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Wind erosion from military training lands in the Mojave Desert, California, U.S.A.

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Military training activities reduce vegetation cover, disturb crusts, and degrade soil aggregates, making the land more vulnerable to wind erosion. The objective of this study was to quantify wind erosion rates for typical conditions at the Marine Corps Air Ground Combat Center, Twentynine Palms, CA, U.S.A. Five Big Spring Number Eight (BSNE) sampler stations were installed at each of five sites. Each BSNE station consisted of five BSNE samplers with the lowest sampler at 0·05 m and the highest sampler at 1·0 m above the soil surface. Once a month, sediment was collected from the samplers for analysis. Occurrence of saltating soil aggregates was recorded every hour using Sensits, one at each site. The site with the most erosion had a sediment discharge of $311\,\mathrm{kg\,m^{-1}}$ over a period of 17 months. Other sites eroded much less because of significant rock cover or the presence of a crust. Hourly sediment discharge was estimated combining hourly Sensit count and monthly sediment discharge measured using BSNE samplers. More simultaneously measured data are needed to better characterize the relationship between these two and reconstruct a detailed time-series of wind erosion. This measured time-series can then be used for comparison with simulation results from process-based wind erosion models such as the Wind Erosion Prediction System (WEPS), once it has been adapted to the unique aspects of military lands.

Keywords: BSNE sampler; Sensit; sediment discharge; saltation

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Introduction

Desert ecosystems are fragile, as seen recently in northern China, where drought and overgrazing have caused land degradation with wind erosion resembling the dust bowl days of the 1930s in the U.S.A. (Armstrong, 2001). The Sahelian region of West Africa has seen dramatic changes over the past decades, with decreasing rainfall, vegetation and wildlife on the southern fringes of the Sahara desert (Kanemasu *et al.*, 1990; Gijsbers *et al.*, 1994; Le Barbe & Lebel, 1997; Wezel & Haigis, 2000).

Desert ecosystems may degrade for several reasons, such as drought, overgrazing, excessive animal trampling and, in the case of military lands, training and testing activities (Hu *et al.*, 1997; Milchunas *et al.*, 1999). Most training activities result in a loss of vegetation (Krzysik, 1994) and recovery rates for creosote bush [*Larrea tridentata* (Sessé & Moc. Ex DC.) Coville] have been estimated to range from 46 to hundreds of years (Webb *et al.*, 1983). Military training destroys biological crusts that are responsible for reducing soil loss by wind in arid environments (Cole, 1990). Recovery of biological soil crusts is generally slow and may require years to decades (Botherson *et al.*, 1983; Johansen & St. Clair, 1986; Cole, 1990). Training activities also affect soil properties including compaction, soil aggregation, and surface roughness (Wu *et al.*, 1997; Whitecotton *et al.*, 2000). Training impacts from tracked and wheeled vehicles can be significant, depending on the frequency, duration, and intensity of these activities (Gee-Clough & Salokhe, 1988).

Degraded land becomes more vulnerable to wind erosion. Military land managers need to know how different management practices influence wind erosion potential. The USDA-ARS Wind Erosion Research Unit (WERU) in Manhattan, Kansas is developing a process-based Wind Erosion Prediction System (WEPS, Hagen, 1991; Wagner, 2001) for the simulation of wind erosion from agricultural fields under different management scenarios such as alternative cropping and tillage systems. It has the potential to meet the need of military land managers if it can be adapted to the unique aspects of such lands.

Until recently, actual measurements of wind erosion in the field were scarce. Fryrear (1986) developed a field dust sampler and named it the Big Spring Number Eight (BSNE). Fryrear *et al.* (1991) describe a methodology for wind erosion measurements on a circular field with a radius of 91 m. Using this methodology, wind erosion was measured at sites in five different states for the verification of WEPS (Fryrear, 1995). Sterk (1997) measured wind erosion on a 2400 m^2 rectangular field in Niger, West Africa. His measurements showed that spatial soil loss and deposition can vary greatly.

A sensor used by Fryrear *et al.* (1991) and other researchers is the Sensit (Gillette & Stockton, 1986), a piezoelectric device that produces a signal upon impact of saltating soil aggregates. It has been used in both open field and wind tunnel environments. The instrument has proven useful for determining the threshold friction velocity at which erosion by wind starts. Use of the Sensit to measure horizontal sediment mass movement would provide much better time resolution than that obtained from sediment samplers such as the BSNE.

The objective of this study was to quantify wind erosion rates for typical conditions at the Marine Corps Air Ground Combat Center (MCAGCC), Twentynine Palms, CA, U.S.A., and to identify additional data required to parameterize WEPS for application on military lands.

Study sites

MCAGCC is located in the Mojave Desert within San Bernardino county in southern California (Fig. 1). Average daily temperatures at Twentynine Palms range from 9°C

