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Field Experiments for Evaluating Wind Erosion Models

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Abstract: Erosion of soil by wind is a serious problem in many arid regions throughout the world. Agricultural producers, as well as managers of non-agricultural lands, need to know how different management practices impact wind erosion. For this purpose, several wind erosion models have been developed. Models, however, need to be tested using experimental data. This paper reviews wind erosion field research, emphasizing recent contributions, and describes experiments and measurements required to evaluate wind erosion models. Three types of data are needed to evaluate wind erosion models: airborne sediment flux, meteorological data and data describing the condition of the field surface. The Big Spring Number Eight (BSNE) and the Modified Wilson and Cooke (MWAC) samplers are the most widely used collectors of airborne sediment. The Sensit and the Saltiphone do not collect sediment, but continuously record the occurrence and intensity of saltating particles. Additional work is needed to investigate their use for the actual quantification of sediment flux. Several researchers have developed some type of continuously weighing sampler: a sampler and an electronic scale combined in one apparatus. These devices are not yet fully operational and are expensive. Their cost has to decrease if they are to be used more widely. More research is also needed on methods to continuously measure soil moisture at the soil surface. Radiation data such as surface albedo may be useful in this regard.

Key words: Airborne sediment flux, BSNE, Sensit, soil moisture, albedo.

Many arid regions in the world experience a serious problem of erosion of soil by wind. Arid ecosystems are fragile, as seen recently in northern China, where drought and overgrazing (Armstrong, 2001), and deforestation (Fryrear, personal communication) have caused land degradation with resultant wind erosion resembling the dust bowl days of the 1930's in the USA. The Sahelian region of West Africa has seen dramatic changes in the past few decades, with decreasing rainfall, vegetation and wildlife on the southern fringes of the Sahara Desert. Arid ecosystems may degrade for several reasons, such as prolonged drought, overgrazing and, in the case of military lands, training and testing. Agricultural lands are adversely impacted by soil tillage that leaves little residue on the soil surface and by cropping systems that leave the soil surface bare for long periods of time, making it more vulnerable to wind erosion.

Agricultural producers, as well as managers of non-agricultural lands, need to know how different management practices impact wind erosion. The Wind Erosion Research Unit (WERU) of the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) in Manhattan, Kansas, USA, is developing a process-based Wind Erosion Prediction

System (WEPS, Hagen, 1991; Wagner, 2001) for the simulation of wind erosion and dust emission for different management scenarios, including different cropping and tillage systems. Models such as WEPS, however, need to be tested in the field (Hagen, 1991).

Until recently, actual measurements of wind erosion under field conditions were scarce. More data need to be collected to test wind erosion models under a broad range of climatic, soil, and management conditions (Fryrear, 1995). The Wind Erosion Customer Focus Meeting, organized by WERU in December 1998, listed the completion of an extensively field tested WEPS as WERU's number one priority.

The objectives of this paper are to review wind erosion field research, emphasizing recent contributions, and to describe experiments and measurements needed to evaluate wind erosion models. First, equipment used for measurement of wind erosion in the field will be discussed.

Measurement Techniques and Equipment

Equipment has been developed to sample wind blown sediment during a dust/sand storm. These sampling devices are known as samplers, traps, catchers, or collectors of sediment, sand, soil or dust. Fryrear (1986) developed a field dust sampler and named it Big Spring Number Eight (BSNE, Fig. 1). The BSNE is probably the most widely used sampler in wind erosion field research. Another frequently used sampler is the Modified Wilson and Cooke (MWAC) sampler (Fig. 2). It was originally developed by Wilson and Cooke (1980) and later modified by Kuntze *et al.* (1990).

Using a wind tunnel, Goossens *et al.* (2000) determined the efficiency of several samplers for wind speeds between 6.6 and 14.4 m s^{-1} using sediments of three different sizes with median diameters of 132, 194, and 287 µm. Efficiencies of the MWAC ranged between 90 and 120% and those of the BSNE ranged between 70 and 130%.

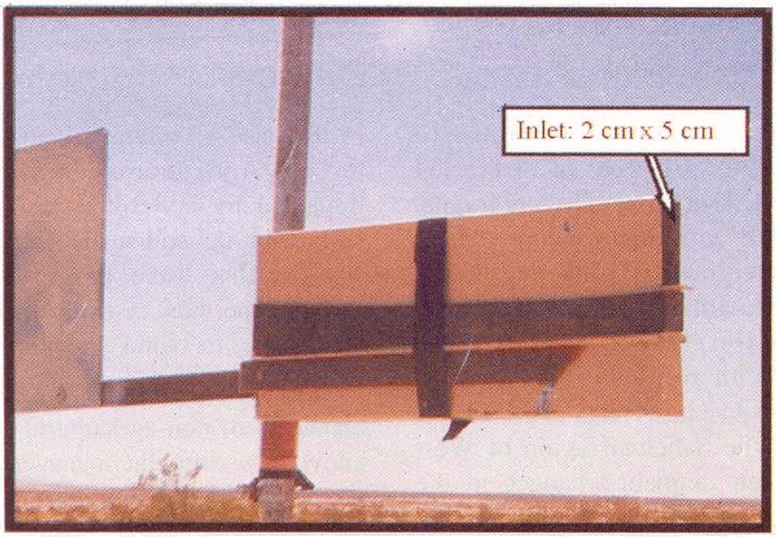

Fig. 1. BSNE airborne sediment sampler.

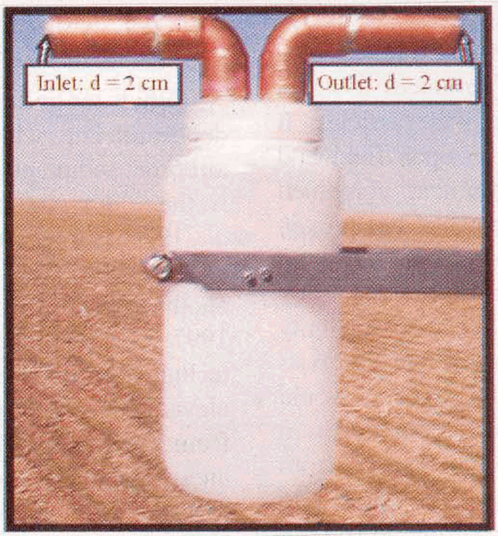

Fig. 2. MWAC airborne sediment sampler. This version was constructed at the Wind Erosion Research Unit in Manhattan, Kansas, USA. It is larger than what most other researchers have used.

