Aeolian Research 1 (2009) 27–43

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Sediment losses and gains across a gradient of livestock grazing and plant invasion in a cool, semi-arid grassland, Colorado Plateau, USA

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A R T I C L E   I N F O

Article history:
Received 26 November 2008
Revised 25 February 2009
Accepted 10 March 2009

Keywords:
Drylands
Dust
Global change
Land use
Wind erosion

A B S T R A C T

Large sediment fluxes can have significant impacts on ecosystems. We measured incoming and outgoing sediment across a gradient of soil disturbance (livestock grazing, plowing) and annual plant invasion for 9 years. Our sites included two currently ungrazed sites: one never grazed by livestock and dominated by perennial grasses/well-developed biocrusts and one not grazed since 1974 and dominated by annual weeds with little biocrusts. We used two currently grazed sites: one dominated by annual weeds and the other dominated by perennial plants, both with little biocrusts. Precipitation was highly variable, with years of average, above-average, and extremely low precipitation. During years with average and above-average precipitation, the disturbed sites consistently produced 2.8 times more sediment than the currently undisturbed sites. The never grazed site always produced the least sediment of all the sites. During the drought years, we observed a 5600-fold increase in sediment production from the most disturbed site (dominated by annual grasses, plowed about 50 years previously and currently grazed by livestock) relative to the never grazed site dominated by perennial grasses and well-developed biocrusts, indicating a non-linear, synergistic response to increasing disturbance types and levels. Comparing sediment losses among the sites, biocrusts were most important in predicting site stability, followed by perennial plant cover. Incoming sediment was similar among the sites, and while inputs were up to 9-fold higher at the most heavily disturbed site during drought years compared to average years, the change during the drought conditions was small relative to the large change seen in the sediment outputs.

1. Introduction

The generation of aeolian sediment remains a topic of major concern worldwide, as both source and sink areas are impacted by the gain or loss of sediment. Loss of the fine soil fraction via wind erosion decreases the fertility and water-holding capacity of the source soils, thus reducing the productivity and nutrient content of plants growing in these soils (Ebeid et al., 1995; Erdman, 1942; Neff et al., 2005). As in the past, dust continues to fertilize diverse landscapes, including Amazonia (Swap et al., 1992), older Hawaiian Islands (Chadwick et al., 1999), islands in the Caribbean Sea and off the coast of California (Muhs et al., 2007, 2008), drylands (e.g., Capo and Chadwick, 1999; Neff et al., 2005; Reynolds et al., 2001), and subalpine and alpine zones (Muhs and Benedict, 2006). Large amounts of deposited aeolian dust result in loess deposits that provide rich agricultural landscapes (see Goudie and Middleton, 2006). However, many ecosystems are receiving high levels of sediment deposition within short time periods which can bury biological soil crusts, vegetation or alter competitive interactions of plants via changes in soil nutrients. In addition, the increased deposition of dust on snowpack may increase the rate of snowmelt and thus increase the timing and the availability of run-off water (Painter et al., 2007).

Changes in aeolian sediment emission and deposition over time have been recently documented. In western North America, for example, drying of pluvial lakes over millennia during the late Pleistocene and early Holocene (e.g., Benson et al., 1990) apparently led to increased dust deposition close to and far from the lakes (Machette, 1985; Reheis et al., 1989, 1995; Reynolds et al., 2006; Wells et al., 1985). Studies of alpine lake sediments in western North America reveal up to eight times more dust flux during the past 150 years than during the prior several millennia (Neff et al., 2008). The influences of greatly increasing dust flux on these short time spans of a decade to a few centuries are uncertain.

Much of the atmospheric dust in western North America is generated in sparsely vegetated dryland settings (Reynolds et al., 2003; http://esp.cr.usgs.gov/info/dust/inventory/). The cover and type of vegetation influence the amount of wind-blown sediments produced at such settings, with site stability increasing with

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doi:10.1016/j.aeolia.2009.03.001

greater plant cover (Lancaster and Baas, 1998; Okin, 2008). Soil surfaces covered with physical and biological soil crusts in these dryland regions are very stable unless disturbed, and the stability conferred by well-developed crusts is great enough that wind erosion is minimal even with a dramatic decrease in vascular plant cover (reviewed in Belnap, 2003; Marticorena et al., 1997). During historic times in western North American drylands, however, soil-surface disturbances caused by plowing, livestock grazing, mining, and by the use of both off-road recreational and military vehicles have depleted the natural components that stabilize desert soils. Thus, soil loss appears to have increased dramatically in these regions (Neff et al., 2008).

Surface disturbance also enhances the invasion of exotic annual plants such as *Bromus* spp. and *Salsola* spp. (D'Antonio and Vitousek, 1992). Whereas high annual plant cover can be present in years with high rainfall, annual plants often do not germinate in drought years, leaving soils barren and vulnerable to erosion. Rodents colonize invaded areas, and their burrowing activity leaves multiple patches of bare soil that can be mobilized by wind. In addition, growth of annual plants in wet years often produces sufficient fuels to carry fire in following dry years. In the short term, fire creates ash, which is easily moved by wind, while decreasing plant and crust cover and thus increasing the vulnerability of soils to wind erosion. Although post-fire vegetation sometimes provides more cover and protection than pre-fire vegetation, more often the repeated burning of areas maintains the dominance of annuals and an increased vulnerability to soil erosion (Vermeire et al., 2005). A synergistic effect may also be created when one or more of these factors (surface disturbance, invaded landscapes drought) occur together, and large amounts of soil can be eroded in a short time. In addition, as current climate models predict an increase in temperature of 4–6 °C and a decrease of as much as 20% precipitation for this region (Christensen et al., 2007), the resultant decline in soil moisture will decrease plant cover and slow the recovery of disturbed plants and crusts (Pulwarty et al., 2005), all of which will likely further increase the frequency and magnitude of wind erosion events.

Whereas there have been many studies examining the impact of intensive agriculture on sediment production and nutrient loss (e.g., Bielders et al., 1999, 2002; Ebeid et al., 1995; Erdman, 1942), few studies have measured landscape-scale sediment emission from soils that have been disturbed by activities other than intensive agriculture. A limited number of studies have focused on the potential erodibility of a site, using a wind tunnel (Belnap and Gillette, 1997; Marticorena et al., 1997) or models of air flow patterns and vegetation (Bowker et al., 2007; King et al., 2005; Okin and Gillette, 2001). Nevertheless, only a few studies have documented the rates of sediment movement over long time periods or under differing land use and climatic conditions (e.g., Breshears et al., 2003; Whicker et al., 2008; Wolfe and Helm, 1999). To address this lack of information, we conducted a 9-year (1999–2007) study, utilizing sediment collection devices and aeolian-particle flux detectors to measure the input and outgo of aeolian sediment at sites that have received different types and intensity of land use over the past 150 years.

2. Methods

2.1. Site Descriptions

This study was conducted on the central Colorado Plateau about 70 km south of Moab, Utah, USA (Fig. 1). The four selected sites lie within a 10 km radius adjacent to and within Canyonlands National Park (NP), and all are at an elevation of approximately 1600 m. Climate data (Western Region Climate Center – http://www.wrcc.dri.edu/) show the long-term annual average rainfall

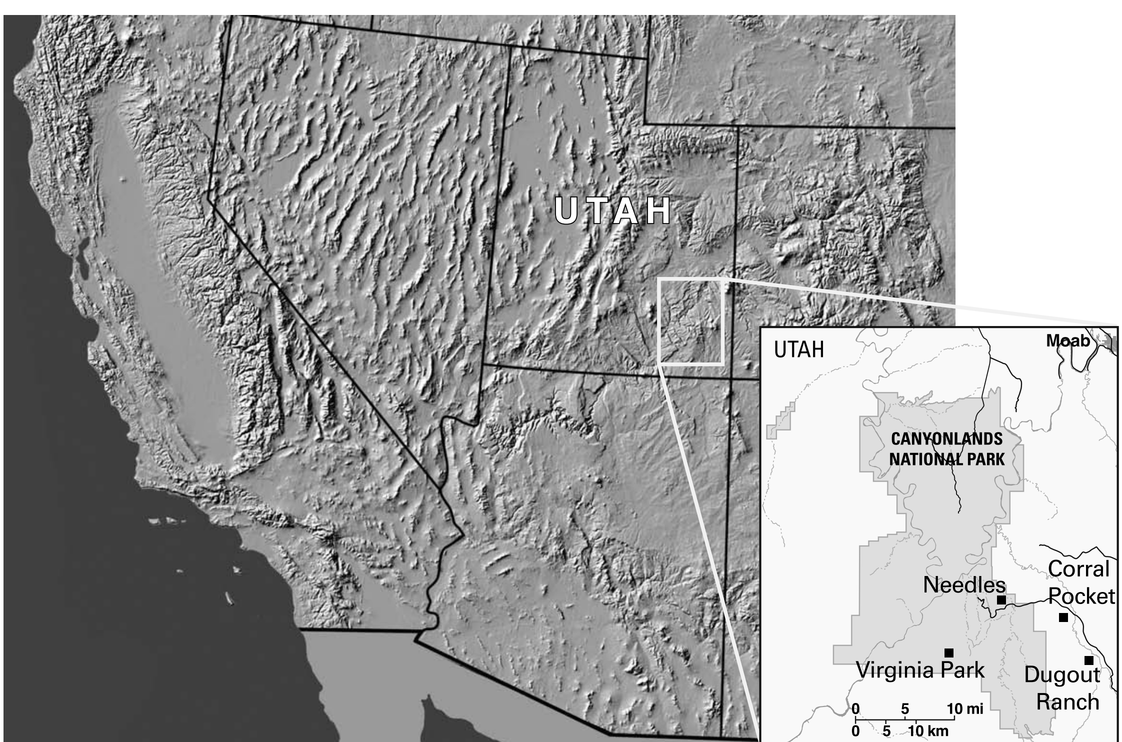

Fig. 1. A map of the study sites. Two sites (Needles and Virginia Park) are within Canyonlands National Park, and thus are not grazed by livestock, whereas the other two sites (Corral Pocket and Dugout Ranch) are outside the park boundary and are grazed by livestock.

