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Developments in Measurement and Models for Suspension-Dominated Wind Erosion

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ABSTRACT

In recent years, many urban areas in the Western U.S. have experienced concentrations of airborne dust particulates, which exceeded the federal health standards. The policy considerations raised by the impact of eolian dust from upwind agricultural sources on downwind air quality have emphasized the need for improved prediction methods. Most current wind erosion models predict average annual or seasonal erosion amounts, and only approximate estimates of suspended dust emissions are available. Furthermore, most wind erosion research has been conducted on sandy soils and the derived models consider the vertical (suspension) component of wind erosion as negligibly small in comparison to the horizontal (saltation/creep) component. A project on the Columbia Plateau of Eastern Washington State was initiated to develop an empirical method to estimate dust emissions on a wind event basis. Three years of field measurements, wind tunnel tests and laboratory analyses have been combined to provide a wind erosion equation and a related vertical flux dust emission model. Continuing data analysis indicates that suspension may dominate as the primary mode of transport in the study region due to the significant amounts of suspension-size particles prevalent in the regional soils. The application of contemporary wind erosion measurement techniques to loess soils are discussed in terms of project results.

INTRODUCTION

Determining release rates of aerosol-size particulates from disturbed soils during wind erosion events is a critical step needed to incorporate air quality prediction into wind erosion models. During high wind events, large quantities of PM_{10} and $PM_{2.5}$ may be released from eroding source areas and transported long distances downwind as a fraction of the suspension component of the eroded soil. Particulate aerosols arise from the soil surface when it is abraded by saltating aggregates and mineral grains and from direct entrainment from the soil surface by turbulent eddies in surface winds (Kind, 1992; Loosmore and Hunt, 2000). Wind erosion prediction models generally consider the aerosols generated by these processes as a portion of the suspension component of the eroded soil (Mirzamostafa et al., 1998). The particle size distribution of aerosols arising from wind erosion has been measured by several means (Gillette et al., 1974; Gillette and Walker, 1977; McTainsh et al., 1997) and modeled mathematically (Shao et al.,1993; Marticorena and Bergametti, 1995; Zobeck et al., 1999). Previous methods used to quantify aerosol release rates for wind erosion of soils include, among others, sandblasting aggregates in laboratory settings (Alfaro et al., 1998), measuring concentrations of fine particles during wind tunnel experiments (Arkin and Perier, 1974; Mirzamostafa et al. 1998; Weinan et al., 1998) and by direct field measurements (Gillette et al., 1972, 1997).

A primary objective of the Columbia Plateau PM_{10} Project was to develop an empirical model to predict the contribution of dust emissions from wind erosion of agricultural fields to regional PM_{10} concentrations (Saxton, 1995b). A two-step model was developed which first predicts the horizontal flux of eroded soil from factors known to cause and control wind erosion, then subsequently estimates a corresponding vertical flux of PM_{10} for the erosion event (Saxton et al., 1998). In this model the PM_{10} flux is estimated directly from the horizontal soil flux, not as a fraction of the suspension component. Model development required specialized equipment for data collection, which cannot be easily employed by action agencies interested in assessing the potential erodibility and dust emission from soils in lands under their purview. Thus, a second project objective was to develop tools, which would allow field agents to estimate soil erodibility and dust emission potential with readily available methods and equipment. This paper will present an overview of the model and a tool for assessing the dust emission potential of disturbed loessial soils.

MATERIALS AND METHODS

A two-step approach was used to relate the potential for wind erosion under natural winds and conditions common to the Columbia Plateau to particle size analysis of soil samples. The first step was to estimate soil erodibility for the range of regional soil classes encountered on the Columbia Plateau by a combination of experimental techniques. Erodibility was measured under natural winds at three field sites and with a wind tunnel at forty field sites (Saxton et al., 1998). The second step was to relate the erodibility found for the wind tunnel trials to the size distribution of samples taken from the soil surface at the trial sites.