Shao *et al.* (1993) investigated the efficiency of a version of the BSNE that included a rain hood. Their conclusions were similar: an efficiency of 90% for sand, becoming less efficient for particles smaller than 100 μm, with 40% efficiency for particles less than 10 μm.

Typically, samplers are arranged vertically with the lowest sampler just above the soil surface and the highest sampler at e.g., 1.5 m above the soil surface (Fig. 3). Sampled sediment is collected and weighed after each erosion event (dust storm) or at a regular interval, e.g., once a week, month, etc. Weights are converted to sediment flux per m^2. For each sampler station, sediment flux is fitted to an equation such as:

$$q(z) = a(z+1)^b \quad \text{... (1)}$$

where,
$q(z)$ is sediment flux (kg m^{-2}), z is height of the sampler opening above the soil surface (cm), and a and b are fitting parameters (Fig. 4). Fryrear and Saleh (1993) and Sterk and Raats (1996) discuss the vertical distribution of wind-eroded sediment in detail. Sediment discharge at a sampler station is determined by integrating equation 1 from 0 to e.g., 200 cm:

$$Q = \int_0^{200} q(z)\,dz = \frac{a}{b+1}\left[(200+1)^{b+1} - 1\right] \quad \text{...(2)}$$

where,
Q is sediment discharge (kg m^{-1}). Field soil loss or deposition (Mg ha^{-1}) can then be calculated from the sediment discharge crossing the field boundaries. Thus, several sampler stations, located on the field boundaries, are required.

Another class of sampler does not collect material moved by wind, but continuously records the occurrence and intensity of saltating particles without collecting them. The Sensit and the Saltiphone are the most prominent devices in this class. The Sensit (Gillette and Stockton, 1986; Fig. 5) is a piezoelectric device that produces a signal upon impact of saltating soil particles. It has been used both in the open field and in wind tunnels. The instrument, combined with wind speed measurements, has proven useful for the determination of the threshold friction velocity at which soil erosion by wind starts. Use of the Sensit to not only detect, but also quantify horizontal soil mass flux would be very useful since it would provide much better time resolution of erosion during a single storm than one can get from sediment samplers such as the BSNE and the MWAC (van Donk *et al.*, 2002). A sensor with a similar function as the Sensit is the Saltiphone (Spaan and van den Abeele, 1991; Fig. 6). The sensing element of the Saltiphone is a microphone that produces a signal upon the impact of saltating grains. Like the Sensit, it is useful for assessing the threshold friction velocity.

Other techniques determine erosion/deposition rates without measuring horizontal airborne sediment flux. One such method is the ^{137}Cs isotope technique (Ritchie *et al.*, 1974; Harper and Gilkes, 1994; Chappell *et al.*, 1996; Yan Ping *et al.*, 2001) and another is using erosion pins (Huang *et al.*, 1997; Gachimbi and Ndathi, 1997). These techniques measure changes in soil surface elevation and their temporal resolution varies from days to several decades. In semi-arid areas soil surface elevation changes result from erosion by both wind and water, making it impossible to use these methods to determine the erosion rate caused by only one of these two processes (Visser and Sterk, 2001). Because of this and the low time resolution, these methods are not suitable

Fig. 3. Station with 6 BSNE samplers. The bottom 2 samplers have smaller openings and share a wind vane.

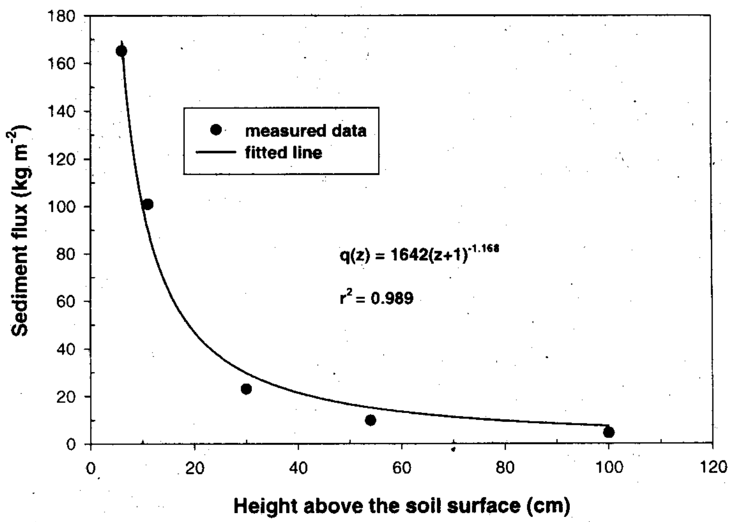

Fig. 4. Sediment flux for January, 2001 on a site near Twentynine Palms, California, USA. The area under the fitted curve represents sediment discharge.

for testing process-based wind erosion models.

Field Experiments

Bagnold (1941) was probably the first to simultaneously measure wind speed and airborne sediment flux. He conducted his experiments on sand dunes in the Libyan Desert using pitot tubes at four heights, a buried trap for sand creep and a sampler with an opening 12.7 mm wide and 0.76 m high for saltation. Since Bagnold, other researchers have conducted wind erosion measurements in the field. Some had the purpose of evaluating a wind erosion model; others did not have this explicit objective.

Experiments for evaluating wind erosion models

Fryrear *et al.* (1991) describe a setup for wind erosion measurements on a circular field with a radius of 91 m. Wind erosion was measured at 25 sites in 13 different states in the USA with a total of 51 site-years to be used for the verification of WEPS (Fryrear *et al.*, 1998). The most intensive data collection took place on a sandy soil near Big Spring, Texas, USA. BSNE samplers were arranged vertically to sample horizontal sediment discharge. Sensits were used to identify periods with sediment movement and to determine relative sediment flux. Weather data also were collected on site and included wind speed, wind direction, solar radiation, relative humidity, air temperature, and rainfall. Temporal field site characteristics that were measured periodically included surface roughness, plant/residue cover, and dry aggregate size distribution.