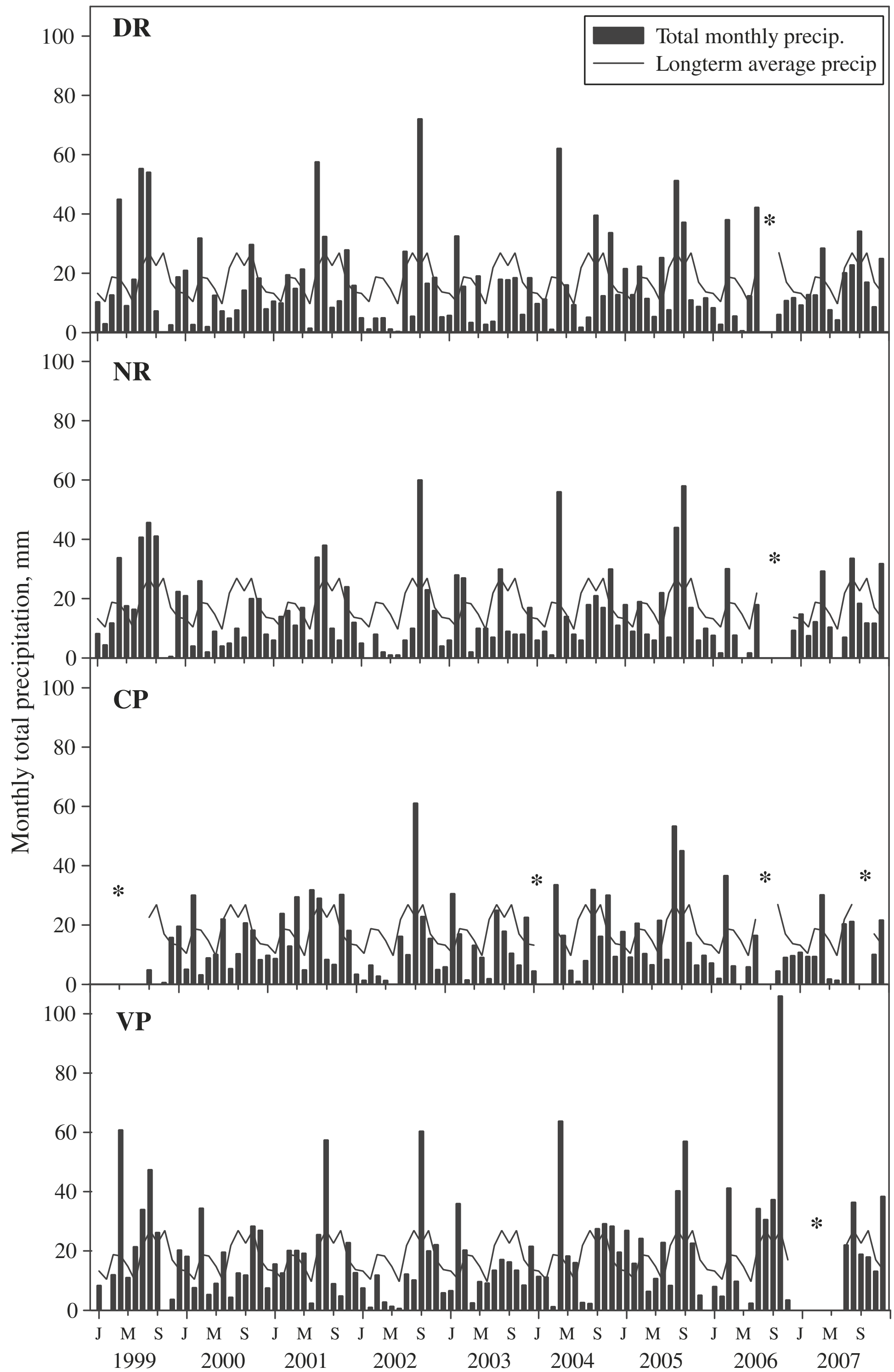

Fig. 2. Precipitation at the sites. The solid line represents the long-term average precipitation, with the individual bars showing the precipitation received at the site during the study period. An asterisk (*) and a broken line indicate that data are missing for that period.

at these sites is 215 mm, with approximately 35% occurring as summer monsoons (late July–September; Fig. 2). The maximum annual average high temperature is 20.2 °C, whereas the minimum annual average low temperature is 3.7 °C. Evaporation exceeds precipitation during most of the growing season. Soils at all four sites are young, alkaline, well-drained fine sandy loams with weak or little horizonation derived primarily from calcareous sandstone parent material and atmospheric dust inputs. At all four sites, the dominant vegetation was once perennial grasses; however, two of these sites are now dominated by exotic annual plants.

Livestock grazing began in this area in the late 1800s. Prior to the introduction of domesticated livestock, the only hooved animals in the region were small groups of deer and pronghorn. Due to very limited free surface water, these animals frequented the lower elevation lands only during winter months when snow provided a source of water. Therefore, the continuous presence of livestock in this area constitutes a dramatic change in the type and intensity of soil surface disturbance than what was previously present. The four sites used in this study have had different land-use histories since livestock were introduced. The Dugout Ranch (DR; Fig. 1) site was once perennial grassland. It was plowed and planted in alfalfa for 2–5 years sometime before 1960, after which these activities ceased. This site is currently dominated by the exotic annuals *Chorispora tenella* (present March–June) and *Salsola kali* (present July–September; all taxonomy follows Welsh et al., 2003), and the soils between the plants are bare or covered by a thin layer of cyanobacteria and physical crusts. This site has been, and is currently, grazed yearly in the spring and fall. The Needles Residence (NR) site was grazed every spring and fall until 1974. This area was once native perennial grassland; however, grazing converted this landscape into one now dominated by the native annual *Lappula occidentalis* (present March–June) and the non-native annuals *Bromus tectorum* (present September–June) and *Salsola kali*. The soils between the plants are either bare or covered by a very thin layer of sparse cyanobacteria and physical crusts. The Corral Pocket (CP) site is currently grazed in the spring and fall. It is dominated by the perennial grasses *Hilaria jamesii* and *Stipa hymenoides* and the perennial shrub *Gutierrezia sarothrae*. Similar to the DR and NR sites, the soils between the plants are bare or covered with a thin layer of sparse cyanobacteria and physical crusts. Virginia Park (VP) has never been grazed by domestic livestock as it is surrounded by high rock walls and has no free surface water. It is currently dominated by the native perennial grasses *S. hymenoides*, *S. comata*, and *H. jamesii*. Soils between these grasses are covered by a well-developed biological soil crust dominated by perennial lichens and mosses. The DR site is 23 km from VP, CP is 17 km from VP, and the NR site is 12 km from VP.

2.2. Sample Collection and Analysis

At each study site, a meteorological station was established to measure air temperature, wind speed and direction (at 3 m height), relative humidity, and solar radiation. Soil temperature and moisture were measured at 10 cm depth. The meteorological data were collected at 1-s intervals and averaged and summed over 60 min. Vertical sediment inputs at each site were collected by deposition traps consisting of circular cake pans mounted on 2-m-high posts. A piece of stainless steel hardware cloth was set 3–4 cm below the pan rim, and marbles were placed on top of the hardware cloth, filling the area between the hardware cloth and the rim of the pan. This simulates the effect of a gravelly surface and prevents the sediment that has filtered or washed into the pan bottom from being blown back out (Reheis, 2006). The efficiency of these pans compared to deposition at ground level varies with surface vegetation; in areas with very low vegetation such as grasslands, true deposition rates may be as much as 2 times greater at ground level than that measured at a 2-m height (Reheis and Kihl, 1995). Sediment emissions from each site were measured using sediment collection samplers that were installed on poles and fitted with vanes to orient them into the wind and that had a 2×5 cm opening (BSNE [Big Springs Number Eight] Wind Aspirated Dust Sampler, Custom Products and Consulting, Big Springs, TX; Fryrear, 1986). Three samplers were mounted per pole at 15, 50, and 100 cm above the soil surface. The horizontal sediment flux was calculated by dividing the weight of the sediment collected by the opening size of the BSNE (10 cm^2) and the duration of the sampling period; thus, BSNE measures are reported in g/m^2 opening/day. To compare more easily with horizontal flux values reported in earlier studies, we report the values from each sampling height separately as well as additively, rather than using the equation presented in Shao and Raupach (1992) and Gillette et al. (1997), which creates an integrated value over the space between the ground and the highest box. Therefore, our reported additive value is a conservative estimate as it does not account for sediment present at heights between the samplers. We assumed particle collection efficiency was 100%; thus, the measurements reported are a low estimate (manufacturer's efficiency tests using fine sand report 90% efficiency). At the CP site, plants obstructed the collectors for part of the time during 2002 and 2003, and thus the sediment weight again may be lower than would have been collected without the obstruction. The following sample times also had values missing for the upper and/or middle sampler: DR: DOY (Julian Day-of-Year) 129–263, 2001, middle sampler; NR: DOY 312, 2003–DOY 48, 2004, top sampler; CP: DOY 214–234, 2002 and DOY 18–142, 2005, top and middle samplers; and VP: DOY 215–272, 2002 and DOY 313, 2003–DOY 49, 2004, top sampler. Saltating particles were measured with a 5–10 cm high, automated particle-flux detector (SENSIT Wind Eroding Mass Sensor, Sensit Co., Portland, ND) containing a piezoelectric crystal, which records particle impact as an electronic pulse. A zone of approximately 50 cm was disturbed around the SENSITs while servicing. All data were downloaded, and the BSNEs sampled, seasonally and can be viewed at http://esp.cr.usgs.gov/info/sw/clim-met. The deposition traps were sampled bi-annually. Photographs showing vegetation condition were taken at each collection time at each site and are posted at http://esp.cr.usgs.gov/info/sw/clim-met/photos/index.html.

Permanent line transects for vegetation and ground cover characteristics were measured near the beginning (spring 2001) and the end (fall 2006 and spring 2007) of the study period, using point hits at each meter along two 30-m transects located upwind of the sediment collectors and starting about 1 m from the collection zone. Soils were collected from each site at the surface (0–1 cm) and deeper (0–10 cm) along these transects. Thirty subsamples were composited into two replicates per site (except 0–1 soils, VP, where $N = 1$). A pocket penetrometer (Handheld Penetrometers, QA Supplies, Norfolk, VA) was used to measure the strength of the soil surface, and a field-modified soil stability index (Herrick et al., 2001) was used to assess the stability of surface and subsurface soils at 10 stops along the transect (subsurface values indicate the inherent stability of the soil resulting from soil aggregates formed by roots, organic matter, fungi, and other materials, whereas surface soil stability indicates the contribution of physical and biological soil crusts). Because we encountered extremely stable soils in VP, Herrick method, increasing the top value from 6 to 9 (Belnap et al., 2008).

