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# Sand flux in the northern Chihuahuan desert, New Mexico, USA, and the influence of mesquite-dominated landscapes

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[1] Measurements of sand flux over areas with different vegetation in the Chihuahuan desert show that mean, height-integrated, horizontal flux values for mesquite-dominated sites were higher than those for other kinds of vegetation. Sand transport over mesquite areas displayed seasonal variability for most years. This seasonal variability roughly followed the variability of strong winds. Sand transport rates for collectors within a short distance downwind of mesquite bushes were small compared to those for collectors at the end of streets (elongated patches of bare soil) aligned with wind direction. The increased rate of sand transport (wind erosion) associated with mesquite is important because mesquite-dominated areas are increasing in the northern Chihuahuan desert and are therefore responsible for increasing land degradation (desertification). *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1809 Hydrology: Desertification; 1815 Hydrology: Erosion and sedimentation; 5415 Planetology: Solid Surface Planets: Erosion and weathering; *KEYWORDS:* dust emissions, desert vegetation, sand transport, Chihuahuan desert, mesquite

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## 1. Introduction

[2] In many desert areas, long-distance transport of soil nutrients and particulate matter is only possible by air because water-based transport is limited to closed basins. Aeolian transport of dust from deserts is extremely important to the global budget of aerosols [*Ginoux et al.*, 2001; *Tegen and Fung*, 1994]. Although some deserts are practically devoid of vegetation, other deserts are sparsely vegetated. Our work was concerned with the dust emissions by wind erosion from vegetated deserts, specifically, the northern part of the Chihuahuan desert, at the National Science Foundation's Jornada Long Term Ecological Research (LTER) site near Las Cruces, New Mexico, USA. For this desert environment, *Schlesinger et al.* [1990] hypothesized that vegetation changes are caused by alteration of soil nutrients. Additionally, development of a patchy distribution of soil nutrients follows from the invasion and persistence of shrubs. He identified nutrient-rich areas that develop under shrub canopies as "islands of fertility," compared to the adjacent intershrub spaces that lose soil nutrients by wind and water erosion. This paper documents the variation of wind erosion by vegetation type and contributes to understanding how wind erosion might drive these changes in soil nutrients in mesquite dunelands.

[3] Previous work by *Marticorena et al.* [1997] showed that sandy soils of the Jornada LTER site had the greatest potential for sand movement of any undisturbed soil type. Recently, *Gillette et al.* [2004] showed that horizontal sand fluxes are good surrogates for vertical dust flux measurements. Relying on this concept, we measured horizontal sand fluxes in several kinds of vegetation communities, as a surrogate for vertical dust flux measurements.

[4] In the sandy soils of the Jornada LTER, mesquite (*Prosopis glandulosa*) is the dominant plant, and creosote (*Larrea tridentata*) is widespread. Black grama grass (*Bouteloua eriopoda*), dominant about 50 years ago [*Buffington and Herbel*, 1965], is still found. Besides mesquite, creosote, and black grama grass, the other two of the five most dominant plant species at the Jornada LTER are tar bush and playa grasses [*Huenneke et al.*, 2001]. The five plant species of the Jornada LTER were represented at 15 sites deemed biologically representative for the Jornada LTER program. These 15 sites were called net primary productivity (NPP) sites, consisting of three representative sites for each of the five dominant plant species. Our experiments were largely conducted at these sites and at one other site.

[5] The primary goal of this work was to gather evidence that would address two hypotheses: (1) mesquite dunelands

**Table 1.** Universal Transverse Mercator Coordinates for the North American Datum of 1927 (UTM NAD27) (Zone 13) for the Four Mesquite Sites

| Site | Coordinates, m | Altitude, m |
|---|---|---|
| MNORT | 332,36 E, 3,610,376 N | 1328 |
| MRABB | 331,480 E, 3,609,545 N | 1325 |
| MWELL | 326,307 E, 3,608,925 N | 1324 |
| Scrape site | 334,950 E, 3,605,041 N | 1321 |

possess the most active sand movement (and consequently, largest dust emissions) among the predominant vegetation types of the Jornada LTER NPP sites; and (2) within the mesquite dunelands, sand moves most actively in elongated bare soil areas (streets) that are oriented in the direction of the strongest winds. To address these hypotheses, we measured sand fluxes among the five predominant vegetation types, and we conducted additional, more detailed measurements of sand fluxes at the three NPP sites that were dominated by mesquite. At two of the three mesquite sites we noted large, elongated, bare areas of sandy soil between the mesquite bushes, named "streets" by *Okin and Gillette* [2001]. Many of these streets were elongated in the same direction as the dominant wind direction at these sites: southwest to northeast.

[6] Previous to the present study, a study was carried out by *Gillette and Chen* [2001] on a specially treated, unvegetated flat site located 5–10 km from our three mesquite sites. This site, "Scrape site," located in the same large mesquite duneland area as our mesquite sites, had surficial soil that was similar to all three mesquite sites: sandy material loosely covering flat, ephemerally crusted soil. We regarded the Scrape site as a comparison site that showed the effect of lack of vegetation for soils similar to our mesquite sites.

## 2. Methods and Experimental Details

### 2.1. Study Sites and Observation Periods

[7] The names given to the NPP sites were constructed as follows: MNORT derives from "M" (for mesquite) and "nort" (the first four letters of a descriptor, in this case, north). The other two mesquite sites, MRABB and MWELL, derive from "rabbit" and "well." Other examples of NPP names used are CSAND, a Creosote bush site having sandy soil, and GIBPE, a Grama grass site where there once was a site called "IBPE."

[8] The three mesquite sites and the Scrape site were located within fenced areas at the U.S. Department of Agriculture Jornada Experimental Range (JER). The sites are within 8 km of each other, and the altitudes of all four sites are within 5 m of 1325 m (Table 1). The topography at MNORT and MWELL was rolling, with coppice dunes in varying stages of development formed around mesquite bushes. MWELL was located on a bench adjacent to the top of a caliche scarp; its soil was thinner, and the topography was flatter. MWELL did not have coppice dunes associated with its mesquite bushes, although some bushes had small sand accumulations at their bases. The mesquite bushes of MWELL were mostly smaller than those of MNORT and MRABB. Details of the Scrape site are given by *Gillette and Chen* [2001].

[9] The Scrape site measurements began in 1996 and cover the full time of the mesquite site measurements. Measurements for sand flux commenced in July 1998 at two of the mesquite sites (MNORT and MRABB) and in February 2000 at the third mesquite site (MWELL). The data considered in this paper continue until 31 March 2003 for MNORT and MWELL. After 20 August 2002 until 31 March 2003, mean sand fluxes for MRABB were estimated using only one sand flux value for each of the three 3 month time periods. We used linear regression equations to estimate the mean flux from the single measured flux value. These regression equations used all time periods before 20 August 2002 to relate each collector position at MRABB to the mean of all collector positions at MRABB. We chose the sand flux collector for the position that had the largest $r^2$ coefficient and used its regression formula to estimate the mean flux after March 2004; the other collectors were removed.