Field Erosion: The field wind erosion sites were installed at three locations; HHH, T-16, and RITZ (Horse Heaven Hills region near Prosser, WA; T-16 Ranch near Lind, WA; near Ritzville, WA). All sites had silt loam soil developed from loess, some containing abundant volcanic ash. The on-site meteorology was recorded by cup

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anemometers located at heights of 0.1, 0.75, 1.5, 3.0 and 5.0 m, thermocouples at 0.1, 2.0 and 5.0 m and a tipping-bucket rain gage at 1.5 m. Stream-wise soil erosion was measured at each site using twelve sets of BSNE (Fryrear, 1986) airborne soil collectors arranged in three rows across a 110 x 54 m rectangular grid at heights of 0.1, 0.2, 0.5, 1.0, and 1.5 m (Stetler and Saxton, 1996). The BSNEs were located in the prevailing downwind corner of summer fallow fields, each with a fetch of at least 200 m. Creep samplers were installed within the BSNE arrays to collect sediment traveling at heights of 0.0, 5.0 and 7.5 mm above the soil surface. The streamwise mass flux, representing the total mass of soil traveling through 1 m of field width and to1.5 m height for the duration of the collection period, was calculated by integrating the concentration profile defined by mean sample mass at each collection height. The soil erodibility index, EI, was defined as the intrinsic susceptibility of a tilled soil to erosion by wind when not protected by surface cover, roughness, crusting, or soil moisture. EI was calculated as the ratio of the measured erosion, adjusted to bare soil conditions during a windstorm (Q_t), to the total wind energy (W_t) during that erosive period (Saxton et al, 1998).

Wind Tunnel Studies: A portable wind tunnel measuring 1.0 m, wide, 1.2 m high, 13 m long (Pietersma et al., 1996) was used to measure the relative susceptibility to erosion of a wide variety of soils. Relative erodibility trials were conducted for five replications on forty fields representative of seven major soil classes. For each field trial, a standard surface was prepared by removing all residue and roughness from the surface with a steel garden rake. Constant wind speeds of 18 ms^{-1} at the 1.0 m height were generated over each replication for 10 minutes. Sieved sand was introduced at the upwind end of the tunnel at a constant rate of 90 g min^{-1} to supply an abrader to initiate erosion. Eroded material was collected using a vertically integrating (modified Bagnold) slot sampler connected in series with a high efficiency cyclone and vacuum. The catch from the wind tunnel trials was partitioned by replacing the catch bag at regular time intervals during each trial. Relative erodibility has previously been reported as a ratio of the average soil loss from a set of wind tunnel trials to that from a representative highly erodible site. In this paper, we will report relative erodibility in terms of the soil mass eroded per unit of area per unit of time.

Particle Size Analysis: Five silt loams representing soil types encountered on the Columbia Plateau were analyzed by common dispersed and non-dispersed techniques. The dispersed techniques included laser diffraction (Malvern Instrument[†], Malvern, England) and resistance pulse measurement (Coulter Electronics[†]). The laser diffraction technique has previously been compared to the sieve and pipette method (Gee and Bauder, 1986) for a range of soils (Bittelli, 1998) with quite comparable results. Non-dispersed size distributions of the soils were measured by dry sieving and aerodynamic particle sizing. Dry sieving was conducted on a Rotap[†] rotary sieve shaker and a Gilson[†] Sonic Sifter. The aerodynamic particle sizer was an Amherst Process Instruments Aerosizer[†], operated with the AeroDisperser[†] head.

All of the dispersed techniques require sample pretreatment and sieving: Carbonates are removed by boiling with sodium acetate, organic matter is oxidized by boiling with hydrogen peroxide, dissolved elements are removed by centrifugation and the primary particles are dispersed with sodium hexametaphosphate. All samples are then agitated for 12-16 hours before analysis. Both the pipette analysis and the resistance pulse measurement analysis are conducted in conjunction with sieve measurements of the sand-sized particles. Sands were removed by wet sieving with 53 μm and 100 μm wire mesh screens before resistance pulse measurement. For the sieve and pipette technique, the sand is separated from the dispersed soil by wet sieving with a 53 μm wire mesh screen and then fractionated by dry sieving with 1000, 500, 250, 125 and 53 μm wire mesh screens. Soil samples analyzed by laser diffraction were pre-screened with a 1000 μm wire mesh screen.