Particle-size analysis was performed on samples from the two types of sediment traps and bulk soils at the sites from 1998 to 2005. Prior to analysis, all samples were prepared by digesting organic matter using 30% hydrogen peroxide. Sodium hexametaphosphate was added to all samples to aid in disaggregation. Particle size was determined as a volume percentage using a laser-light scattering analyzer capable of measuring particles greater than 0.05 μm. Particle size classes for the BSNE samples were defined according to the Wentworth scale, in which clay is <3.9 μm, silt 3.9–63 μm, very fine sand 63–125 μm, fine sand 125–250 μm; medium sand 250–500 μm; coarse sand 500–1000 μm, and very coarse sand 1000–2000 μm. All other particle size classes are defined by the USDA scale, which varies from the Wentworth scale only in that clay is <2μm; silt 2–50 μm; very fine sand 50–100 μm; fine sand 100–250 μm. Cyanobacteria-dominated soils were also analyzed for chlorophyll *a* concentrations, used as a proxy for cyanobacterial biomass. After extraction in acetone, concentrations of chlorophyll *a* were measured using high performance liquid chromatography (HPLC) analysis according to a slightly modified version of the method of Karsten and Garcia-Pichel (1996).

Soil characteristics were compared across sites using ANOVA following normality testing with a Kolmogorov–Smirnov test that used a Lilliefors significance level (for which probabilities less than 0.01 are reported as 0.01, probabilities greater than 0.10 are reported as 0.5, and for intermediate values, an approximate probability is computed). If the ANOVA was significant and the data were homogenous, as determined by Levene's test for homegeneity of variance, the Tukey's Honestly Significant Difference test was used to determine which values were significantly different from each other. If the ANOVA was significant, but the data were not homogenous, Dunnett's T3 was used to determine which values were significantly different from each other. Correlations between variables were calculated using Spearman's rho rank test. All statistical analyses were done using SPSS v16.

3. Results

3.1. Soils

Soils at all the sites are sandy, as measured at two depths (0–1 and 0–10 cm), containing 53–76% sand (Table 1). The fine and very fine sand fractions dominated the sand, with the medium to very coarse fractions representing less than 10% of the sand at all the sites. Clay content was similar among the sites (8–13%), with silts showing a greater range (16–37%). Soils at DR had lower sand and higher silt than those at NR, reflecting the higher silt content in the bedrock sources of the surficial deposits at DR, whereas soil texture at CP and VP was very similar. The more easily blown soil fractions (clay + silt + fine sand + very fine sand) were fairly similar among the sites, ranging from 89% to 98%. The texture of the 0–1 and 0–10 cm samples was very similar within a site, with the exception of silt at VP (28% at 0–1 cm, 20% at 0–10 cm).

3.2. Precipitation

Monthly precipitation during the study period was well below average for 60 of the 108 months of the experimental period (Fig. 2). The period from September 2001 to September 2003 contained exceptionally dry months. For example, at the NR site only 12 mm of rain fell between February and June 2002, compared to a long-term average of 72 mm. The months between April and July 2003 were similarly very dry, with only 29 mm of rain falling compared to the long-term average of 63 mm.

3.3. Vegetation and Ground Cover

The variability in the cover of vegetation, plant litter, biological soil crusts, and bare soil during the experimental period was very different among the sites (Fig. 3 and Table 2; for photos of all years, consult http://esp.cr.usgs.gov/info/sw/clim-met/). At DR, the cover of plants and plant litter ranged widely, from very low cover of 10% in May 2001, when drought limited the cover of annual plants, to much higher cover of 57% in May 2007, when higher precipitation resulted in a higher cover of annual plants. The development of biological soil crusts was very low at this site at all sample dates, as indicated by the low values of well-developed crust cover and chlorophyll *a*. Measures of soil surface stability were also low at all measurement times. In addition, subsurface and surface soil stability values were similar, revealing that physical or biological soil crusts contributed little to soil stability. Because there were no perennial plants at this site, and the soil surfaces were not protected by physical or well-developed biological crusts, the stability of this site depends on the widely variable cover of annual plants and the litter produced by them. Therefore, this site would be highly vulnerable to erosion in drought years with low annual cover.

At NR, plant and plant litter cover was highly variable among sampling times (33–69%). As at DR, cover at this site consisted mostly of transient components (annual plants and annual plant litter), and values for chlorophyll *a*, surface penetrometer, and surface soil stability were low at all sampling times. The similarity between stability of surface and subsurface soil indicated little soil protection was offered by physical or biological soil crusts. Therefore, the low cover of perennial plants, plant litter, and biocrusts (3–25%) renders this site highly vulnerable to erosion in drought years with low annual plant cover.

The CP site had a much higher perennial cover than DR or NR, but this cover was also highly variable (9–35%). Annual cover was highly variable as well (0–15%). Combined plant, plant litter, and well-developed biocrust cover ranged from 22% in 2001 to

Table 1

Soil texture of surface (0–1 cm) and subsurface (0–10 cm) soils at each site and texture of captured sediment. Reported sand fraction values represent a portion of the total sand fraction; thus, totaling the sand fraction values will equal the % sand value. BSNE and vertical input collector values are averages of all collection dates. DR=Dugout Ranch; CP=Corral Pocket; NR=Needles Residence; VP=Virginia Park. Particle size classes for the BSNE samples were defined according to the Wentworth scale, in which clay is <3.9 μm, silt 3.9–63 μm, very fine sand 63–125 μm, fine sand 125–250 μm; medium sand 250–500 μm; coarse sand 500–1000 μm, and very coarse sand 1000–2000 μm. All other particle size classes are defined by the USDA scale, which varies from the Wentworth only in that clay is <2 μm; silt 2–50 μm; very fine sand 50–100 μm; fine sand 100–250 μm.

Site		% Clay	% Silt	% Sand	Sand fractions (% of total sand)					% Easily blown particles
					% Very coarse	% Coarse	% Medium	% Fine	% Very fine	
DR	Soil 0–1 cm	10	37	53	0	1	4	33	14	95
	Soil 0–10 cm	11	34	54	0	1	4	33	16	95
	BSNE	8	36	56	0	0	3	19	37	100
	Vertical input collectors	16	55	28	0	0	1	14	14	99
CP	Soil 0–1 cm	10	25	66	1	3	8	35	20	89
	Soil 0–10 cm	9	27	63	1	3	7	34	18	89
	BSNE	5	30	66	0	0	3	20	44	98
	Vertical input collectors	9	42	48	0	0	2	22	24	97
NR	Soil 0–1 cm	9	19	71	0	0	5	49	18	95
	Soil 0–10 cm	8	16	76	0	1	5	48	21	94
	BSNE	5	24	71	0	0	7	26	39	93
	Vertical input collectors	11	47	42	0	0	3	20	20	98
VP	Soil 0–1 cm	10	28	62	0	0	2	35	25	98
	Soil 0–10 cm	13	20	67	0	0	2	41	25	98
	BSNE	7	28	65	0	0	0	22	42	100
	Vertical input collectors	13	54	31	0	0	1	13	18	99

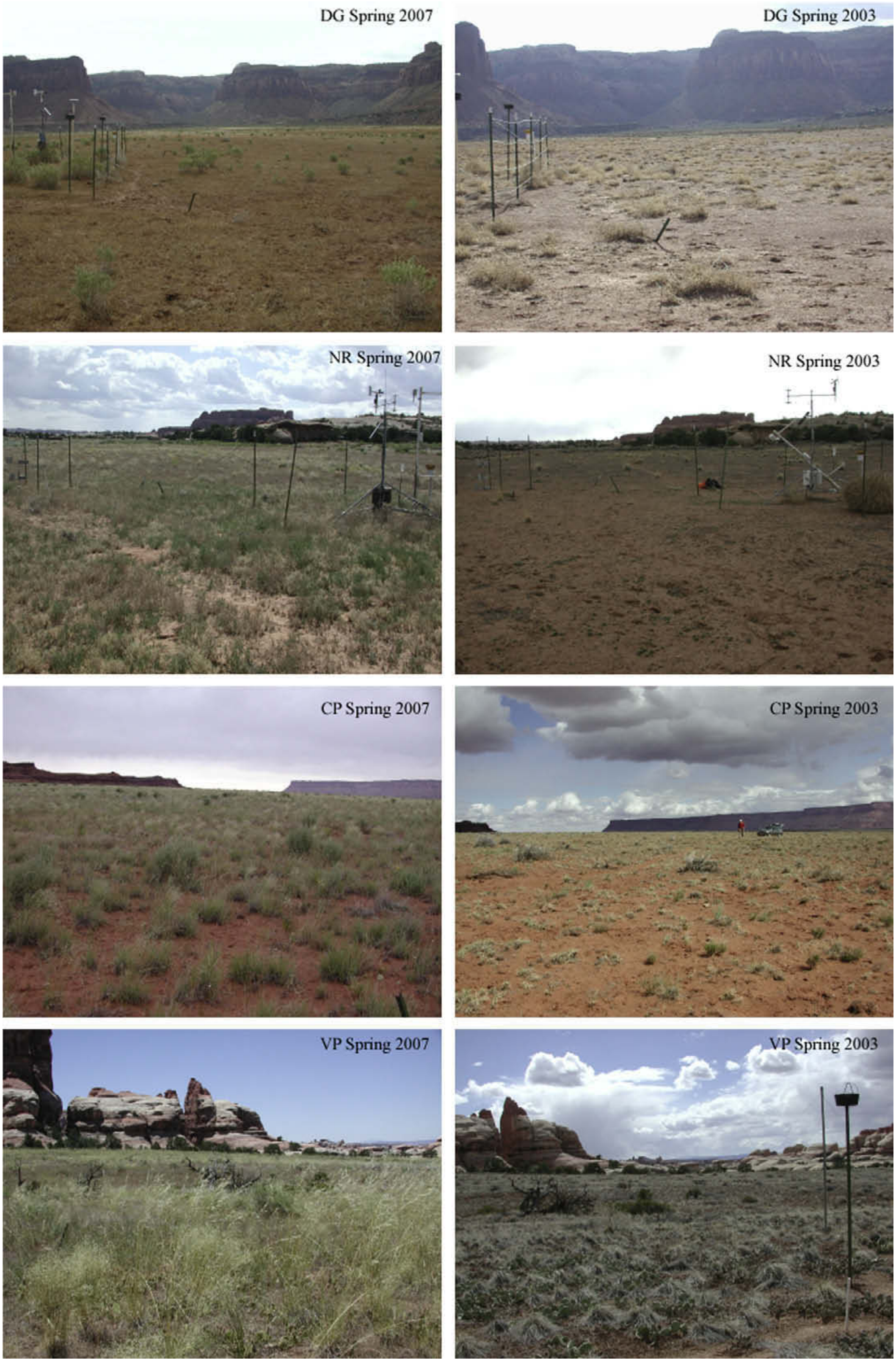

Fig. 3. Photos of the vegetation at the four sites during a relatively dry (2003) and wet (2007) spring.