[10] Horizontal time- and height-integrated sand fluxes measured at the 12 nonmesquite NPP sites were measured at the same time to compare with the fluxes measured at the three mesquite NPP sites. The 12 nonmesquite sites were all located within 17 km of the three mesquite sites. Altogether, the 15 NPP sites measured were representative of the five most important vegetation types of the northern Chihuahuan desert: mesquite, creosote bush, tar bush, playa grass, and grama grass. "Playa grass" indicated several different kinds of grasses growing in topographic depressions [*Huenneke et al.*, 2001; L. F. Huenneke et al., manuscript in preparation, 2004].

[11] Soil information was summarized from *Bulloch and Neher* [1980] and our interpretation of the soil maps therein. The soils at MNORT and MRABB were Pintura and Onite soils with fine sand and loamy fine sand surface textures (U.S. Department of Agriculture (USDA) classification). The soil at MWELL was a Pajarito soil with a surface texture of fine sandy loam. This soil was located on an alluvial fan below the margins of a piedmont. Calcium carbonate deposits can be seen in road cuts near the site, and the soil above the carbonate deposits is shallow. The loose surface material and the underlying crust material at the Scrape site were analyzed with respect to chemical components and size distribution by *Gillette and Chen* [2001]. Three loose surface samples were all found to be "sand" texture (USDA classification), and two of the three crustal samples were "loamy sand" and the third was "sandy loam"; that is, the loose surface material was of a much coarser composition than the underlying crustal material. Since measurements at the Scrape site show that the crust was being abraded and lowered by wind erosion (measured by monthly measurements of the distance to the crust from a fixed horizontal bar, parallel to and above the soil surface), the particle size results suggest that the fine material abraded from the crust was being removed by wind erosion. After interpreting the textures of the surface soils given by *Bulloch and Neher* [1980] and by *Gillette and Chen* [2001] we expected that for equal erosion fetch lengths the MNORT and MRABB soils would be more erosive than the Scrape site and MWELL soils. Also, because the Scrape site had vegetation-free erosion fetch lengths of up to 100 m, we expected it to have the largest fluxes.

[12] All of the NPP sites were located in large areas that were relatively homogeneous. MWELL had a dirt road running east-west, but it was upwind only for south to

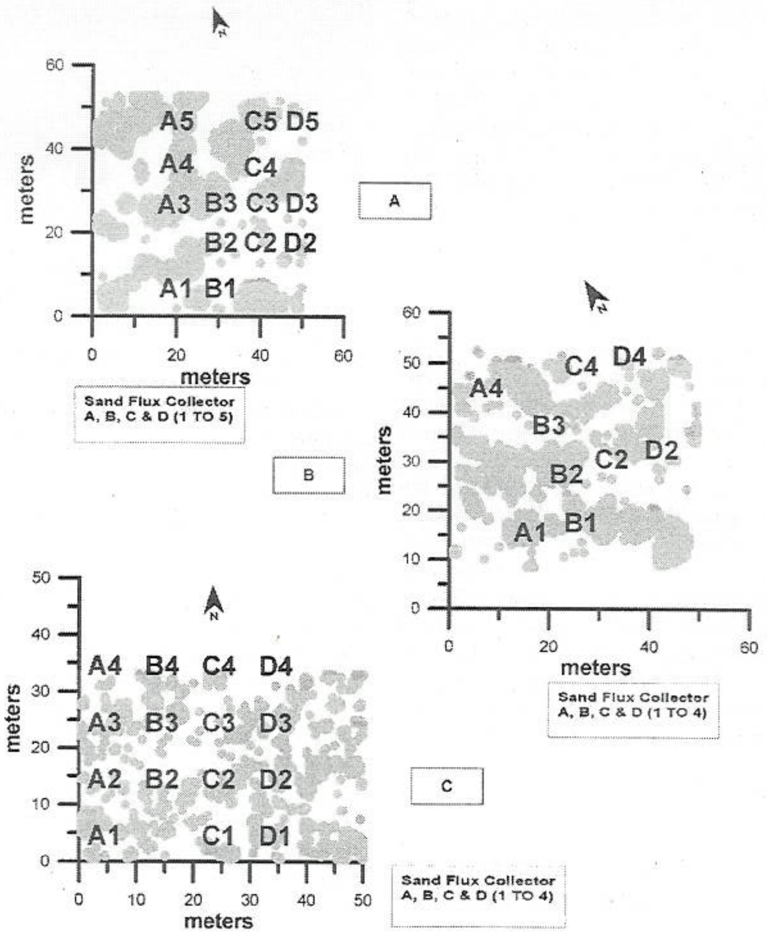


**Figure 1.** Maps of three mesquite sites showing the position of mesquite bushes and sand collectors. At MNORT and MRABB the 15 m tower is a short distance north of the grid (off the diagram). (a) MNORT site. (b) MRABB site. (c) MWELL site.

southwest winds. The creosote bush sites were located on mountain slopes. All the playa sites were in topographic lows and were flat. All the tar bush sites were flat.

## 2.2. Experimental Methods

### 2.2.1. Sediment Flux Measurements

[13] Because of large inhomogeneities observed in preliminary measurements of sand flux rates at the mesquite sites, we used averages of sand fluxes obtained on the nodes of 4 × 4 grids having 10 m separation distances for MWELL (Figure 1c) and MRABB (Figure 1b) and a 4 × 5 grid also having 10 m separation distances for MNORT (Figure 1a). The grid was established from an arbitrary point, with the directions of the grid lines running north-south and east-west at MWELL but within 30° of north-south and east-west at MRABB and MNORT. Each grid node was identified by an alphabetical letter A–D (with A at the left side of the grid) and a number 1–4 or 5 (with 1 being the lowest and 4 or 5 being the highest on the grid). The mapping coordinates for the vegetation were skewed compared to the coordinates for the Big Spring Number Eight (BSNE) grid for MRABB (see Figure 1b). The mapping coordinates for the vegetation were skewed compared to the coordinates for the BSNE grid for MNORT and MRABB but were the same for MWELL. This skewing is apparent for the grids in Figures 1a and 1b but not in Figure 1c.

[14] The grids made it possible to collect enough samples to give a representative mean value for the time- and height-integrated mass fluxes for each site. Detailed vegetation maps with 0.5 m resolution were prepared for the three sites in the summer of 1999. These maps included bare soil, mesquite bushes, and other species of plants; however, at the time of the survey, other species of plants were almost negligible and are not shown. For MNORT and MRABB, streets were quite obvious (Figures 1a and 1b). Bare areas were seen for MWELL, but the elongation and organization into well-defined streets were not obvious (Figure 1c).

