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Comparative rates of wind versus water erosion from a small semiarid watershed in southern Arizona, USA

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ABSTRACT

The relative erosion rates of wind and water erosion have rarely been studied simultaneously and are poorly quantified. In this study, wind and water erosion rates were simultaneously measured and compared over 2 yrs for a small rangeland watershed in the Santa Rita Experimental Range in southern Arizona. Average horizontal, wind-driven sediment flux was 7.0 g m^{-1} d^{-1} during the study period. The combined soil erosion rate by water and wind was 7.60 t ha^{-1} yr^{-1}, with only 0.08 t ha^{-1} yr^{-1} attributed to wind during the 2 yrs. The results of this study showed that rates of soil erosion by water greatly exceeded rates of erosion by wind during the study period in this small watershed. Comparison between these results and other recent studies in the same area suggest that measurements of horizontal sediment fluxes by wind and water are not necessarily indicative of relative net soil erosion rates on a unit area basis because the measurements of the wind flux sediment cannot be considered as mass of soil loss per unit area per unit time.

1. Introduction

In arid and semiarid regions, both wind and water erosion are serious land degradation processes, and may occur contemporaneously. Rates of wind and water erosion can be significant, particularly where vegetation cover is sparse, such as in shrub-dominated rangelands. Nearing et al. (2005) reported rates of water erosion from shrubland and grassland hillslopes in southeastern Arizona of 5.6 and 3.2 t ha^{-1} yr^{-1}, respectively. Nearing et al. (2007) reported measured water-induced sediment yields from seven small shrub and grass watersheds in southeastern Arizona ranging from 0.07 to 5.7 t ha^{-1} yr^{-1}. In both studies, the shrubland produced significantly more erosion and sediment yield than did the grassland sites. Lane and Kidwell (2003) reported rates of water-induced sediment yields of 0.06, 1.48, 3.67, and 4.21 t ha^{-1} yr^{-1} from four small watersheds in the Santa Rita Experimental Range of southern Arizona. Their results also indicated that sites where shrubs (mesquites) were removed, and hence grass cover was greater, had lower erosion rates.

Very few measurements of wind erosion rates on non-agricultural lands in semiarid regions have been made. Breshears et al. (2003) studied horizontal and vertical fluxes of wind driven sediment fluxes at a shrub site and a forested site in New Mexico and at a grassland site in Colorado. Using the measurements of vertical fluxes in conjunction with wind velocity measurements they computed soil erosion rates by wind. The reported median erosion rates from wind for the vertical mass flux measurements were extremely low: 0.055 t ha^{-1} yr^{-1} for the shrubland, 0.030 t ha^{-1} yr^{-1} for the grassland, and 0.033 t ha^{-1} yr^{-1} for the forest. Water erosion rates were estimated using linear extrapolations of rainfall simulation experiments using excess rainfall depths for 2-yr return storm events, and as the reported rates of water and wind erosion were 0.0044, 0.15, and 0.0083 t ha^{-1} yr^{-1} for the same shrub, grassland, and forest sites, respectively. These were apparently quite stable sites, as the rates of erosion reported were negligible compared to those measured on other rangeland sites.

Unlike the deserts of Africa and Asia with bare sand dunes, the deserts in the arid and semiarid southwestern United States are sparsely vegetated and usually vegetated by shrubs and desert grasses. In southern Arizona, the semiarid desert grassland has experienced nearly a century of velvet mesquite (*Prosopis velutina Woot.*) expansion (Platt, 1959; Cable and Martin, 1973; McClaran, 2003). Soil erosion by wind is an important factor in redistributing soil and nutrients from intercanopy spaces to the canopy patches of the woody shrubs in the transition process of grasslands to shrublands (Okin et al., 2006). The heterogeneous arrangement of vegetation patches play a major role on controlling surface

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erodibility and wind erosion in semiarid rangeland environments, particularly in semiarid mesquite-dominated shrublands (Okin and Gillette, 2001; Okin, 2005). Scale controls the erosional processes (Okin et al., 2006). At the plant-interspace scale the erosivity of the wind is controlled by differences in the surface shear stresses of the wind over the soil surfaces, including the effects of downwind sheltering of the surface near a plant, momentum extraction, and trapping of sediment at the base of the plant. Variable soil and vegetation patterns also influence redistribution of sediment or dust at larger scales (Okin et al., 2006). Significant horizontal mass flux has been observed on surfaces with high vegetation cover in the semiarid deserts of the southwestern United States (Li et al., 2008; Okin, 2008). Sediment and dust deposition also occurs within the very near downwind area underneath plant canopies (Li et al., 2009; Okin et al., 2001, 2006).

The study of wind erosion has focused on single aeolian transport processes rather than sediment mass budget (Sterk et al., 1996). To quantify the mass of wind-blown sediment passing the point of measurement, mass sediment flux is usually determined by integrating the mass flux profile as a function of height (Sterk and Raats, 1996). Previous analyses derived from the measurements on agricultural lands or bare fields (Fryrear and Saleh, 1993; Sterk and Raats, 1996; Hagen et al., 2010) developed several equations to describe the vertical distribution of mass flux, including power, exponential, and combined forms. Most of these relationships were derived using data collected on a bare soil; however, horizontal mass flux can be greatly impacted by vegetation, particularly if the spatial patterns of the vegetation are anisotropic (Okin, 2005; Okin et al., 2006). Recent studies suggested that porous vegetation has strong impact on downwind surface shear stress profiles, particularly those with tall cover, which determine the horizontal mass flux profile (Okin, 2005, 2008).