62% cover in 2007. Much of this variability was likely due to grazing cattle in the spring and fall. As with DR and NR, soil surface stability was limited at this site as indicated by low values of the chlorophyll *a*, surface penetrometer, and surface soil stability indices. There was little influence of physical or biological crusts at this site, as indicated by the small difference between surface and subsurface stability indices. The presence of perennial plants likely reduces the susceptibility of this site to wind erosion compared to DR

Table 2
Percent plant cover, soil stability measures, and soil chlorophyll *a* content at the different sites at various sample times. Different letters indicate statistically significant difference ($P < 0.05$) between the sites within a sampling date. DR=Dugout Ranch, CP=Corral Pocket, NR=Needles Residence, and VP=Virginia Park.

Ground Cover	Sampling Date	DR	NR	CP	VP
Perennial plants %	**May 2001**	1 ± 1	0	9 ± 1	32 ± 3
	Sep. 2006	0	7 ± 7	17 ± 3	22 ± 2
	May 2007	0	5 ± 2	35 ± 5	18 ± 2
Annual plants %	**May 2001**	7 ± 1	40 ± 6	7 ± 1	0
	Sep. 2006	30 ± 7	8 ± 5	0	0
	May 2007	45 ± 5	57 ± 7	15 ± 5	30 ± 17
Litter %	**May 2001**	2 ± 0	1 ± 1	4 ± 0	15 ± 1
	Sep. 2006	25 ± 15	18 ± 15	25 ± 2	30 ± 3
	May 2007	12 ± 2	7 ± 3	12 ± 2	8 ± 2
Well-developed biological soil crust %	**May 2001**	0	2 ± 2	2 ± 2	53 ± 2
	Sep. 2006	0	0	0	48 ± 5
	May 2007	0	0	0	42 ± 12
Bare ground/thin biological soil crust %	**May 2001**	90 ± 2	57 ± 9	78 ± 2	0
	Sep. 2006	45 ± 8	67 ± 3	58 ± 3	0
	May 2007	43 ± 3	28 ± 2	38 ± 8	2 ± 2
Protected soil surfaces %	**May 2001**	10	43	22	100
	Sep. 2006	55	33	42	100
	May 2007	57	69	62	98
Soil Characteristics					
Surface stability index	**May 2002**	2.3 ± 1.3[a]	1.6 ± 1.7[a]	1.0 ± 0.0[a]	6.3 ± 1.0[b]
index score	**May 2005**	1.3 ± 0.1[a]	2.2 ± 0.2[b]	1.1 ± 0.1[a]	6.9 ± 0.4[c]
	May 2007	1.2 ± 0.2[ab]	1.7 ± 0.2[b]	1.0 ± 0.1[a]	8.2 ± 0.3[c]
Subsurface stability index index score	**May 2005**	1.7 ± 0.2[b]	1.1 ± 0.1[a]	1.1 ± 0.1[a]	1.4 ± 0.1[ab]
Surface penetrometer	**Sep. 2006**	1.5 ± 0.2[a]	1.5 ± 0.1[a]	1.7 ± 0.1[a]	3.3 ± 0.1[b]
force in kg/cm^2	**May 2007**	1.4 ± 0.3[b]	1.4 ± 0.2[b]	0.5 ± 0.1[a]	
Surface chlorophyll *a* content µg chla/g soil	**May 2002**	0.6 ± 0.1[a]	0.7 ± 0.2[a]	0.6 ± 0.1[a]	3.9 ± 1.0[b]

or NR; however, the lack of physical/biological crusts and the presence of grazing animals result in soils vulnerable to erosion during years of low annual plant cover.

Perennial vascular plant cover in VP was higher than that at the other three sites (18–32%). The cover of plant and plant litter ranged from 47 to 56% and thus was much less variable than the other three sites. In addition, unlike the other three sites, all the soil surfaces between the plants in VP were covered with a well-developed perennial lichen–moss biological soil crust. Thus, there was virtually no bare ground at this site, regardless of variability in vascular plant cover. The soil crust conditions were reflected in the high values for chlorophyll *a*, surface penetrometer, and soil surface stability index. The surface stability index was also far higher than the subsurface stability index, reflecting the presence and stabilizing effect of the biological soil crusts. Consequently, no surfaces are exposed to wind erosion at this site, even when rainfall or annual plant cover is low.

3.4. Wind Speed

Wind speeds were significantly different among the sites during the experimental period (Fig 4). Overall, winds blew at average hourly speeds >2 m/s for the longest at DR, followed by NR and CP (total hours were 50,348 h, 21,854 h, and 22,980 h, respectively; Table 3), with the lowest number of hours recorded at VP (17,280 h). The number of hours that average wind speeds were above 8 m/s was also highest at DR (1242 h), followed by CP (161 h) and NR (93 h), while VP did not have any sustained winds above that speed. When the peak wind speed for a given hour was averaged among all recorded hours, the sites showed similar values at wind speeds less than 8 m/s. However, there were no values above that speed class for VP and none above 9.99 m/s at NR (likely due to the high rock walls at these sites), unlike CP and DR. Short bursts of high wind speeds occurred at all the sites (DR: 29 m/s; NR: 27 m/s; CP: 24 m/s; VP: 26 m/s). Most winds that produced SENSIT impacts were from the SW as that is the main wind direction in the spring (data not shown). At all sites, relatively higher wind speeds were more frequent from March to October during the dry years of 2002–2003 than during those months in the preceding or antecedent wetter years (data not shown).

3.5. Particle-Flux Detector (SENSIT)

All sites showed SENSIT impacts occurred at even our lowest wind speed class (2.00–2.99 m/s; Table 3). Total SENSIT impacts, both over time and during extreme events, were far higher at the DR site when compared to the other sites. The DR site had multiple months when the number of SENSIT impacts exceeded 120,000/month (Fig. 5). The maximum number of impacts/h (513,990) also occurred at DR and at an hourly average wind speed at or greater than 11 m/s. The NR and CP sites had the next most active soil surfaces. The VP site consistently had a very low number of SENSIT impacts, indicating a very stable soil surface. (It should be noted that the biological soil crusts at the VP site had to be disturbed around the SENSIT probe for servicing the probe and downloading the data. Thus, it is likely that values would have been close to zero at the VP site had soil disturbance not been required to obtain our measurements.) As would be expected, the number of impacts/h increased with the wind speed class in a non-linear fashion.

Overall, SENSIT impacts were fairly low at all sites until March 2002 (Fig. 5). At DR, extremely high sediment mobility was seen during the very dry months of March–September 2002 and

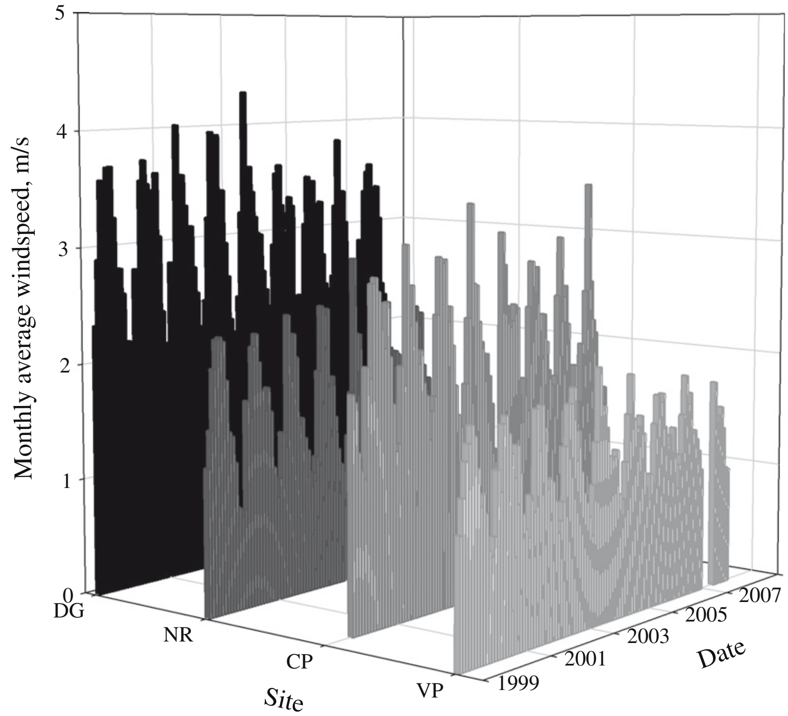

Fig. 4. Weekly average wind speeds at the different sites throughout the experimental period.

April–May 2003. High sediment movement was also recorded in May–October 2003 and then again in May 2006 and March 2007. At NR, peaks in SENSIT activity were seen in February and April 2003. Unfortunately, the SENSIT at CP was not working properly during 2002 through early spring 2003, and thus we missed any large events during that time at that site. In contrast to the other sites, SENSIT impacts at the VP site did not increase during the drought period.

Because the duration and speed of winds varied among the sites, we standardized the average number of SENSIT impacts in a given wind speed class by the number of hours that the wind blew within that class (fourth and fifth columns, Table 3). When we used only wind speed classes common to the three disturbed sites (2.00–9.99 m/s), the DR site had 11,590 average SENSIT impacts/h, CP had 2485 impacts/h, and NR had 912 impacts/h (derived from data in Table 3). When we compared values among all four sites (thus using the common wind speed classes of 2.00–7.99 m/s), impacts/h were highest at DR, followed by NR, CP, and VP (1103, 534, 178, and 44 impacts/h, respectively).