Van Pelt *et al.* (2001) used Fryrear's measured data to compare it to simulations with the Wind Erosion Equation (WEQ, Woodruff and Siddoway, 1965). Comparison was complicated because WEQ does not

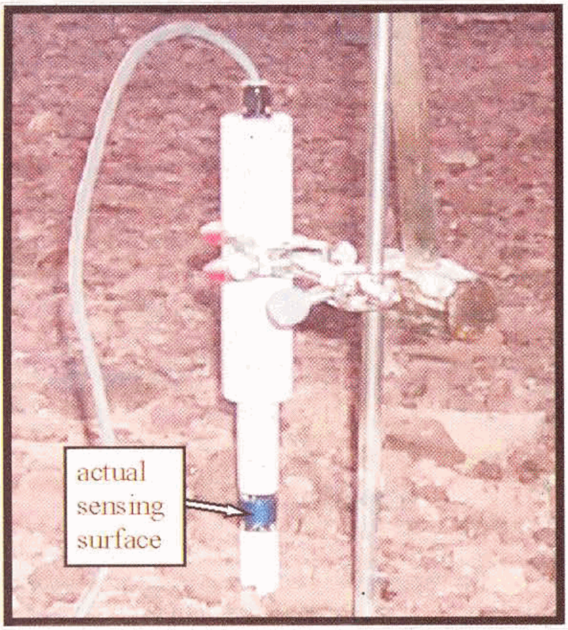

Fig. 5. Sensit automated, continuous saltation detector.

use actual wind data corresponding to the period of erosion measurement, but a climate factor that reflects an historical long-term average wind speed for a particular location. Overall, WEQ predicted only 53% of the total measured erosion. It underestimated 11 of the 14 periods investigated by as much as a factor of nine. One of the conclusions was that 'in spite of the sophistication of our data collection and predictive models, there are probably sources of variability in any field that we may not ever be able to quantify and predict'. Other researchers, including Sterk (1997) and van Donk and Skidmore (2001) also found high spatial variability in sediment discharge in their experimental fields. High spatial variability is probably typical for most fields. Large spatial variations in erosion occurred even on experimental fields where attempts were made to make them uniform for purposes of the experiment (Hagen, 2001).

Zobeck *et al.* (2001) used Fryrear's measured wind erosion data to compare to erosion simulated by the Revised Wind Erosion Equation (RWEQ, Fryrear *et al.*, 1998), which makes estimates of wind erosion based on a single event wind erosion model that includes factors for wind, rainfall, soil roughness, the erodible fraction of soil, crusting, and surface residue. The study included 41 storm events at six locations. There was a significant correlation between measured and predicted field soil loss. There were many possible explanations for the discrepancies between measured and predicted results. The input factors were often measured many weeks before or after an erosion event and they were measured using a variety of methods. In addition, the exact period of erosion was not well represented by the wind factor. By definition, the wind factor was calculated for the entire day of the erosion event. For some erosion events, the wind actually blew prior to midnight of the erosion day, but its effect was not included in the simulation.

Hagen (2001) used Fryrear's measured wind erosion data to compare with WEPS simulations. He found reasonable ($r^2 = 0.65$) agreement between measured and predicted soil loss. However, several of the field surface parameters needed for WEPS were not measured and had to be estimated. Crust cover fraction was estimated from cumulative rainfall since the last tillage operation. The aggregate and crust dry stabilities were assigned average values based on soil texture. The surface soil was assumed to be air dry during the erosion events.

To test WEPS, van Donk and Skidmore (2001) conducted a field experiment near Burlington, CO, USA, on a silty loam with small winter wheat plants and 1200 kg ha^{-1} of flat corn residue. Equipment used were BSNE samplers and Sensits. Relevant weather elements were measured and status of living vegetation, residue, topsoil, soil roughness, soil surface moisture, and crust condition were recorded at three points in time during the 5-month experimental period. There was one significant dust storm during this period with large variations in sediment discharge on the 600 m by 400 m field. Sensit particle count and wind speed were closely correlated (Figs. 7 and 8). These data allow for the determination of threshold wind speed above which soil erosion by wind starts (Fig. 8). WEPS overestimated the protection against wind erosion provided by small wheat plants. It needs a provision to account for standing biomass that is not uniformly spaced, such as wheat plants in the field.

Wind erosion experiments not explicitly designed for evaluating models

Helm and Breed (1999) deployed Sensits to measure airborne sediment transport for

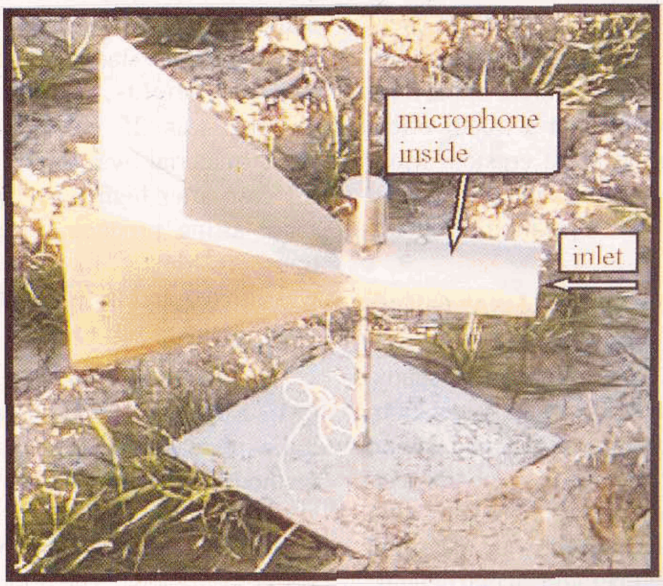

Fig. 6. Saltiphone automated, continuous saltation detector.

