Wind Erosion and Fugitive Dust Fluxes on Agricultural Lands in the Pacific Northwest

K. Saxton, D. Chandler, L. Stetler, B. Lamb, C. Claiborn, B.-H. Lee

Abstract. *With recent emphasis of agricultural wind erosion and associated dust emissions impacting downwind air quality, there is an increased need for a prediction method to estimate dust emissions and ambient particle concentrations on a wind event basis. Most current wind erosion methods predict average annual or seasonal erosion amounts, and only very approximate estimates of suspended dust emissions are available. A project in the Columbia Plateau of eastern Washington State was initiated to develop an empirical method to estimate dust emissions for this region. Field measurements, wind tunnel tests, and laboratory analyses were combined to provide an empirical wind erosion equation and a related vertical flux dust emission model. While based on measured data, the model has not been independently verified. When combined with a transport-dispersion model and calibrated, estimates of downwind particulate concentrations compared reasonably with those measured.*
Keywords. *Wind erosion, Wind tunnel, Dust, Emission, PM10, Columbia Plateau.*

With the advent of the 1990 Clean Air Act came the responsibility to monitor and control fugitive dust particulates less than 10 micron aerodynamic diameter (PM_{10}) in urban regions. The basis for this legislation was research findings which indicated that exposure to high concentrations of PM_{10} contributes to respiratory problems. Urban areas on the Columbia Plateau of eastern Washington, Northern Oregon, and the Idaho Panhandle have exceeded the PM_{10} standard numerous times since measurements were started in 1985. Several of these occasions occurred during days of obvious regional agricultural wind erosion (Saxton, 1995a). Although the physical processes contributing to wind erosion and its control through agricultural practices are reasonably well understood, the predictive methods currently in use were not designed to estimate fine suspendible dust emissions. Thus, the Columbia Plateau was chosen as a region to study relationships between PM_{10} emissions and wind erosion from agricultural fields.

Historically, wind erosion prediction technology has been based on empirically derived relationships among the major variables found to influence wind erosion. The wind erosion equation (WEQ) expresses that wind erosion results from interactions between wind forces and field conditions in terms of soil characteristics, surface roughness, vegetative cover, and the upwind erodible field length in the direction of wind travel (Chepil, 1941; Woodruff and Siddoway, 1965). The equation estimates the average annual mass of soil transported off the downwind edge of an agricultural field. This approach does not allow the total erosive soil loss to be partitioned either spatially between categories of soil transport mechanisms (creep, saltation and suspension) or temporally between individual wind erosion events. Similarly, no clear relationships have been developed between suspended particle concentration and that portion which is PM_{10}.

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 estimate a corresponding vertical flux of PM_{10} for the erosion event.

An empirical equation was first developed to predict Q_e, the streamwise (horizontal) flux of eroded soil on an event basis (Saxton et al., 1996). Similar in form to the WEQ, the calculated horizontal erosion flux, Q_e, was based on the major variables known to effect an erosion event defined as:

$$Q_e = f(W_e, SE, SC, K, WC) \qquad (1)$$

where
- Q_e = event eroded soil
- W_e = event wind energy
- SE = soil erodibility
- SC = vegetative surface cover
- K = soil surface roughness
- WC = soil surface wetting and crusting

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It was proposed that the vertical flux of suspended particulates could be related to the horizontal flux of eroded soil. Field observations have shown that suspended dust concentration is a function of height (Chepil and Woodruff, 1957; Gillette, 1977; Gillette and Passi, 1988; Nickling, 1978; Nickling and Gilles, 1989, 1993), and the corresponding vertical flux of particle mass can be defined as:

$$F = -K_A \frac{\partial c}{\partial z} \quad (2)$$

where
- F = vertical aerosol flux (g $m^{-2}s^{-1}$)
- K_A = aerosol exchange coefficient
- c = particle concentration (g m^{-3})
- z = height (m)

By relating equation 2 to a similar expression for momentum flux in an air column (Gillette et al., 1972, 1974; Gillette and Passi, 1988), vertical dust flux can be determined using:

$$F = C_d U_1^2 \left[-\frac{(M_2 - M_1)}{(U_2 - U_1)} \right] \quad (3)$$

where
- F = vertical dust flux (g $m^{-2}s^{-1}$)
- C_d = drag coefficient
- U_1, U_2 = mean wind velocities at heights 1 and 2 (m s^{-1})
- M_1, M_2 = mean dust concentrations at heights 1 and 2 (g m^{-3})