Each of the dispersed techniques uses a different approach to determine the equivalent diameter of measured particles. The laser diffraction instrument employs a 2 mW HeNe 633 nm laser and calculates equivalent spherical particle diameter from Mie scattering theory for 65 size increments smaller than 1000 μm. The Coulter counter instrument measures electrical resistance pulses produced by silt and clay particles suspended in a balanced electrolyte solution as they pass through 50 μm and 140 μm apertures. The silt and clay fractions are determined in the pipette method by solving Stoke's Law for settling time to 10 cm for spherical particles <2 μm, <5 μm, <10 μm and <20 μm.

Similarly, the non-dispersed particle sizing techniques also operate on different principles of measurement. The rotary and sonic sieves both measure the geometric diameter of the particle, for ranges of measurement with some overlap. The rotary sieve oscillates a stack of six sieves horizontally 278 times per minute and taps the stack vertically 150 times per minute. Standard eight inch diameter wire mesh sieves with nominal opening of 4000, 2000, 1400, 1000, 710, 500, 355, 250, 180, 125, 90, 63 and 45 μm were used. The sonic sieve oscillates a column of air through a stack of electroformed sieves at 60 Hz while alternately tapping vertically and horizontally 60 times per minute. Soil samples were pre-sieved with a 250 μm wire mesh sieve and then sieved with 150, 100, 63, 45, 30, 15 and 10 μm electroformed sieves.

The Aerosizer operates on the principle of measuring the aerodynamic time of flight of a particle accelerated through twin 3mW lasers. The machine has several user-controlled parameters that were set to promote the widest range of particle size measurement with the least force applied to the particles.

[†]Commercial names are only for more complete reader information and do not imply endorsement.

RESULTS AND DISCUSSION

A relationship was determined between the Erodibility Index determined from individual events at the field sites and the values of relative soil loss, R, from the wind tunnel runs at those sites (Fig. 1, Saxton et al., 1998). This relationship was instrumental in the construction of the empirical modeling approach developed by Saxton et al. (1998) because it allowed the erodibility measurements conducted under natural conditions to be applied to the variety of soil types on which wind tunnel trials were conducted.

Results from the five particle size analysis techniques were first compared within the dispersed and non-dispersed approaches. The laser diffraction method was selected as superior to the Coulter counter as a dispersed approach counter results exhibited, to varying degrees, a discontinuity in the cumulative particle size at the joining of the sieve and Coulter counter values; 3) the Coulter counter is unable to count particles less than 2 μm, requiring the technique to be coupled with sedimentation if the clay fraction is to be included in the particle size distribution.

The dry sieving results were a better representation of the non-dispersed particle size distribution than those from the Aerosizer. The Aerosizer significantly dispersed the particles introduced to the instrument and therefore did not measure because; 1) the results were more similar to those found by the sieve and pipette method (Bittelli 1998); 2) the Coulter non-dispersed distributions. A combination of sonic and rotary sieves were found to consistently provide a continuous non-dispersed particle size distribution. Sieving methods have the additional benefits of ease of operation and economy.

Disparity between particle size distributions from non-

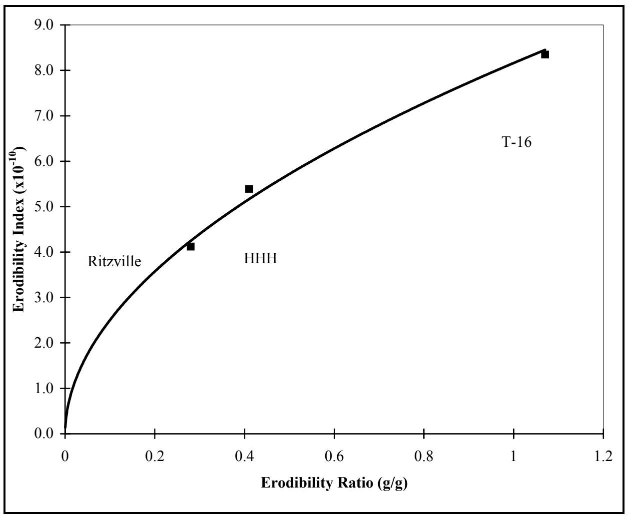

Figure 1. Correlation of the Erodibility Index (EI) at the field sites with the Relative Erodibility Ratio, R, from the wind tunnel data at the sites.