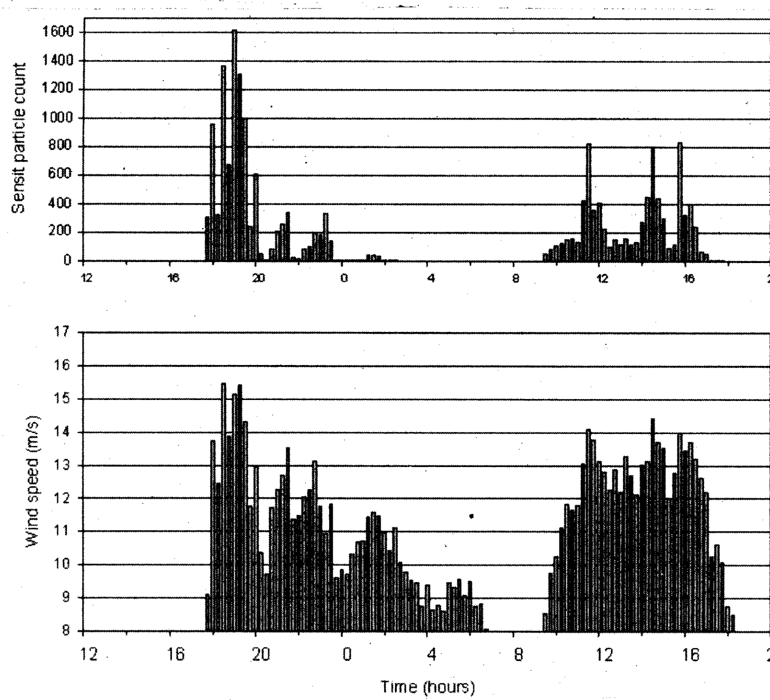

Fig. 7. Wind erosion on a field near Burlington, Colorado, USA on 17 and 18 December, 2000. Wind speed was measured at a height of 2 m. Data are 15 minute averages.

natural desert areas at three sites in New Mexico and Arizona, USA. Wind speed and precipitation were also measured. Short-term antecedent precipitation had a minor effect on the vulnerability to wind erosion. More long-term antecedent precipitation encouraged growth of vegetation, reducing wind erosion.

In southern New Mexico, USA, Gillette and Chen (2001) measured wind erosion over a period of three years on a flat, sandy, and crusted site that was without vegetation. Three meteorological stations and seven BSNE stations were placed in a line transect. At each meteorological station, precipitation was measured, wind speed was measured at four heights, air temperature at two heights, and Sensits were positioned at four heights. At each BSNE station samplers were placed at three heights. The threshold friction velocity was 25 cm s^{-1} when supply of loose material was unlimited, which was the case after high wind speed events with sandblasting producing fresh sediment for transport. Most of the time however, supply was limited and threshold friction velocities were greater, up to 100 cm s^{-1}.

Gillette *et al.* (1997) estimated vertical PM_{10} flux for a saline playa of Owens (dry) Lake in California, USA, using the gradient method, and measuring PM_{10} concentration at two heights. They also measured the total horizontal airborne sediment discharge using BSNE samplers. The ratio of the vertical

PM_{10} flux and the total horizontal sediment discharge was consistent with that found previously for sandier soils.

Bielders *et al.* (2001) derived field scale sediment balances in western Niger from airborne sediment fluxes measured using BSNE samplers. Sediment discharge in a cultivated field increased linearly with distance (up to 80 m) from a non-erodible boundary, regardless of wind power. Sediment discharge in an adjacent fallow decreased exponentially with distance into the fallow. Up to 17.5 Mg ha^{-1} soil loss and 10.5 Mg ha^{-1} deposition were measured in a single storm in the field and fallow, respectively. A second study was set up in a newly cleared, 8 ha farmer's field equipped at 87 locations with BSNE samplers. Spatial variability of sediment discharge (kg m^{-1}) and sediment balance (Mg ha^{-1}) was high. The field had a net deposition of 5.4 Mg ha^{-1} in 1998, but a net soil loss of 5.0 Mg ha^{-1} in 1999. This difference was attributed to changes in ground cover and differences in sediment influx from adjacent fields.

Hupy (2001) installed BSNE samplers in southern New Mexico, USA, on nine study sites with differing vegetative covers and soil surface textures. The entire study area occupied approximately 1 km^2. Sediment was collected over the course of five separate wind events in March and April 2000. Two stations consisting of five BSNE samplers, with openings at heights of 5, 10, 20, 50, and 100 cm, were placed at each of the nine sites. Stations were placed 2 m apart in areas most representative of the site. At

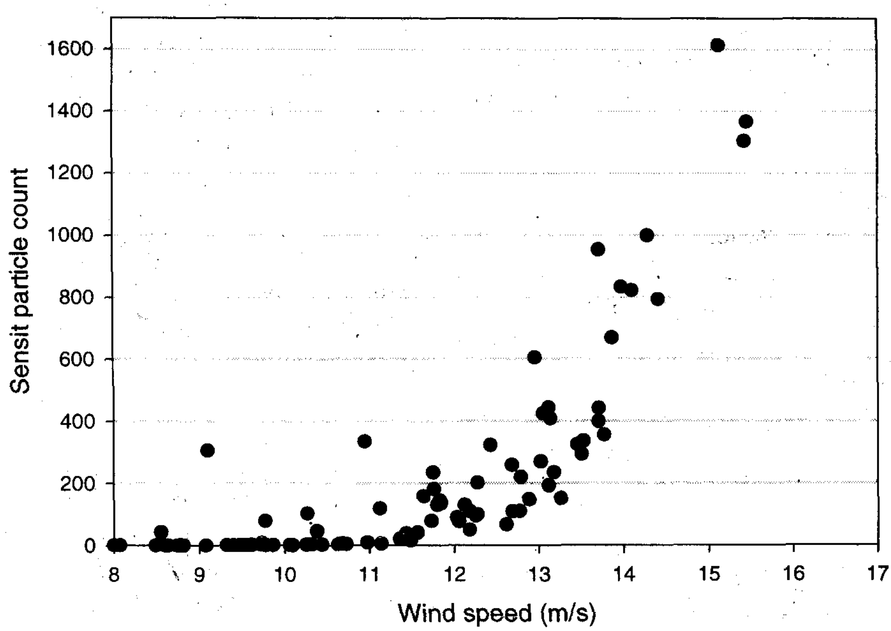

Fig. 8. Determination of threshold wind speed from Sensit and wind speed data. Wind speed was measured at a height of 2 m. Same data as in Fig. 7.

two of the sites, wind profile data, wind direction and saltation activity were recorded. Anemometers were set up at heights of 15, 50, 100, and 200 cm. A Sensit was deployed to measure periods when saltation took place. Percent vegetation cover was determined along linear transects at each site. Soil samples were randomly taken to a depth of 5 cm along these transects to determine soil texture and crust thickness. The results unexpectedly showed very little difference in sediment discharge among most of the sites. A somewhat different experimental design, with upwind/downwind BSNE stations to quantify erosion from each site, might have yielded more insight.