Two observations emerge from these data. First, at any average hourly wind speed interval, the maximum number of impacts/h and the average impacts/h were lowest at VP compared to the other three sites, with the magnitude of the difference between VP and the other sites increasing non-linearly with wind speed. For instance, at winds of 2.00–2.99 m/s, the maximum impacts/h at DR were 3.6 times higher than those at VP, whereas at 6.00–6.99 m/s, maximum impacts/h at DR were 78.7 times higher than those at VP. Second, when winds exceeded 3.99 m/s, the maximum number of impacts/h was almost always highest at DR, and the average number of impacts/h was always highest at DR.

3.6. BSNE Measures

The annual total sediment collected in the BSNEs at each site shows the effects of aridity on aeolian activity (Fig. 6). Compared to the more average years, large amounts of sediment were collected with the BSNEs during the extremely dry years of 2002 and 2003 at the three disturbed sites, especially DR and NR (DR: 53 g/m^2/day during average years versus 3045 g/m^2/day for drought years; NR: 47 g/m^2/day during average years versus 209 g/m^2/day for drought years; CP: 53 g/m^2/day during average years versus 155 g/m^2/day during drought years). The sediment weights from DR during 2002–2003 are a conservative estimate, as the collectors filled up much more rapidly than we could visit the site to empty them. However, VP had a much lower average annual sediment yield than the disturbed sites, both for all years and during 2002–2003 (16 g/m^2/day during the average years versus 26 g/m^2/day in the drought years). Total amounts of sediment captured in the BSNEs for the years 1999–2007 (when BSNEs were deployed at all sites) showed that the DR site produced an order of magnitude more sediment than the other two disturbed sites (DR: 2288 g; NR: 241 g; CP: 215 g), and these three disturbed sites produced far more than the undisturbed VP site (55 g). However, when the extreme years of 2002–2003 were not included, the three grazed and/or annualized sites produced a similar average sediment weight over time, whereas the undisturbed VP site produced much lower average sediment. As expected, the sediment in the lowest BSNE collection sampler always weighed more than the middle or upper collection samplers, because more sediment moves close to the soil surface than at greater heights and contains more sand (Fig. 6).

The particle-size distribution of collected BSNE sediments varied little among the years 2000–2005 at a given site (Fig. 7). Sand dominated the weight of the collected sediments during all years. There was little difference in percent sand between the soil surface and the BNSE collections (Table 1). Interestingly, the amount of clay in the BSNEs was consistently lower than that found in the surface soils, especially at the CP and NR sites. Silt was variable, with higher values in the BSNE collections relative to the surface soils at CP and NR and with little or no difference at DR or VP. As expected, there were no very coarse or coarse sand fractions found in the BSNE collections, although there were small amounts in the surface soils (Table 1). Medium sand fractions were lower in the

Table 3
Values for wind speeds and SENSIT hits recorded between January 1, 1999 and May 15, 2007. Column 1, average hourly wind speed: average hourly wind speed classes for all wind speeds >2 m s^{-1} recorded at each site; Column 2, number of hours at average speed: total number of hours at each site at which the average hourly wind speed was within a given wind speed category; Column 3, average peak wind speed for all hours at speed: the average of the hourly peak wind speed for each hour within a given wind speed class; Column 4, total number of SENSIT hits for all hours at speed: sum of all SENSIT hits recorded during all hours that the average hourly wind speed fell within a given wind speed class; Column 5, maximum number of SENSIT hits/h: maximum number of SENSIT hits recorded in 1 h for all the hours where average hourly wind speed fell within each wind speed class; Column 6, average SENSIT hits/h for all hours at speed (Column 2/Column 4): the average number of SENSIT hits per hour for all hours that the average wind speed fell within a given wind speed category. DR: Dugout Ranch; CP: Corral Pocket; NR: Needles Residence; and VP: Virginia Park.

Average hourly wind speed (m s^{-1})	Number of hours at average speed				Average peak wind speed for all hours at speed				Total number of SENSIT hits for all hours at speed				Maximum number of SENSIT hits/h				Average SENSIT hits/h for all hours at speed			
	DR	NR	CP	VP	DR	NR	CP	VP	DR	NR	CP	VP	DR	NR	CP	VP	DR	NR	CP	VP
2.00–2.99	19,941	10,166	10,838	11,189	5	6	6	7	21,980	21,130	41,098	10,660	1411	1108	4556	389	1	2	4	1
3.00–3.99	13,351	5302	5457	4633	7	8	7	10	114,532	25,469	66,851	6060	17,110	4418	6749	474	9	5	12	1
4.00–4.99	7807	3564	3351	1246	8	9	9	12	219,775	39,746	73,662	2298	63,795	4799	7341	520	28	11	22	2
5.00–5.99	4315	1797	1909	180	10	11	11	15	156,365	39,746	63,284	575	12,364	4257	25,776	166	36	22	33	3
6.00–6.99	2381	709	953	28	12	12	12	17	432,652	86,488	69,771	304	20,696	14,536	13,010	263	182	122	73	11
7.00–7.99	1311	223	311	4	13	14	14	18	1,110,480	82,639	10,660	102	67,555	24,748	1333	98	847	372	34	26
8.00–8.99	690	82	125	0	14	16	15		1,732,154	116,129	18,720		118,080	27,686	3848		2514	1416	150	
9.00–9.99	329	11	22	0	16	18	17		2,623,032	5879	12,850		267,000	5084	7596		7973	534	584	
10.00–10.99	133	0	13	0	18		19		2,573,858		11,301		235,360		5527		19,352		869	
>10.99	90	0	1	0	20		20		7,116,204		1922		513,990		1922		79,069		1922	
32 < Sum < 8	49,106	21,761	22,819	17,280	55	60	59	79	2,055,784	295,218	325,326	19,999	182,931	53,866	58,765	1910	1103	534	178	44
Sum	50,348	21,854	22,980	17,280	123	94	130	79	16,101,032	417,226	370,119	19,999	1,317,361	86,636	77,658	1910	110,011	2484	3703	44

BSNE collections than the surface soil at all sites except NR. The biggest differences between the surface soils and the BSNE collections were in the fine sand fractions: at all sites, fine sands were substantially under-represented in the BSNEs, and very fine sands highly over-represented in the BSNEs, when compared to the surface soils.

3.7. Correlations Among BSNE, SENSIT, Wind Speed, and Rain

Masses of samples collected in BSNEs (bottom, middle, and top collection samplers, and total for all collection samplers) were strongly and positively correlated with average SENSIT impacts/h at the disturbed sites (DR: $R = 0.84–0.88$; NR: $R = 0.57–0.88$; CP: $R = 0.66–0.75$; Table 4) where sediment movement rates were high. The correlation between BSNE and average hourly SENSIT values was much lower at VP ($R = 0.44–0.48$, with the correlation for the top sampler not significant) where sediment movement rates were very low. Similarly, BSNE mass (for all samplers separately and total mass) was positively and highly correlated with the sum of SENSIT impacts at all sites except for VP, for which there was no significant correlation (DR: $R = 0.74–0.76$; NR: $R = 0.58–0.87$; CP: $R = 0.60–0.70$). Average wind speed and average peak wind speed showed a lower, but still relatively strong, correlation with BSNE masses at DR and CP. At NR, only the middle and top collection samplers were significantly correlated with wind measures. At VP, only the top collection sampler was significantly correlated with average wind speed.

Total rainfall might be expected to correlate negatively with BSNE weights, as wet soil surfaces would be less likely to produce aeolian sediment. Although these factors were not significantly correlated at NR, VP, or CP, there were significant negative correlations at DR ($R = -0.46$ to -0.53). When all the data were analyzed together, the only correlation between rainfall and average SENSIT impacts was at DR ($R = -0.41$); the only correlation between rainfall and sum SENSIT impacts was at VP ($R = 0.60$). However, when only the summer months of July, August, and September were combined and tested, there were significant positive correlations between precipitation and SENSIT impacts (DR: $R = 0.45$; NR: $R = 0.54$; CP: $R = 0.53$; and VP: $R = 0.45$).

3.8. Deposition Traps

Average vertical sediment inputs (these values include carbonates and soluble salts but not organic matter) collected by the deposition traps were highest at DR (32 g/m^2/year), lower at ND (21 g/m^2/year) and CP (19 g/m^2/year), and lowest at VP (14 g/m^2/year; Fig. 8). At the DR site, sediment inputs varied widely among years and included changes in the sand, silt, and clay fractions. Annual inputs at the NR site were similar to CP until 2006, at which point they increased substantially at NR for both 2006 and 2007 compared to CP and previous NR collections. The increased inputs were mostly related to an increase in the sand fraction. As sand particles are heavy and cannot travel far, these increases may have been due to local disturbance such as rodent activity. Trapped sediment at VP and CP showed little change through time, ranging from 10–18 g/m^2/year to 11–26 g/m^2/year, respectively. Over the 9-year study period, DR had a total sediment input of 286 g/m^2, compared to 188 g/m^2 at NR, 169 g/m^2 at CP, and 127 g/m^2 at VP (collections at the CP site started in 1999, and the 2006 collection at VP was lost; for these total numbers, the yearly average input from the other years at each site was substituted for the missing data). We found no consistent correlation between vertical sediment input and average and peak wind speed or average and total rainfall.

