette and Pitchford*, 2004; *Gillette et al.*, 2006; *Li et al.*, 2007, 2008a, 2008b], fewer studies have investigated the physical and chemical properties of the eroded sediments. Particularly, detailed quantitative studies examining the nutritional and chemical properties of windblown sediments are absent. Additionally, because of the sorting of particles by wind, the surface soil texture becomes coarser and depleted in soil organic matter [*Larney et al.*, 1998]. As a result, surface soil may exhibit very different characteristics relative to the uneroded, original soil.

[7] This is the fourth in a series of papers that investigate the role of wind erosion in ecosystem change in desert grasslands. In this study, we examine the effects of enhanced wind erosion on the texture of surface soil, the characteristics of carbon (C) and nitrogen (N) in the windblown sediments, and C and N pools in detailed particle-size fractions. In previous papers, we reported aeolian sediment flux and soil nutrient loss from the site [*Li et al.*, 2007], and the effects of wind erosion on the spatial heterogeneity of soil organic carbon and plant nutrients in the erosion-dominated and deposition-dominated environments [*Li et al.*, 2008a, 2008b].

2. Methods

2.1. Site Description

[8] The study site is located at the USDA-ARS Jornada Experimental Range (JER), 35 km northeast of Las Cruces, New Mexico. The JER is in the northern part of the Chihuahuan Desert, which occurs in the Mexican Highland section of the Basin and Range Province. The climate of the JER is classified as warm and typical of arid, semidesert grassland. Mean annual air temperature is 15.6°C. June and January are the hottest and coolest months with average maximum temperature of 36°C and 13°C, respectively. Precipitation averages 247 mm annually and is far exceeded by average potential evapotranspiration of 2,300 mm per year [*Gibbens et al.*, 2005]. Dominant wind erosion events happen from early March to May though erosive events can occur anytime throughout the year. The topography of the Jornada Basin consists of gently rolling to nearly level uplands, interspersed with swales and old lake beds [*Buffington and Herbel*, 1965]. Soil development is strongly determined by topographic position, parent material, and climatic fluctuations during the Quaternary, with sands and sandy loams generally widespread [*Bulloch and Neher*, 1977; *Gile et al.*, 1981].

[9] Two field sites were located in Pasture 11 of the JER, separated by about 3 km. These two sites represent typical plant communities of the JER, having nearly level terrain and an elevation of 1200 m above sea level. Although both sites are identified as grassland, different grass species dominate each. Site 1 is dominated by *Sporobolus* spp. (primarily *S. flexuosus* and *S. contractus*) and mesquites shrubs. Site 2 is dominated by *Bouteloua eriopoda* and mesquite shrubs. *Bouteloua eriopoda* was the dominant plant 50 years ago and has over time been replaced by mesquite shrubs [*Gibbens et al.*, 2005]. Soils at both sites are dominated by coarse sand (0.5–1.0 mm), overlying a petrocalcic horizon >1 m below the surface.

2.2. Experimental Methods

[10] An experiment designed to enhance aeolian activity and wind erosion was established in March 2004 for Site 1 and July 2004 for Site 2. Detailed experimental setup was described in the study by *Li et al.* [2007]. In brief, a 25 × 50 m rectangular plot area, parallel with prevailing winds at the JER, was selected at each site. In the plot area, all grasses, perennial semishrubs such as *Gutierrezia sarothrae*, and perennial forbs were removed (hereafter referred to as "grass cover reduction" only). Shrub cover was low at both sites at the beginning of the experiment, and shrubs were not removed. Reduced cover on the plots was maintained during the entire experimental period.

[11] Within each plot, fifty soil samples of 2.5 cm diameter were taken from the top 5 cm from a 5 × 10 m subplot located in the center of the 25 × 50 m wind erosion enhanced plot area. Sample locations were determined from a random number generator prior to fieldwork. Soil samples were collected in July 2004 and 2 years later in July 2006. Windblown sediment was collected using 2.5 m-tall Big Spring Number Eight (BSNE) sediment samplers [*Fryrear*, 1986]. Each BSNE was composed of an upright post with six traps positioned approximately 0.12, 0.3, 0.45, 0.9, 1.6, and 2.5 m above the soil surface [*Li*, 2008]. The traps collect windblown sediment through an opening of 50 mm high and 20 mm wide, with an efficiency of 90% (ratio of collected flux to actual flux) for sand particles [*Shao et al.*, 1993]. Detailed arrangement of BSNE samplers was described in the study by *Li et al.* [2008a]. Briefly, in each plot area, we installed two groups of samplers, separated by about 15 m along the prevailing wind direction. Each group consisted of three BSNEs and were placed 3–4 m apart approximately along the center of a 5 × 10 m subplot, lined

up perpendicular to the prevailing wind. Windblown sediment samples were collected twice per year in early March (sampling period from previous July to March) and middle July (sampling period from March to July) from 2004 to 2006. The long duration of the sampling period is required to achieve sufficient windblown sediment samples to allow complete chemical and physical analysis using projected procedures.

[12] Following *Breshears et al.* [2003], the horizontal transport rate of windblown sediments (units of g m^{-1} day^{-1}) was calculated by the amount of material collected at each of the sampling heights divided by the width of the sampler opening (20 mm) and sampling time interval. Soil C and N pools in the windblown sediments are often characterized by "enrichment ratio, *E*", which relates the content of nutrients and organic matter in the sediment to those in the bulk soil. In addition to enrichment ratios of C and N, we also calculated enrichment ratios for particle-size fractions, such as the enrichment of soil particles with diameter <50 μm, E_{D50}.