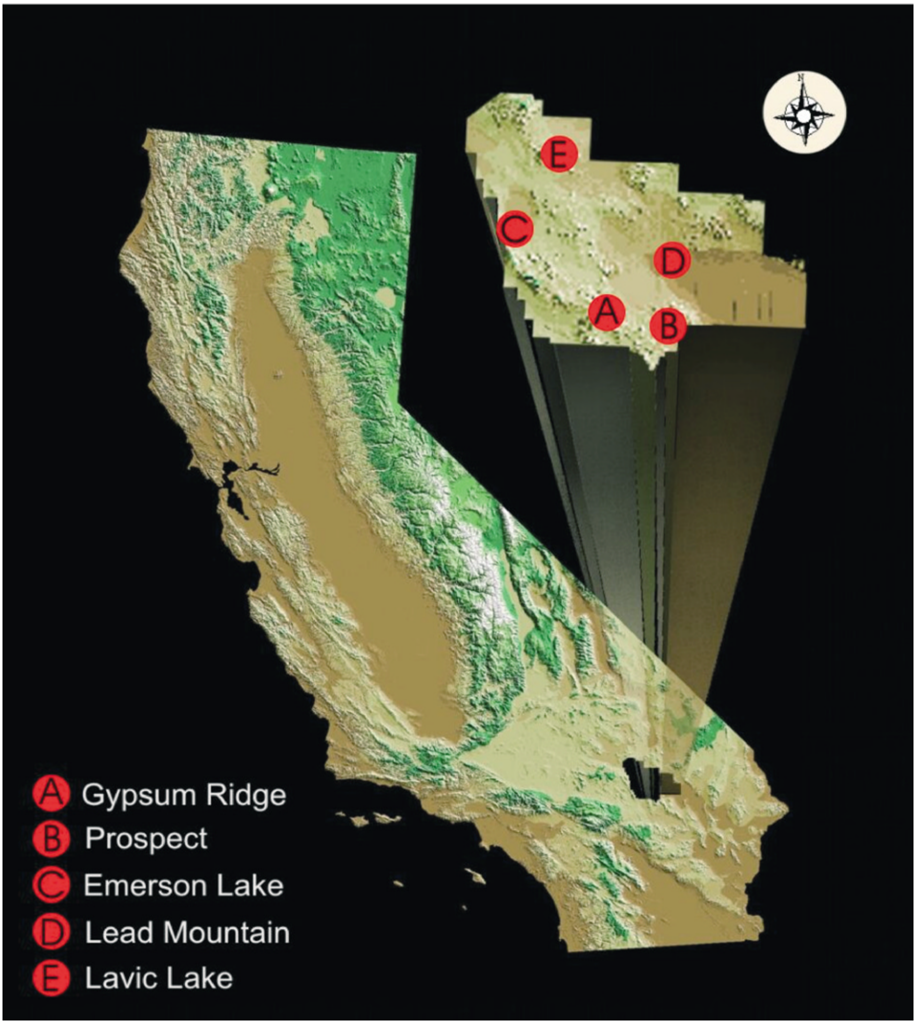

Figure 1. Location of the MCAGCC and the five experimental sites in the state of California, U.S.A. The sites are Gypsum Ridge (34°19'N, 116°10'W, elevation = 570 m), Prospect (34°17'N, 116°00'W, elevation = 670 m), Emerson Lake (34°27'N, 116°24'W, elevation = 700 m), Lead Mountain (34°24'N, 115°51'W, elevation = 370 m), and Lavic Lake (34°37'N, 116°16'W, elevation = 730 m).

to 31°C with average daily highs of 39°C in July and lows of 2°C in January. Annual precipitation ranges from 35 to 130 mm but is extremely variable between years (Polis, 1991). Rain is most common in the winter (October–March) making up 60–80% of annual precipitation. Prevailing winds vary throughout the year. Winter winds are generally from the north-west while summer winds are from the south-west. The strongest winds generally occur in the fall from the north-west with velocities up to $34\,\mathrm{m\,s^{-1}}$.

Plant communities at MCAGCC are generally described as desert shrub with the dominant perennial species consisting of creosote bush, burro bush [*Ambrosia dumosa* (A. Gray) W.W. Payne], cheese bush (*Hymenoclea salsola* Torr. & A. Gray), and Joshua tree (*Yucca brevifolia* Engelm.). Areas dominated by creosote and Burro bush make up

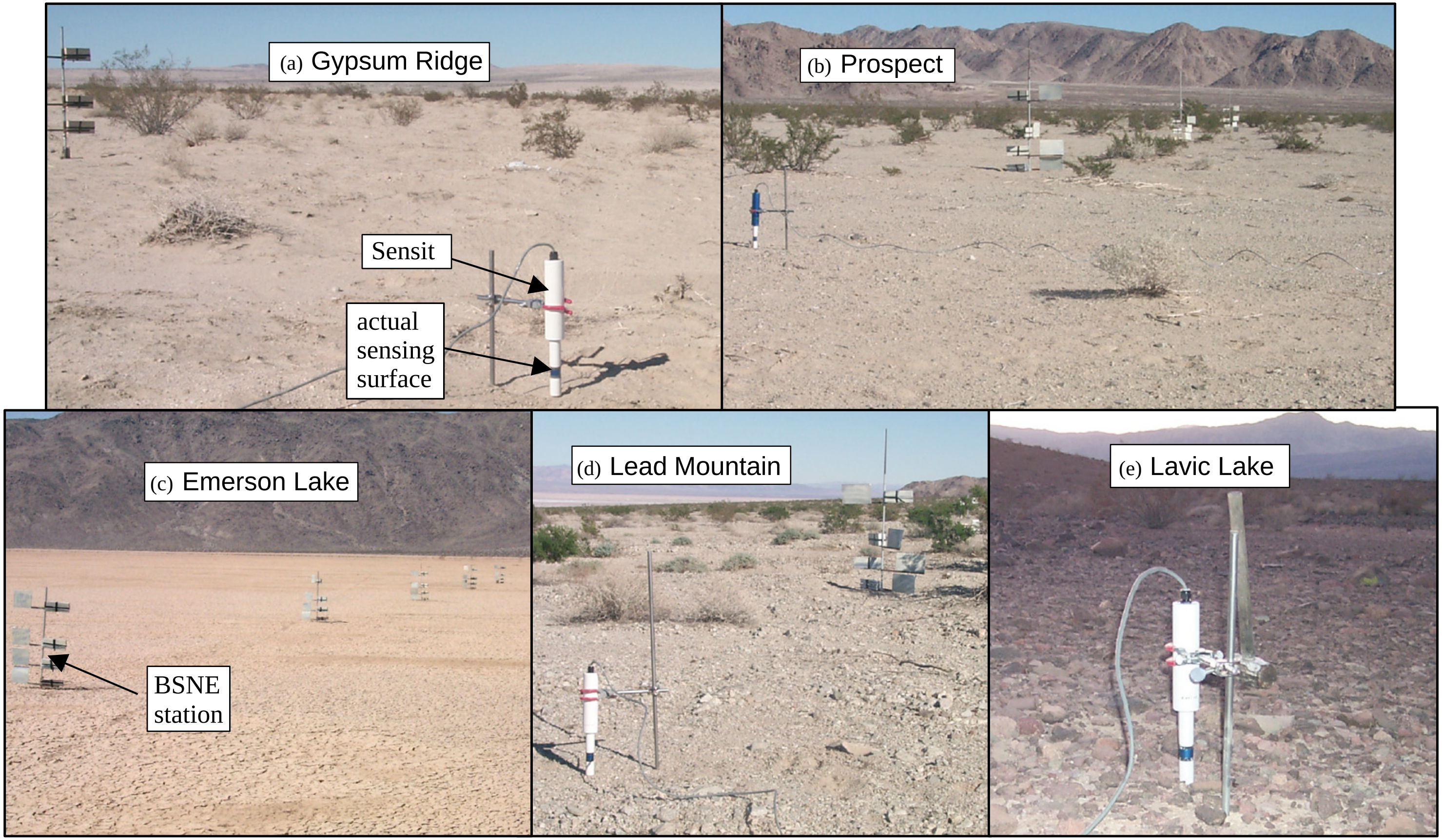

Figure 2. Experimental sites with BSNE sediment samplers and Sensit saltation detectors at the Marine Corps Air Ground Combat Center (MCAGCC).