Despite the potential importance of wind and water erosion in semiarid environments, these two forms of erosion are usually studied as separate processes (Visser et al., 2004). We know little about the relative magnitudes of wind erosion with respect to water erosion in semiarid regions. In this study, we developed a method for assessing net loss and gain by wind erosion and water erosion for a specified land area so that net loss or gain of material within the control area due to wind and water could be directly compared. Our objectives were to report relative rates of soil erosion, in the sense of net loss or gain per unit area, by wind and by water from a semiarid rangeland watershed in the Santa Rita Experimental Range in southeastern Arizona.

2. Materials and methods

2.1. Site information

Field work was carried out on watershed 76.8 (http://www.tucson.ars.ag.gov/dap/) at an elevation of approximately 1160 m (Fig. 1) on the Santa Rita Experimental Range (SRER), 45 km south of Tucson, AZ, USA. Mean annual precipitation has been measured at 377 mm (1937–2007; SRER raingauge #45; http://ag.arizona.edu/SRER/data.html). From April to mid-June, conditions are hot and dry, with daytime temperatures often exceeding 40 °C in June. In late June to early July and continuing through September the North American Monsoon (Adams and Comrie, 1997) generates thunderstorms that account for approximately 50% of annual rainfall and nearly all of the soil erosion by water. Monsoon rains end around mid-September, with October and November usually being dry. Winters (December to March) are cooler with occasional night-time frosts, and slow-moving frontal storms that account for approximately 30% of the annual rainfall. For most of the year, the winds are westerly but become south-southeasterly during the monsoon. Mean annual wind speed of approximately 1.75 m s^{-1} and a mean wind speed of 1.90 m s^{-1} during the dry months of the monitoring period.

The area of watershed 76.8 is 1.12 ha, with average slope of 4.2% and main channel length of 165 m. The soil is a Sasabe sandy loam. The surface 10 cm contains 0.43% organic matter, 10.5% rock fragments (>2 mm), and 85%, 8%, and 7% sand, silt, and clay, respectively, the <2 mm fraction. Vegetation at the watershed is dominated by velvet mesquite (*P. velutina Woot.*), non-native Lehmann lovegrass (*Eragrostis lehmanniana*), burroweed (*Isocoma tenuisecta*), prickly pear (*Opuntia engelmannnii*), and barrel cactus (*Ferocactus wislizeni*).

Vegetation characteristics were surveyed on a sample plot 20 m by 30 m in the watershed. All vegetation having height greater than 0.15 m was surveyed. One height and two measurements of width, perpendicular to each other, were taken on each plant. The percent cover represents the ground area covered by vegetation as viewed from above and was determined from the sum of the plan view area of each plant, using the mean width of each plant as the plant diameter. The mesquite canopy cover was approximately 53% with canopy heights reaching approximately 4 m, and with an additional ~10% cover of perennial grasses, forbs, and subshrubs.

2.2. Wind erosion measurements

The limits of the areas under wind erosion measurements were determined by the boundary of watershed 76.8 (Fig. 1). Horizontal mass fluxes of wind-blown sediment were obtained using 18 masts equipped with Modified Wilson and Cooke (MWAC) samplers. The sampler was made of plastic bottles with an inlet and outlet tube bent at a 90° angle (Wilson and Cooke, 1980) with an inner diameter of 7.0 mm. This type of sampler has been independently tested by Goossens and Offer (2000) and Goossens et al. (2000), who found the efficiency of MWAC is greater than 90% for wind speeds between 2 and 5 m s^{-1} for the saltation in the laboratory and field. All the MWAC samplers were installed at each of six sites along the watershed boundary (Fig. 1). We devised fixed directional samplers that allowed us to sample horizontal wind sediment flux in eight compass point directions. There were two sets of directional sampler units, one total-load (wind vane) sampler unit (that pivoted with the wind direction), and one creep sampler at each sample plot. The directional samplers were mounted on two poles with four samplers on each at 90° apart (oriented in orthogonal directions) at two separate heights (0.2 and 0.6 m) for a total of 16 MWAC samplers. Thus, one pole had bottles at two heights pointing (N, E, S, W) and the other pole had bottles at two heights (same heights as pole 1) pointing (NE, SE, SW, NW) (Fig. 2). The total-load sampler contained eight bottles on a wind vane at heights (0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, and 2.0 m) such that the sample openings were always pointed into the wind. The purpose of the total-load samplers was to measure total flux from all directions at the six sample locations. The purpose of the directional sampler was to enable delineation of the total flux into eight directional components. We performed a test between the directional samplers at three different angles (0°, 22°, and 45°) with two wind velocities (10 and 15 m s^{-1}) in a wind tunnel versus a standard MWAC with the same size opening always at 0° deviation from the tunnel axis. Because of a possible positional bias in the tunnel, the test was run twice with the position of the sampler and the directional sampler switched between runs. Two tests were run at each angle and wind speed. The mean ratio of mass collection rate in the standard MWAC to that for the directional samplers is shown in Fig. 3 at different angles and wind velocities. The average ratio mass collection rate in the directional sampler to the mass collection rate for the standard MWAC sampler was 0.97 ± 0.18 ($n = 12$). The findings