2.3. Laboratory Analyses

[13] In the laboratory, each soil sample and BSNE sediment sample was air-dried and sieved to remove roots and debris >2 mm. Sediment samples were then weighed to 0.001 g. Detailed grain-size analyses of surface soil and windblown sediments samples were conducted using Ro-Tap Test Sieve Shakers. Each sample was shaken at 278 oscillations per minute for 10 minutes. The recoveries of sample materials after the grain-size analysis averaged 99.5% of sample weight. In this study, soil and windblown sediments were partitioned into five size fractions, adapted from USDA definitions. We used 50 μm as the silt-sand boundary and designated the 500– to 2000 μm fraction as coarse sand, 250– to 500 μm as medium sand, 125– to 250 μm as fine sand, 50– to 125 μm as very fine sand, and <50 μm as the silt and clay fraction.

[14] All windblown sediment samples were analyzed for total organic carbon (TOC) and total nitrogen (TN). About 1–5 g of subsample was obtained by passing each sediment sample through an open pan riffle sampler. Each of these subsamples was then pulverized with a ball mill (Cianflone Scientific Instruments Corporation, Pittsburgh, PA). TOC and TN analyses were conducted on a Shimadzu TOC-V_{CSN} total organic carbon analyzer with a SSM-5000 solid sample analyzer and a TNM-1 total nitrogen measuring unit. In addition, all size fractions of windblown sediment samples collected at the height of 0.3 m, which normally had enough sample for the TOC-V_{CSN} analyzer, were also analyzed for TOC and TN. The recoveries of TOC and TN are 96% and 93%, respectively.

2.4. Statistical Analyses

[15] The mean and standard deviation of horizontal sediment flux and TOC and TN in the windblown sediments were calculated at each of the two study sites during the experimental period. Preliminary examinations suggested that both sediment flux and TOC and TN content at Site 1 and Site 2 were not significantly different. Therefore results from these two sites were considered to be replicates. Comparisons of C/N ratios for the different size fractions were conducted using one-way analysis of variance (ANOVA). A post hoc comparison of means following a significant ANOVA was done with a Tukey's studentized test. Soil

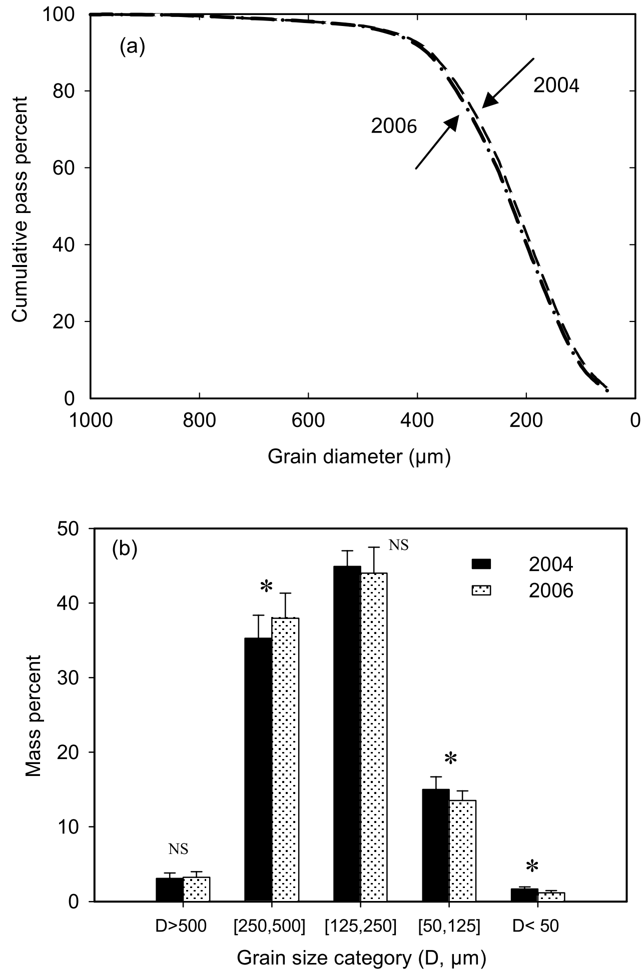

Figure 1. Effects of enhanced wind erosion on the soil texture of the top 5 cm of soil. (a) Overall change. (b) Changes of mass percentage in different size fractions. Asterisks indicate significant differences in individual size fractions, and NS indicates no significant difference (*t* test, p < 0.05 level, n = 50).

textures before and after wind erosion were compared using paired *t* tests for different particle-size fractions. Additionally, changes of TOC and TN content, C/N ratio, and enrichment ratios of TOC and TN in the windblown sediment with height were fit to an exponential model in the form:

$$Y = y_0 + a\left(1 - e^{-bx}\right)$$

where Y is one of the factors above, X is the height of BSNE traps, y_0, a, and b are constants determined by the regression, and y_0 indicates the level of factors in the surface soil (X = 0). All statistics, except for regressions, were conducted using the program SAS 9.1 for Windows with p < 0.05 for significance.