The drag coefficient may be defined as (Priestly, 1959):

$$C_d = \left(\frac{u_*}{U_1} \right)^2 \quad (4)$$

which when substituted into equation 3 yields:

$$F = u_*^2 \left[-\frac{(M_2 - M_1)}{(U_2 - U_1)} \right] \quad (5)$$

The friction velocity, u_*, may be described by the logarithmic wind profile equation:

$$U_z = \frac{u_*}{k} \ln \frac{z}{z_0} \quad (6)$$

where
- U_z = wind velocity (m s^{-1})
- u_* = friction velocity (m s^{-1})
- z = height above surface (m)
- k = dimensionless Von Karman constant of 0.4
- z_0 = aerodynamic roughness height of zero average velocity (m)

Substitution of equation 6 into equation 5 yields the working equation:

$$F = \frac{-k\, u_* (M_2 - M_1)}{\ln \left(\frac{z_2}{z_1} \right)} \quad (7)$$

Thus, this research involved quantifying the variables for horizontal mass flux during a wind erosion event (eq. 1), then defining the related wind profile characteristics and PM_{10} concentrations to estimate vertical dust emissions (eq. 7).

Materials and Methods

Independent experiments were conducted to develop separate relationships which describe the effect of each of the variables of equations 1 and 7 on the total dust emission from a given soil type and farming practice. One set of experiments was conducted with instrumented field sites to assess the effect of naturally occurring windstorms on erosion and dust emissions for soil conditions representative of farming practices common to the Columbia Plateau. Another set of experiments was conducted using a portable wind tunnel designed to define: (1) the effect of surface residue and soil surface roughness on wind erosion; and (2) the relative erodibility for the soils encountered on the Columbia Plateau. Testing with the wind tunnel at the instrumented field sites provided calibration of the erodibility factors for these soils. Additional soil analyses were conducted in the laboratory to determine the readily available PM_{10} content.

Field Erosion

The field wind erosion sites were installed at three Washington locations; HHH, T-16 and RITZ (Horse Heaven Hills region near Prosser, Wash.; T-16 Ranch near Lind, Wash.; near Ritzville, Wash.). All sites had silt loam soil developed from loess, some containing abundant volcanic ash. HHH and T-16 were located on Shano very fine sand and silt loam soils (*Xerollic Camborthids*). RITZ had Ritzville silt loam soil (*Andic Aridic Hapllustolls*). These soils generally have 50 to 65% dispersed silt particles, 25 to 45% sand, 5 to 10% clay, and organic matter 0.5 to 1.0% making them highly susceptible to wind erosion and suspended dust emissions.

The field site meteorology was recorded by cup 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 raingage at 1.5 m. Data were continuously recorded as 15 min averages, then decreased to one minute when the average wind speed at 3.0 m height exceeded a threshold of 6.4 m s^{-1} (14.0 mph). The threshold velocity was estimated as that causing saltation of 0.50 mm sand as indicated by the relationship (Bagnold, 1941):

$$u_{*t} = A \left(\frac{\sigma - \rho}{\rho} gd \right)^{0.5} \quad (8)$$

where
- u_{*t} = threshold friction velocity (m s^{-1})
- A = empirical coefficient of turbulence approximately equal to 0.1 for particle friction Reynolds number > 3.5

σ = particle density for quartz grains (2.65 g cm^{-3})
ρ = air density (1.22×10^3 g m^{-3})
g = acceleration due to gravity (9.80 m s^{-2})
d = mean particle diameter (mm)

Then use equation 6 to solve for U at z = 3.00 m and a typical z_0 = 1.22 mm. Once the initiation threshold was exceeded, the data were logged as 1-min averages until the 15-min average wind speed at 3.0 m dropped below an arbitrary cessation threshold of 5.75 m s^{-1} (12.6 mph).