Overall, the particle size distribution of sediments in the deposition traps did not reflect that found in the local soil

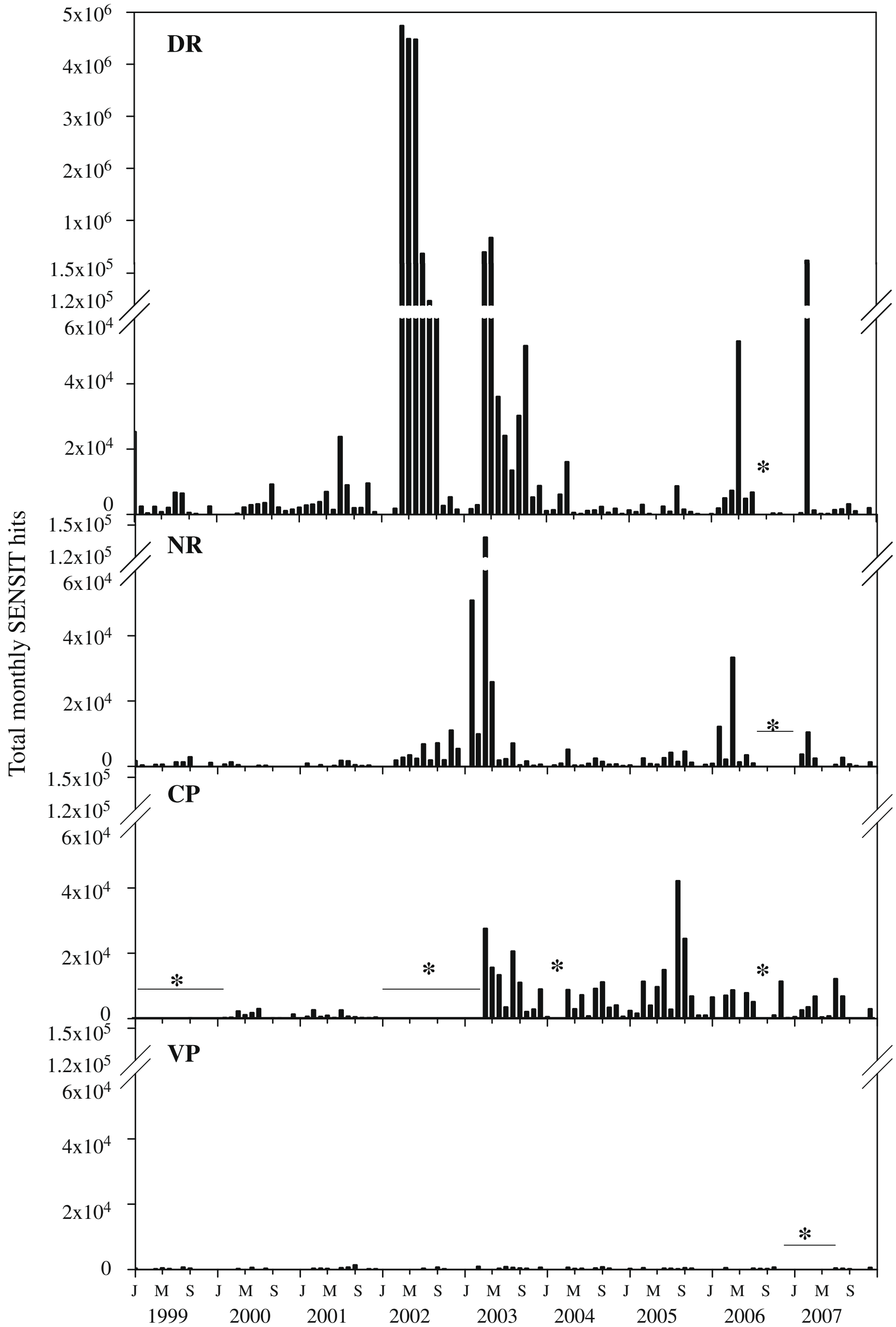

Fig. 5. Total SENSIT impacts per month at the four sites. An * alone indicates missing data for one month; an * with a line indicates missing data for multiple months. Note the broken axis required for the months with large numbers of SENSIT impacts.

surface (Table 1). As expected (Reheis et al., 1995), sand, being heavier, was highly under-represented in the vertically deposited sediment, whereas the lighter silt and clay particles were highly over-represented relative to the soil surface at all the sites. Particle sizes of sediment inputs compared to those of the BSNE sediments gave similar results: sand in the input material was under-represented, and silts and clays were over-represented. This was also expected, as most of the sediments are likely far-travelled silt and clay particles, whereas horizontally collected sediments collected in BSNEs would be mostly from local sources and contain more sand. There were a few notable exceptions to this: in 2002, there was a large increase in sand in the deposition traps at all sites. A similar increase was seen in the sand content of the deposition traps in 2003 at NR and CP and in 2006 and 2007 at NR. As previously noted, these increases were likely due to large amounts of locally derived sand in the air column.

4. Discussion

4.1. SENSIT and BSNE Studies

The wind speeds at which soil-particle movement was detected by the SENSITs in this study were much lower (2 m/s) than are

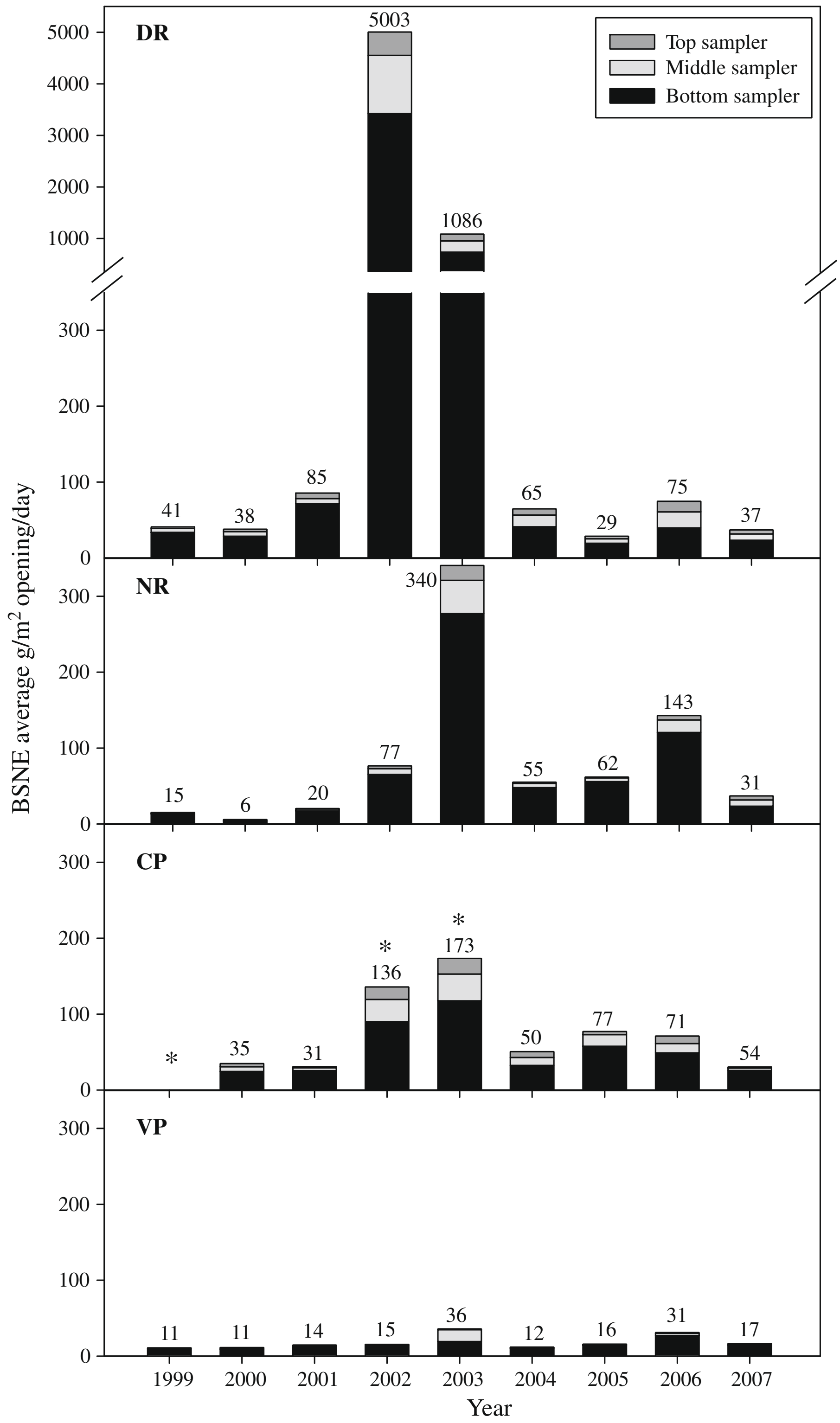

Fig. 6. Wind-eroded sediment collected in BSNEs by year. Each sampler has a different colored bar for the weights of the bottom, middle, and top samplers. The numbers above the bars are the combined weight for all three samplers. An * indicates that one or more of the samplers was obstructed for a subset of time during the year; thus, the values may be lower than what would have been collected without the obstruction. The following sample times had missing data from upper or middle collection samplers: DR: DOY (Julian Day-of-Year) 129–263, 2001, middle sampler; NR: DOY 312, 2003–DOY 48, 2004, top sampler; CP: DOY 214–234, 2002 and DOY 18–142, 2005, top and middle samplers; and VP: DOY 215–272, 2002 and DOY 313, 2003–DOY 49, 2004, top sampler.

generally reported in the literature (e.g., 4 m/s, Stout, 2001; 7 m/s, Whicker et al., 2002). However, results from our wind tunnel studies on these same soils also show soil-particle movement at 1.5 m/s and corroborate the SENSIT data (Belnap, unpublished data). When standardized for wind speed and duration, the highly disturbed DR site had 4.7-fold higher average SENSIT impacts/h than the less disturbed (but still grazed) CP site and 12.7-fold higher than the less disturbed (but no longer grazed) NR site. The SENSIT impacts/h at