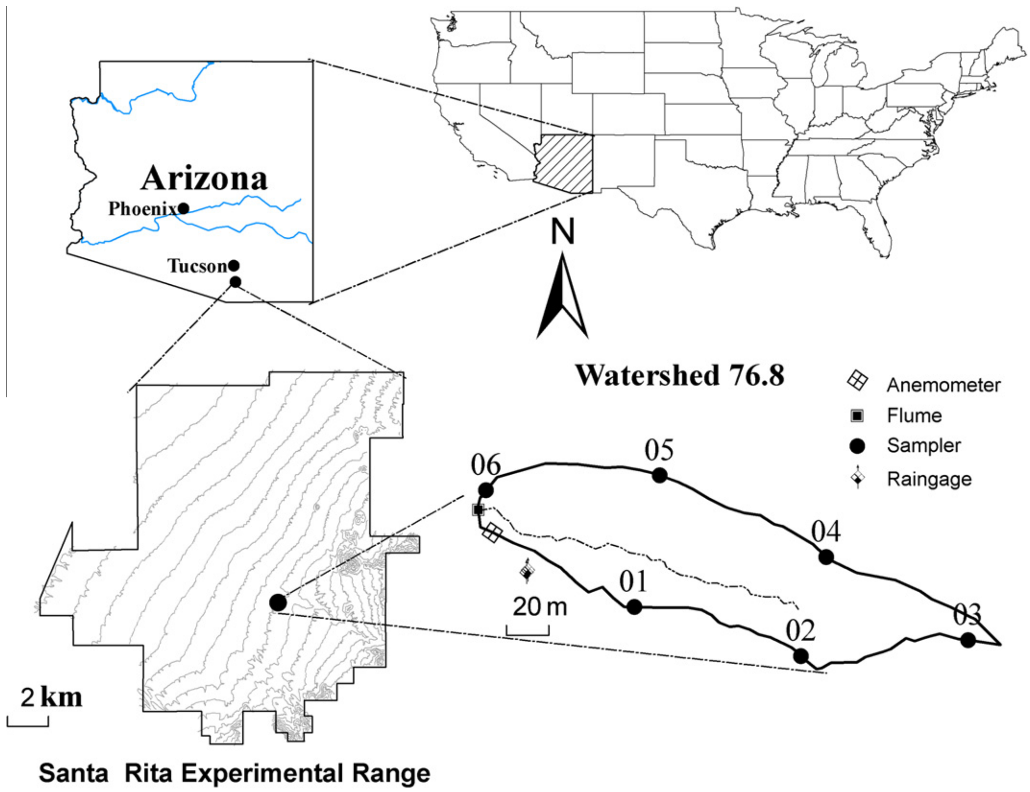

Fig. 1. Location of study area.

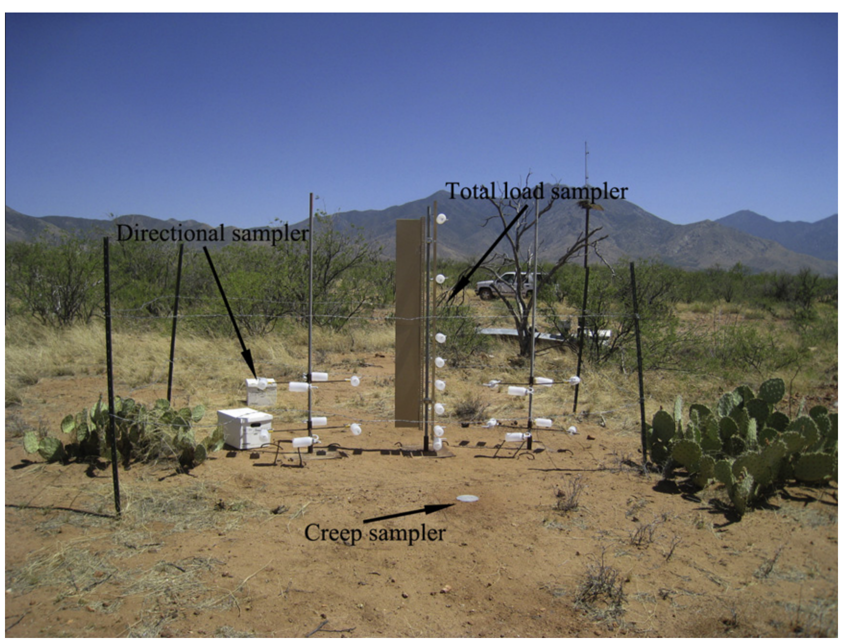

Fig. 2. Pivoting total MWAC sampler, fixed directional samplers, and creep sampler used in the study.

suggested that the sampling efficiency of the directional samplers was similar to that of the standard MWAC sampler. However, a calibration of collection efficiency was precluded because we have only two values and could not measure particle size in the real time during the measurement periods.