[15] For points where mesquite covered the node location the collector was prevented from rotating and consequently could not work. We did not place collectors at these nodes. We measured the sand flux collected for five individual storms using a sand flux collector surrounded by mesquite plants that had sufficient bare soil within the plants to install the collector. To these five flux measurements, we compared the sand fluxes for the same five storms for an identical sand

flux collector located 5 m perpendicular to the wind direction of the "within mesquite" collector. Both collectors had the same distances of bare soil upwind of mesquite bushes, and both were located on the same street at MNORT. The ratio of the fluxes of the "within mesquite" to the "outside of mesquite" was $0.022 \pm 0.17$. Because this ratio was small but highly variable, we set the sand flux where a mesquite occupied the grid node to zero. Mesquite-covered nodes are not shown in Figures 1a, 1b, or 1c; fluxes for these positions were set to zero.

[16] To measure the flux of wind-blown sand, we used BSNE collectors. The collectors and their calibration were described by *Fryrear* [1986]. The BSNE is a sheet metal slot-type collector consisting of a rectangular "mouth" and deposition pan. A wind vane orients the mouth of the sampler into the wind. The BSNE is a passive "virtual impactor" into which sand is blown and trapped by fine screens placed in top vents that allow the air to exit the sampler. Because of the large Stokes numbers of the sand particles collected, the simple collectors maintain 90% efficiency (ratio of collected flux to actual flux) for sand particles (50 μm to 2 mm diameters) for all winds [*Shao et al.*, 1993]. The BSNE collectors were mounted on poles at each grid node for nominal heights of 0.05, 0.1, 0.2, 0.5, and 1 m above the surface for sampling periods of ~3 months for the duration of the study. Special studies were done having sampling periods of 1 or 2 days. The mouth openings of the BSNE collectors are rectangular: 2 cm wide for all heights and 1 cm high for 0.05 and 0.1 m heights and 5 cm high for the other three heights.

[17] The accumulated horizontal mass flux $m(z)$ (units of mass per unit area) for the five heights ($z$) was fitted to the empirical formula used by *Shao and Raupach* [1992]:

$$m(z) = ce^{-[az+bz^2]}, \tag{1}$$

where $a$, $b$, and $c$ are constants having dimensions of inverse length, inverse length squared, and mass per unit area, respectively. After fitting the measured sand flux accumulations ($m(z_i)$) collected at height $z_i$ ($i = 1-5$) to equation (1) the height- and time-integrated mass flux,

$$Q = \int_0^{1m} m(z)dz, \tag{2}$$

where $Q$ has units of mass per length, was integrated from 0 to 1 m above ground. This $Q$ is the total mass of sand carried horizontally during a sampling interval by the wind in a 1 m layer of 1 cm width perpendicular to the wind. The fit was desirable for integrating the data because the slope of the curve was small from the ground to the top of the saltation layer and steep from the top of the saltation layer to 1 m high. The fit of BSNE data to equation (1) gave an average $R^2$ value of 0.96 with a standard deviation of 0.027. Height- and time-integrated mass flux values smaller than 1 g cm$^{-1}$ were eliminated because the samples were too small to give well-formed vertical profiles. Because the nominal sampling duration of 3 months differed slightly, we standardized by calculating mean daily $Q$. Mean daily $Q$ for an individual site was total $Q$ for the period divided by the number of days in the sampling period. Mean daily $Q$ may also refer to a vegetative type (mesquite, grama, creosote, playa, or tar bush). In addition to the height- and time-integrated horizontal mass flux $Q$ and the mean daily $Q$, we calculated a simple index of the relative vertical gradient of mass flux "delt" having the units of cm$^{-1}$, which was defined as

$$\text{delt} = [m(50\text{ cm}) - m(10\text{ cm})]/[c \times 40\text{ cm}], \tag{3}$$

where $c$ was evaluated from fitting equation (1) to each set of $m(z)$ data. The constant $c$ has the same units as $m$ (50 cm) and $m$ (10 cm). The length of 40 cm used in equation (3) was simply 50 cm−10 cm. Interpretation of the index delt gave a sense of the distance of travel for the particles collected in the BSNE. For example, a positive delt was interpreted as a nonlocal source that was depositing into the area of the BSNE. We took a negative delt as evidence for a local source.

#### 2.2.2. Wind Direction and Saltation Event Data

[18] Towers containing wind direction vanes were located to the northeast of the MNORT and MRABB grids and near the center of the MWELL grid. A single NRG® wind vane was placed at 7.5 m. Fast-response horizontal mass flux Sensit® sensors were placed at the three mesquite sites near the center of the grids. Each Sensit sensor was exposed at a height of 5 cm above the ground surface. The sensor consists of a ring of piezoelectric material mounted on a steel cylinder 2.54 cm in diameter. It responds to particle impacts on the ring surface and converts the responses to counts. These sensors have been previously used by *Stockton and Gillette* [1990] to sense airborne sand movement. Sensit instrument responses were used to detect saltation at the three sites. Together, the wind vanes and particle sensors provide information on wind direction during erosion events.

#### 2.2.3. Rain Data

[19] Rainfall data were available from nearby rain gauges. These included the Rabbit rain gauge, south of both MNORT (1.5 km distant) and MRABB (0.5 km distant). We used data from the West Well rain gauge for the MWELL site (0.6 km distant). The rain gauges were operated by the USDA Agricultural Research Service.

#### 2.2.4. Other Descriptors of the Mesquite Sites

[20] Vegetative cover at each grid was estimated by summing the grid nodes designated "mesquite bush" on the vegetation maps and then dividing by the total number of grid nodes on the map. During the time of mapping, few nonmesquite plants existed on the three sites. Heights were measured for plants within 30 m of the 15 m towers.

[21] A probability distribution of the street (elongated area of bare soil) length $L$ (in meters) versus direction $\Theta$ (in degrees), prob($L|\Theta$), was determined from the digitized maps of the mesquite sites. For each map pixel (representing a square of 0.5 × 0.5 m) the length of the street extending forward and backward in a given direction was calculated and stored with the pixel location and the direction. This length was calculated for each pixel for 16 direction intervals starting with 0° and ending at 180°, incremented by 11.25°. The street lengths were sorted into classes with the boundaries of 0, 2, 4, 8, 16, 32, and 64 m. The probability prob($L|\Theta$) for a given 11.25° direction interval was the total number of pixels having street length lying