3. Results

3.1. Change of Surface Soil Texture

[16] The cumulative pass percent curve for soil samples of 2006 was consistently lower than that of 2004 (Figure 1a), suggesting that surface soils became coarser with enhanced

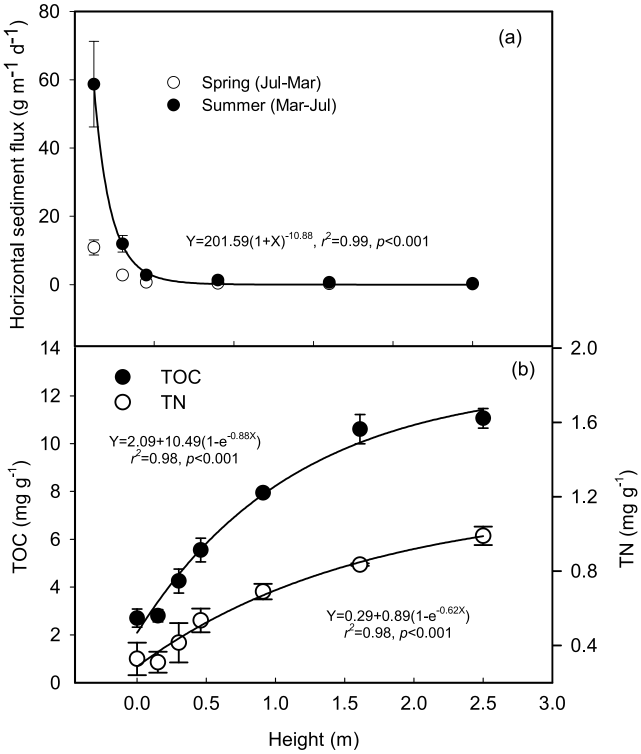

Figure 2. (a) Horizontal sediment flux and (b) TOC and TN content in the windblown sediments as a function of height. Error bars are one standard error for horizontal sediment flux and one standard deviation for TOC and TN, respectively. Values of TOC and TN in surface bulk soil (represented by height zero) were obtained from the study by *Li et al.* [2008a]. The curves show the average results of both study sites during the entire experimental period, $n = 48$.

wind erosion over the experimental period. In addition, we calculated changes of soil texture in different particle-size categories during the 2-year experimental period (Figure 1b). At the beginning of the experiment, dominant soil particles were distributed in the size categories of medium (250–500 μm) to fine sand (125–250), which accounted for 35.28% and 44.91% of the total mass, respectively. Particles with diameters >500 μm (coarse sand) and <50 μm (silt and clay) only represented 3% and <2% of the total mass, respectively. After two windy seasons, mass percentage of medium sand (250–500 μm) increased significantly to 37.96% (paired t test, $p = 0.03$), while only slight changes occurred in coarse and fine sand categories. On the other hand, soil particles in the ranges of 50–125 μm (very fine sand) declined significantly from 15.01% in summer 2004 to 13.55% in summer 2006 (paired t test, $p = 0.02$), and a similar significant depletion also occurred for soil particles with diameter <50 μm (silt and clay) during this period.

3.2. Windblown Sediment Flux and C, N Distribution

[17] During the experimental period at the JER, average horizontal sediment flux ranged from about 11 to 0.2 g m^{-1} day^{-1}, and decreased as a function of height (Figure 2a). Statistical analysis showed that the decrease can be optimally described by a revised power function [*Goossens*, 2004]. At heights lower than 0.5 m, horizontal sediment flux occurring during the summer time (March to July) was substantially greater than that of the spring period (July–March). At heights greater than 0.5 m, horizontal sediment flux during the summer was only slightly different from that of the spring. Figure 2b shows that the concentration of TOC ranged from 2.8 mg g^{-1} at a height of 0.12 m (the lowest BSNE traps) to 11 mg g^{-1} at a height of 2.5 m (the highest BSNE traps), and the concentration of TN went from 0.32 mg g^{-1} at a height of 0.12 m to 0.99 mg g^{-1} at a height of 2.5 m. The increase of TOC and TN content with height is described by a function of exponential rise to maximum with high significance ($r^2 = 0.98$, $p < 0.001$).

[18] Similar to the vertical distribution of TOC and TN, both C/N ratio and enrichment ratio (E) for TOC and TN in the windblown sediment increased exponentially with height (Figure 3). C/N ratio varied from 8.5 to 11.2, and E_{TOC} and E_{TN} ranged from 1 to about 4 at the heights between 0.12 and 2.5 m, respectively. It is noteworthy that windblown sediments were more enriched in TOC relative to that of TN at all heights monitored. Similar to the change of TOC and TN with heights, both C/N and enrichment ratios of TOC and TN fit well with the designated exponential model.

3.3. Sediment Particle Fractions and Associated C, N Distribution

[19] Detailed particle-size analyses of windblown sediments (0.12–2.5 m) and surface soil (0–5 cm) are shown in

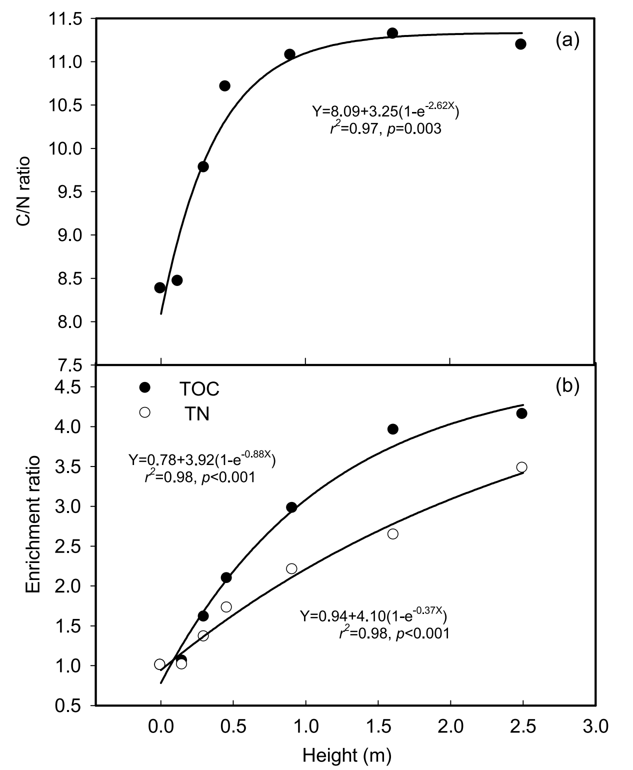

Figure 3. (a) Change of C/N ratio and (b) the enrichment ratios of TOC and TN in the windblown sediments as a function of height. The curves show the average results of both study sites during the entire experimental period. Height of zero represents surface bulk soil. $n = 48$.