88% of MCAGCC, which has been used for military training since 1941 and is the largest Marine Corps base in the world. Currently the installation is used to support military air operations, artillery, and ground maneuvers.

Disturbance by military activities was mapped at MCAGCC prior to this study using 1953 black and white and 1990 color aerial photographs (Giessow *et al.*, 1998). Stereoscopic analyses of photographs were used to map disturbance patterns into three broad groups: low, medium, and high. Disturbance regimes were mapped based on visual loss of woody vegetative cover between 1953 and 1990. Low-, medium-, and high-disturbance regimes represent less than 25%, 25–75%, and greater than 75% shrub cover loss, respectively.

Five sites (Figs 1 and 2) were selected for this study from medium-disturbance regimes, which include approximately 24% of all installation lands or 40% of historically used military training lands at MCAGCC. The study sites remained available to training throughout the study. Percent visible tracking by military vehicles along a permanent 100 m line transect randomly located at each study site was collected from 1997 to 2001 (Table 1; Giessow *et al.*, 1998). The wide range in annual tracking of sites was not unexpected due to annual rotation of training activities among training areas at MCAGCC. The continued military utilization of the sites used in this study indicates a disturbed environment susceptible to soil loss via both wind and water erosion processes.

A soil survey of MCAGCC, conducted by the USDA-NRCS (1997), was used to determine the soil type at each site. The soil surfaces at Gypsum Ridge (Cajon series; mixed, thermic Typic Torripsamments) and Prospect (Arizo series; sandy-skeletal, mixed, thermic Typic Torriorthents) are somewhat similar, both being very sandy with moderate shrub cover. Emerson Lake (playas, unclassified) is a heavily crusted dry lake bed without any vegetation. Lead Mountain (Carrizo series; sandy-skeletal, mixed, hyperthermic Typic Torriorthents) is rocky with moderate shrub cover, while Lavic Lake (Owlshead series; loamy-skeletal, mixed, superactive, thermic, shallow Cambidic Haplodurids) is extremely rocky and sparsely vegetated.

Table 1. *Percent visible tracking by military vehicles along a permanent 100 m line transect and primary shrubs at each of the five study sites (Giessow et al., 1998)*

	Gypsum Ridge	Emerson Lake	Lavic Lake	Lead Mountain	Prospect
Year	Visible tracking (%)				
1997	19·5	5·7	20·1	26·4	50·0
2000	2·4	7·5	16·6	40·2	18·7
2001	3·6	21·5	26·1	2·6	9·9
	Primary shrubs (1997–2001)				
	Ambrosia dumosa, *Encelia frutescens*, *Psorothamnus emoryi*, *Larrea tridentata*	None	*Ambrosia dumosa*, *Encelia frutescens*, *Larrea tridentata*	*Ambrosia dumosa*, *Krameria erecta*, *Krameria grayi*, *Larrea tridentata*	*Ambrosia dumosa*, *Encelia frutescens*, *Larrea tridentata*

Methods

Five BSNE sampler stations were installed at each site, 20 m apart from each other in a line transect (Fig. 2c). Each BSNE station consisted of five BSNE samplers with openings centered at 5, 10, 30, 55, and 100 cm above the soil surface. The two lowest samplers had openings 20 mm wide and 10 mm high; the other three samplers had openings 20 mm wide and 50 mm high. Each BSNE sampler rotates independently so that it is constantly facing upwind. Measurements were made from March 2000 to October 2001.

Once a month, BSNE samplers were emptied in plastic bags and the actual heights of the sampler openings were measured. Samples were weighed in the laboratory and weights were converted to sediment flux per square meter. For each BSNE station, sediment flux was fitted to

$$q(z) = a(z+1)^b \qquad \text{(Eqn 1)}$$

where $q(z)$ is the sediment flux (kg m^{-2}), z is the height of the sampler opening above the soil surface (cm), and a and b are fitting parameters (Fig. 3). Sediment discharge, passing a BSNE station, was determined by integrating Eqn (1) from 0 to 200 cm:

$$Q = \int_0^{200} q(z)\mathrm{d}z = \frac{a}{b+1}\left[(200+1)^{b+1} - 1\right] \qquad \text{(Eqn 2)}$$

where Q is the sediment discharge (kg m^{-1}). We only measured sediment flux up to 100 cm, but a small amount of fine suspended material was sometimes being transported above 100 cm. Therefore, to represent more of the total horizontal sediment discharge, we integrated to a height of 200 cm rather than 100 cm.

Aggregate size of wind-blown sediment collected from the BSNE samplers was analysed for Gypsum Ridge (March and May 2000) and Prospect (March 2000) using

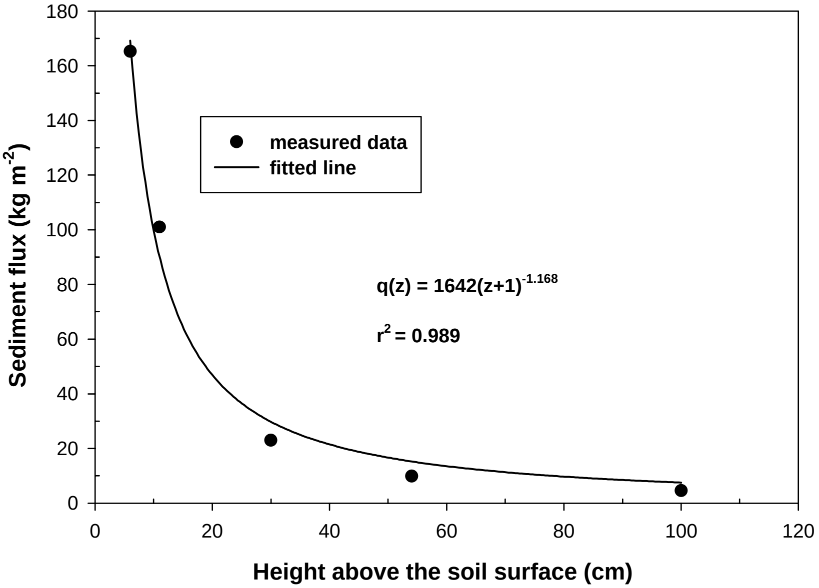

Figure 3. Sediment flux at five different heights above the soil surface at Gypsum Ridge, 2 January – 3 February 2001. BSNE sampler station was at the 80 m position in the transect (Table 2).

a sonic sifter (ATM Corporation, Milwaukee, Wisconsin) with 5, 10, 20, 53, 106, and 150 μm sieves. These sieve sizes were chosen such that the size distribution of the sediment could be fully characterized. Samples were sieved for 3 min, starting with approximately 2 g of sediment. Just enough power was applied to keep the material on the 7·6 cm diameter sieves in motion.