Creep samplers were also installed at the measuring site to collect particles moving on the ground. The creep sampler was a flat plate with a hole in the center so that creeping material fell through the hole and into a jar. The hole in the aluminum lid was 5.4 mm in diameter. The advantage to these samplers was that plant materials, dead bugs, and large pieces of gravel tended to roll over the hole and thus not block it and interfere with the measurement.

The MWAC and creep samplers were monitored from March 2008 to March 2010. Wind-blown sediments caught in the samplers were collected approximately every month on average, with

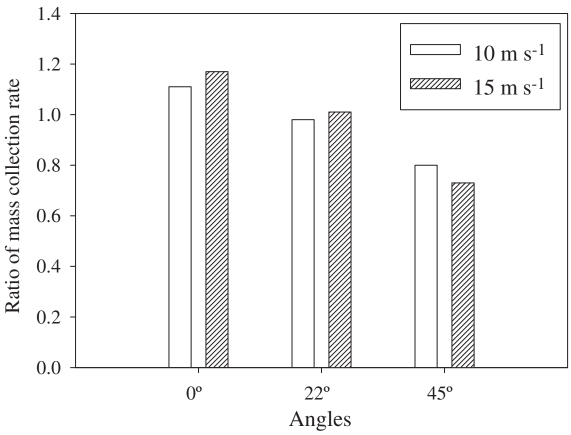

Fig. 3. Mean ratio of mass collection rate between the standard MWAC and the fixed directional MWAC samplers.

greater frequency depending on wind conditions and amount of sediment collected. The samples were removed from the sampler by washing with distilled water, transferred into small aluminum weighing dishes, oven-dried at 100 °C (>24 h) to a constant mass, and weighed. The horizontal mass flux was calculated by dividing the mass of the sediment collected by the sampler inlet area at each height and integrating through the depth of the measured profile; i.e., 2 m height. For the creep samplers, the horizontal sediment mass flux was calculated by dividing the mass of the sediment collected by the diameter of the hole of the sampler. Because overland water flow from large storms usually filled the jar of the creep sampler in the summer monsoon season, data analyses were performed without creep sampler masses during the sampling interval when runoff events occurred. During the monitoring period, there were three time intervals (of 24) in which creep samplers were buried. For these three intervals, we used only the samplers above surface and fit the regression through the bottom sampler to the ground in order to calculate the total horizontal sediment mass flux. The horizontal mass flux and sampler height data were then used to estimate the total sediment flux of wind-blown sediment at each location. The total horizontal sediment flux was the sum of that from the total-load sampler and creep sampler at each location.

An anemometer and wind vane located at the watershed was used to measure wind speed (average and peak gust) and wind direction at a height of 3 m (Fig. 1). Data were sampled and recorded at an acquisition rate of 30 min with a data logger. The information for the speed and the direction of the wind has been collected continuously since 2004 (Scott et al., 2008).

Since the study area had vegetation cover that was mainly a mixture of shrubs and grass, models of the mass flux vertical profile commonly applied to bare surfaces were not used (Okin, 2005, 2008). We used direct interpolation of the measurements as a function of height. The mass fluxes averaged across the adjoining eight heights on the total-load sampler were multiplied by the sum of half of the distances between the sampling heights, and then summed up to obtain the total horizontal sediment flux. The flux from creep samplers was included in the total horizontal sediment flux.

For each monitoring period, aeolian sediment mass budget was estimated from the difference between the incoming and outgoing sediment mass fluxes along the watershed boundary at each location. The total-load samplers and creep samplers collected the total sediment flux from all directions, and that flux was then partitioned according to the masses sampled from the eight directional samplers in order to determine what was coming from which direction. The samples from the directional samplers at two heights were extrapolated to determine the weighting factor for the eight directions (N, NW, W, SW, S, SE, E, and NE) to partition the total horizontal sediment flux. From the eight directions, the relative amounts of incoming and outgoing sediment flux were determined along the boundary of watershed. We integrated the in-bound and out-bound flux across the entire watershed boundary to estimate a net flux to and from the watershed area using the following methods.

Let X_{ij} ($i = 1,\ 2;\ j = 1$–8) denote the mass collection from the directional samplers at each location. The weighting factors (Y_j) are given by:

$$Y_j = \frac{X_{1j} + X_{2j}}{\sum_{j=1}^{8}(X_{1j} + X_{2j})}, \tag{1}$$

where 1 or 2 subtending X denotes one of the two heights, 20 and 60 cm, respectively, of directional samplers, j is the one of the eight directions (N, NW, W, SW, S, SE, E, and NE).

Let α_j ($j = 1$–8) denote the angle (clockwise) between the tangent line of the boundary line at each location and the eight directions, and M (g m^{-1}) denote the mass sediment flux at the location. The net sediment mass budget (S) blown into the watershed at a location on the boundary is given by:

$$S = \left(\sum_{j=1}^{8}(\sin\alpha_j) * Y_j\right) * M. \tag{2}$$

To determine the mass balance across the whole watershed, the watershed boundary was split into 5 m segments. The tangent of each segment was estimated as a straight line between start and end points, and the angles between the tangent line and each of the eight directions were calculated. Between measuring points, the mass fluxes were estimated by linear interpolation of measured sediment mass fluxes from directional samplers and total sampler at each mast. The weighting factor (Y_i) and net soil loss (S) were estimated using Eqs. (1) and (2) at each point. The net mass balance passing into the watershed across each segment was calculated by multiplying the length of each segment and the average net soil loss for the segment. The mass balances across the watershed were calculated by summing the net masses passing through all the segments for each monitoring period.