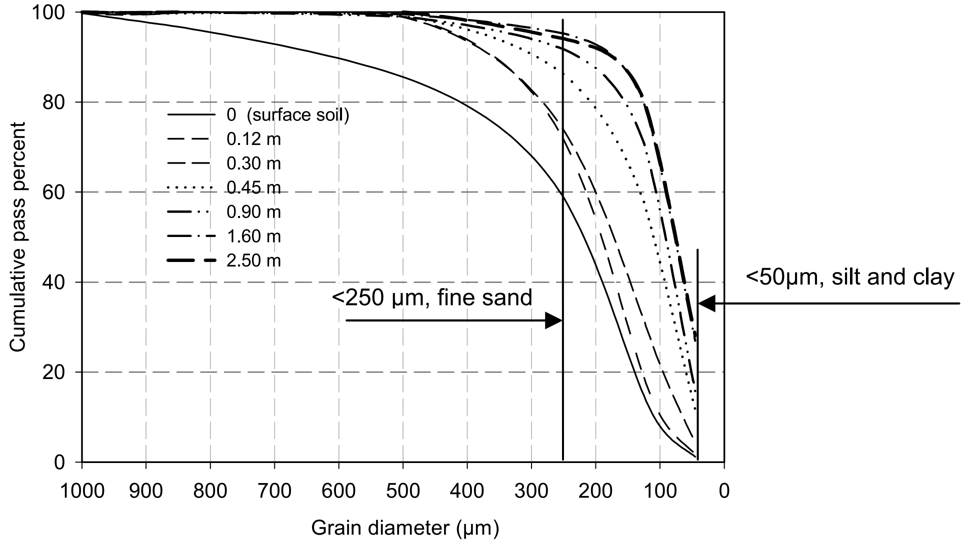

Figure 4. Grain-size distribution curves for bulk soil and windblown sediments at different heights. Coarser samples are indicated by lower curves.

Figure 4. Samples became systematically finer as the height increased from 0 to 2.5 m, and eroded sediments were substantially finer relative to the surface soil from which they originated. Moreover, windblown sediments may be distinct from surface soil for particles smaller than fine sand ($D < 250$ μm). While only 58% of particles in the surface soil are finer than 250 μm, nearly 73% of particles in the eroded sediment had the diameter <250 μm. In addition, windblown sediments collected at heights above 0.45 m were substantially finer than sediments collected at heights of 0.12 and 0.3 m (Figure 4). Figure 5 shows that windblown sediments collected at 2.5-m height had nearly 24 times greater content of D50 particles than the surface soil. The enrichment of D50 was remarkably greater than that of the enrichment of TOC and TN (Figure 3b).

[20] We also analyzed TOC and TN content in particle-size fractions in windblown sediments collected at the height of 0.3 m. Figure 6 shows that more than 50% (by weight) of the particles have diameters between 125 and 250 μm, and a slightly lower of 50% (by weight) of TOC and TN were found in this size fraction. Particle sizes greater than 500 μm only accounted for a very small percent of the sediment, and they are extremely poor in both TOC and TN. However, we found that particles <50 μm accounted for 2% of the total mass, but

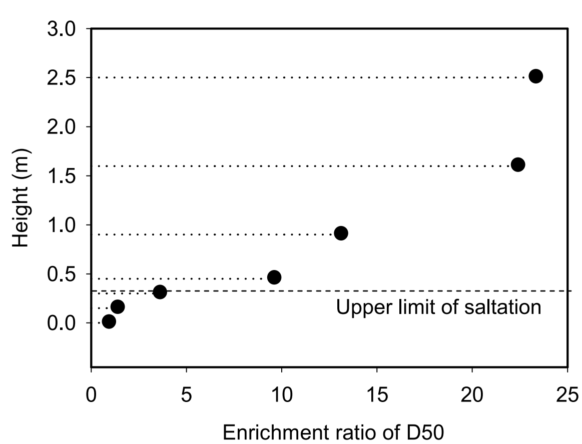

Figure 5. Enrichment factor (E) of particle size <50 μm (D50) in the windblown sediments. E was calculated based on mass percentage of D50 particles in the windblown sediments compared with bulk surface soil.

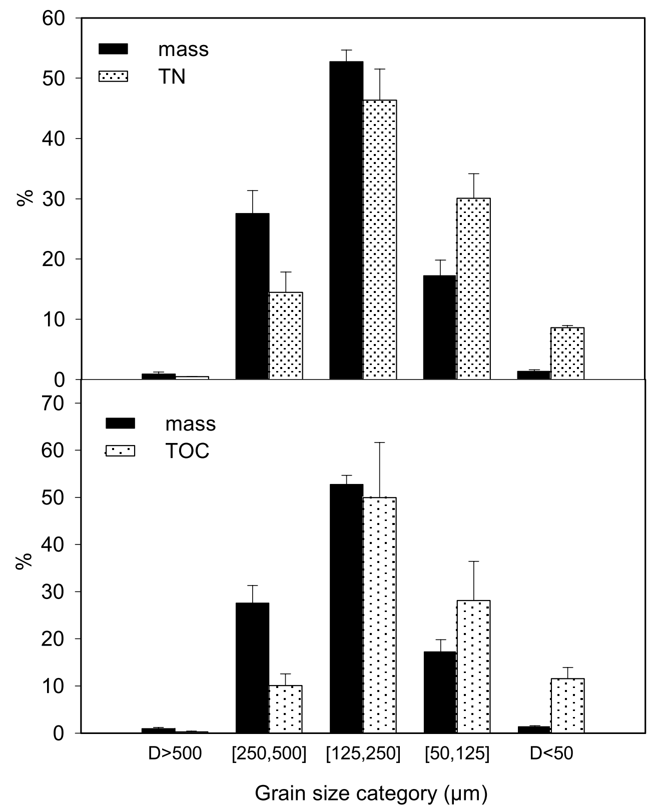

Figure 6. Mass distributions in relation to TOC and TN distribution in particle-size fractions in the windblown sediments. Sediment samples were from the 0.3 m BSNE traps. Error bars are one standard deviation. n=12.