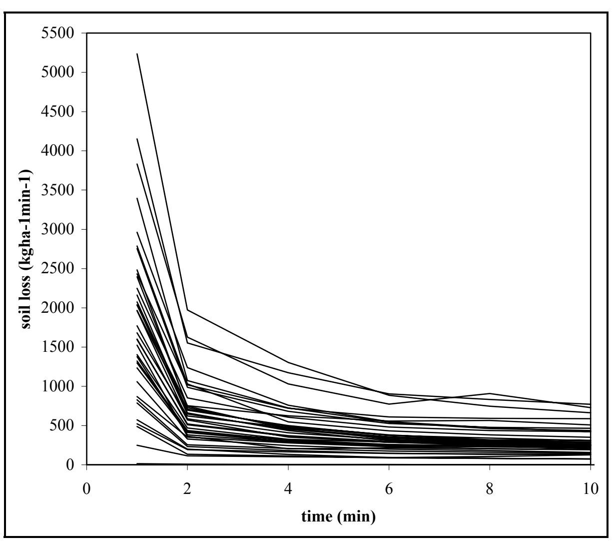

Figure 2. The mass of soil collected incrementally from wind tunnel trials at forty field sites.

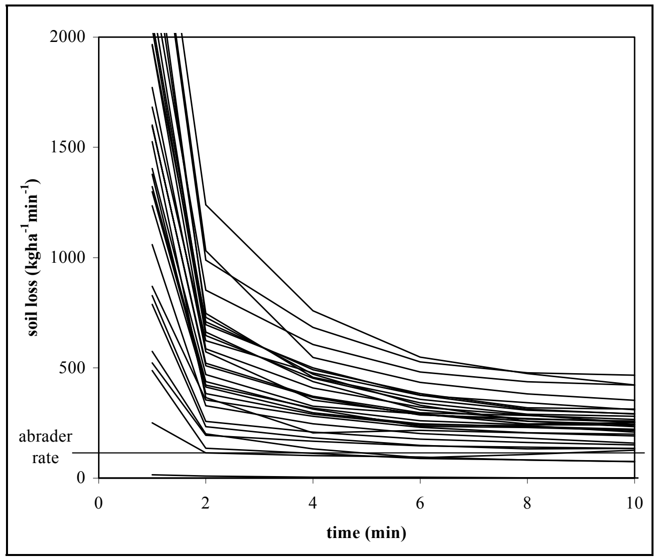

Figure 3. The mass of soil collected incrementally from wind tunnel trials at non-sandy sites.

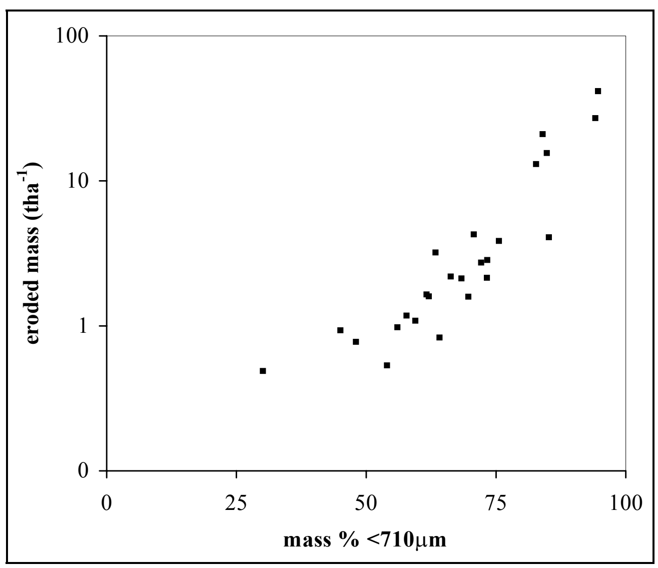

Figure 4. The mass of soil collected for the last 6 minutes of the wind tunnel trials vs. the mass percent of the non-dispersed field surface sample less than 710μm.

dispersed and dispersed methods varied with soil texture. Whereas all methods tested give similar results for sandy soil, the dispersion significantly effects the particle size distribution as soil clay and organic matter fractions increase. Thus, non-dispersed methods were chosen as the most consistent representation of particle size distributions for assessment of wind erosion potential.