Van Donk *et al.* (2001) quantified wind erosion rates for typical soil, vegetation, and disturbance regimes that occur at the Marine Corps Air Ground Combat Center, Twentynine Palms, California, USA. Five BSNE sampler stations were installed in a line transect at each of the five sites. Each BSNE station consisted of five BSNE samplers. Once a month, sediment was collected from the samplers for analysis. Occurrence of saltating soil particles was measured continuously using Sensits, one at each site. The site with the most erosion had a total sediment discharge of 311 kg m^{-1} over a period of 14 months. Other sites eroded much less because of significant rock cover or the presence of a crust. Sensit particle count and sediment discharge measured with BSNE samplers are related and a detailed time series of wind erosion can be reconstructed combining these data (Fig. 9). This measured time series can be used for comparison with simulation results from process-based wind erosion models such as WEPS.

Sterk (1997) measured wind erosion on a rectangular field of 60 x 40 m in Niger. His measurements showed that soil loss/deposition can have a high spatial variability. Visser and Sterk (2001) argue that wind and water erosion should be studied simultaneously in semi-arid zones, where the two processes contribute about equally to soil degradation. They give the example of the West African Sahel, where strong windstorms often precede rainstorms. Sediment transported by wind in one direction may be moved by water in another direction. Therefore, both processes should be studied simultaneously to better understand the impact of wind and rainfall on soil degradation. Visser and Sterk (2001) further emphasize that for results from different studies to be comparable and for their extrapolation from one region to another, it is important that quantification techniques and methodologies be standardized.

Visser (2001) describes the experimental design of research on the impact of both wind and water erosion on soil fertility in a sub-catchment of the Katchari catchment in northern Burkina Faso. At three different morphological units (a valley floor, a dune and a gravel crust), measurements on wind and water erosion were conducted. At each field MWAC samplers, Saltiphones and runoff plots were installed. There was enough sand and silt available in the soils for the formation of a thin crust, having implications for both water and wind erosion.

Rajot and Valentin (2001) assessed the mass balance (erosion vs. deposition) of sediments <20 μm transported by wind at the scale of a village land unit (25 x 25 km). Measurements were carried out near Niamey, Niger, during three years

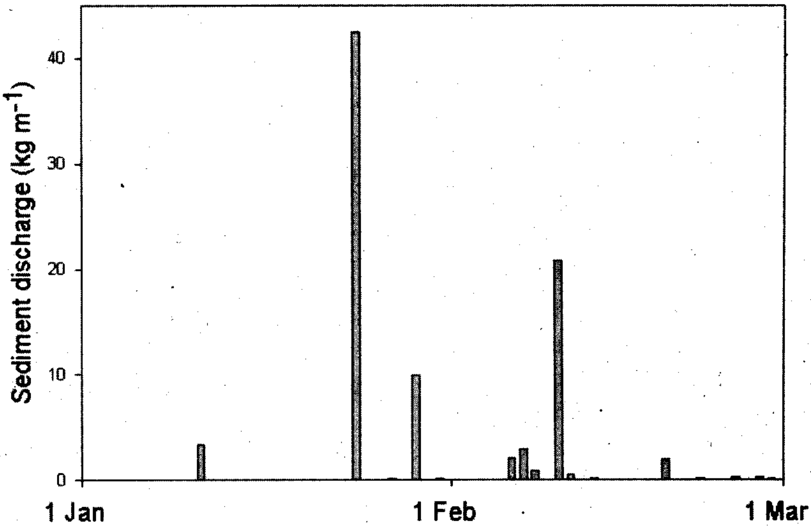

Fig. 9. Daily sediment discharge (kg m^{-1}) on a site near Twentynine Palms, California, USA, based on monthly sediment discharge measured using BSNE samplers and daily Sensit particle count.

(1996-1998) in a cultivated field and in a fallow area. The total deposition flux was measured directly by means of two passive CAPYR samplers (Orange *et al.*, 1990), located at the center of each surface type at 3 m above the soil surface. Deposited sediment was collected daily by filtration of the solution on preweighed 0.45 μm filters. The mass due to particles <20 μm was subtracted from the deposition mass using the particle size distribution obtained by Herrmann (1996). The vertical erosion flux of particles >20 μm was estimated by assuming that it was a fraction of the horizontal saltation flux, which is much easier to measure (Gillette, 1977). The horizontal saltation flux was measured year long using four stations placed in the center of the fields. Each station was equipped with three BSNE samplers at heights of 10.0, 22.5 and 35.0 cm. Deposition fluxes in the field and in the fallow were similar. In the field, wind erosion reached its maximum in May and June when vegetative cover was minimal. The field net balance between deposition and erosion was negative in 1996 and 1998 and slightly positive in 1997. In the fallow area, wind erosion was always very low in comparison with the field, leading to systematic positive net balance between deposition and erosion. These results were extrapolated to the village scale based on land use. At this scale, the balance was positive, indicating a net deposition of aeolian sediments of 0.36 Mg ha^{-1} y^{-1}.