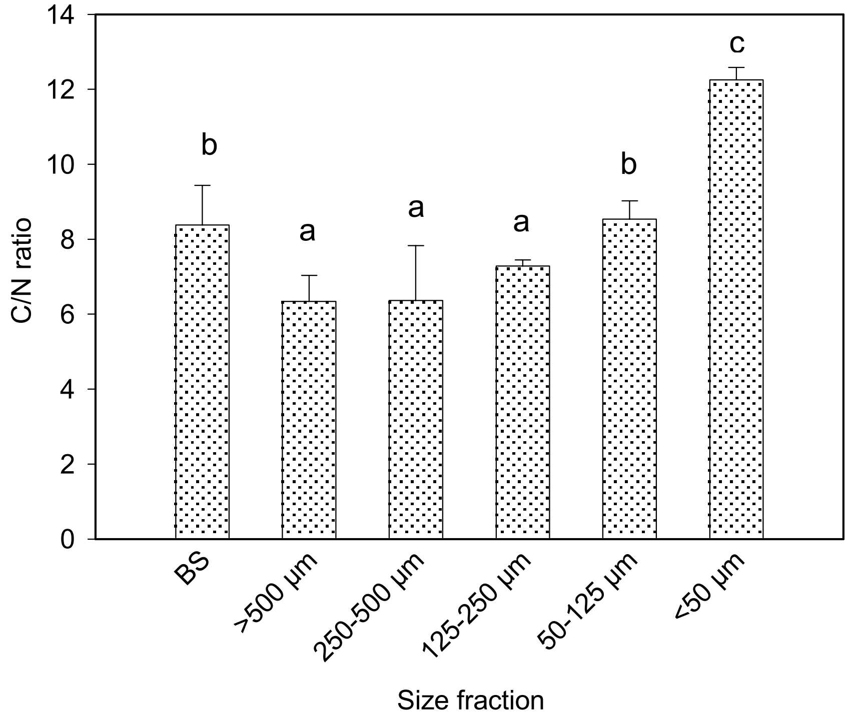

Figure 7. Carbon/nitrogen ratio in the particle-size fractions of windblown sediment caught at the height of 0.3 m. Different letters indicate that the corresponding C/N ratios were significantly different from one other at the $p < 0.05$ level by one-way analysis of variance (ANOVA). Surface bulk soil (BS) was also included for comparison. Error bars are one standard deviation.

accounted for 12% of TOC and nearly 9% of TN in the windblown sediments.

[21] For the windblown sediments collected at 0.3-m height, C/N ratios of different particle-size fractions fell in the range of 6.3 to 12.3 with higher C/N corresponding to finer particle-size fractions (Figure 7). C/N ratios of particle-size fractions >125 μm were actually not significantly different from other size fractions, whereas C/N ratios of particle size <50 μm were significantly higher than those of the other particle-size fractions. C/N ratios in the particle-size fraction <50 μm at 0.3-m height were approximately equal to that of the bulk sediment at the highest BSNE traps (2.5 m) (Figure 3), while C/N ratios in the particle-size fraction of 50 to 125 μm were similar to that the bulk surface soil.

4. Discussion

[22] Relatively few studies have provided quantitative analyses of changes in soil texture affected by wind and detailed grain-size fractions in windblown sediments. *Lyles and Tatarko* [1986] found that wind erosion over a 36-year period increased surface soil sand content by 6.5% and decreased silt content by 7.2% on a cropland in western Kansas. In a semiarid cultivated pasture in southeastern Australia, *Leys and McTainsh* [1994] found that wind erosion caused an increase in the particle content >250 μm and a decrease in particles with diameters 75–210 μm and <2 μm over a period of 20 weeks. In the wind erosion susceptible JER, significant depletion occurred for both soil particles 50–125 μm (very fine sands) and <50 μm (silt and clay) during the 2-year experimental period. These observations indicate that fine soil particles were preferentially depleted by enhanced wind erosion. It should be pointed out that none of these studies, including this one, considered sediment addition through atmospheric dust deposition. Long-term monitoring at the JER shows that atmospheric deposition averages 33.5 g m^{-2} yr^{-1}, and about 58% of the deposited material is silt or clay sized particles [*Peters*, 2002]. Therefore the estimated loss of fine particles was the net consequence of wind erosion and atmospheric deposition, and thus the loss caused by wind erosion alone may be underestimated. *Neff et al.* [2005] further suggest that the loss of soil fines due to erosion following disturbance, such as grazing, may be an important mechanism leading to nutrient depletion in arid and semiarid regions.

[23] Detailed particle-size analysis on surface soil and windblown sediment gave insights on the time it would take for the top 5 cm soil to be depleted in specific particle-size categories. Following the method of *Okin et al.* [2001] in calculating the lifetime of soil nutrients at Jornada, and using the vertical mass flux of 2.15 kg m^{-2} yr^{-1} [*Li et al.*, 2007], we estimated that silt and clay particles could be depleted in about 5 years. Although coarser particles tend to have a longer lifetime, all very fine sands (50–125 μm) may be depleted within 10 years in this wind susceptible environment.