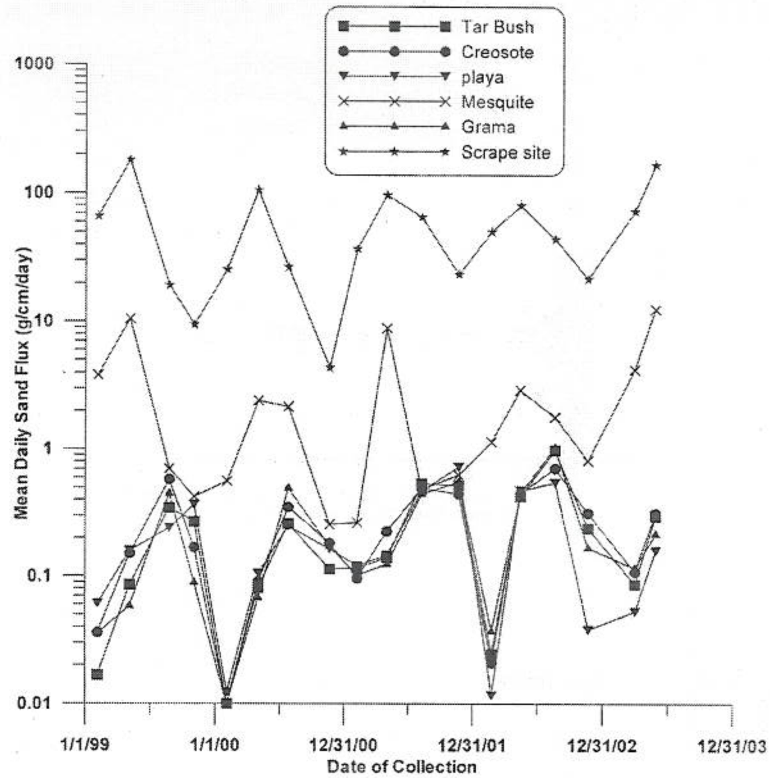


**Figure 2.** Mean daily horizontal mass flux versus date of collection for the means of five vegetation types and the Scrape site. The averaging period was approximately 3 months. Each mean was calculated for the three sites with the same vegetation type, and each point is plotted at the end of the averaging period. The Scrape site mean was based on three measurements taken within an area similar to the mesquite study sites but scraped free of vegetation. All sampled sites were located within a circle having a radius of 10 km centered at the headquarters of the U.S. Department of Agriculture Jornada Experimental Range.

within one of the eight bins divided by the total number of pixels on the map. We used prob($L|\Theta$) to estimate the expected street lengths [$\int L$ prob($L|\Theta$)$dL$] versus $\Theta$ for the three mesquite sites.

## 3. Results

### 3.1. Sand Fluxes for the Dominant Vegetation Types of the Jornada LTER

[22] Figure 2 shows 3 month mean daily horizontal mass flux versus date of collection for our five vegetation types and the Scrape site. Mean sand emission values for mesquite-dominated sites were higher than the mean emission rates for other kinds of vegetation for the winter and spring seasons. Mesquite site mean daily $Q$, although substantial compared to the nonmesquite sites, were always lower than those at the Scrape site. During the spring season, mesquite fluxes always reached to within 1–10% of the Scrape site fluxes and reached these levels over half the time during the winter season. For the fall season, when there was little wind erosion in the northern Chihuahuan desert, the mesquite emissions rates are comparable or only slightly higher than the emission rates for the other four vegetation types (Figure 2), and for the summer season (also during which there was little wind erosion), 20% of the sampling periods were within 1–10% of the Scrape site fluxes.

[23] These data support the first hypothesis: mesquite-dominated sandy soil areas had larger movements of sand by the wind than other vegetated sites at the Jornada, even though this increased emission rate took place only during half of the year. There was no apparent repeating annual pattern for the nonmesquite sites, although one might argue for low annual mean fluxes for 2000, higher annual mean fluxes for 2002, and intermediate annual fluxes for 1999 and 2001. Although mesquite gives the least wind erosion protection of the major vegetation types in the northern Chihuahuan desert, it still reduces wind erosion by ~90% compared to that for a bare surface having similar soil.

[24] The quantity delt defined in equation (3) gave information on the source of the material captured by the BSNE collectors. Data from all samplers were used for considering delt values: this included the mesquite sites (MNORT, MRABB, MWELL) and all the other sites. In almost every case the delt values were negative (Figure 3a). In Figure 3a we plotted delt versus accumulated daily sand flux (the number of days in a sampling period times the mean daily sand flux). We interpret higher concentrations

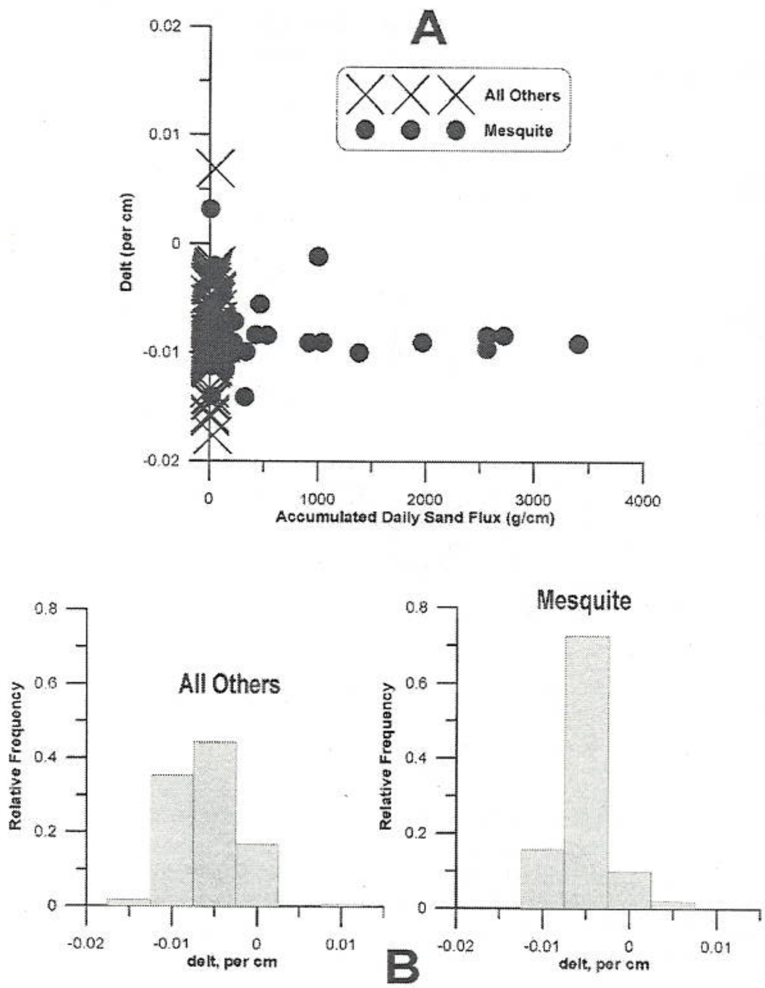


**Figure 3.** (a) "Delt," a relative index of vertical mass flux gradient defined by equation (3) plotted versus the time- and height-integrated mass flux for the sampling period. (b) Relative frequency of delt for mesquite sites and all other sites.

nearer to the ground as evidence for an upward flux of particles in the area near the samplers. Relative frequencies for delt values for mesquite sites and all other sites show that mesquite sites had a slightly narrower distribution, with approximately the same mode value ($\sim$0.01 cm$^{-1}$) as the other sites (Figure 3b). Among the vegetated sites the mesquite sites had the largest accumulated daily sand fluxes (Figure 3a), and these fluxes occurred for a narrower range of delt values than the other NPP sites (Figure 3b). However, some delt values were positive. We interpreted these observations to mean that most but not all of the time, the dominant sources for all our sampling sites were close to the samplers.