Soil surface moisture is an important factor governing the initiation of soil movement by wind. Cornelis *et al.* (2001) used a laboratory wind tunnel to test an important component of wind erosion models: threshold friction (shear) velocity as a function of surface wetness. Six models predicting the threshold friction velocity for particle detachment from wet soils were tested. The experiments were conducted on prewetted dune sand with moisture contents ranging from 0.003 kg kg^{-1} (air dry) to 0.040 kg kg^{-1}. Sand samples were exposed to different wind speeds for two minutes. Moisture content was determined gravimetrically before and after the experiment and saltation of sand particles was recorded with a Saltiphone. Based on results of these experiments, models by Saleh and Fryrear (1995) and Shao *et al.* (1996) greatly overestimated the 'wet' threshold friction velocity, probably because these models were not calibrated on dune sand. Model comparison showed large differences among the predicted results. At a moisture content close to -1.5 MPa, the increase relative to the dry threshold friction velocity ranged from 6 to 179% (Cornelis *et al.*, 2001). These large differences were attributed to differences in experimental procedures and equipment, the granulometrical characteristics of the sediments tested (McKenna-Neumann and Nickling, 1989) and differences in physico-chemical properties such as salt content of the soils used (Nickling, 1984).

Measurements Required for Evaluating Wind Erosion Models

Three types of data are needed to evaluate wind erosion models. First, there is the airborne horizontal sediment discharge, which is an important dependent variable, or output, that most process-based wind erosion models, such as WEPS, attempt to simulate. Even if a model does not simulate discharge, but field soil loss, as does WEQ, it is still appropriate to measure discharge, since field loss can be calculated from mass (discharge) crossing the field boundaries. Then there are the independent variables, or input data, which can be separated into two broad categories: meteorological data and data describing the condition of the field surface.

Sediment discharge

If field loss or deposition is to be determined, stations with samplers such as the BSNE (Fig. 3) or MWAC should be placed at least on the boundaries of the experimental field. If there are enough samplers, they can also be installed inside the field, which will give more information about the spatial variability (Visser and Sterk, 2001). In tropical and sub-tropical semi-arid regions, many wind erosion events are immediately followed by rainstorms. Under such conditions, an important consideration for selecting a sampler type is the sensitivity to splash erosion. As wind speeds usually remain high at the beginning of the rain, much splash material can be trapped in the samplers, and it is impossible to distinguish it from wind blown material afterwards (Visser and Sterk, 2001).

For testing process-based models it is important to collect sediment after every erosion event. Samplers are emptied using e.g., plastic bags (be aware of possible problems with static electricity) or metal cans. A problem with samplers may be that not only sediment, but also water (rain, snow) is caught, making the sediment very difficult and tedious to collect. In severe cases, it may even be impossible to collect sediment when water has washed sediment out of the sampler before it is collected. This problem was recognized in Australia, where a rain hood was developed for use with the BSNE sampler (Shao *et al.*, 1993). Collected sediment is weighed in the laboratory and sediment discharge for a sampler station can be calculated, as explained earlier. Determining sample aggregate size distribution can be a challenging issue; a sonic sifter will yield an entirely different distribution than that obtained from air separation techniques (Fryrear, personal communication).

The occurrence and intensity of saltating soil particles can be continuously recorded with Sensits and/or Saltiphones. These data can be combined with sediment discharge obtained using samplers (BSNE, MWAC, etc.), located near a Sensit, to reconstruct sediment discharge at the much better time resolution of the Sensit data (van Donk *et al.*, 2002; Fig. 9). Detailed data like this will be useful when comparing measured data with simulation results from process-based wind erosion models. The Sensit versus sampler discharge relationship can also be used to estimate sediment discharge for periods when measurements from samplers are not available.

This estimation method assumes a linear relationship between Sensit particle count and sediment discharge. The relationship may not be perfect for several reasons: (1) Sensits may be saturated at high levels of sediment discharge, (2) Sensit particle count is usually only measured at one height, e.g., 0.05 m, whereas sediment discharge results from an integration of measurements at several different heights between 0 and e.g., 1.5 m, and (3) smaller size particles may be more difficult for the Sensit to detect. Research is needed to more firmly establish the relationship between Sensit (or Saltiphone) particle count and sediment discharge.

Several researchers (Lee, 1987; Janssen and Tetzlaff, 1991; Jackson, 1996; Bauer and Namikas, 1998) have combined the features of samplers such as the BSNE and those of continuous, automated devices such as the Sensit. Most of their products are some type of continuously weighing sampler: a sampler and an electronic scale combined in one apparatus. These devices are not much used (yet), but would certainly be very helpful in wind erosion research. One such device, the SUSTRA (Janssen and Tetzlaff, 1991), has been used in field research in Germany (Funk, 1995), but its efficiency is very dependent on wind speed and particle size (Goossens *et al.*, 2000; Goossens and Offer, 2000), making its use more complicated.

More work is needed to make these continuously weighing samplers fully operational and cheaper, so they can be more widely used. The cost of samplers is important, since many are needed to characterize the typically large spatial variability. Even if non-collecting sensors like the Sensit or Saltiphone could fully quantify sediment discharge without additional samplers, it would still be useful to actually collect sediment samples if aggregate size distribution and/or chemical analysis is desired.

A dust sampler is needed if the study focuses on air quality, necessitating quantification of suspension transport. Also, if the loss of soil nutrients is to be quantified, it is necessary to measure suspended dust, as the smallest soil particles contain the highest concentration of soil nutrients (Figs. 10 and 11). However, when sand transport is studied, for instance as part of dune

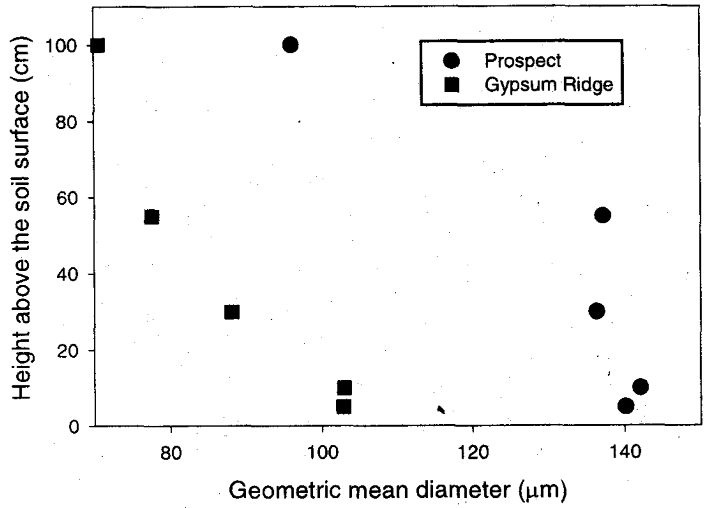

Fig. 10. Geometric mean diameter of airborne sediment at the sites of Prospect and Gypsum Ridge, near Twentynine Palms, California, USA.

formation studies, sampling dust is not relevant (Visser and Sterk, 2001).