Occurrence of saltating soil particles/aggregates was measured from January to October 2001 using a Sensit (Sensit Company, Portland, North Dakota), which has a 360° active surface and, thus, has no need to rotate like a BSNE sampler. At each of the five sites, one Sensit was installed 30 m into the line transect of BSNE samplers (Fig. 2(a)). The center of the active surface of the Sensit was located 0·06 m above the soil surface. As saltating aggregates strike the active surface, an electrical pulse is generated. These pulses were counted and recorded using a CR10X data logger (Campbell Scientific, Logan, Utah). The number of counts were summed at 10 s intervals and hourly count totals were recorded. Recorded data were transmitted once a day from the data logger to a PC at WERU in Manhattan, Kansas, using a mobile phone system: a cellular transceiver with RJ11 interface (Alltel, Manhattan, Kansas) and a telephone modem (COM200, Campbell Scientific). The system was powered using a solar panel (MSX20R, Campbell Scientific) and a sealed, lead acid battery with a capacity of 115 Amphours.

In the proximity of each site, wind speed was measured at a height of 1·0 m and hourly averages were recorded. Wind power density (Skidmore, 1998) was calculated as

$$WPD = \rho(u_i^2 - u_t^2)^{3/2} \quad \text{(Eqn 3)}$$

for $u_i > u_t$, where WPD is the wind power density (W m^{-2}) during 1 h, ρ is the air density (kg m^{-3}), u_t is the threshold wind speed (m s^{-1}), and u_i is the measured hourly average wind speed (m s^{-1}). The relationship between Sensit count (and horizontal sediment movement) and wind power density is nearly linear for a single storm (Skidmore, 1998). Wind energy (WE in J m^{-2}) for a period of N hours was calculated as

$$WE = 3600 \sum_{i=1}^{i=N} WPD \quad \text{(Eqn 4)}$$

In January 2001, near each BSNE station at each site, about 6 kg of soil was collected randomly from approximately the top 5 cm of the surface using a flat shovel. This sampling method seems reasonable for these sites which were not highly stratified in the top 5 cm. None of the sites had a crust, except for Emerson Lake which had a very thick crust of 5 cm or more. Our sampling method would not be advisable for surfaces that are highly stratified, such as surfaces with a thin biological crust (Belnap & Gillette, 1998) or 'desert pavement' surfaces, where a shallow layer of larger, non-erodible, gravel covers a layer of smaller size material that is more erodible.

Texture and aggregate size distribution are important parameters determining soil erodibility. The texture of each soil sample was analysed using the pipette method (Gee & Bauder, 1986). For each soil sample of approximately 6 kg, aggregate size distribution was determined using a rotary sieve (Chepil, 1962; Lyles *et al.*, 1970) with 76, 45, 19, 6·4, 2·0, 0·84, and 0·42 mm sieves. A portable sieve shaker (model RX-24; Tyler, Inc.; Mentor, Ohio) was used for finer material using 250, 106, and 46 μm sieves with a diameter of 12·7 cm. Each sample was sieved for 5 min starting with approximately 30 g of sediment. A sonic sifter (ATM Corporation, Milwaukee, Wisconsin), using a 10 μm sieve with a diameter of 7·6 cm, was used for the finest material. Each sample was sieved for 3 min starting with approximately 2 g of sediment. The aggregate size distribution was mathematically described according to Wagner & Ding (1994).

Dry aggregate stability is related to how easily soil is abraded by saltating material. The less stable aggregates are, the more they will be abraded (Hagen *et al.*, 1992). Dry aggregate stability was determined, only for Emerson Lake, with an apparatus developed by Boyd *et al.* (1983) using aggregates with diameters between 6·4 and 19 mm. For the other four sites, the material in this size range was too hard (rocks) to be crushed with the apparatus. Wet aggregate stability was determined using the method described by Kemper & Rosenau (1986).

Results and discussion

The Gypsum Ridge and Prospect sites are very sandy and have the most aggregates in the erodible size class (defined as aggregates with diameters <0·84 mm, Table 2). A sample subset of detailed erosion data (Table 3) is discussed first to explain the meaning of the summarized erosion data (Table 4). At Gypsum Ridge in January 2001, the sediment discharge was 58 kg m^{-1} for the BSNE station located at 80 m into the transect (Table 3). This was calculated from sediment flux at the five different heights, using Eqns (1) and (2) (Fig. 3). Sediment discharge for the other four BSNE stations was calculated using the same procedure. Average sediment discharge for the five BSNE stations was 62 kg m^{-1}. Standard deviation was 10 kg m^{-1}. Averages and standard deviations are presented in Table 4 for all five sites and all months for the entire measurement period.

Table 2. *Field conditions for the five sites at MCAGCC, material was collected in January 2001*

	Gypsum Ridge	Prospect	Emerson Lake	Lead Mountain	Lavic Lake
Sand (%)*	91	90	23	82	56
Silt (%)*	6	8	33	15	34
Clay (%)*	3	2	44	3	10
Texture classification (USDA)	Sand	Sand	Clay	Loamy sand	Sandy loam
Aggregates <0·84 mm (%)*	79	60	17	27	17
Minimum aggregate size (mm)[†]	0·028	0·043	0·002	0·011	0·007
Maximum aggregate size (mm)[†]	82·3	89·8	46·5	45·2	50·0
GMD (mm)[†]	0·222	0·471	10·31	5·85	21·1
GSD (mm mm^{-1})[†]	3·9	12·0	11·4	25·0	15·8
Coefficient of determination[†]	0·995	0·997	0·979	0·991	0·931
Rocks >2 mm (%)*	10	30	0	66	81
Dry aggregate stability (ln[J kg^{-1}])			2·61		
Wet aggregate stability (%)	0	0	2·5	0	0

*Average of five samples: one near each BSNE station.

[†] Obtained by fitting a cumulative distribution function (Wagner & Ding, 1994) to the average of the measured cumulative aggregate size distribution using Tablecurve (SPSS Inc. Chicago, Illinois) software. GMD, geometric mean diameter; GSD, geometric standard deviation.