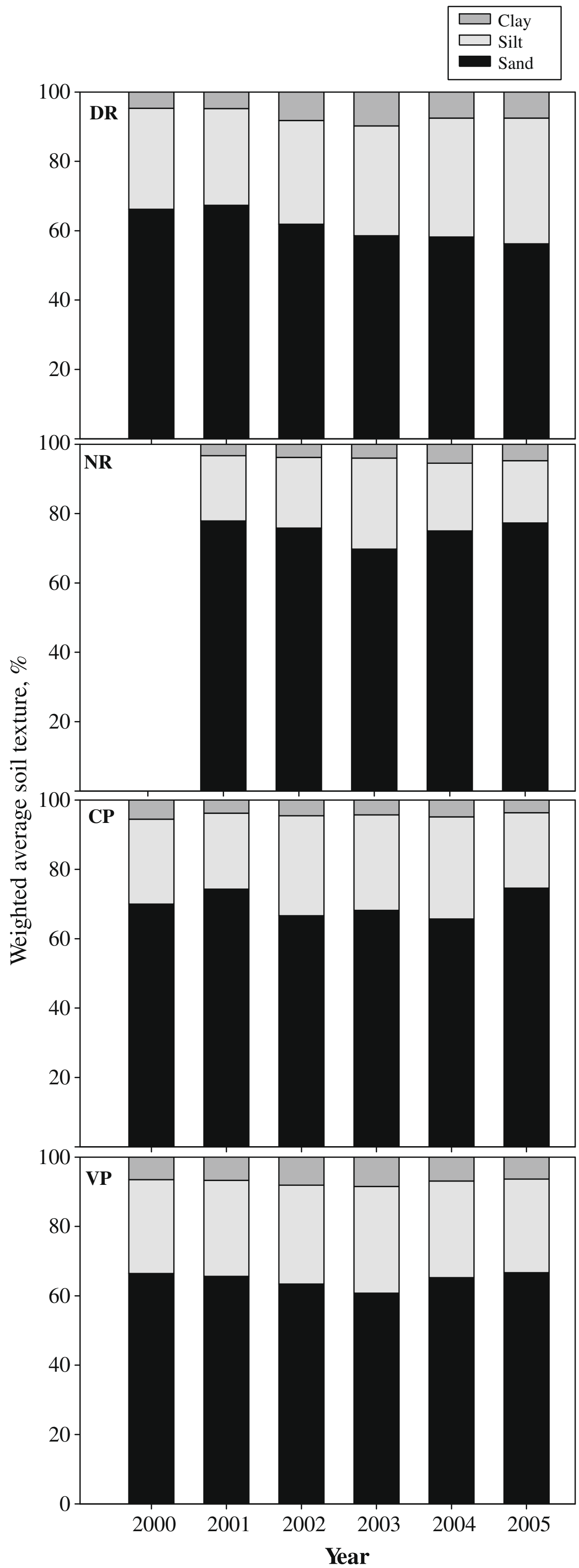

Fig. 7. The weighted average texture of sediments collected in all BSNE collectors 2000–2005, weighted by the amount of sediment in each of the top, middle, and bottom samplers. Most of the sediment collected was sand, followed by silt and then clay. Particle size classes for the BSNE samples were defined according to the Wentworth scale, in which clay is <3.9 μm, silt 3.9–63 μm, very fine sand 63–125 μm, fine sand 125–250 μm; medium sand 250–500 μm; coarse sand 500–1000 μm, and very coarse sand 1000–2000 μm.

DR were 25-fold over those at the undisturbed VP site. Unfortunately, we could not find any previous studies in the literature where SENSIT impacts were compared among disturbance types or sites with varying soil stability.

Although there are more studies using BSNEs, most have been limited to sites known to consistently produce very large amounts of sediment over short time periods, generally as a result of intensive agricultural activities. The sediment produced from these sites ranged from 14 to 2120 kg/m^2/day (Michels et al., 1995; Sheridan, 1981; van Donk et al., 2003; Wang et al., 2004; Zobeck and Fryrear, 1986) in areas as diverse as the western US, Niger, and Inner Mongolia, China (Table 5). In contrast, this study focused on horizontal sediment emissions from, and vertical inputs to, a more vegetated and typical semi-arid landscape with different past and current disturbance regimes over a 9-year period. In this study, we collected an average of 16 g/m^2/day in the BSNEs at the undisturbed site. Other studies in similar areas report collecting 1.5–23 g/m^2/day (Breshears et al., 2003; Offer and Goossens, 2004; Visser et al., 2004; Whicker et al., 2008). Thus, the amounts of horizontal sediment movement from dryland areas not subjected to intensive agriculture are fairly similar.

Sediment production increases in these dryland areas after both past and current disturbances, and the different land uses in the landscapes used in this study have resulted in a widely ranging vulnerability to wind erosion. For example, our DR site (annual grass cover, disturbed by current grazing) produced 41 times more sediment over the course of this 9-year study than the never grazed VP site, whereas the NR (not grazed for 45 years with annual cover) and CP (currently grazed with perennial cover) sites produced 4–4.6 times the sediment as VP during the 9 years. Other studies have reported increases of 3–70 times after disturbance by livestock and fire (Li et al., 2007; Vermeire et al., 2005; Whicker et al., 2002, 2008; Table 5).

However, most wind erosion studies have found that only a few extremely windy days or months account for most sediment moved from a site (e.g., Michels et al., 1995; van Donk et al., 2003; Visser et al., 2004; Zobeck and Fryrear, 1986), and disturbance history can profoundly influence how much soil is lost during these extreme events. During the drought year of 2002, sediment production from the currently disturbed, annualized, and previously plowed (DR) site was 57 times greater than the average sediment produced during all the other years at that same site and 334 times the sediment produced from the ungrazed VP site during that same year (2002). At the NR and CP sites, sediment increased by up to 4 times in 2002 compared to other years at the same site. Thus, extreme years can also be responsible for most of the sediment eroded from a site, with disturbance history playing a major role in how much sediment is eroded in response to climate conditions.

We found a strong, positive correlation between total sediments collected by the BSNEs and both average and average peak wind speed at the DR ($R = 0.62$ and 0.66, respectively) and CP ($R = 0.70$ and 0.73, respectively) sites. This relation was much weaker or not present at NR and VP, where higher wind velocities occurred less often and for less time than at DR and CP. We could not find any other studies that reported on this relationship. A study by Whicker et al. (2002) found a relation ($r^2 = 0.48$–0.52) between peak wind velocity and the mass concentration of aeolian sediment collected by a high volume sampler over a 2-week period. That study, however, revealed a much weaker relation between the average wind speed and total suspended particles ($r^2 = 0.25$–0.27) than in our study. Whereas sediment movement at their study site appears to be heavily dependent on extreme wind events, sediment movement at our most windy site (DR) appears to be driven by a wide range of wind speeds.

Table 4
The correlation coefficients (*R* values) for BSNEs, SENSIT, wind speed, and rain. BSNE values are totals across a collection period (generally 4 months) whereas the SENSIT values are hourly for the entire measurement period.

			Average SENSIT	Sum SENSIT	Average wind speed	Average peak wind speed	Rain
DR	BSNE	Bottom	0.87	0.74	0.62	0.66	−0.46
		Middle	0.86	0.74	0.58	0.63	−0.53
		Top	0.84	0.75	0.58	0.62	−0.52
		Total	0.88	0.76	0.62	0.66	−0.49
	SENSIT	Average	NA	0.93	0.54	0.55	−0.41
		Sum	0.93	NA	0.50	0.48	ns
NR	BSNE	Bottom	0.87	0.86	ns	ns	ns
		Middle	0.81	0.83	0.47	0.47	ns
		Top	0.57	0.58	0.54	0.54	ns
		Total	0.88	0.87	ns	ns	ns
	SENSIT	Average	NA	0.96	ns	ns	ns
		Sum	0.96	NA	0.52	ns	ns
CP	BSNE	Bottom	0.69	0.60	0.62	0.67	ns
		Middle	0.75	0.70	0.71	0.73	ns
		Top	0.66	0.60	0.76	0.78	ns
		Total	0.72	0.64	0.70	0.73	ns
	SENSIT	Average	NA	0.91	0.69	ns	ns
		Sum	0.91	NA	ns	ns	ns
VP	BSNE	Bottom	0.44	ns	ns	ns	ns
		Middle	0.48	ns	ns	ns	ns
		Top	ns	ns	0.42	ns	ns
		Total	0.45	ns	ns	ns	ns
	SENSIT	Average	NA	0.80	ns	ns	ns
		Sum	0.80	NA	ns	ns	0.60

4.2. Vertical Sediment Inputs into Deposition Traps

Vertical sediment (sand, silt, clay) inputs collected in the deposition traps at our sites ranged from 10 to 97 g/m^2/year, depending on the year, with most years ranging from 10 to 39 g/m^2/year (Table 5). For comparison, other studies have shown a range of average values from <1 to 276 g/m^2/year, with most values between 6 and 20 g/m^2/year (Littmann, 1997; Offer et al., 1992; Reheis and Kihl, 1995; Reheis, 2006). (For a more complete review of comparative studies, see Reheis and Kihl, 1995.) Thus, the sediment inputs at our site appear to be lower than those observed in the Mojave Desert and lower than other studies in the Negev and Europe.

4.3. Controls on Horizontal Sediment Flux

4.3.1. The Role of Biological Soil Crusts in Stabilizing Soils

Sediment movement was significantly lower at VP than at the other three sites, even during the extreme drought years, whether measured by SENSIT (total impacts or impacts/h at a given wind speed) or BSNEs. This was likely due to the VP site having virtually no bare ground during the study period (except where data collection has required trampling of the soil surface) due to the presence of perennial plants, lichens, and mosses. As a result, the soils are highly stable, as indicated by all our stability indices. The CP site has a significant perennial plant component but lacks perennial lichens or mosses on the soil surface. Instead, only a very thin layer of cyanobacteria is present during the several months that cattle are absent from the area. Thus, 38–80% of the soil surface is essentially barren at the CP site for much of the year, and the stability of this exposed soil is low. All measures of sediment flux show much higher values at CP than VP, indicating that a well-developed biological soil crust is more important than perennial vascular plants in reducing wind erosion. Well-developed biological soil crusts with perennial mosses and lichens have repeatedly been shown to be essential for dryland soil stability in both laboratory wind-tunnel experiments (e.g., McKenna Neuman and Maxwell, 2002) and field wind-tunnel experiments (e.g., Belnap and Gillette, 1997, 1998; Leys and Eldridge, 1998; reviewed in Belnap, 2003 and Warren, 2003).

4.3.2. The Effect of Annual Plants Replacing Perennial Plants on Sediment Movement

Previous studies have shown that the type and cover of vegetation is important in determining wind speed at the soil surface and therefore the amount of sediment that can be moved (Lancaster and Baas, 1998; Okin et al., 2006; Wolfe and Nickling, 1993). Perennial plants generally have stiffer stems, more litter built up around their bases, and a less variable cover year-to-year, regardless of rainfall, compared to annual plants. Thus, they offer better protection from soil erosion than annual plants. In addition, the gap size between the plants is critical in determining the erodibility of soil (Okin, 2008). In drought years, a decline in annual plant cover results in a greater gap size between plants, thus increasing the vulnerability of soils at these sites to erosion.