Meteorological data

Most wind erosion models use shear stress at the soil surface as the driving force for sediment movement. Shear stress is related to friction velocity:

$$\tau = \rho \, u_*^2 \quad \text{...(3)}$$

where,

τ is shear stress (N m^{-2}), ρ is air density (kg m^{-3}) and u_* is friction velocity (m s^{-1}), which can be calculated from wind speed measured at a known height and the aerodynamic roughness:

$$u_* = \frac{k \, u(z)}{\ln (z/z_0)} \quad \text{...(4)}$$

where,

k is the von Karman constant (0.4), u(z) is the wind speed (m s^{-1}) at height z (m), and z_0 is aerodynamic roughness (m). Wind speed should be measured and preferably be duplicated (2 or more measurements at the same height, e.g., 2 m) because of the risk of sensor failure when data are needed most, i.e., during wind erosion events when wind speeds are greatest. Duplication also provides a good quality check of the data: if the measurements match then the data are probably good; if they do not match then one or more of the anemometers do not function properly.

To determine z_0, wind speed should be measured at several heights such that a logarithmic wind profile is obtained. It may be impractical to continuously record wind profile data, because of the risk of fouling bearings of anemometers close to the ground with moving sediment. A wind profile may be taken at times when sediment is not moving. Research is needed to develop instrumentation that would make it practical to continuously measure wind profiles without the risk of fouling sensors with moving sediment. Air temperature should be measured at a minimum of two heights to correct for non-neutral atmospheric conditions. Alternatively, z_0 may be calculated from measured soil surface roughness and biomass parameters.

Wind direction should be measured, so that the effects of windbreaks, distance from a non-erodible boundary, effective distance between ridges, etc., can be taken into account. Measuring soil surface moisture is important, especially for soils that do not dry rapidly after a rain such as soils with a fine texture and soils during periods of modest evaporation, e.g., during winter in temperate climates. If the surface is wet, much greater friction velocities are needed to move the soil (Cornelis *et al.*, 2001). Soil moisture is very difficult to measure right at the surface. It can be measured gravimetrically using the sampling method described by Reginato (1975) and practiced by Durar *et al.* (1995) and van Donk and Skidmore (2001). Sampling at the surface becomes challenging for a rough surface that is not well defined. Non-automated sampling only produces water contents at a few sparse points in time. Continuous, automated sampling is needed, because surface soil moisture can change very rapidly. However, most automated sensors are not suitable for use near the soil surface. An automated sensor that may be promising for use close to the surface is the dual probe (Campbell *et al.*, 1991; Kluitenberg and Philip, 1999), but closer to the surface it becomes more challenging to keep soil-sensor contact, which is critical for proper functioning of the sensor.

Albedo (short wave reflection coefficient calculated from incoming and reflected short wave radiation) indicates soil surface wetness, as shown in Fig. 12. The soil surface at this site was dry on April 8, 9 and 10. It was wetted by rain on the evening of April 10 and on April 11. The albedo on

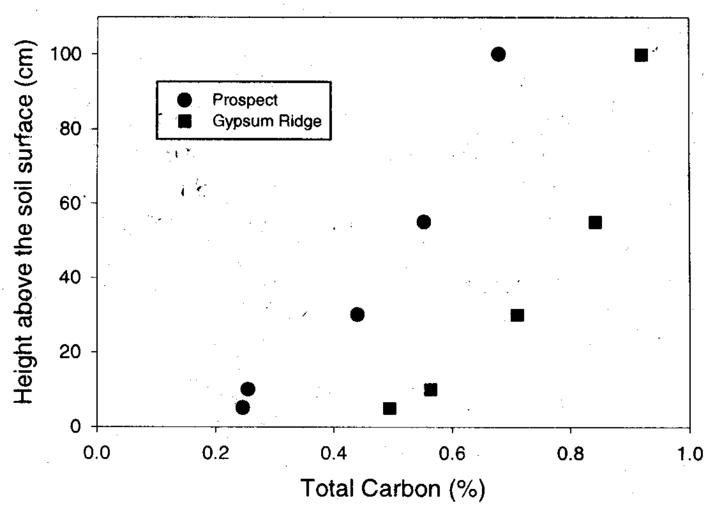

Fig. 11. Carbon concentration of airborne sediment at the sites of Prospect and Gypsum Ridge, near Twentynine Palms, California, USA.

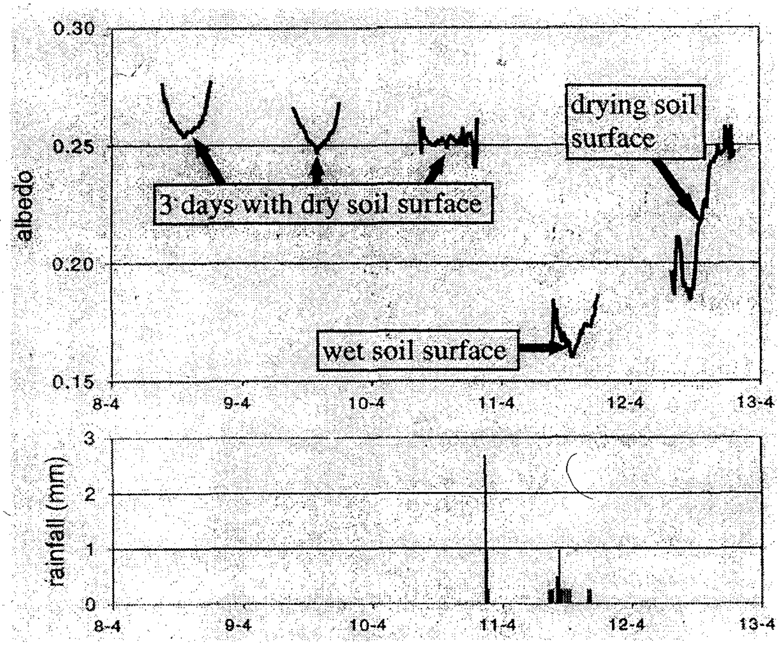

Fig. 12. Albedo and rainfall for 8 April through 12 April, 2001 on a field near Burlington, Colorado, USA. Albedo decreases after rain has wetted the soil surface. It increases again on 12 April, as the soil surface is drying.