Since the samplers were in the field for an extended period, we conducted a study to quantify potential effects of rain splash on the wind erosion measurements. Rainfall simulations were conducted near the study site using a Walnut Gulch rainfall simulator (Paige et al., 2003) with the MWAC samplers in the plots. Rainfall intensities of 63.5 and 180.0 mm h^{-1} were used. No measurable splash was collected from the wind samplers in the experiment, and therefore we assume that that the effects of rain splash were negligible on the MWAC wind erosion measurements.

2.3. Water erosion measurements

Runoff and sediment yields were measured with a calibrated, Santa-Rita type supercritical flume and traversing slot sediment samplers at the outlet of watershed 76.8 (Renard et al., 1976; Smith et al., 1981). Precipitation, runoff and sediment have been collected on eight watersheds (1.1–4.0 ha) in the Santa Rita Experimental Range, including watershed 76.8 since 1975. The features and principles of data collection for these flumes can be found in several previous publications (Smith et al., 1981; Nearing et al., 2007; Nichols et al., 2008; Lane and Kidwell, 2003).

Duncan's multiple range tests was used to determine significant differences in mean sediment fluxes at $P = 0.05$ using the SAS program (SAS Institute Inc., 2003).

3. Results

3.1. Wind and precipitation conditions in the study period

Mean daily wind speeds ranged from 0.5 to 5.7 m s^{-1} during the monitoring period, and daily peak 30-min average wind speeds ranged between 1.4 and 9.4 m s^{-1} (Fig. 4). The strongest winds occurred in the spring with 30-min average velocities up to 15 m s^{-1} at 3 m height. The 2008 monsoon precipitation totaled 360 mm, starting on June 26th (41.8 mm; Fig. 4), followed by a distinct ramp-up period with nearly daily precipitation until July 11th (74.5 mm). Following a large storm on August 3rd (34.3 mm; Fig. 4) there was a dry period from August 4th to 24th. The final storms of the season occurred on September 10th and 11th (13.3 mm and 21.8 mm, respectively; Fig. 4). Four storms caused significant runoff and erosion, those being recorded on June 26, July 11, 19, and August 3. For 2009, the amount of precipitation was 187 mm, in which 139 mm occurred during the monsoon (Fig. 4). Only one storm caused significant runoff and erosion, recorded on July 19, 2009. Compared to the long-term (1937–2007) mean annual precipitation (377 mm), the year of 2008 was significantly wetter (438 mm), while year 2009 was significantly drier (Fig. 4). However, during the spring windy seasons (March–May), both years were particularly dry (15 mm and 25 mm, respectively) with respect to the long-term mean precipitation of 35 mm (1937–2007).

3.2. Sediment fluxes by wind

Sediment from the MWAC sample bottles were collected 24 times during the period of March 2008 to March 2010. Horizontal wind-driven flux rates were expressed as mean daily values, Q, calculated as total flux rates for the period divided by the number of days within each sampling period (Fig. 5). Greater sediment flux occurred in spring and summer ($P = 0.05$) during the monitoring period (Fig. 5). Greater flux during this period may have been associated with frontal activities which led to stronger wind events (Brazel and Nickling, 1986) along with a longer dry antecedent period. Measured sediment fluxes were significantly less during the fall and winter seasons ($P = 0.05$). These results were in general agreement with those of Helm and Breed (1999), who reported that dominant wind erosion events occur during spring and summer in the southwestern USA.

Mean daily horizontal wind driven flux, Q, ranged from less than 1.0 to 51.1 g m^{-1} d^{-1} with the standard deviations from less than 1.0 to 13.7 g m^{-1} d^{-1} the measurement period, and mean daily Q of all the six sites was 7.0 g m^{-1} d^{-1} averaged over the full study period.

3.3. Sediment balances within the watershed due to wind and water erosion

The wind-blown sediment mass budgets across the watershed boundary were estimated with the method presented above for each of the measuring periods. Sediment budgets due to wind erosion for the different sample periods ranged between a net loss over the area of 0.030 t ha^{-1} and a gain of 0.005 t ha^{-1}. Net soil losses were found for most of the periods, while net gains were observed during portions of November, January, and February, which indicated that net sediment deposition occurred within the watershed at those times. The largest net erosion occurred during the spring, which was also the windier time period.