[24] The rapid and significant depletion of fine soil particles in the surface soil correspond to the enrichment of soil C and N in the windblown sediments (Figure 2b and Figure 3b). The enrichment ratios (E) of TOC and TN we measured are well within the range of other studies conducted in similar semiarid grasslands of the southwestern United States

[*Zobeck and Fryrear*, 1986b; *Li et al.*, 2007]. Results from this study further show that E_{TN} is consistently smaller than that of E_{TOC}, and this pattern has also been observed in undisturbed control plots at the JER [*Li et al.*, 2007]. It is suggested that N, next to water, is the resource that most often limits net primary production in the Chihuahuan Desert [*Fisher et al.*, 1987]. The limited N supply in desert soils is not the result of slow nutrient cycling; rather, rates of N transformations and loss are relatively fast, leading to low levels of nutrient accumulation [*Peterjohn and Schlesinger*, 1991; *Schlesinger et al.*, 1990].

[25] *Gillette and Walker* [1977] suggest that the size distribution of eroded sediments close to the ground that travel in saltation strongly reflect the sediments from which they were derived. Results from this study show that grain-size distribution for eroded sediments at heights below 0.45 m have high similarity with the parent soil (Figure 4), indicating that samples lower than 0.45 m are probably dominated by saltating sands. There was a clear difference in the distribution curves produced from sediment samples >0.45 m compared to the lower heights, suggesting samples higher than 0.45 m probably collect sediments moving mainly in suspension. *Zobeck and Fryrear* [1986a] studied the physical characteristics of windblown sediments in western Texas and found that sediments collected at 0.15 m had clear difference in the grain-size distribution compared to the higher samples. *Leys and McTainsh* [1996] suggest that the primary modes of samples up to 0.25 m are similar to the surface soil. *Gillette and Walker* [1977] and *Nickling* [1983] showed that the parent soil exerts a strong influence over the particle-size distribution of the eroded sediments up to 1 m. For this desert grassland at the JER, we suggest that the saltation zone may lie between 0.30 and 0.45 m based on the grain-size distributions, however, the height of saltation layer, as suggested by *Gillette* [1977], may differ based on soil texture, wind speed, mineralogy and possibly, physical weathering.

[26] The enrichment of clays as sample height increases is expected because fine particles are more easily transported by wind; however, little quantitative data have been reported on the enrichment of such fine particles in the eroded sediments. Our results suggest that, compared to the enrichment of TOC and TN, fine particles are even more enriched in the windblown sediments (Figure 5). In particular, sediments collected at heights above 1.5 m had nearly 25 times more particles with diameter <50 μm than those of the surface soil.

[27] The disproportionately greater amounts of organic C and plant nutrients in the smallest and lightest soil particles are highlighted by detailed analyses of TOC and TN content in windblown sediments in each grain-size fractions. Quantitatively, particles finer than 50 μm only account for 1–2% of the material (by weight), but they represent ~12% of TOC and ~ 9% of TN in the eroded sediment. We did not analyze TOC and TN content in the grain-size fractions of the surface soil. However, given the similarity of particle-size distribution of surface soil and eroded sediment at 0.30-m height, we estimated that surface soil should have similar quantitative patterns of TOC and TN content in fine particles relative to the sediments. Figure 1 shows that enhanced wind erosion has caused significant depletion of fine particles with size <125 μm. Therefore we suggest that a significant soil organic C and nutrient depletion may have occurred during the experimental period. Actually, *Li et al.* [2007] analyzed nutrient contents in the same plot of Site 1, and the authors found that up to 25% of TOC and TN have been depleted from the top 5 cm of soils in three windy seasons.

[28] Detailed C and N analysis shows that the finer the particle size, the higher its C/N ratio (Figure 7). This result corresponds to Figure 3a that C/N ratio increases with increasing height (with finer particles). *Li et al.* [2007] found that bulk windblown sediments have 30–40% higher C/N ratios than those of surface soils. *Amelung et al.* [1998] studied C/N ratios of particle-size fractions of native topsoils in North American grasslands, and these authors found conversely that finer particles had lower C/N ratios. *Amelung et al.* [1998] suggest that in their study the fine sand fraction consists of altered and decomposed organic debris and fine root particles. At the JER, a large portion of the organic matter in fine particles of the windblown sediments may be composed of undecomposed plant residues that have been winnowed by wind. However, coarse fractions in the windblown sediments are almost pure sand where both C and N contents are extremely low and fresh or little altered plant material is largely absent.

5. Conclusions

[29] In a typical desert grassland of southern New Mexico, we found that enhanced wind erosion has changed soil texture significantly over a 2-year period. Specifically, soil particle size in the fractions of 50–125 μm and <50 μm were preferentially depleted, in company with significant increase in the content of soil particles 250–500 μm. In the windblown sediments, TOC and TN content, C/N ratio, and enrichment ratios of C and N all increased with height to maximum according to a 3-parameter exponential function. In addition to the enrichment of C and N in the windblown sediments, our results reveal that fine particles (e.g., $D <$ 50 μm) were enriched to a much higher degree at height than C and N. Significantly, our results further show that nearly 12% of TOC and 9% of TN were found in the particles with diameter <50 μm, which account for only 1–2% of the mass of windblown sediments. This observation highlights that the loss of even a small fraction of fine particles may indicate a substantial depletion of soil C and N in this wind susceptible environment.

[30] **Acknowledgments.** We thank Jacquie Hui, Mike Abrams, Emilee Carpenter, Melissa Castiano, Lorelei Alvarez, and Tom Zhao for their assistance in field work and laboratory analysis. Kris Havstad, John Anderson, Eddie Garcia, Rob Dunlap, and David Thatcher from the headquarters of the USDA-ARS JER are also appreciated for their invaluable assistance with field work during this study. This research was supported by the National Science Foundation (DEB 0316320) and LTER grant (DEB 0080412).

