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Comparison of measured wind tunnel and SWEEP simulated soil losses

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ABSTRACT

Wind erosion estimates from the Single-event Wind Erosion Evaluation Program (SWEEP) model of the Wind Erosion Prediction System (WEPS) were compared to wind tunnel experiments. The influences of wind speed and soil texture were investigated. From a previous study, soil losses were measured directly in a wind tunnel using three soil types (sandy loam, loamy sand, and sand), each under three free-stream wind speed conditions (10, 18, and 26 m s^{-1}). A different sand soil from another experiment was also tested under five wind speeds from 10 to 18 m s^{-1} over intervals of 2 m s^{-1} using a sediment trap and a flux profile estimating method. The comparison of measured and estimated agricultural soil losses under non-extreme winds (less than 18 m s^{-1} in the wind tunnel) was good. The loamy sand comparison had an error less than 6% while the sandy loam soil had an error of about 35%. SWEEP underestimated the amount of erosion with the sand soil. However, because the estimating equations used in SWEEP to predict soil parameters for agricultural soils are not directly applicable to pure sand surfaces, this was expected. When conducting SWEEP simulations, it is recommended to use the actual aggregate size distribution (ASD) data, if available, rather than relying on SWEEP's ASD parameter values being estimated from other soil properties.

1. Introduction

Wind erosion is a major factor in land degradation in arid and semi-arid regions around the world. It can also result in serious environmental and health problems far from the wind erosion source (Zobeck and van Pelt, 2006). The prediction of soil erosion by wind is important to agricultural production, environmental quality, the identification and reduction of air pollution sources, and the evaluation of socio-economic activities (including agricultural management and engineering construction) which can contribute to wind erosion (Nordstrom and Hotta, 2004).

The Wind Erosion Prediction System (WEPS) model developed by the United States Department of Agriculture Agricultural Research Service (USDA-ARS) is a useful tool for understanding wind erosion activity since it can simulate wind erosion under various surface conditions (Wagner, 2013). The model has given a reasonable prediction of the spatial distribution of mass transport at several field research sites (Deumlich et al., 2006; Funk et al., 2004; Hagen, 2004; Visser et al., 2005).

WEPS provides a stand-alone erosion submodel with a separate interface named SWEEP (Single-event Wind Erosion Evaluation Program). In SWEEP, the simulation region is divided into a grid of uniform rectangular cells, and then the static threshold friction velocity at which erosion begins for each cell is determined. The threshold is calculated based on surface conditions, including random and oriented roughness, flat and standing biomass, crust and rock cover, amount of loose erodible mass on the crust, aggregate size distribution, density of the crusted surface, and surface wetness. Soil loss and deposition are then calculated for discrete periods when friction velocity exceeds the static friction velocity threshold. The user must supply the initial surface conditions along with subdaily wind speeds and daily direction in SWEEP from estimated or measured data (Feng and Sharratt, 2007).

SWEEP is useful for investigating wind erosion processes, soil erodibility, soil mass loss, and spatial distribution of surface erosion for different soil and wind conditions during a single windstorm event. One of its unique functions (shared by WEPS) is its ability to reflect the modification of the soil surface (surface update) during the erosion process, including removal and entrainment of mobile soil and creation of new erodible material. Changes in the amount of mobile surface aggregates (dmt_{los}, kg m^{-2}) during a time interval (Δt) over a distance segment (Δx) based on mass balance concepts as defined by Hagen (2007) is:

$$dmt_{los} = (q_i - q_0 + qss_i - qss_0)\Delta t/\Delta x + F_{an} C_{an} q_i \Delta t \quad (1)$$

where: q_0 and q_i are the horizontal saltation/creep soil discharge (kg/m s^{-1}) out of and into a cell; qss_0 and qss_i are the horizontal suspended soil discharge (kg/m s^{-1}) out of and into a cell; F_{an} is the mass fraction of q_i impacting immobile clods and crust; and C_{an} is the coefficient of abrasion of immobile clods and crust (m^{-1}). Likewise, other surface conditions are also updated during the erosion event, including the mass of mobile soil on a crusted surface, the volume of rock >2.0 mm diameter in the soil, random roughness

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height, etc. Soil erosion stops when the friction velocity is less than the dynamic threshold friction velocity value.

A wind tunnel is useful in studying wind erosion by conducting simulations in controlled boundary and sand supply conditions (Hagen, 1999). In a wind tunnel, wind speed is stable and wind direction does not change, so the eroded soil can be measured more accurately. A limited number of studies have evaluated SWEEP in simulating wind erosion over different surfaces during field wind events, but comparison work with wind tunnel experiments is absent from the literature.

The objective of this study was to examine the performance of SWEEP by comparing its simulated soil losses with wind tunnel measurements and to investigate the influence of wind speed, soil texture, and surface updating on wind erosion.