Table 3. *Sediment flux (kg m^{-2}) for Gypsum Ridge, 2 January–3 February 2001 for five BSNE stations spaced 20 m apart*

Height (cm)	0*	20*	40*	60*	80*
	Sediment flux (kg m^{-2})				
5	205	205	221	145	165
10	174	112	148	95	101
30	27	24	23	22	23
55	11	10	10	9	9
100	5	5	5	4	4
	Sediment discharge (kg m^{-1})				
	71	69	65	45	57

The bottom row shows sediment discharge (kg m^{-1}) resulting from vertical integration of the sediment flux (Eqns (1) and (2), Fig. 3).
*Location of BSNE station in transect (m).

Sediment discharge for the entire measurement period was greatest at Gypsum Ridge, followed by Prospect (Table 4), as would be expected from the smaller aggregates and the smaller percentage of rocks >2 mm at Gypsum Ridge (Table 2). The other three sites had much less erosion. At Emerson Lake, the thick crust protects sediment against moving, while at Lead Mountain and Lavic Lake non-erodible rocks dominate (Table 2). Wind erosion at any of the sites was small compared to what has been measured at other locations. Highly erodible, burned grassland in Meade, Kansas, had sediment discharges as high as 800 kg m^{-1} per storm (Skidmore, unpublished data).

Erosion did not follow the same pattern in time for the different sites. In March 2000, sediment discharge at Prospect was twice that at Gypsum Ridge, but in May 2000 discharge at Gypsum Ridge was much greater than that at Prospect (Fig. 4, Table 4). This was probably caused by much greater wind speeds (data not shown) at Gypsum Ridge during this period.

Monthly sediment discharge, measured using BSNE samplers, and wind energy for Gypsum Ridge were poorly correlated (Fig. 5). Threshold wind speed (u_t) used in the calculation of wind energy (Eqns (3) and (4)) was 10 m s^{-1}. This was the average wind speed at which sediment started to move as determined from Sensit and wind speed data. Using other values (8 and 12 m s^{-1}) for u_t did not improve this correlation.

The poor correlation may have been caused by several factors. There may have been different amounts of erodible material available from month to month. Also, vegetation likely changed with the seasons. The surface may have been wet at the time of a storm, causing sediment discharge to be low while wind energy was high. Finally, wind direction may be a factor, since the amount of source material is not likely to be equal in all directions around a sampler. Interpretation then becomes more complicated considering that one-monthly BSNE sample may be the result of several storms that came from different directions.

To understand wind erosion processes, data are needed at a much greater time resolution than a month. The high-resolution Sensit data may be useful in this regard, if the relationship to sediment movement is known. Gillette *et al.* (1997) reported a linear relationship between Sensit count and sediment movement. Monthly sediment discharge, measured using BSNE samplers, and Sensit count for Prospect support the assumption of a linear relationship (Fig. 6). During the period that Sensits and BSNE samplers were simultaneously active, Gypsum Ridge had only 1 month (January 2001) with significant wind erosion. The other three sites did not have any month with

Table 4. *Monthly sediment discharge (kg m^{-1}), measured using BSNE samplers, for March 2000–October 2001 and Sensit data summary*

From	To	Gypsum Ridge		Prospect		Emerson Lake		Lead Mountain		Lavic Lake	
		Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.
02-Mar	01-Apr	18·10	2·49	35·55	21·37	0·26	0·25	0·31	0·13	1·21	0·49
02-Apr	09-May	9·93	1·12								
10-May	31-May	77·45	13·22	1·53	0·96	0·78	0·18	0·08	0·07	0·35	0·07
01-Jun	26-Jun	6·60	1·39	11·44	5·46	0·26	0·38	0·06	0·04	0·30	0·11
27-Jun	29-Jul	1·47	0·64	1·22	1·16	0·00	0·00	0·11	0·08	0·23	0·08
30-Jul	27-Aug	54·80	14·18	23·85	6·26	1·14		3·45	1·54	1·54	0·77
28-Aug	29-Sep										
30-Sep	04-Nov	1·01	0·40	1·03	0·45	0·10	0·03	0·61	0·31	0·02	0·04
05-Nov	01-Dec	1·22	0·51	0·17	0·07	0·10	0·03	0·13	0·07	0·10	0·02
02-Dec	01-Jan	45·68	11·12	5·94	1·84	0·12	0·13	0·38	0·14	0·14	0·06
02-Jan	03-Feb	62·05	10·50	0·46	0·28	0·08	0·05	0·28	0·15	0·27	0·07
04-Feb	28-Feb	28·86*		0·32*	Rainwater in the samplers made it impossible to collect sediment						
01-Mar	29-Mar	0·88	0·43	0·43	0·41	0·57	0·32	0·35	0·17	1·41	0·32
30-Mar	03-May	1·72	0·91	0·63	0·48	0·57	0·14	0·42	0·22	0·67	0·07
04-May	31-May	0·34	0·10	0·33	0·25	0·29	0·25	0·15	0·05	0·41	0·10
01-Jun	23-Jun	0·31	0·19	0·77	0·37	0·34	0·02	0·20	0·10	0·12	0·03
24-Jun	04-Sep	Flooding: many of the lower samplers were filled with water-eroded sediment!									
05-Sep	02-Oct	0·47	0·26	3·82	2·68	0·44	0·12	0·04	0·02	0·13	0·06
03-Oct	10-Nov	0·44	0·62	22·30	9·03	0·26	0·12	0·04	0·02	0·07	0·01
Entire period		311·33		109·79		5·30		6·61		6·97	
Both active period[†]		66·21		28·74		2·54		1·48		3·08	
Sensit count[†]		1,422,137		1,709,166							
Counts per (kg m^{-1})		21,479		59,472							

*Estimated from Sensit data, no BSNE measurements for this month.

[†] Totals for period that BSNE samplers and Sensits were simultaneously active: January, March–June, September, October 2001.