The precipitation was 438 mm during 2008, which was wetter than the historical mean annual precipitation (377 mm between 1937 and 2007). Major thunderstorms generated four runoff events in 2008, all of which occurred during the summer monsoon season. Soil losses by water erosion from the four events were 1.9, 11.2, 0.9, and 0.5 t ha^{-1}, respectively (Fig. 6). The largest storm occurred on July 11, with 74.5 mm total precipitation and a maximum measured intensity of 105 mm h^{-1}. The return period for this storm was 40 yrs based on the previous 35 yrs' precipitation data at the study site. This event was responsible for 77% of the measured erosion by water for the entire sample period. The 187 mm of rainfall measured in 2009 was dry compared to the mean annual precipitation (377 mm: 1937–2007), with only one

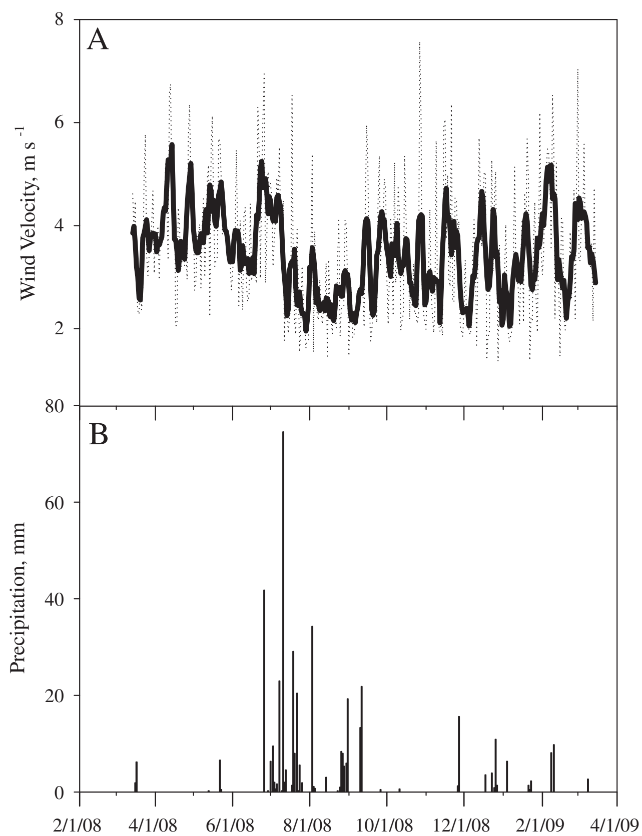

Fig. 4. (A) Daily maximum 30-min average wind velocities (dotted line) and their 5-day moving averages (dark solid line) at 3 m height and (B) daily precipitation at Watershed 76.8 from March 2008 to March 2010.

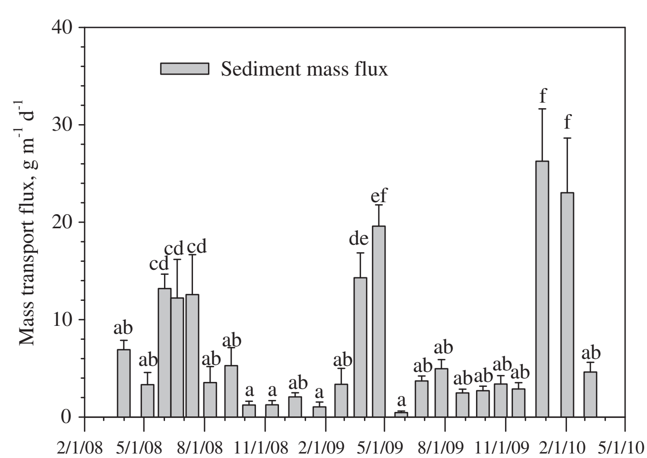

Fig. 5. Wind-blown horizontal sediment mass flux during the period of March 2008 to March 2010. Each value is the mean of six sites (±SE), and each bar is plotted at the end of the monitoring period. Different letters above the bar indicate significant differences at $P = 0.05$ (Duncan's test).

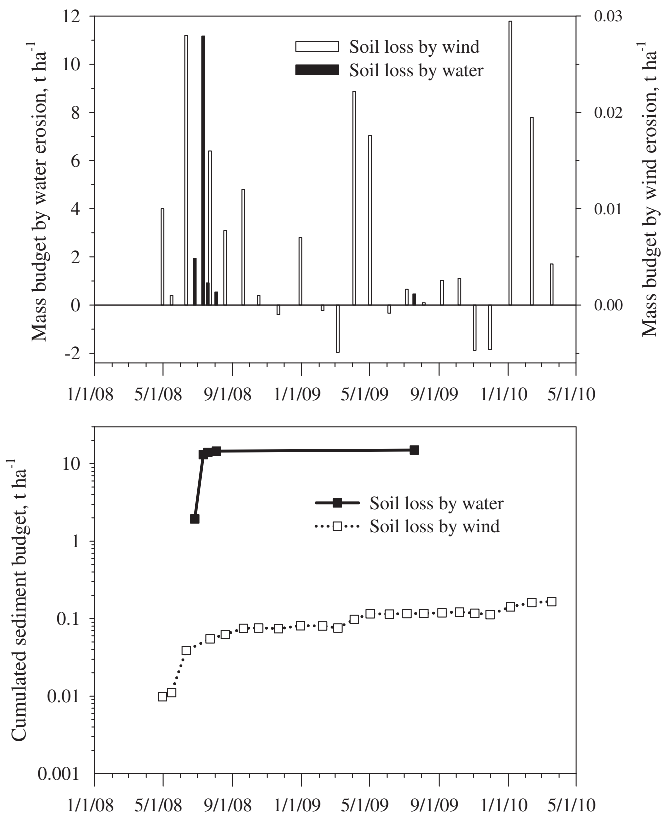

Fig. 6. Comparison of sediment mass budget with time (top) and accumulated over the monitoring period (bottom) due to wind and water erosion for the whole watershed area (note different scales for wind and water erosion rates).