Streamwise soil erosion was measured at each site using twelve sets of BSNE (Fryrear, 1986) airborne soil collectors arranged in three rows across a 110 × 54 m rectangular grid at heights of 0.1, 0.2, 0.5, 1.0, and 1.5 m (Stetler and Saxton, 1996). Creep samplers (a buried rotating vane with inlet slot to collect sediment traveling at heights less than 7.5 mm above the soil surface, developed by D. W. Fryrear, USDA/ARS, Big Springs, Texas) were also deployed within the BSNE arrays. To ensure measuring the maximum carrying capacity of the streamwise flux of eroded soil, the BSNE samplers were located in the prevailing downwind corner of summer fallow fields, each with a fetch of at least 200 m. Sample collections were periodic depending on the occurrence and magnitude of events. Samples were air dried only if the BSNE samplers had collected water during the sampling period. A mean sample mass was calculated for each collection height. The vertical mass distribution of the six sample means was statistically fit by a double exponential equation of the form:

$$m(z) = Ae^{-Bz} + Ce^{-Dz} \qquad (9)$$

where
m(z) = sample mass collected at height z (g)
z = sample height (m)
A, B, C, D = regression constants

The streamwise mass flux, Q_e, representing the total event mass of soil traveling through 1 m of field width and integrated to 1.5 m height (for the duration of the collection period) was calculated by integrating equation 9 as:

$$Q_e = \int_0^{1.5} \left(Ae^{-Bz} + Ce^{-Dz}\right) dz \qquad (10)$$

Simultaneous sampling of PM_{10} for the duration of each windstorm was accomplished using high-volume constant flow samplers (hi-vols) (General Metal Works, Village of Cleves, Ohio) with PM_{10} inlet heads at 1.5 m and 2.5 m above the soil surface (Stetler and Saxton, 1995). The hi-vols were powered by portable generators electronically controlled to operate between the 3.0 m wind velocity initiation and cessation thresholds. High volume filters were removed at the same time that the BSNE samplers were emptied, then desiccated for 48 h prior to weighing.

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 soil erodibility for five replications on thirty fields representative of seven major soil classes. For each field trial, a standard surface was prepared by removing all large residue and clod roughness from the surface with a steel garden rake (60-mm-long tines with 23 mm opening). Constant wind speeds of 18 m s^{-1} at the 1.0 m height were generated over each replication for 10 min. Eroded material was collected using a vertically integrating isokinetic slot sampler 3 mm wide × 0.75 m high (modified Bagnold type, Stetler et al., 1997) connected in series with a high efficiency cyclone and vacuum. The mean soil erodibility for each major soil class was divided by the mean of a large area, very erosive soil class (L1A) to yield the mean relative erodibility ratio, R, as shown in table 1.

Table 1. Average dust index (D), relative erodibility (R), and estimated soil erodibility (SE) values for major soil classes (Boling et al., 1998) on the Columbia Plateau study region*

Regional Soil Class	Dust Index (D) $\times 10^{-2}$ (g g^{-1}) Avg.	S.D.	Relative Erodibility Ratio (R) Avg.	S.D.	Soil Erodibility (SE) $\times 10^{-10}$ (kg m^{-1}/g s^{-2})
L1A	0.68	0.10	1.00	0.20	8.20
L2A	0.95	0.51	0.55	0.17	6.10
L3	0.56	0.30	0.36	0.12	4.92
L4	1.09	0.70	0.42	0.13	5.32
L5	0.72	0.13	0.14	0.03	3.05
L1B	0.45		0.48		5.67
L2B	0.55	0.25	0.32	0.09	4.62
Ds	0.53		0.41		5.27
Dq	0.07		1.44		9.84
De	0.29		0.25		4.10

* Note: Multiply the reported table values by the exponent expression for actual values.

Roughness and residue trials were conducted with the wind tunnel on 68 plots at field locations near Lind and Prosser, Washington (Horning et al., 1998). Each plot was described in terms of the roughness and residue present on the soil surface, the moisture content and soil description for the top 2.5 cm of the soil. Random roughness standard deviation (K, cm) was estimated by visually comparing test plots with photographs of well-documented random roughness conditions commonly used for water erosion predictions (McCool et al., 1996). While related, this roughness is not the same descriptor as the aerodynamic roughness, z_o. Residue cover was estimated by visual comparisons with photographs published by the Soil Conservation Service (USDA-SCS, 1992) and soil moisture contents were determined gravimetricly. The eroded material collected in the slot sampler system for each of three one-minute tests (velocities of 12, 15 and 18 m s^{-1} at 1.0 m height) was converted to a flux rate for a unit width by dividing the mass collected by the slot width. A soil loss ratio, SLR, which describes the reduction in soil loss under various residue or roughness treatments independent of the soil erodibility properties, was calculated by dividing the combined 3-min flux rate from a test plot by the flux rate of the standard bare, raked surface for that soil type:

$$SLR = \frac{F_{treat}}{F_{std}} \qquad (11)$$

where

SLR = soil loss ratio

F_{treat} = flux from a treated plot (g m^{-1} 3-min^{-1})