[25] One large value of accumulated daily sand flux for a positive delt (taken to be evidence for deposition from an upwind source) was investigated for the playa site P-SMAL for the period ending 2 May 1999. Wind records and inspection of the site showed that there was a strong sand-producing mesquite source area directly upwind at a distance of $\sim$50 m and that a large dust storm occurred during the sampling period. Since the source area for this accumulated daily sand flux was a mesquite area and not the playa area, the data point was removed.

[26] Another site, MWELL, was located within 20–50 m north of an unpaved road that had traffic of up to five vehicles per day. This site's delt data were examined for evidence of deposition of dust from the road rather than local emissions by wind erosion. Of the profiles examined, only one 3 month period had a positive delt and 91% of the values were equal to or less than $-0.01$ (the mode of the mesquite delt frequency distribution). We interpreted these data as showing that the road dust contributions were a small part of the total collected sediment.

[27] To compare the effects of different types of vegetation on sand fluxes from sandy soils similar to the soil for the mesquite sites, we identified all of the nonmesquite sites that had sandy-textured soil (C-SAND, a creosote bush site, and G-IBPE, a grama grass site). The C-SAND and G-IBPE daily mean sand fluxes were very close to the means of all creosote bush and all grama grass fluxes (Figure 4) and lower than the mesquite site fluxes, especially during the spring and winter seasons (Figure 2).

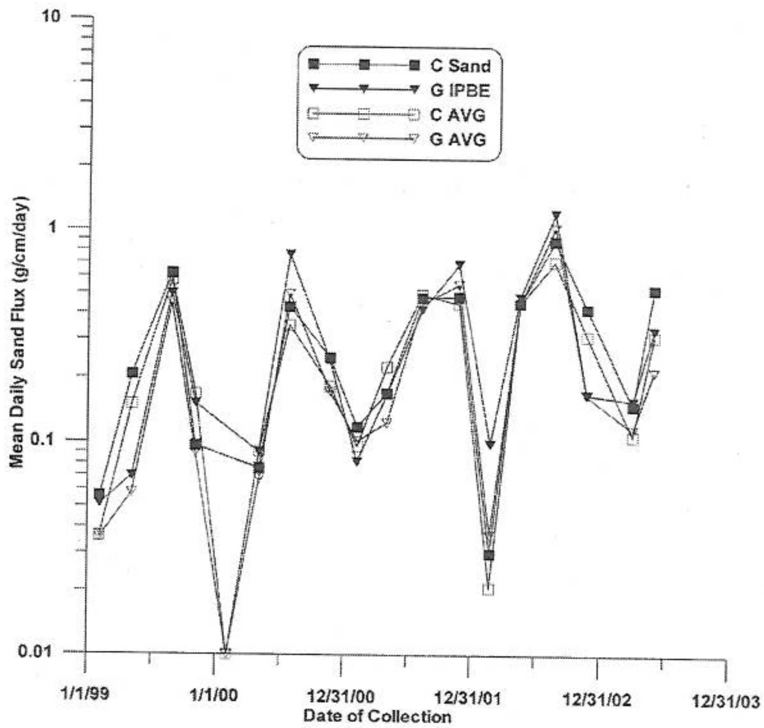


**Figure 4.** Mean daily horizontal time- and height-integrated sand flux versus date of collection, comparing the means of the individual grama grass (G-IBPE) and creosote bush sites having sandy-textured surface soil (C-SAND) to the averaged flux values for creosote and grama grass vegetation types (G-AVG and C-AVG). The averaging period was approximately 3 months. The flux values for the sites with sandy soil for grama grass and creosote are very similar to the averaged flux values for other sites with comparable vegetation types.

Specifically, with only one exception, mean daily fluxes for the mesquite sites were larger than those for C-SAND and G-IBPE for periods when the daily mean flux for the Scrape site was larger than 50 g $cm^{-1}$ $d^{-1}$ for the 3 month sampling period. These data showed that for these periods the mesquite sites had larger mean daily fluxes than any other vegetation type, even if sandy surface soils were present.

### 3.2. Distribution of Sand Flux at Three Mesquite-Dominated Sites

[28] The three mesquite sites were spatially inhomogeneous (Figures 1a, 1b, and 1c). A 15 April 2000 sand storm was selected to show the variability of horizontal sand flux with location for a single sand storm. To measure daily $Q$ for a single storm, BSNE collectors were emptied before the storm and collected immediately after the storm. Single-storm daily $Q$ can be higher than the routinely measured 3 month mean $Q$ because they do not include in the average several days of zero fluxes. Single-storm $Q$ values for MNORT on 15 April 2000 at several locations are shown in Figure 5a.

[29] The strongest winds for that storm were from the west. The three largest sand flux accumulations for MNORT occurred at A5, A4, and B3. These are locations with more than 20 m west-east fetch upwind of their collectors. The next largest sand flux accumulation for MNORT occurred at D5, a location that had at least west-east upwind fetch on its southwest to northeast oriented street. Note that the two smallest sand flux accumulations occurred at D2 and C5, positions that were about 5 m downwind of mesquite bushes. For MRABB the flow of sand had no obvious direction (see Figure 5b). In section 3.4 we will discuss how a strong growth of annual plants in the streets of MRABB following a season of larger-than-normal rainfall diminished the sand transport at MRABB. Lastly, at MWELL the mean of the accumulated sand fluxes was smaller than that for MNORT for the same storm. Five of the 15 samplers collected 0.1 g $cm^{-1}$ or less accumulated sand for the entire duration of the storm, and the largest accumulated flux occurred at a site (D4) very near a gopher disturbance. For a west wind at this site it is readily seen from Figure 1c that fetch lengths for all the collectors were typically smaller than a few meters.