major thunderstorm on July 19 that caused soil losses by water erosion of 0.46 t ha^{-1}. Fig. 6 shows the cumulative mass balances of aeolian sediment over the study period. The cumulative sediment yield (loss) by water erosion was estimated at 14.60 and 0.46 t ha^{-1} for the monsoon of 2008 and 2009, respectively, with an average for the 2 yrs of 7.53 t ha^{-1} yr^{-1}. Polyakov et al. (2010) found that this watershed had an average sediment loss of 2.31 t ha^{-1} yr^{-1} for the period of 1975–2008. Net loss by wind was 0.07 and 0.09 t ha^{-1} for the periods of March 2008 to March 2009 and March 2009 to March 2010, respectively, giving an average for the 2 yrs of 0.08 t ha^{-1} yr^{-1}.

4. Discussion and conclusions

The horizontal wind blown sediment flux measured in this study of 7.0 g m^{-1} d^{-1} during the monitoring period falls within the range of sediment mass fluxes reported in the literature (Gillette and Pitchford, 2004; Vermeire et al., 2005; Li et al., 2007; Breshears et al., 2009). Breshears et al. (2009) reported an average horizontal sediment flux of 4.9 g m^{-1} d^{-1} from a study conducted by Field (2009) using BSNE samplers for periods of 12 months on a site also located in the Santa Rita Experimental Range, which was similar to our result (7.0 g m^{-1} d^{-1}).

The ratio of water erosion to wind erosion found in our study, in terms of net soil losses over the study area, was approximately 200 to 1 for the first sampling period of March 2008 to March 2009, and approximately 5 to 1 for the second period of March 2009 to March 2010. The results give a snapshot of the relative importance between wind and water erosion in a semiarid watershed. However, it should be noted that both water and wind erosion are characterized by high spatial and temporal variability in semi-arid regions. Sediment production rates in semiarid environments are generally defined by high magnitude, low frequency rainfall events (Nearing et al., 2007). Long-term data (34 yrs) showed that sediment yields ranged between 0.85 and 6.69 t ha^{-1} yr^{-1} in the Santa Rita Experimental Range (Polyakov et al., 2010). There are no long-term measurements of wind erosion in the study area, and however, measurements of wind erosion for 7 yrs of study at Big Spring, TX, showed that wind erosion varies over nearly an order of magnitude from 39.9 to 287.8 t ha^{-1} (Van Pelt and Zobeck, 2004). Therefore, the ratio between water and wind erosion is highly dependent on the rainfall and wind conditions, as the 2 yrs of data show. This highlights the need for monitoring over a range of seasonal conditions, especially for wind erosion measurements. As there are no long-term wind erosion measurements in the study area, it is instructive to put the data in context to the long-term water-induced sediment record for this site. Sediment yield from the 2008 monsoon accounted for approximately 19% of the total sediment yield by water erosion during the past 34 yrs for this watershed. This type of variability is not unexpected. Lane and Kidwell (2003) reported results for 16 yrs of measurements for four of the small watersheds monitored by USDA-ARS in the Santa Rita, including watershed 8 used in the current study. They reported that the year with the largest sediment yield accounted for between 18% and 26% of the total sediment yield for that period (Lane and Kidwell, 2003). This illustrates the significance of extreme years for characterizing erosion rates (the monsoon of 2008 might be considered to fall into that category), as well as the inherent difficulties in measuring long-term erosion in general.

The mean annual sediment yield caused by water for this watershed for the 34 yr period spanning 1975–2008 was 2.31 t ha^{-1} yr^{-1} (Polyakov et al., 2010), which is a ratio of approximately 29 to 1 water to the 2-yr wind erosion measurement. Lane and Kidwell (2003) reported a slightly greater measured sediment yield rate of 3.67 t ha^{-1} for the same watershed for the period of 1976–1991 using the same flume and traversing slot sediment samplers.

One obvious question is whether the study period was representative of a longer time period in terms of wind erosion. In order to assess how the wind erosion rates measured from March 2008 to March 2010 compare to the long term wind erosion rates, wind speed data during the monitoring period were compared to that measured over a period of 2004 and 2008. Fig. 7 shows cumulative relative distribution of daily average and maximum wind speeds at the study location for the years 2004 to 2008. The results suggested that wind conditions during the study period were representative of the most recent 5 yr period.

Breshears et al. (2003) reported median wind erosion rates, using vertical mass flux measurements, of 0.055 t ha^{-1} yr^{-1} for a shrubland, 0.030 t ha^{-1} yr^{-1} for a grassland, and 0.033 t ha^{-1} yr^{-1} for a forest in Colorado and New Mexico. Our measured wind erosion rate of 0.080 t ha^{-1} yr^{-1} is comparable with these measurements. An erosion rate of 0.080 t ha^{-1} yr^{-1} translates to a denudation rate of approximately 0.7 mm per 100 yrs (using a soil bulk density of 1.23 g cm^{-3}). These rates are all extremely small compared to many other commonly reported rates of erosion by water, even in non-agricultural areas (Nearing et al., 2005, 2007). Breshears et al. (2003) reported estimated annual water erosion rates of 0.0044, 0.15, and 0.0083 t ha^{-1} yr^{-1} for the same shrubland, grassland, and forest sites as reported above, respectively. Water erosion rates in that study were estimated based on extrapolations of previously conducted rainfall simulation experiments from the same sites, assuming linear estimates of erosion from infiltration-excess rainfall rates based on 2-yr return frequency storms. Both of these assumptions (linear extrapolation and the 2-yr event) could have caused underestimations of the long-term water erosion rates. Compared to measured rates of soil erosion