F_{std} = flux from a smooth, bare surface plot (g m^{-1} 3 min^{-1})

Soil Dustiness Index

It is the smaller soil particles that are suspended and emitted upward out of the horizontal flow of eroded material. To predict the emission of PM_{10} from the horizontal erosion for a given soil, PM_{10} mass percent available for suspension from a soil, D, was determined by a laboratory procedure on soil samples taken at the wind tunnel erodibility sites. Samples were passed through a 2 mm sieve to remove all residue and larger aggregates. Sub-samples of 0.50 g from a microsplitter were injected into a sampling bell by a small, uniform blast of air. The air was aspirated from the bell through a PM_{10} separation head and the re-suspended dust continuously weighed by a tapered element oscillating microbalance (TEOM; Rupprecht and Patashnick, Co., Inc., Albany, New York) until particulate levels returned to background levels. The dustiness index of the sample, D, was calculated as:

$$D = \frac{m_{sp}}{m_s} \qquad (12)$$

where

D = dustiness index

m_{sp} = mass of suspended PM_{10} particles collected by TEOM (g)

m_s = mass of soil suspended sample < 2 mm (g)

Average D values for the regional soil classes are shown in table 1. Because much less energy is required to entrain loose particles of soil than to detach particles from a larger aggregate, only the “free” particles were measured by this method. Abrasion of larger aggregates such as by saltating particles was not included. Subsequent preliminary analyses have shown that a method that includes abrasion will increase the dust index two to five times, particularly where higher clay and organic matter content results in significant aggregation.

Results

The data sets were combined into a prediction methodology to estimate horizontal wind erosion and vertical suspended dust emissions. While the field data were measured over an entire event, or the combination of several events depending on the frequency of servicing the measurement equipment, the prediction equations were developed such that they would represent any given period of input data and flux calculations. The variables required to define the horizontal erosion flux (eq. 1) were first analyzed, then connecting relationships to the vertical dust flux (eq. 7) were defined.

Wind Erosion Flux

The variables related to a minimal definition of wind erosion flux within a farm field are shown in equation 1. Each of these must be defined or evaluated to provide the spatial and temporal variability required within a given study region and the variation within farming systems.

Surface Cover and Roughness. Percent surface cover (SC) and soil surface random roughness (K, the standard deviation of surface height variations estimated by photo comparisons) were found to exert a synergistic control on wind erosion, in close agreement with the results of Fryrear (1985). The regression equation (Horning et al., 1998) developed from the wind-tunnel trials to estimate the effectiveness of residue cover and random roughness was:

$$SLR = e^{-0.05SC} \times e^{-1.32K} \qquad R^2 = 0.51 \qquad (13)$$

where

SLR = soil loss ratio

SC = flat residue cover (%)

K = random roughness (cm)

This relationship shows that maintaining surface plant residue is a very effective and practical method to control wind erosion (Woodruff et al., 1977). Significant decreases can also be achieved with increases in random roughness (clods) and oriented roughness (ridges) (Chepil, 1941; Fryrear, 1984).

Wind Energy. Several equations have been used to relate the streamwise flux of eroded soil to approximately the cubic power of either wind velocity at a fixed height or shear velocity (Greely and Iverson, 1985). Following the form of Lettau and Lettau (1978), we calculated event wind energy as:

$$W_e = \rho \sum_{0}^{n} U^2 (U - U_t)\, \Delta t \qquad (14)$$

where

W_e = wind event energy (g s^{-2})

ρ = air density (1.2 × 10^3 g m^{-3})

U = average wind velocity, for each Δ t, at 3 m height (m s^{-1})

U_t = average threshold wind velocity, for each Δ t, at 3 m height (m s^{-1})

n = number of measurement intervals for which U ≥ U_t

Δ t = time interval of average velocity measurement (s)

Wind energy for the correlation analyses of measured erosion and emission data was calculated using only the one-minute average velocities which were above the threshold velocity during the event. While not a true kinetic energy value, the values by equation 14 provide good estimates for the “effective” or “causative” energy related to wind erosion.