References

Amelung, W., W. Zech, X. Zhang, R. F. Follett, H. Tiessen, E. Knox, and K. W. Flach (1998), Carbon, nitrogen, and sulfur in particle-size fractions as influenced by climate, *Soil Sci. Soc. Am. J.*, *62*, 172–181.

Archer, S., D. S. Schimel, and E. A. Holland (1995), Mechanisms of shrubland and expansion—Land-use, climate or CO_2, *Clim. Change*, *29*, 91–99.

Augustine, D. J., and D. A. Frank (2001), Effects of migratory grazers on spatial heterogeneity of soil nitrogen properties in a grassland ecosystem, *Ecology*, *82*, 3149–3162.

Betancourt, J. L. (1996), Long and short-term climate influences on southwestern shrublands, in *Proc. Shrubland Ecosyst. Dyn. Changing Environ.*, *INT-GRT-338*, edited by J. R. Barrow et al., pp. 5–9, US Department of Agriculture, Forest Service Intermountain Research Station, Ogden, Utah.

Breshears, D. D., J. J. Whicker, M. P. Johansen, and J. E. Pinder III (2003), Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystems: Quantifying dominance of horizontal wind-driven transport, *Earth Surf. Proc. Land.*, *28*, 1189–1209.

Buffington, L. C., and C. H. Herbel (1965), Vegetation changes on a semi-desert grassland range from 1858-1964, *Ecol. Monogr.*, *35*, 139–164.

Bulloch, H. E., Jr., and R. E. Neher (1977), *Soil Survey of Dona County Area, New Mexico, Soil Conservation Survey*, United States Department of Agriculture, Washington, D. C.

Coppinger, K. D., W. A. Reiners, I. C. Burke, and R. K. Olson (1991), Net erosion on a sagebrush steppe landscape as determined by cesium-137 distribution, *Soil Sci. Soc. Am. J.*, *55*, 254–258.

D' Almeida, G. A. (1986), A model for Saharan dust transport, *J. App. Meteorol.*, *25*, 903–916.

Fisher, F. M., J. C. Zak, G. L. Cunningham, and W. G. Whitford (1987), Water and nitrogen effects on growth and allocation patterns of creosote-bush in the northern Chihuahuan Desert, *J. Range Manage.*, *41*, 387–391.

Fryrear, D. W. (1986), A field dust sampler, *J. Soil Water Conserv.*, *41*, 117–120.

Gibbens, R. P., R. P. McNeely, K. M. Havstad, R. F. Beck, and B. Nolen (2005), Vegetation changes in the Jornada Basin from 1858–1998, *J. Arid Environ.*, *61*, 651–668.

Gile, L. H., J. W. Hayley, and R. B. Grossman (1981), Soils and geomorphology in the basin and range area of southern New Mexico-Guidebook to the Desert Project, *Memoir 36*, N.M. Bureau of Mines and Mineral Resources, Socorro, N. M.

Gillette, D. A. (1977), Fine particulate emissions due to wind erosion, *Trans. ASAE*, *20*(5), 890–897.

Gillette, D. A., and K. J. Hanson (1989), Spatial and temporal variability of dust production caused by wind erosion in the United States, *J. Geophys. Res.*, *34*, 2197–2206.

Gillette, D. A., and A. M. Pitchford (2004), Sand flux in the northern Chichuhuan desert, New Mexico, USA, and the influence of mesquite-dominated landscapes, *J. Geophys. Res.*, *109*, F04003, doi:10.1029/2003JF000031.

Gillette, D. A., and T. R. Walker (1977), Characteristics of airborne particles produced by wind erosion of sandy soil, high plains of the west Texas, *Soil Sci.*, *123*, 97–110.

Gillette, D. A., and W. Chen (2001), Particle production and aeolian transport from a "supply-limited" source area in the Chihuahuan Desert, United States, *J. Geophys. Res.*, *106*, 5267–5278.

Gillette, D. A., J. E. Herrick, and G. A. Herbert (2006), Wind characteristics of mesquite streets in the Northern Chihuahuan Desert, New Mexico, USA, *Environ. Fluid Mech.*, *6*, 21–275.

Goossens, D. (2004), Net loss and transport of organic matter during wind erosion on loamy sandy soil, in *Wind Erosion and Dust Dynamics: Observations, Simulations, Modeling*, edited by D. Goossens and M. Riksen, pp. 81–102, ESW Publ., Wageningen, Netherlands.

Goudie, A. S. (1983), Dust storms in space and time, *Prog. Phys. Geog.*, *7*, 502–530.

Kerr, R. A. (2008), Climate change hot spots mapped across the United States, *Science*, *321*, 909.

Larney, F. J., M. S. Bullock, H. H. Janzen, B. H. Ellert, and E. S. Olson (1998), Wind erosion effects on nutrient redistribution and soil productivity, *J. Soil Water Conserv.*, *53*(2), 133–140.

Leys, J. F., and G. H. McTainsh (1994), Soil loss and nutrient decline by wind erosion-cause for concern, *Aust. J. Soil Water Conserv.*, *7*(3), 30–40.

Leys, J. F., and G. H. McTainsh (1996), Sediment fluxes and particle grain-size characteristics of wind-eroded sediments in southeastern Australia, *Earth Surf. Proc. Land.*, *21*, 661–671.

Li, J. (2008), Integrated research on aeolian processes and soil biogeochemistry in the desert grassland of southern New Mexico, Ph.D. dissertation, Univ. of Virginia, Charlottesville, Va.