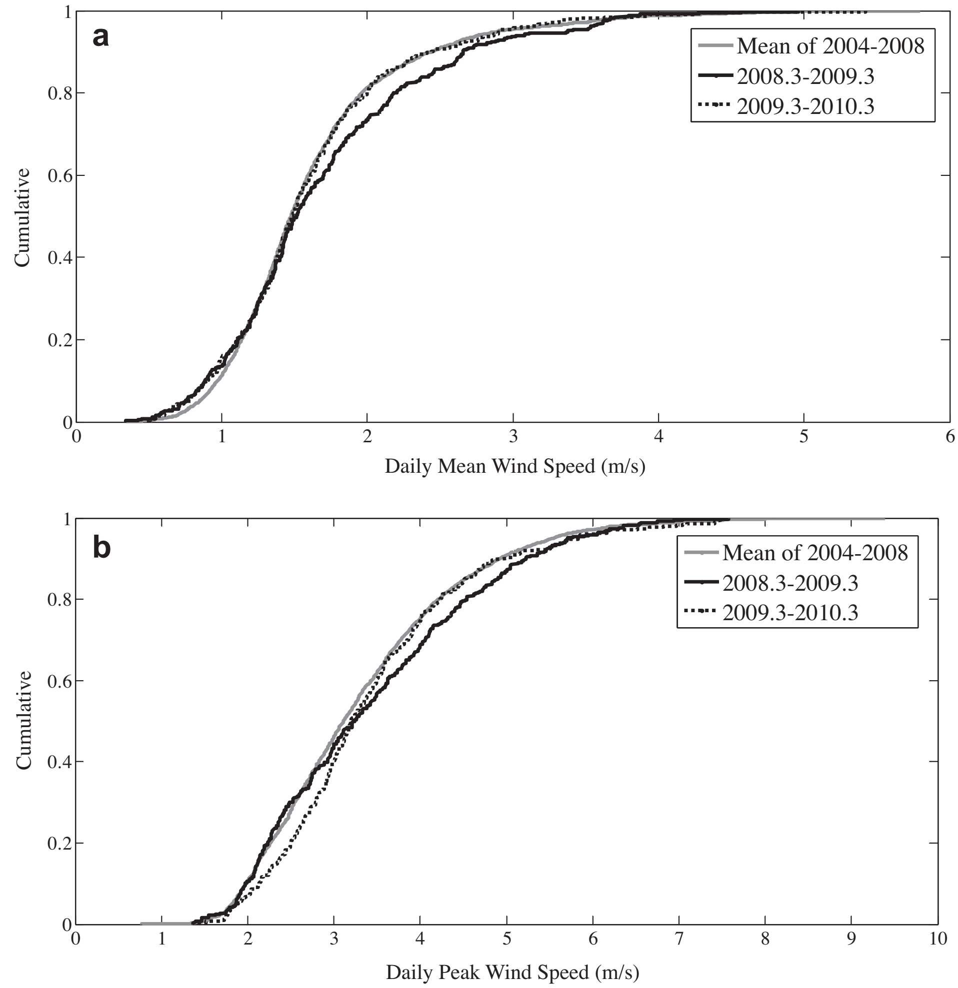

Fig. 7. Cumulative frequency distribution of (a) daily average wind speed and (b) maximum 30-min wind speed for the years of 2004–2008 and the study period.

by water in this and other studies, all of the measured and estimated erosion rates reported by Breshears et al. (2003) were essentially negligible, with the possible exception of the water erosion rates for the grassland.

Recent studies of wind erosion in natural environments (Breshears et al., 2003, 2009; Field, 2009) have focused on comparative rates of sediment flux by wind and water, without definition of sediment contributing area. In the case of erosion by water it may be relatively easy to delineate the boundaries for the source area of sediment, while that definition for wind erosion measurements can be more difficult. Flux of wind blown sediment cannot be considered as erosion in terms of mass of soil loss per unit area per unit time unless the source area of horizontal wind transport is defined. In other words, one does not know with the wind flux measurements alone where the sediment originated, whether from the immediate area or from far away. Erosion is by definition a mass balance problem and is addressed by considering fluxes into and out of a control volume (or area). It is essential in studies that undertake measurements of rates of both wind and water erosion that sediment contributing areas be defined in order for soil loss rates to be quantified.

The results of this study indicated that rates of soil erosion by water greatly exceeded rates of erosion by wind in this small watershed in southeastern Arizona over the period of study. Given the paucity of erosion data, particularly for erosion caused by wind, much more work needs to be conducted using scientifically defensible methods to identify dominant processes and quantify longer-term rates of erosion in semiarid regions. Due to the temporal variation of wind and water erosion, long term field data from measurements on the same surface and area are needed to compare average water and wind erosion rates in the future studies, ideally combined with the use of well-calibrated physically-based soil erosion models to extrapolate and extend the temporal record.

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