[30] Curves A, B, and C of Figure 6 show the expected length of street versus wind direction for MNORT, MRABB, and MWELL, respectively. The largest fluxes for the three mesquite sites occurred in MNORT. Here sand channeled down the streets that possessed west-east orientation. Figure 6 shows that MNORT possessed longer street fetch lengths for south to west winds than did MRABB or MWELL. Since the strongest winds for the Jornada LTER sites occur for SSW to west winds [*Helm and Breed*, 1999], the orientation of the mesquite streets favors stronger sand

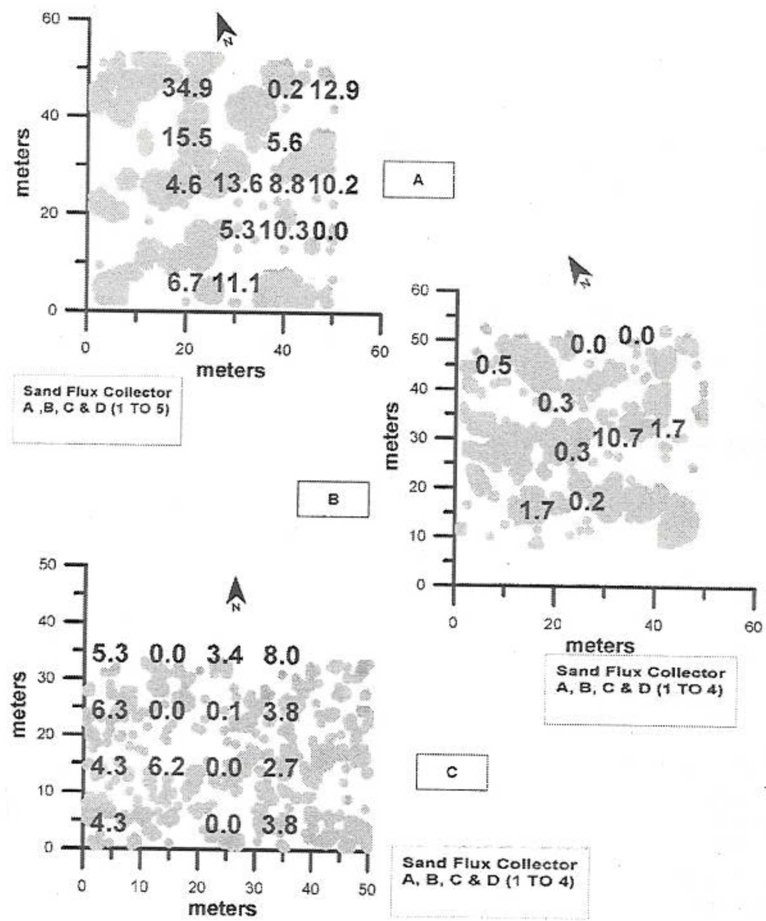


**Figure 5.** Maps of the storm horizontal time- and height-integrated sand flux (g $cm^{-1}$ per storm) at three mesquite sites for 15 April 2000. Mesquite plants are indicated by shading; bare soil has no shading. Sand flux at the sampling point is indicated. (a) MNORT site. (b) MRABB site. (c) MWELL site.

fluxes in the streets of MNORT compared to MRABB or MWELL.

### 3.3. Generalized Shapes of the Sand Flow Patterns at MNORT, MRABB, and MWELL

[31] Detailed maps of mean daily $Q$ for 3 month periods for MNORT, MRABB, and MWELL resembled Figures 5a, 5b, and 5c. To show the similarity of all the sand flow patterns for the 3 month periods of collecting, we calculated ratios of the individual station $Q$ to the mean of all $Q$ in the array. We then calculated the mean and standard deviation of this ratio for all measured periods (Table 2). The number of 3 month periods from 1999 to 2002 used for these ratios is 16 for MNORT, 17 for MRABB, and 12 for MWELL. Refer to Figures 1a, 1b, and 1c for the locations used in Table 2. The means show the shape of the $Q$ patterns, and the standard deviations show the variability about the mean for the 3 month periods.

[32] The pattern of mean values at MNORT showed that the largest $Q$ ratio was at A5 and that $Q$ ratio increased consistently from A3 through D3, from C4 to D5, and from C5 to D5. These increases are consistent with the patterns of Figure 5a. Only two of the 20 positions for MNORT had standard deviations of >50% of the mean. This showed that the general shape of the sand flux maps was similar from one 3 month period to the next and that the map was reasonably representative of the MNORT sand flux patterns overall. For this to occur, necessary conditions included (1) a strong dominance of west to southwest directions for winds strong enough to cause wind erosion, (2) a strong influence of the mesquite bushes to channel wind erosion to the west and the southwest, or (3) a combination of both. The dominance of southwest winds was documented by *Breed and Reheis* [1999]; the dominant directions for the longest streets shown by curve A in Figure 6 are SSW to west.

[33] MRABB data overall showed very high $Q$ values at C2, similar to those of the single storm (Figure 5b). However, 6 of the 16 positions had standard deviations larger than half the mean and larger variability in the pattern of $Q$ than seen at MNORT. The streets for MRABB were predominantly northwest-southeast. The only strong feature of the MRABB pattern was the very strong peak at C2. Thus although curve B in Figure 6 shows that MRABB had well-developed streets, the fact that their direction differed from the predominant south-

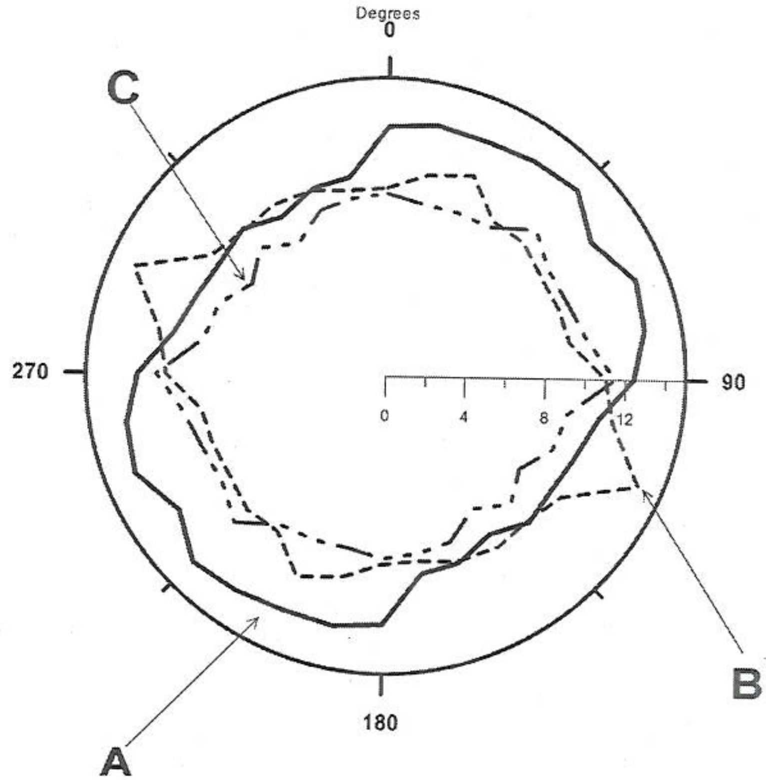


**Figure 6.** Expected lengths in meters of elongated bare soil patches (streets) versus direction in degrees: A, MNORT site; B, MRABB site; C, MWELL site.

west-northeast direction for wind erosion probably contributed to the smaller mean $Q$ at MRABB compared to that at MNORT. Additionally, the section 3.4 discusses the ephemeral growth of vegetation within the streets of MRABB that probably caused the larger variability in the $Q$ pattern.