Li, J., G. S. Okin, L. Alvarez, and H. Epstein (2007), Quantitative effects of vegetation cover on wind erosion and soil nutrient loss in a desert grassland of southern New Mexico, USA, *Biogeochemistry*, *85*, 317–332.

Li, J., G. S. Okin, L. Alvarez, and H. Epstein (2008a), Effects of wind erosion on the spatial heterogeneity of soil nutrients in two desert grassland communities, *Biogeochemistry*, *88*, 73–88.

Li, J., G. S. Okin, L. J. Alvarez, and H. E. Epstein (2008b), Sediment deposition and soil nutrient heterogeneity in two desert grassland ecosystems, southern New Mexico, *Plant Soil*, doi:10.1007/s11104-008-9850-7.

Liu, T. S (1985), *Loess and the Environment*, p. 215, China Ocean Press, Beijing.

Lyles, L., and J. Tatarko (1986), Wind erosion effects on soil texture and organic matter, *J. Soil Water Conserv.*, *41*, 191–193.

Manabe, S., and R. T. Wetherald (1986), Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide, *Science*, *232*, 626–628.

Manabe, S., and R. T. Wetherald (1987), Large-scale changes of soil wetness induced by an increase in atmospheric carbon dioxide, *J. Atmos. Sci.*, *44*, 1211–1236.

Neff, J. C., R. L. Reynolds, J. Belnap, and P. Lamothe (2005), Multi-decadal impacts of grazing on soil physical and biogeochemical properties in southeast Utah, *Ecol. Appl.*, *15*(1), 87–95.

Nickling, W. G. (1983), Grain-size characteristics of sediment transported during dust storms, *J. Sediment Petrol.*, *53*, 1011–1024.

Okin, G. S., and D. A. Gillette (2001), Distribution of vegetation in wind-dominated landscapes: Implications for wind erosion modeling and landscape processes, *J. Geophys. Res.*, *106*, 9673–9683.

Okin, G. S., B. Murray, and W. H. Schlesinger (2001), Degradation of sandy arid shrubland environments: Observations, process modeling, and management implications, *J. Arid Environ.*, *47*(2), 123–144.

Okin, G. S., N. M. Mahowald, O. A. Chadwick, and P. E. Artaxo (2004), The impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems, *Global Biogeochem. Cycles*, *18*, GB2005, doi:10.1029/2003GB002145.

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

Peterjohn, W. T., and W. H. Schlesinger (1991), Factors controlling denitrification in Chihuahuan Desert ecosystem, *Soil Sci. Soc. Am. J.*, *55*, 1670–1694.

Peters, D. P. C. (2002), Plant species dominance at a grassland-shrubland ecotone: An individual-based gap dynamics model of herbaceous and woody species, *Ecol. Model.*, *152*(1), 5–32.

Reynolds, J. F., R. A. Virginia, R. R. Kemp, A. G. de Soyza, and D. C. Tremmel (1999), Impact of drought on desert shrubs: Effects of seasonality and degree of resource island development, *Ecol. Monogr.*, *68*, 69–106.

Scanlon, T. M., K. K. Caylor, S. Manfreda, S. A. Levin, and I. Rodriguez-Iturbe (2005), Dynamic response of grass cover to rainfall variability: Implications for the function and persistence of savanna ecosystems, *Adv. Water Resour.*, *28*, 291–302.

Schlesinger, W. H., A. F. Raikes, A. E. Hartley, and A. F. Cross (1996), On the spatial pattern of soil nutrients in desert ecosystems, *Ecology*, *77*, 364–374.

Schlesinger, W. H., and A. M. Pilmanis (1998), Plant-soil interactions in deserts, *Biogeochemistry*, *42*, 169–187.

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

Schlesinger, W. H., T. J. Ward, and J. Anderson (2000), Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico. II: Field plots, *Biogeochemistry*, *49*, 69–86.

Seager, R., et al. (2007), Model projections of an imminent transition to a more arid climate in southwestern North America, *Science*, *316*, 1181–1184.

Shao, Y., M. R. Raupach, and P. A. Findlater (1993), Effects of salation bombardment on the entrainment of dust by wind, *J. Geophys. Res.*, *98*, 12,719–12,726.

Smith, S. D., T. E. Huxman, S. F. Zitzer, T. N. Charlet, D. C. Housman, J. S. Coleman, L. K. Fenstermaker, J. R. Seemann, and R. S. Nowak (2000), Elevated CO_2 increases productivity and invasive species success in an arid ecosystem, *Nature*, *408*, 79–82.

Zobeck, T. M., and D. W. Fryrear (1986a), Chemical and physical characteristics of windblown sediment. I: Quantities and physical characteristics, *Trans. ASAE*, *29*(4), 1032–1036.

Zobeck, T. M., and D. W. Fryrear (1986b), Chemical and physical characteristics of windblown sediment. II: Chemical characteristics and total soil and nutrient discharge, *Trans. ASAE*, *29*(4), 1037–1041.

Zobeck, T. M., D. W. Fryrear, and R. D. Pettit (1989), Management effects on wind-eroded sediment and plant nutrients, *J. Soil Water Conserv.*, *44*, 160–163.

H. E. Epstein, Department of Environmental Sciences, University of Virginia, Clark Hall, 291 McCormick Road, Charlottesville, VA 22904-4123, USA.

J. Li, Department of Biological and Environmental Engineering, Soil and Water Laboratory, Cornell University, 162 Riley-Robb Hall, Ithaca, NY 14853, USA. (jl2428@cornell.edu)

G. S. Okin, Department of Geography, University of California, 1255 Bunche Hall, Box 951524, Los Angeles, CA 90095, USA.