April 11 had decreased to about 0.17 from about 0.25 when it was dry on the previous days. On April 12 the soil surface dried and the albedo went back up to about 0.25. The advantage of albedo is that it is an indicator of soil moisture at the very surface of the soil, which is needed in wind erosion research. This has been recognized by other researchers, e.g., Idso *et al.* (1975). Skidmore *et al.* (1975) had good results using a similar idea. They designed an active sensor, emitting near-infrared radiation at different wavelengths and measuring the reflectance. More research is needed on methods to continuously measure soil moisture at the very surface of the soil. This will not only benefit wind erosion research, but other research as well, such as studies on evaporation from the soil and water conservation.

Albedo is also a good indicator of the presence of a snow cover. This information is very important in wind erosion field research in temperate climates during winter, since a snow cover may make the difference between soil being moved by wind or not. Snowfall and snow cover are difficult to measure in an automated fashion. A regular tipping bucket rain guage does not capture snow very well, making albedo valuable for this purpose.

Relative humidity of the air should be measured since it affects surface soil moisture (Gregory and Darwish, 2001; Gregory and Darwish, 1990; Belly, 1964). Precipitation, net radiation and soil temperature should also be measured to help estimate soil surface moisture if this cannot be adequately measured. These weather elements are also important if soil hydrology is modeled, as is done in WEPS.

Soil surface conditions

Field surface conditions should be measured whenever they change significantly. Status of living vegetation, residue, topsoil, soil roughness, and crust condition should all be recorded. To quantify living vegetation, the number of plants from a known area is counted and their heights measured (as standing in the field; not stretched out). Leaves and stems should be separated, since the more rigid stems are much more effective in reducing wind erosion. Leaf area and stem silhouette area are measured using a leaf area meter. In addition, leaf and stem dry mass (in oven for 24 hours at 70°C) should be measured.

Standing residue elements should be counted and their widths and heights measured. Manual methods of counting and measuring provide accurate but slow results, making it costly to obtain representative samples for large fields. Fox and Wagner (2001) developed a device using a laser distance sensor to obtain estimates of stem counts, widths, and heights. These estimates were compared to values obtained using manual counting and measurement. At a scan speed of 2 meters per minute in wheat straw with a stem population of 800 per m^2, counts were estimated accurately, but width and height were underestimated consistently. The apparatus is still under development.

Above-ground flat residue can be collected within a frame of known area. Collected residue is then air dried and weighed in the laboratory. Residue cover can be estimated using a long measuring tape, counting the division marks on the tape that cover pieces of residue. The USDA-Natural Resources Conservation Service (NRCS) has guidelines for the exact procedure.

A few kg of soil should be collected from the top 0.05 m. In the laboratory this soil is used for the following analyses: soil texture using e.g., the method of Gee and Bauder (1986), aggregate size distribution using e.g., a rotary sieve (Chepil, 1962; Lyles *et al.*, 1970) for the larger sizes and using a sonic sifter for the finer material. The aggregate size distribution can be described mathematically according to Wagner and Ding (1994). Dry aggregate stability (Boyd *et al.*, 1983; Hagen *et al.*, 1995) and wet aggregate stability (Kemper and Rosenau, 1986) should also be determined.

Soil roughness can be measured using a pinmeter (Wagner and Yu, 1991; Skidmore *et al.*, 1994). In case of a ridged field, measurements are taken perpendicular to the ridges (ridge roughness) and parallel with the ridges (random roughness). Pinmeter photographs can be taken using either a digital camera or a standard camera followed by digitization. The digital image can be analyzed using software such as SigmaScan Pro (SPSS Inc., Chicago, Illinois, USA[1]). Roughness is expressed as the standard deviation of pin positions, which should be corrected for left to right trends, i.e. downward or upward trends of pin positions from the

[1] Mention of brand names is for information purposes only and does not imply endorsement by USDA-ARS.

left side to the right side of the pinmeter. Such trends increase standard deviation without contributing to soil roughness. Methods for measuring soil roughness are desired that are less complicated, less expensive, and do not require much training. The chain method (Saleh, 1993, 1997) has these advantages, but it also has some weaknesses (Skidmore, 1997). A method, using only a straight edge, is in development. Ridge height and ridge spacing should also be measured. Topography should be characterized, since it changes wind speed near the surface.

Crust (consolidated zone) thickness and crust dry stability (Boyd *et al.*, 1983; Hagen *et al.*, 1995) should be measured. Loose material present on a crust should be quantified. This may be accomplished using a vacuum device (Zobeck, 1989) or a soft brush and a dust pan (van Donk and Skidmore, 2001).

Summary and Conclusions

Collecting sufficient data for evaluating wind erosion models is a daunting task, especially for process-based models. Nevertheless, field testing is needed to increase confidence in such models. Airborne sediment flux, meteorological data, and data describing the condition of the field surface are all needed to evaluate wind erosion models. The BSNE and the MWAC samplers are the most widely used collectors of airborne sediment. The Sensit and the Saltiphone do not collect sediment, but continuously record the occurrence and intensity of saltating particles. Their use to quantify sediment flux requires additional research. Continuously weighing samplers have been developed that combine a sampler and an electronic scale in one apparatus. These devices are not yet fully operational and their cost has to decrease if they are to be used more widely.

More research is needed on methods to continuously measure soil moisture at the soil surface. Surface albedo and other radiative data may be useful for this purpose. Other surface variables, including status of living vegetation, residue, soil roughness, aggregate size distribution, aggregate stability, and crust condition should all be measured to successfully evaluate wind erosion models.

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