[34] MWELL showed only one relatively high $Q$ at D4, just downwind of observed gopher digging. At this site, 5 of 16 positions showed a standard deviation greater than half the mean flux. Streets at this site were much shorter than at MNORT and MRABB, even though there was more bare soil than at the other two sites. This site had smaller mesquite bushes scattered more randomly and was more similar to tar bush or creosote bush sites. The shorter streets at MWELL, its finer soil texture, or a combination of both features seemed to exert more influence than the larger area of bare soil.

### 3.4. Mean Sand Transport Rates Versus Time for MNORT, MRABB, and MWELL

[35] Mean daily $Q$ versus time were plotted in Figure 7 for MNORT, MRABB, and MWELL. The spring maxima for sand flux at MRABB were within half of those for MNORT for 1999 and 2001 and 2003. For the years in between (2000 and 2002) the spring maximum of MRABB was around 30% of that for MNORT. The spring maxima sand fluxes for MWELL were typically <20% of those of MNORT. The minima of all three mesquite sites were below 1 g cm$^{-1}$ d$^{-1}$. The maxima for all the mesquite sites were less than the maxima for the unvegetated Scrape site.

[36] The lower maxima observed every other year at MRABB corresponded with observations of drought-susceptible plants flourishing in the streets of MRABB at the same times (J. Anderson, personal communication, 2000). During the same periods we did not observe increased numbers of annual and drought-susceptible perennial plants growing in the streets of MNORT or the bare areas of MWELL. Rainfall was heavy during the summers of 1999 and 2001, making possible the spurts of ephemeral plant growth noted in the MRABB streets (Figure 8). We propose that the rain-fed growth of ephemeral vegetation in the MRABB streets partially explains the difference in MNORT and MRABB emission rates during the spring seasons of 2000 and 2002. We further propose that the shorter streets observed at MWELL and the lack of alignment with the strongest winds led to much lower accumulated sand fluxes during the windy spring seasons compared to MNORT and MRABB. During the summer and fall seasons, all the mesquite sites were consistent in producing little sand flux. MNORT, with long streets aligned with the direction of the strongest winds during the spring season, usually produced the largest accumulated sand flux.

[37] The sand flux did not decrease as one might expect with the "vegetative cover" parameter for the three mesquite sites shown in Table 3. Rather than a simple relationship of increased vegetative cover leading

**Table 2.** Summary Statistics (Mean and Standard Deviation of $Q_{ij}$/Mean $Q$ for that Period)[a]

| | A | B | C | D |
|---|---|---|---|---|
| | | *MNORT* | | |
| 5 | 2.91 | NA | 1.02 | 1.66 |
| | 1.03 | NA | 0.65 | 0.37 |
| 4 | 1.29 | NA | 0.98 | NA |
| | 0.58 | NA | 0.19 | NA |
| 3 | 1.05 | 1.54 | 1.70 | 1.80 |
| | 0.31 | 0.43 | 0.23 | 1.26 |
| 2 | NA | 1.20 | 1.55 | 1.09 |
| | NA | 0.36 | 0.23 | 1.26 |
| 1 | 0.67 | 1.56 | NA | NA |
| | 0.29 | 0.40 | NA | NA |
| | | *MRABB* | | |
| 4 | 0.91 | NA | 0.81 | 0.75 |
| | 0.92 | NA | 0.44 | 0.78 |
| 3 | NA | 1.27 | NA | NA |
| | NA | 0.64 | NA | NA |
| 2 | NA | 1.73 | 4.75 | 1.73 |
| | NA | 0.73 | 2.42 | 1.04 |
| 1 | 2.21 | 1.82 | NA | NA |
| | 0.89 | 0.88 | NA | NA |
| | | *MWELL* | | |
| 4 | 1.58 | 0.26 | 0.85 | 2.46 |
| | 0.27 | 0.18 | 0.20 | 0.17 |
| 3 | 1.07 | 0.18 | 0.39 | 1.99 |
| | 0.74 | 0.25 | 0.28 | 0.83 |
| 2 | 0.89 | 2.13 | 0.66 | 0.44 |
| | 0.38 | 0.38 | 0.52 | 0.35 |
| 1 | 0.74 | NA | 1.22 | 1.14 |
| | 0.50 | NA | 1.01 | 0.15 |

[a]Mean is on the top and standard deviation is on the bottom of each vertical pair. The location of each collection device is given in terms of letter (A–D) and number (1–5 for MNORT and 1–4 for MRABB and MWELL), as is shown in Figures 1a–1c. NA, not available (location was in a bush).

to decreased sand flux, it appears that large patches of vegetation separated by elongated areas of bare soil result in larger fluxes of sand compared to areas with smaller patches of vegetation more randomly spaced. For example, MWELL had the smallest total vegetative cover, yet its mean fluxes were largest only once in seven measurement periods (and not during the windy period). This occurred when all three mesquite sites had very low sand mass fluxes. In this case, a period of intense gopher digging activity was noted immediately upwind of two MWELL collectors. Although MWELL had less vegetative coverage (15.7%) than MNORT (25.4%), we feel that lack of street development in the southwesterly direction of the strongest winds was more important in inhibiting stronger wind erosion based on comparison to MNORT.

## 4. Discussion of Alternate Explanations for Larger Sand Fluxes in Mesquites at the Jornada Site

[38] In an effort to anticipate other explanations for the increased sand flux observed in the mesquite-dominated sites, we discuss alternate explanations for increased sand flux from mesquite-dominated areas and attempt to show that other explanations are either inappropriate or are less probable than the proposed explanation of street alignment with the strongest winds.

### 4.1. Taller Plants Should Protect the Soil Better Than Shorter Plants

[39] One would expect the protection of the soil from the vegetation to be related to bush height, which controls aerodynamic roughness height. Aerodynamic roughness height, in turn, correlates positively with increased threshold friction velocity [*Marticorena et al.*, 1997]. For the same species, one would expect a correlation of plant height with protection of the surface. However, at the C-SAND site, much lower sand flux rates compared to those of MNORT are observed for creosote bushes of about equal height and having similar sandy soil as the mesquite bushes at MNORT. Additionally, MNORT sand fluxes are clearly larger than those at MWELL, and plant height is taller at MNORT that at MWELL. The size of plants at MWELL apparently had less influence for the measured wind erosion rates than soil texture coupled with different orientation of streets relative to the direction of the strongest winds development.

### 4.2. Higher Biomass Density Should Control Wind Erosion Rates

[40] Density of biomass (mass per area) at all NPP sites was roughly the same (L. F. Huenneke, personal communication, 2000). However, sand fluxes at the mesquite sites were clearly larger than for any other vegetated site, even though biomass was roughly the same.