If perennial plants provide more protection from wind erosion than annual plants, we would expect that CP, with its substantial perennial plant component, would have lower sediment erosion than the annualized DR or NR sites. (All these sites lack a perennial moss/lichen cover.) This hypothesis was not supported by comparing average SENSIT impacts/h at wind speeds <6 m/s among the sites (Table 3). However, at wind speeds between 6 and 9 m/s, this hypothesis was strongly supported, as SENSIT impacts at NR and DR were higher than those at CP in any given wind speed class. (The small number of wind hours above 9 m/s at NR and CP obscured this relation at higher speeds.) Therefore, perennial plants

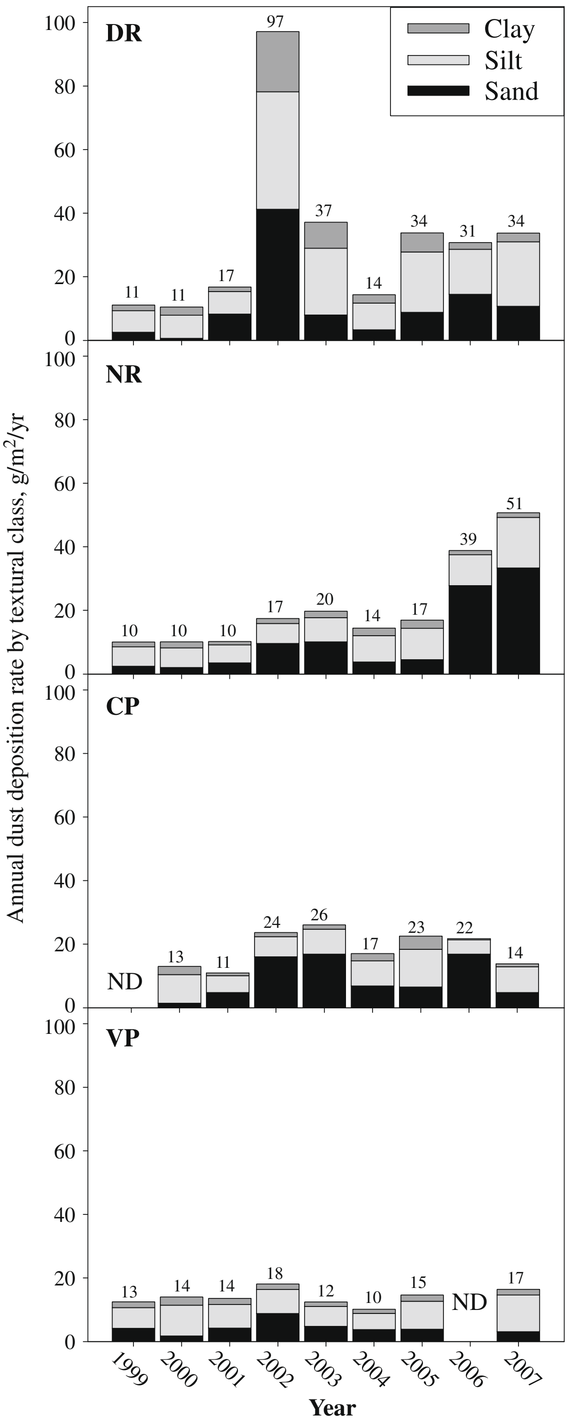

Fig. 8. Vertically deposited sediment input collected in the marble traps by year. Each bar is divided into textural classes. The numbers above the bars are the combined weight for all three samplers. ND: missing data. Particle size classes for these samples were defined according to the USDA scale, in which clay is <2 μm; silt 2–50 μm; very fine sand 50–100 μm; fine sand 100–250 μm; medium sand 250–500 μm; coarse sand 500–1000 μm, and very coarse sand 1000–2000 μm.

appeared better able to protect soil surfaces from wind erosion at higher wind speeds, but not at lower wind speeds, than annual plants.

The DR and CP sites are currently grazed in spring and fall, whereas the NR site has not been grazed for 34 years. However, the annualized NR site supports extremely high rodent populations in the years during and following the years with high plant productivity. The burrows created by the rodents result in large mounds of exposed soil which are highly vulnerable to wind erosion. Thus, the replacement of perennial plants by annual plants has left this site at high risk for wind erosion, despite the cessation of grazing.

4.3.3. The Role of Other Factors in Stabilizing Soils and the Synergy of Surface Disturbance, Annualization, and Drought

Aeolian sediment movement at the DR site was much higher than at the other three sites during almost all recorded wind events, despite the standardization for wind speed and duration and despite strong similarities with the NR site (also annualized, no biological soil crusts, low surface soil stability) and with the CP site (also grazed, no biological soil crusts, low surface soil stability). There are several possible explanations for this: (1) DR surface soils had ~10% more clay/silt and thus less sand than the other three sites, providing more easily moved materials; (2) past plowing rendered this site more vulnerable to wind erosion than grazing and/or annualization; or (3) the combination of annualization, past plowing, and current grazing at DR has significantly increased the vulnerability of soils to wind erosion over sites that are either just annualized (NR) or just grazed (CP).

The difference in soil texture at the DR site, relative to the other sites, was unlikely to have produced such a large increase in sediment movement. It is also unlikely that the plant cover or type alone explains these results. First, plant cover at DR and NP showed a similar range of variability (3–30% at DR; 12–40% at NP) over the measurement time. Second, the dominant plants (*Chorispora tenella* and *Lappula occidentalis*) at these two sites are both present during the same period (March–June) when winds are the highest and soil surfaces are the most susceptible to erosion. Third, both plant types have a rosette of leaves close to the soil surface and are of similar height.

Plowing most certainly affected the vulnerability of the DR site to wind erosion when it first occurred. Although it may seem surprising that an activity abandoned long ago could still affect the wind erodibility of a site, aeolian sediment production from cotton fields abandoned during the past 50 years in the Tucson-Phoenix, AZ, area is far higher than nearby areas used by off-road vehicles or current farming activities (Marcus, 1976; Wolfe and Helm, 1999). As plowing disrupts the soil structure, it may result in soils being vulnerable to wind erosion for long periods of time.

Many studies have demonstrated a close association among drought, the subsequent reduction in annual and perennial vegetation cover, and sediment production from a site (e.g., Goudie, 1978; McTainsh et al., 1999). Similarly, the synergy of drought, annualization, and surface disturbance creates conditions in the high, cold drylands of the central Colorado Plateau where large amounts of sediment are mobilized by wind. Our data also illustrate that these multiple stressors, when added together, generate a non-linear response in sediment movement.

5. Summary and Conclusions

Our results show that although mobilization of aeolian sediment from these semi-arid landscapes was relatively low compared to larger sediment source areas (see Goudie and Middleton, 2006; Prospero et al., 2002), the amount of wind-eroded material was significant when a previously plowed field was subjected concomitantly to drought, replacement of perennial by annual plants, and grazing. It appears that some surface disturbances, such as plowing of dryland soils, may continue to increase sediment production long after the activity has ceased. The replacement of perennial plants by annual plants is also problematic as drought conditions and facilitation of rodent populations can lead to high levels of soil movement under most climatic conditions. Lastly,

Table 5
Sediment loss and sediment inputs from published studies. Where cells are left blank, no data is available.

Sediment Loss					
Highly disturbed dryland sites					
	Range/Maximum (kg/m^2/day)	**Average (kg/m^2/day)**	**Location**	**Soil type**	**Vegetation community type**
Michels et al. (1995)	279	17–19	Niger		
Sheridan (1981)	374		California, USA		Grassland
van Donk et al. (2003)		14	Mojave Desert, USA		Shrubland
Wang et al. (2004)		20	China		Grassland
Zobeck and Fryrear (1986)	34–2120		Texas, USA		Shrubland
Less disturbed agricultural dryland sites after high disturbance/drought					
	Average (g/m^2/day)	**Increase**			
This study	16	3–57×	Utah, USA	Sand	Grassland
Breshears et al. (2003)	1.5		New Mexico, USA	Clay	Grassland
Breshears et al. (2003)	15		New Mexico, USA	Sand	Shrubland
Li et al. (2007)		10×	New Mexico, USA		Grass fire
*Offer and Goossens (2004)	23		Israel		Shrubland
Vermeire et al. (2005)		24×			Sagebrush fire, year 1
Vermeire et al. (2005)		5×			Sagebrush fire, year 2
Visser et al. (2004)	8		Burkina Faso	Sand	
Whicker et al. (2002)		70×	New Mexico, USA	Sand	Larrea fire, year 1
Whicker et al. (2002)		3×	New Mexico, USA	Sand	Larrea fire, year 2
Whicker et al. (2008)		8×	New Mexico, USA	Silt Loam	Forest fire
Sediment Inputs					
	Range/Maximum (g/m^2/day)	**Average (g/m^2/day)**			
This study	10–97	10–39	Utah, USA		
*Littmann (1997)		19	Israel		
Littmann (1997)		36–55	Central rural Europe		
Littmann (1997)		30–60	Central urban Europe		
Offer et al. (1992)	198–276		Negev, Israel		
Reheis and Kihl (1995)	6–114	6–20	Mojave Desert, USA		
*Reheis (2006)	9–21	1–15	Mojave Desert, USA		

*silt/clay only

disturbance of the soil surface by livestock or vehicles, especially during dry, windy years, leads to loss of the biological and physical crusts that stabilize these soils. When more than one of these factors occur together, relatively high levels of aeolian sediment generation occur.

Climate models predict that the western US will experience multiple droughts in the coming years as increased temperatures combine with a likely decrease in precipitation (Andreadis and Lettenmaier, 2006; Christensen et al., 2007; Milly et al., 2005). Increasing drought frequency will lead to a reduction in plant cover and thus a likely increase in wind erosion (Pulwarty et al., 2005). Surface disturbances from recreational activities and those associated with the exploration and development of energy resources are also expected to increase, further destabilizing soil surfaces. With increases in surface disturbances and atmospheric CO_2, a concomitant increase in annual grass invasion is likely (Smith et al., 2000). Annual grasses and drought are expected to result in fires of greater frequency and extent, leading to further increases in sediment production. Because an increase in sediment movement can have many negative effects at the local, regional, and global scale (e.g., Painter et al., 2007), land managers in the western US should consider actively managing for reduction of sediment movement by controlling the type, timing, intensity, and placement of soil-disturbing activities.

Acknowledgements

We thank the many technicians that contributed to this effort and Christy Parry for editorial assistance. Eric Fisher, Todd Preston, Jiang Xiao, and Ken Takagi assisted in sample preparation and analyses. The use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the US Government.

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