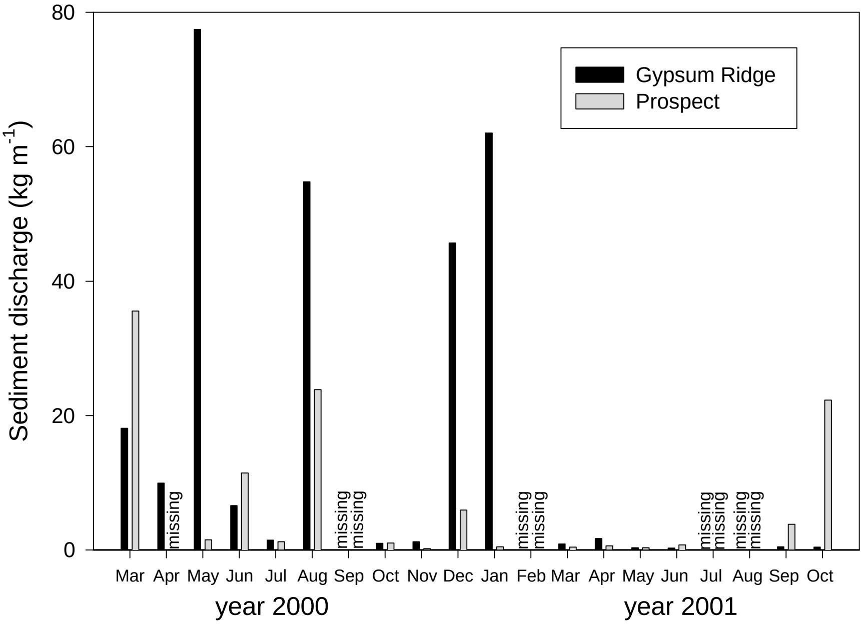

Figure 4. Monthly sediment discharge, measured using BSNE samplers, for Gypsum Ridge and Prospect, March 2000 – October 2001.

significant wind erosion during this period (Table 4). Additional data, representing significant erosion events, are needed to establish the relationship between Sensit count and sediment discharge more firmly.

The BSNE–Sensit relationship may not be perfect for several reasons: (1) Sensits may be saturated at high levels of sediment discharge, (2) Sensits, in this study, only measure at 0·06 m, whereas sediment discharge results from an integration of measurements at five different heights between 0 and 1 m, and (3) smaller size aggregates are more difficult for the Sensit to detect (Gillette *et al.*, 1997).

For the period that Sensits and BSNE samplers were simultaneously active (January, March–June, September, October 2001) sediment discharge at Gypsum Ridge was 66·21 kg m^{-1} and Sensit count was 1,422,137 (Table 4). Thus, 21,479 counts approximate a sediment discharge of 1 kg m^{-1}. This procedure was also followed for the site of Prospect and the results (Table 4) used to reconstruct daily (Fig. 7) and hourly (Fig. 8) sediment discharge. Hourly sediment discharge showed a much better correlation with wind speed (Fig. 9(a)) and wind energy (Fig. 9(b)) compared to data at the time resolution of a month (Fig. 5).

High-resolution data like these will be valuable when comparing measured data with simulation results from process-based wind erosion models such as WEPS. The Sensit–BSNE relationship can also be used to estimate sediment discharge for periods when measurements from the BSNE samplers were not available, such as for February 2001, when rainwater had filled the samplers, making it impossible to collect sediment (Table 4).

More than half of the total wind erosion for the 10 month period in 2001 occurred in a few days (Fig. 7). The Sensit data confirm that erosion did not follow the same pattern in time for the different sites (Fig. 7). The highest peak at Gypsum Ridge (on 24 January) did not coincide with the highest peak at Prospect or any of the other sites. This may be explained by the much greater wind speeds (data not shown) on 24 January at Gypsum Ridge. The first months of 2001 show more sediment movement

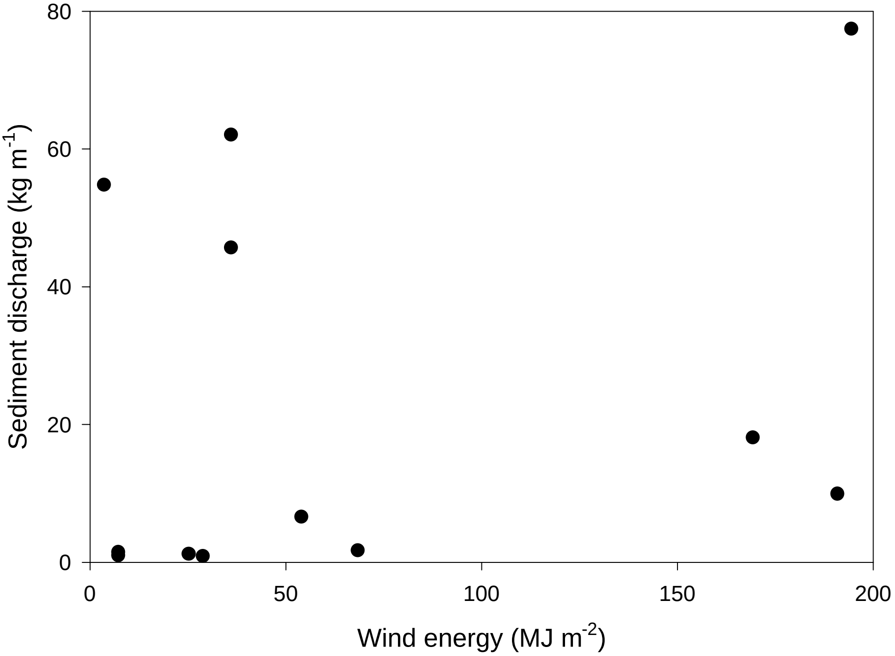

Figure 5. Monthly sediment discharge, measured using BSNE samplers, and wind energy for Gypsum Ridge. Threshold wind speed used in the calculation of wind energy (Eqns (3) and (4)) was 10 m s^{-1}.

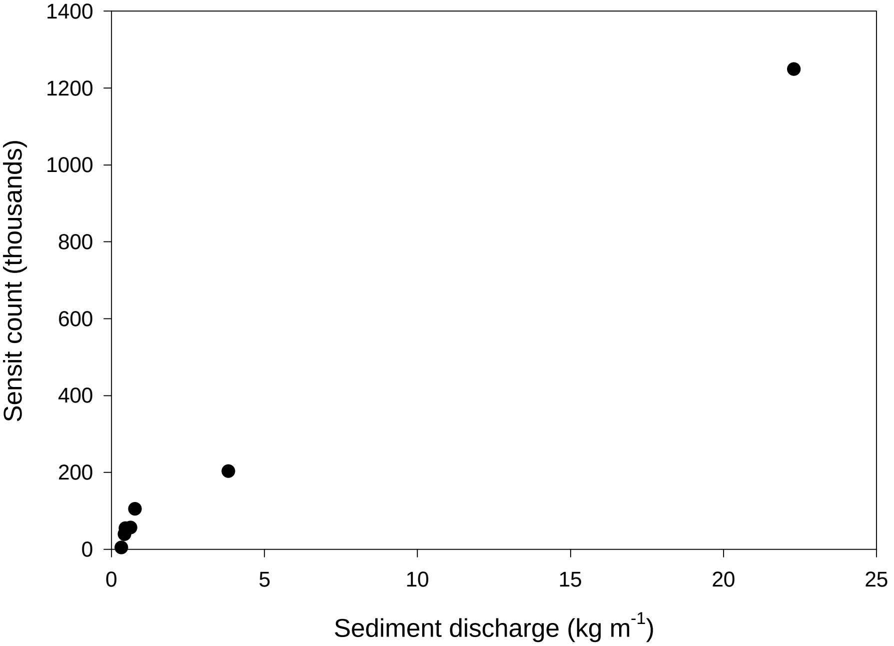

Figure 6. Monthly sediment discharge, measured using BSNE samplers, *vs*. Sensit count for Prospect.

at Gypsum Ridge compared to Prospect (Fig. 7). This can be explained again by the greater wind speeds (data not shown) during this time at Gypsum Ridge. In the second half of 2001 there was more sediment movement at Prospect. Wind data for this period were not yet available to us.