Supplemental analyses have shown that the threshold velocity is a function of the time over which the velocities are averaged. Time durations of one-half to one hour reduce the mean computed velocities, even if all are above threshold, thus the effective threshold for these longer durations must also be of a reduced magnitude (Stetler and Saxton, 1997; Stout, 1998). To represent no erosion from bare, smooth surfaces for no wind energy (i.e., zero intercept) and 1-min average velocities, we found that U_t =

6.0 m s^{-1} was most appropriate; whereas, a value of U_t = 5.5 m s^{-1} was equivalent for hourly average velocities.

Erodibility Index. The soil erodibility index, SE, is a measure of the intrinsic susceptibility of a tilled soil to erosion by wind when not protected by surface cover, roughness, crusting or soil moisture. For well-defined field and soil surface conditions, equation 1 may be rearranged to calculate SE as the ratio of the measured erosion during a windstorm, Q_e, to the total wind energy, W_e, during that erosive period such that:

$$SE = \frac{Q_e}{W_e(SC, K, WC)} \quad (kg\,m^{-1})(g\,s^{-2})^{-1} \qquad (15)$$

For each event, a bare, disturbed soil surface potential erosion, Q_p, was estimated by adjusting Q_e for observed surface roughness and residue conditions for the site at the time of the event. Thus:

$$Q_p = \frac{Q_e}{\left(e^{-0.05SC}\ e^{-1.32K}\right)} \qquad (16)$$

As shown by figure 1 for the T-16 site, SE was calculated for each field site as the slope of the line of Q_p versus W_e from 11 wind erosion events which occurred during 1994 and 1996. Events which followed significant rainfall were observed to have decreased erosion due to wetness and/or crusting and were not used to calculate SE because a method for estimating the WC term to adjust the Q_e value to Q_p was not yet available. Only those events for which WC could be defined as reasonably close to 1.0 were used in the SE calculation.

To provide an estimate of soil erodibility for the range of regional soil classes tested with the wind tunnel, a relationship was determined between the SE determined under natural wind conditions at the three field sites and the values of relative erodibility ratio, R, by the wind tunnel at those sites (fig. 2). Even though limited by only

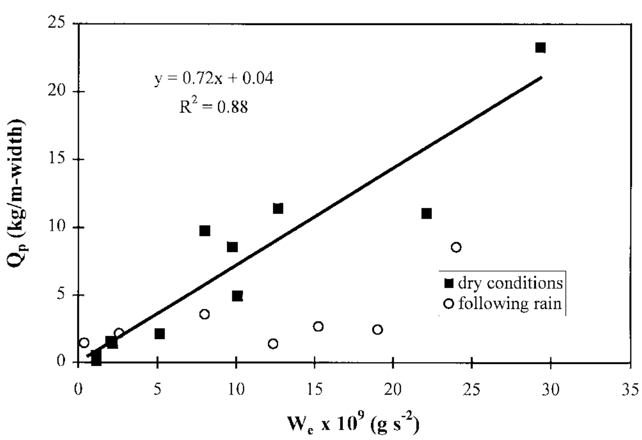

Figure 1–Soil erodibility (SE) calculated as the line slope of event wind energy (W_e) versus potential event horizontal mass flux (Q_p) for field site T-16 for wind storms which occurred during periods when the soil surface was dry and non-crusted. Events which occurred following significant rain are shown for comparison and not used in the regression. (Note: Multiply the reported axes values by the exponent expression for actual values.)