### 4.3. Biotic Crusting and/or Dense Grass Control Wind Erosion

[41] Presence of cryptogamic crusts was found at all three tar bush sites. This biotic crusting, along with the silty soil texture, probably would prevent wind erosion even without tar bush presence [*Marticorena et al.*, 1997]. At the playa grass sites, dense grass provided a 100% cover that was almost always sufficient to prevent wind erosion. However, at creosote sites and grama grass sites, neither 100% grass cover nor cryptogamic crusts were found. Sand fluxes at these sites during the windy seasons were much smaller than at the mesquite sites. Instead, the grama grass and creosote sand fluxes were comparable to those of the tar bushes and playa grasses.

### 4.4. Lack of Disturbance Protects the Soil From Wind Erosion

[42] All the NPP sites were protected from cattle disturbance by fencing. MRABB had disturbance from rabbits, and MWELL had disturbance from gophers. MNORT had no apparent internal disturbances and also shared the largest wind erosion rates.

## 5. Conclusions

[43] The mesquite-coppice dune vegetation type had the largest measured aeolian sand fluxes compared to other important vegetation types for the northern Chihuahuan desert, i.e., creosote bush, tar bush, grama grass, and playa grass. Sand moves most intensely within bare, elongated, sandy-textured soil patches (streets) within the mesquite-coppice duneland. For streets of equal size, those aligned

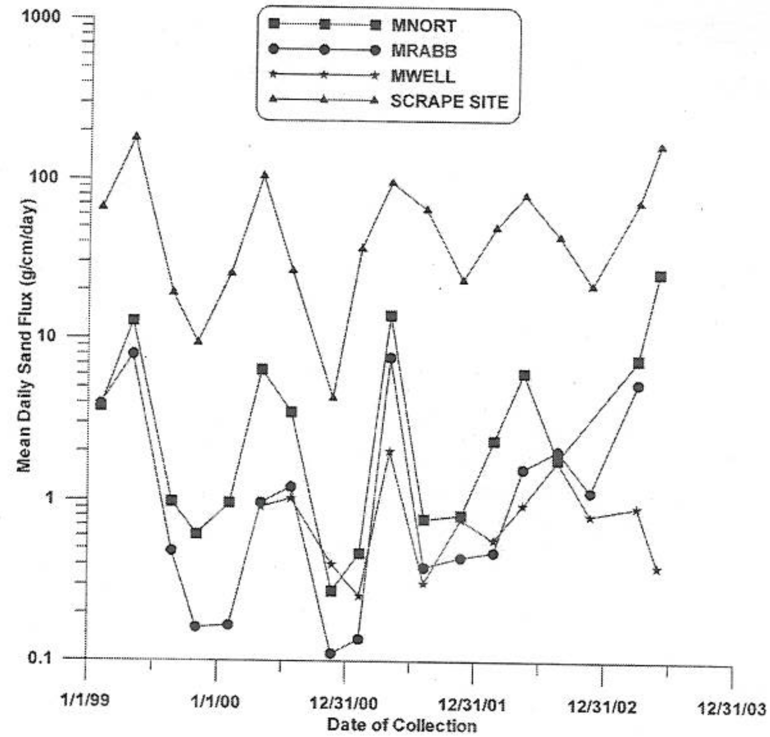


**Figure 7.** Mean daily horizontal time- and height-integrated sand flux versus date of collection for means for the three mesquite sites (MNORT, MRABB, and MWELL) and the Scrape site. The averaging period was ~3 months.

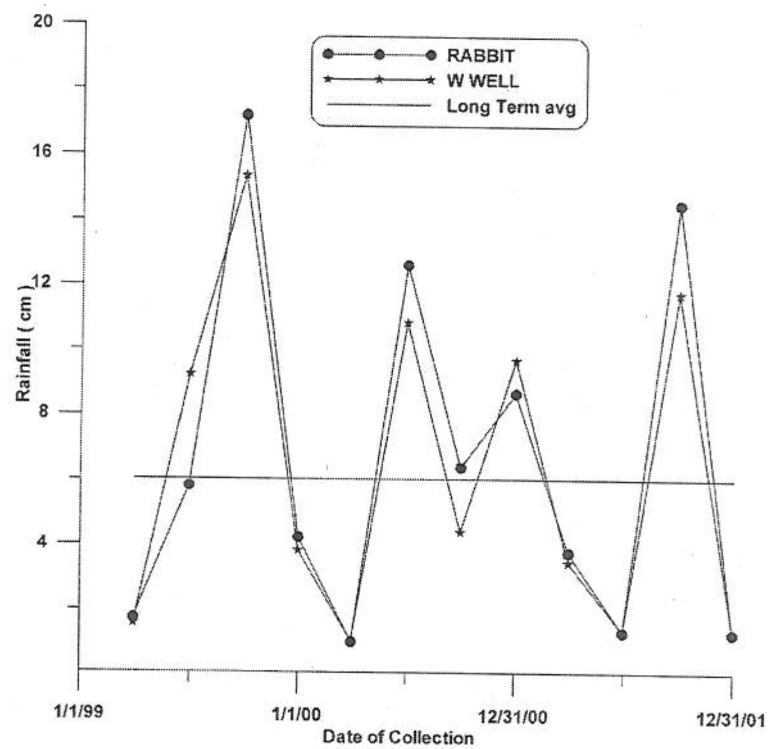


**Figure 8.** Three month averaged rainfall at Rabbit and West Well rain gauges versus date and the long-term average.

Table 3. Properties of the Mesquite Sites[a]

| Property | MNORT | MRABB | MWELL | Scrape Site |
|---|---|---|---|---|
| Vegetative cover, % | 25.4 | 21.4 | 15.7 | 0 |
| Mean height of bushes, m | 1.0 | 1.2 | 0.5 | 0 |
| Standard deviation, m | 0.5 | 0.5 | 0.3 | |
| USDA texture of surface soil[b] | FS to LFS | FS to LFS | FSL | LS to SL |

[a]FS, fine sand; LFS, loamy fine sand; FSL, fine sandy loam; LS, loamy sand; SL, sandy loam.
[b]Not loose material on surface.

with the wind direction possess the most intense aeolian movement; this movement increases with the downwind distance within the streets. The mesquite site with sandy soil and the best-developed streets had the largest sand flux rates. The mesquite site with a fine sandy loam soil and poorly developed streets had the smallest sand flux rates. In mesquite-dominated areas of the northern Chihuahuan desert, both the presence of streets aligned with the strongest winds and sandy soil texture contribute to increased sand movement. We observed that only the mesquite of all the dominant vegetative species of the Jornada LTER formed well-developed streets. The historical displacement of black grama grass by mesquite in our study area is likely partially due to street formation associated with mesquites: the vegetation-free streets do not possess water-consuming competitors for the mesquites. Additionally, part of the soil nutrients eroded from the streets is captured and concentrated in the mesquite bushes and mesquite bush coppice dunes.

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