Aggregate size of wind-blown sediment decreased with height above the soil surface (Fig. 10). Airborne aggregates were larger at Prospect than at Gypsum Ridge, reflecting the aggregate size distribution of the soil surface material (Table 2).

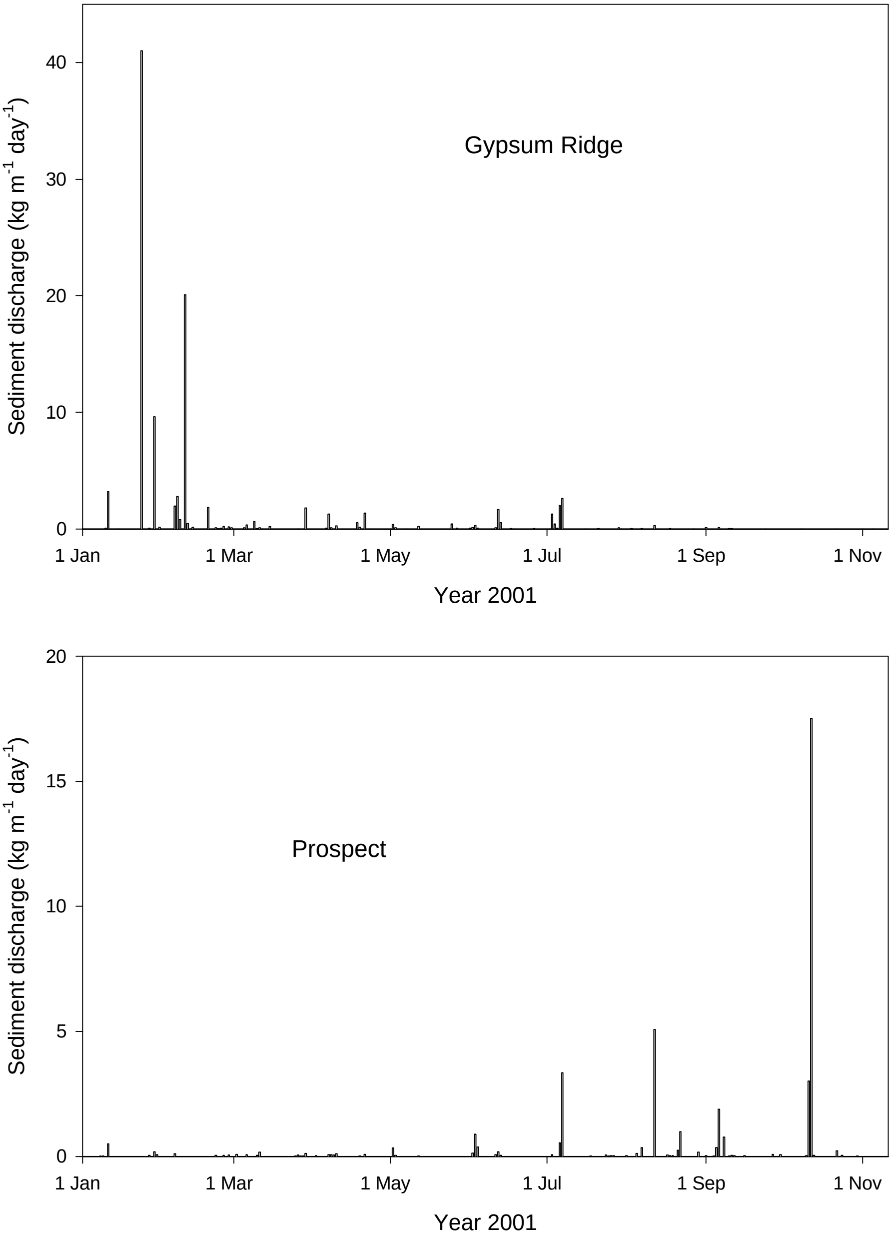

Figure 7. Daily sediment discharge for the first 10 months of 2001, based on daily Sensit count and monthly sediment discharge measured using BSNE samplers.

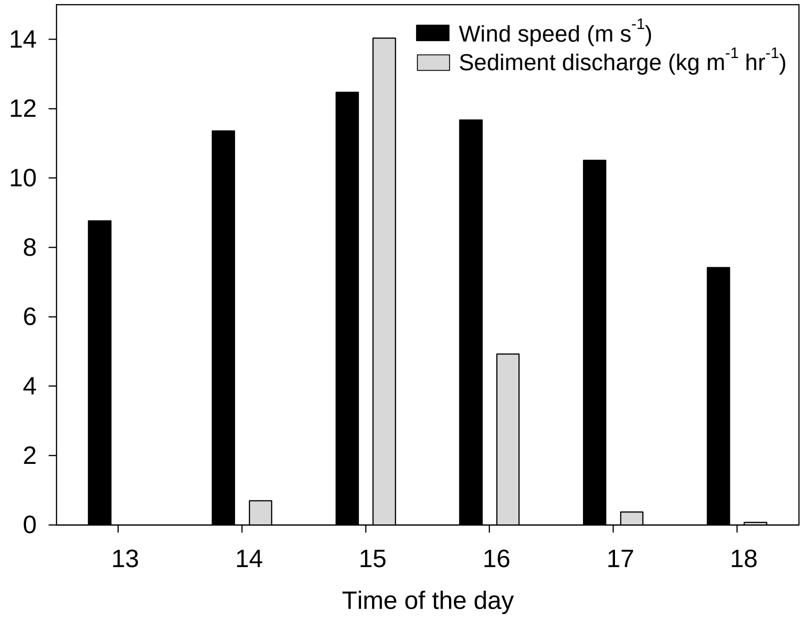

Figure 8. Hourly sediment discharge and wind speed at Gypsum Ridge on 10 February 2001. Hourly sediment discharge is based on hourly Sensit count and monthly sediment discharge measured using BSNE samplers.