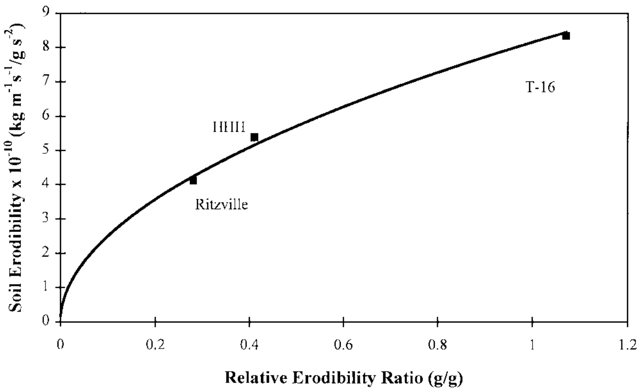

Figure 2–Regression of the Soil Erodibility (SE) at the field sites with the Relative Erodibility Ratio (R) from the wind tunnel data at the sites. (Note: Multiply the reported axes values by the exponent expression for actual values.)

three data points representing the field sites, a regression equation was fitted, forced through the origin, such that:

$$SE = 8.2 \times 10^{-10}\,R^{0.5} \quad (kg\,m^{-1})\,(g\,s^{-2})^{-1} \qquad (17)$$

which was then used to calculate the SE for each soil class from the average of the R values from the wind tunnel trials performed on that soil class (table 1).

Wetness and Crusting. The soil surface wetness and crusting term (WC) reduces the predicted dust emissions depending on the antecedent history of rainfall and cultivation. Values of the WC term varies from 0.0 to 1.0. Lower values represent wet, crusted soils while higher values are for dry, disturbed and non-crusted soils. A predictive capability for WC more accurate than rational judgment has yet to be developed, however its effectiveness to reduce erosion is qualitatively demonstrated by the data of figure 1.

The Horizontal Flux Equation. The variables defined above were combined as linear multipliers in the horizontal flux wind erosion equation such that:

$$Q_e = [W_e \times SE \times (e^{-0.05\,SC} \times e^{-1.32\,K}) \times WC] \qquad (18)$$

where

- Q_e = eroded soil discharge per m field width per delta time (kg m^{-1})
- W_e = erosive wind energy per delta time (g s^{-2})
- SE = soil erodibility (kg m^{-1}) (g $s^{-2})^{-1}$
- SC = surface cover index (% flat residue)
- K = random roughness (cm)
- WC = surface wetness and crusting index

This equation provided estimates for the horizontal soil mass flux of an eroding field for a width of 1.0 m and a height of 1.5 m for a delta time defined by the wind energy. It represents the approximate equilibrium dust transport largely by creep and saltation for the wind energy and field surface condition of the specified event because our data were obtained by instruments not efficient for very fine suspension size particles and not high enough to catch suspended material from much distance upwind.

VERTICAL DUST FLUX

Although the measured soil erosion was less than that expected to occur from the entire field surface, it was closely correlated to the measured PM_{10} concentrations. The vertical flux of PM_{10} (F) emitted during an erosive period was assumed to be a function of horizontal mass flux (Q_e), the soil dustiness (D), and the wind velocity (U) such that:

$$F = f\,(Q_e, D, U) \qquad (19)$$

Simultaneous measurement of PM_{10} concentrations and Q_e during wind erosion events were made to develop relationships between vertical dust flux and wind erosion. The suspended particulate filter mass of PM_{10} measured at 1.5 and 2.5 m height ($m_{1.5}$, $m_{2.5}$) was correlated to the mass of PM_{10} available within the horizontal transport below 1.5 m height during an event. A linear relationship was found as the best fit between $m_{1.5}$, and the PM_{10} fraction of the eroded soil, Q_e times D (fig. 3):

$$m_{1.5} = k_1\, Q_e\, D \qquad R^2 = 0.91 \qquad (20)$$

where

$k_1 = 0.077$ (g) (g-event^{-1})$^{-1}$

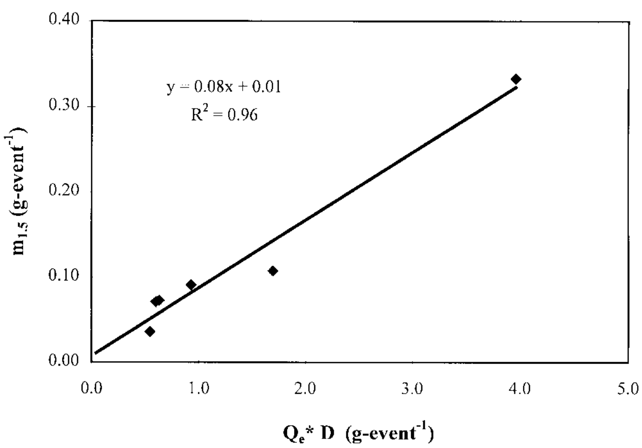

Figure 3–Regression of PM_{10} filter mass at 1.5 m height ($m_{1.5}$) with wind erosion (Q_e) times dust coefficient (D).