The mass collected by each wind tunnel test approximated the response of the soil to a highly erosive wind under unprotected conditions. The eroded mass versus time response of each soil is represented in figure 2 and shows a significant decline following the first 2 minutes of erosion. The mass eroded from the 5 noticeably sandy sites was far greater than that at the remainder of the sites (Fig. 3), however a remarkably similar pattern to the mass-time response exists across all soils tested. The mass response from the non-sandy soils (Fig. 3) rapidly approached an equilibrium rate of erosive soil loss under the steady wind and saltation conditions of the wind tunnel. The larger erosion at the beginning of each trial was attributed to the structure imparted by the disaggregated soil by the plot preparation technique, thus the last 6 minutes of each trial were considered to represent the potential for erosion on an hourly or event basis. The erosion rate was greater that the artificial saltator introduction rate, thus this procedure had minimal impact on the results (Fig. 3).

Lack of significant deposition at most field boundaries following wind erosion events on the Columbia Plateau indicate that suspension is the primary form of soil transport for much of the region. Because of prevailing agronomic practices, the soil surface is commonly disaggregated by tillage operations to the point of being a fine powder. A primary objective of the research project was to assess the potential contribution from agriculture to urban air quality problems many kilometers downwind. Soil erodibility must account for both the direct suspension of soil and saltation-dominated erosion to assess the potential for dust emission from erosion of each of the soils. The erodibility of the soils was previously related to dispersed sand and clay and organic matter content (Chandler and Saxton, 1998). However, dispersed particle size analyses were not found to be related to its potential for dust production.

Soil erodibility and soil dustiness were found to be well represented by two sieve cuts from the rotary sieve analysis of the non-dispersed soil samples. A logarithmic trend is exhibited between the eroded mass collected from the last 6 minutes of the wind tunnel trials and the mass percent less than 710µm (Fig. 4), similar to that observed by Chepil (1941). A similar trend was found for the mass percent less than 63µm, with the exception of the sandy soils. This result indicates the erosion of suspended size particles may occur directly from the surface of many soils, independent of the saltation flux. However, saltation remains the predominant means of erosion of soils with significant sand content is and this form of erosion cannot be predicted from the suspension-size component. Soils that are highly erodible and have high potential for dust emissions may be identified by a plot of mass percent less than 63µm versus mass percent less than 710µm (Fig. 5).

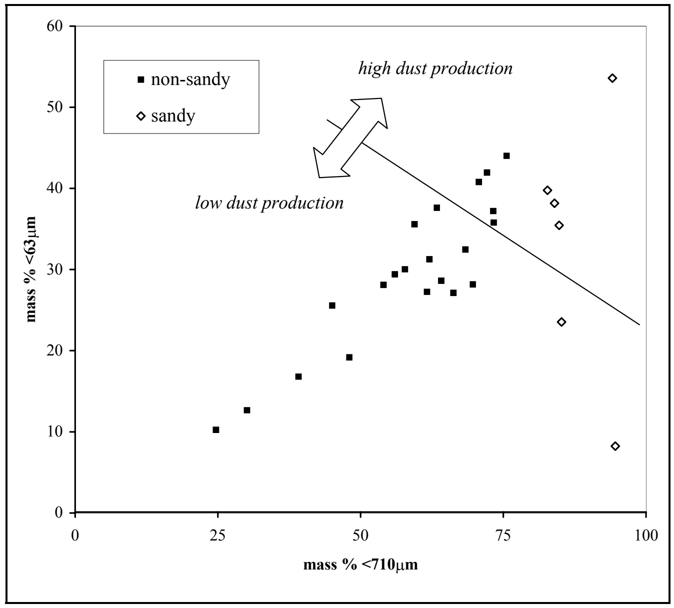

Figure 5. The mass percent of the non-dispersed field surface sample less than 63µm vs. the mass percent of the non-dispersed field surface sample less than 710µm.

CONCLUSIONS

Results from particle sizing techniques were evaluated to relate soil erodibility and dust emission to the particle size distribution of the eroding surface. Two relationships were found to represent the dust emission potential from wind erosion for most of the agricultural soils on the Columbia Plateau showing that: 1) wind erosion is enhanced by the percentage of soil mass of particles less than 710µm, and 2) dust emission is dominated by the freely available material less than 63µm in the soil surface. Thus, the erosion and dust emission potential of a soil can be estimated by only two sieve cuts from a non-dispersed sample of a field soil.

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