WEPS currently simulates wind erosion on agricultural cropland. Data obtained in this study will assist in adapting WEPS for use on non-agricultural land such as range and disturbed lands, e.g. military training lands. It must also be extended to handle simulation for sites that are non-homogeneous and have multi-species vegetation. WEPS simulates management effects by describing agricultural operations as a sequence of specific physical processes that affect the soil, surface, and biomass. The unique military operations need to be analysed and their effects adequately described by the physical processes that WEPS simulates.

To conduct meaningful WEPS simulations, soil surface moisture and soil surface roughness should be available, in addition to the information listed in Table 2. If a crust is present, it should be described in terms of thickness, stability, and type and amount of loose material present on the crust. Biomass should be described in terms of size, spacing, uniformity and rigidity. For fields with agricultural crops, WEPS currently describes biomass in terms of leaf area index and stem area index. The impact of stems on wind erosion reduction is much greater than that of leaves, because of their greater rigidity. This is especially important for systems dominated by woody vegetation, e.g. desert shrub.

Conclusions

The site with the most wind erosion was Gypsum Ridge with a sediment discharge of 311 $\mathrm{kg\,m^{-1}}$ over a period of 17 months. Prospect had the next most erosion with 110 $\mathrm{kg\,m^{-1}}$. These two sites had the largest fractions of aggregates with diameters $<0{\cdot}84$ mm. Other sites eroded much less because of significant rock cover (Lavic Lake and Lead Mountain) or the presence of a thick crust (Emerson Lake).

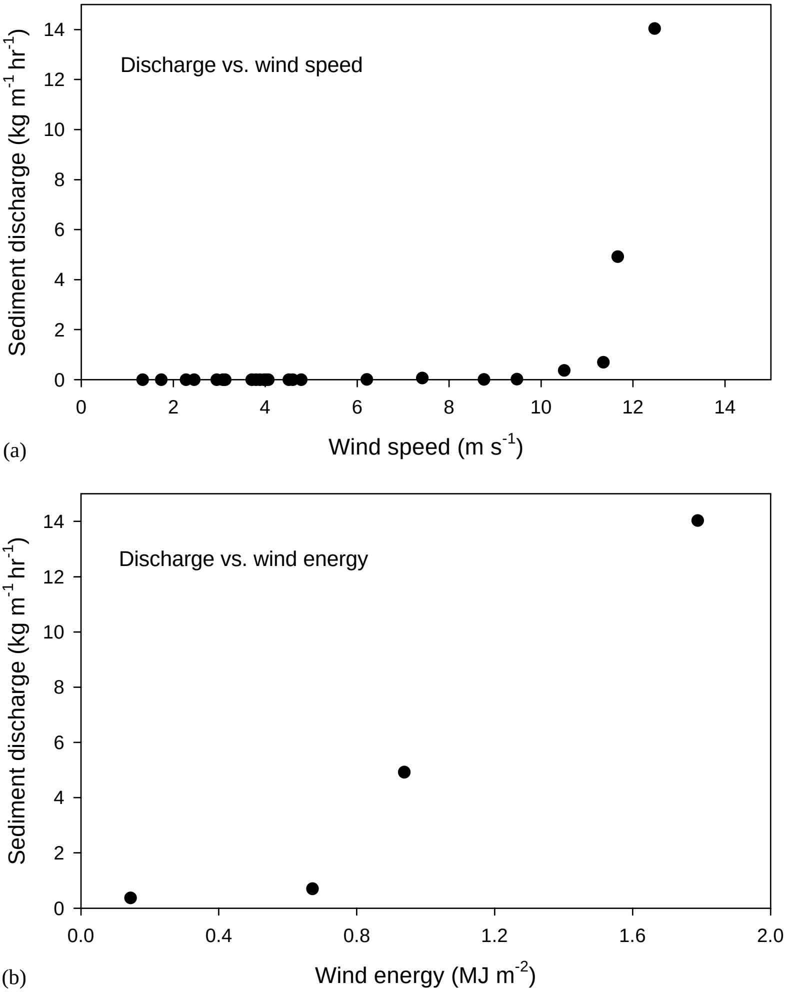

Figure 9. Hourly sediment discharge *vs.* hourly average wind speed (a) and hourly wind energy (b) at Gypsum Ridge on 10 February 2001. Threshold wind speed used in the calculation of wind energy (Eqns (3) and (4)) was $10\,\mathrm{m\,s^{-1}}$, which was estimated with the data of (a).

Hourly sediment discharge was estimated combining hourly Sensit count and monthly sediment discharge measured using BSNE samplers. More simultaneously measured data are needed to better characterize the relationship between these two and reconstruct a detailed time-series of wind erosion. This measured time-series can then be used for comparison with simulation results from process-based wind erosion models such as WEPS.

The latter first needs to be adapted for use on range and disturbed lands such as military training lands. It must be extended to handle simulation regions that are non-homogeneous and have multi-species vegetation. To conduct meaningful WEPS simulations, data describing soil surface conditions affecting wind erosion, including biomass measurements, should be available.

We are grateful to the Strategic Environmental Research and Development Program (SERDP) and the Office of the Directorate of Environmental Programs for providing support for this study. We appreciate the co-operation and support of the MCAGCC installation personnel.

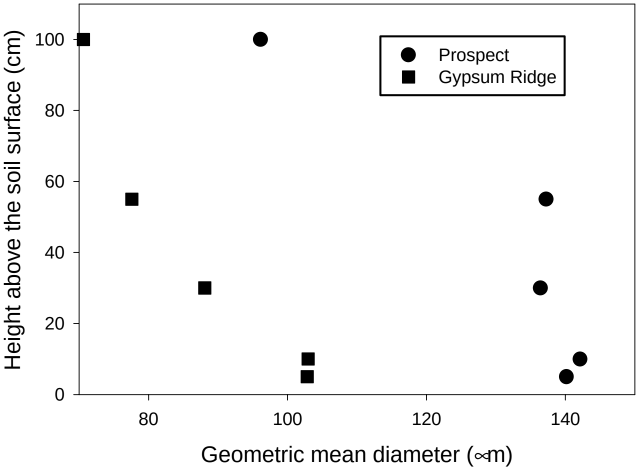

Figure 10. Aggregate size (geometric mean diameter, calculated according to Skidmore & Layton, 1992) of wind-blown sediment at Prospect and Gypsum Ridge.

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