2. Materials and methods

2.1. Wind tunnel experiment

Comparisons between measured and simulated soil erosion were based on the results of two wind tunnel experiments and the outputs from SWEEP simulations. The experiments were conducted in a blow-type non-circulating wind tunnel in the Key Laboratory of Desert and Desertification of the Chinese Academy of Sciences, Lanzhou China. The wind tunnel consists of: a cross section of 1 m width × 0.6 m height, a total length of 37 m with a power section of 2.6 m; an expansion section of 6.4 m; a stabilization section of 1.5 m where a drag screen and honeycomb system were set to reduce large-scale eddies and establish logarithmic wind flow; a compression section of 2.5 m; a working section of 21 m; and a diffusion section of 3 m (Fig. 1). This tunnel is widely used and fully described in previous studies on wind-blown sand activities (Dong et al., 2002; Liu et al., 2011a).

Two experiments, each replicated three times, were used to obtain measured soil loss in the wind tunnel.

1. The first previous experiment used a direct measuring method to examine soil loss quantities and soil-loss vs. time relationships for the three soils by placing the trays on an adjustable balance below the bottom of the working section in the wind tunnel (Liu et al., 2003). A piece the same size as the trays was first cut out of the floor. The upwind edge of the trays was set level with the wind tunnel floor. During the experiment, soil loss with time was measured by reading the instantaneous weight data from the balance. Reference wind speed (free stream velocity) was measured at 20 cm height directly in front of the tunnel working section using a pitot probe. Tests at three wind speed levels, 10, 18 and 26 m s^{-1} were conducted.

Fig. 1. Wind tunnel used in experiment 1.

Three soil samples (sandy loam, loamy sand, and sand) were cut in their original state and placed in wooden trays with dimensions of 95 cm long, 30 cm wide, and 25 cm deep. The soils in each tray were then "plowed" using a hand spade to a depth of 10 cm and smoothed with a straight-edge tool; visible grass residue and roots were hand-picked from the soil. The erosion rate fell faster at higher wind speeds and led to different erosion duration test times for the three wind speed conditions: about 1 h for the 10 m s^{-1} condition, 18 min for 18 m s^{-1} and 6 min for the 26 m s^{-1} one. Thus the temporal change of soil losses were reported with different intervals (time space between two reports): 10, 3, and 1-min of intervals for the 10, 18, and 26 m s^{-1} wind speed conditions, respectively.

2. The second experiment used a prediction equation for the vertical profiles of the saltating sand to calculate the total sand flux passing a downwind sand sampler. Sand materials collected in the Dunhuang Yadarn National Geopark were brought to the laboratory and laid flat on the floor of the wind tunnel 4 m from the upwind edge of the working section. The dimensions of the sand bed were 5 m long, 1 m wide and 10 cm deep (Fig. 2). Sand was chosen as the test material because its properties do not change significantly under human disturbance.

A step-like sand sampler, with ten contiguous 2 × 2 cm openings running the full height of the sampler, was set in the middle of the tunnel floor 1 m behind the sand bed to obtain the vertical distribution of sand flux from 0 to 20 cm height. This kind of sampler is widely used in wind-blown sand observations in the field (Liu et al., 2011b; Zhang et al., 2007). To obtain the temporal change of soil loss, the wind tunnel fan was stopped every 10 min and the sampler was removed to weigh the collected sand at each height. Thus temporal changes in soil loss were reported at 10 min intervals.

Former wind tunnel experiments have shown that the sand transport rate decreases exponentially with height (Dong et al., 2003, 2004; Goossens and Offer, 2000) as

$$M = \mathrm{a}\cdot\exp(\mathrm{b}Z) \tag{2}$$

where M is the quantity of transported material (kg), Z is the height above the surface (m), and a and b are the regression coefficients. The total transported material (kg m^{-1}) was then estimated using Matlab software by integrating Eq. (2) from the surface to 60 cm height (top of the wind tunnel).

Five reference (free stream) wind speeds were tested from 10 to 18 m s^{-1} at 2 m s^{-1} intervals. Wind velocity was measured using pitot tubes at 10 heights (0.5, 0.9, 1.5, 2.2, 4.3, 8.3, 12, 16, 20 and 24 cm above the surface) located 1 m behind the sand bed. The measured wind profiles were fitted to the Prandtl equation which is used as a standard practice in aeolian transport studies (Neuman et al., 2009) as:

$$U(z) = u*/k\cdot\ln(z/z_0) \tag{3}$$

where $U(z)$ is the wind speed value at z (m) height (m s^{-1}), u^* is the friction velocity (m s^{-1}), k is the von Karman coefficient, and z_0 is the roughness length (m). A minimum R^2 of 0.90 and an average of 0.92 were obtained. The values of u^* and z_0 are also provided in Fig. 3.

The soil conditions in the wind tunnel experiments are listed in Table 1. Liu et al. (2003) first reported zero gravel content for sandy loam and 24.4 g kg^{-1} for the loamy sand in the first layer. However, results of that experiment showed 20% and 30% gravel at the surfaces of sandy loam and loamy sand soils, respectively, at the beginning of the test, but the volume gravel fractions which would be used in SWEEP were unknown. An assumption has to be made that gravels were evenly distributed in the soil depths, and these two values were entered in the SWEEP simulation.