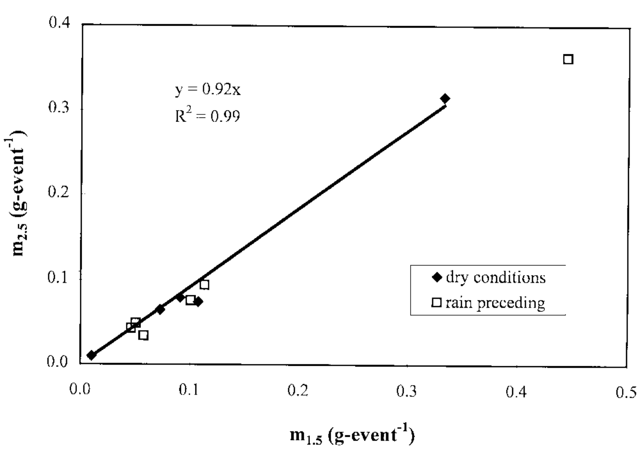

Figure 4–Regression of filter mass for PM_{10} at 1.5 and 2.5 m heights.

A strong, linear relationship was also found between $m_{1.5}$ and $m_{2.5}$ (fig. 4):

$$m_{2.5} = k_2\, m_{1.5} \qquad (R^2 = 0.92) \qquad (21)$$

where

$k_2 = 0.92$ (g g^{-1})

While the regressions between $m_{1.5}$, $m_{2.5}$ and Q_e were made between mass values collected over one or more wind episodes comprising an event, we assumed the same relationships to hold for any time period. Thus, we estimated mean hourly concentrations of PM_{10} at 1.5 and 2.5 m ($M_{1.5}$ and $M_{2.5}$) for application in the vertical flux equation 7 by first estimating 1-h PM_{10} mass by equations 20 and 21 ($m_{1.5}$ and $m_{2.5}$), then dividing this mass by the 1-h air volume aspirated through the filter such that:

$$M_{1.5} = \frac{m_{1.5}}{k_3 \Delta t} \quad \text{and} \quad M_{2.5} = \frac{m_{2.5}}{k_3 \Delta t} \qquad (22)$$

where

k_3 = the sampler flow rate (0.0189 m^3 s^{-1})

Δt = delta time of erosion wind energy (eq. 14) (s)

Substitution of equations 22 into equation 7, for z_1 = 1.5 m and z_2 = 2.5 m yields the composite relationship to estimate vertical PM_{10} flux for any partial time within a wind event given the associated Q_e and D definitions.

$$F = K_f\, \bar{u}_*\, Q_e\, D(\Delta t)^{-1} \quad (\text{g m}^{-2}\ \text{s}^{-1}) \qquad (23)$$

where

$$K_f = \frac{-k\left(k_1 k_2 - k_1\right)}{k_3 \ln\left(\frac{2.5}{1.5}\right)} = 0.26 \quad (\text{g s})\left(\text{kg m}^2\right)^{-1} \qquad (24)$$

Applications. The wind erosion and emissions model was interfaced as a sub-model with a meteorological-driven air quality transport-dispersion-deposition model to estimate atmospheric particulate concentrations on a regional scale during dust storm events (Claiborn et al., 1998). This combined model integrated information of wind and soil characteristics, vegetation, management practices, and moisture conditions at a 1 km^2 scale over the 134 000 km^2 study region to calculate dust emissions, transport, deposition, and downwind ambient PM_{10} concentrations.

Figure 5 shows the estimated spatial distribution of average PM_{10} emission rates across the Columbia Plateau during a 1-h simulated windstorm for typical farmland conditions about the middle of September. The high variability in emission rates are largely the result of differences in surface cover (land use) and the erodibility and dustiness index of soils in the region. The highest dust emissions occur mainly in the predominant wheat-fallow areas, and in association with the L1 and L2 soil classes (Boling et al., 1998). This map of PM_{10} emissions is essentially a "hazards" map reflecting soil characteristics and land use patterns.

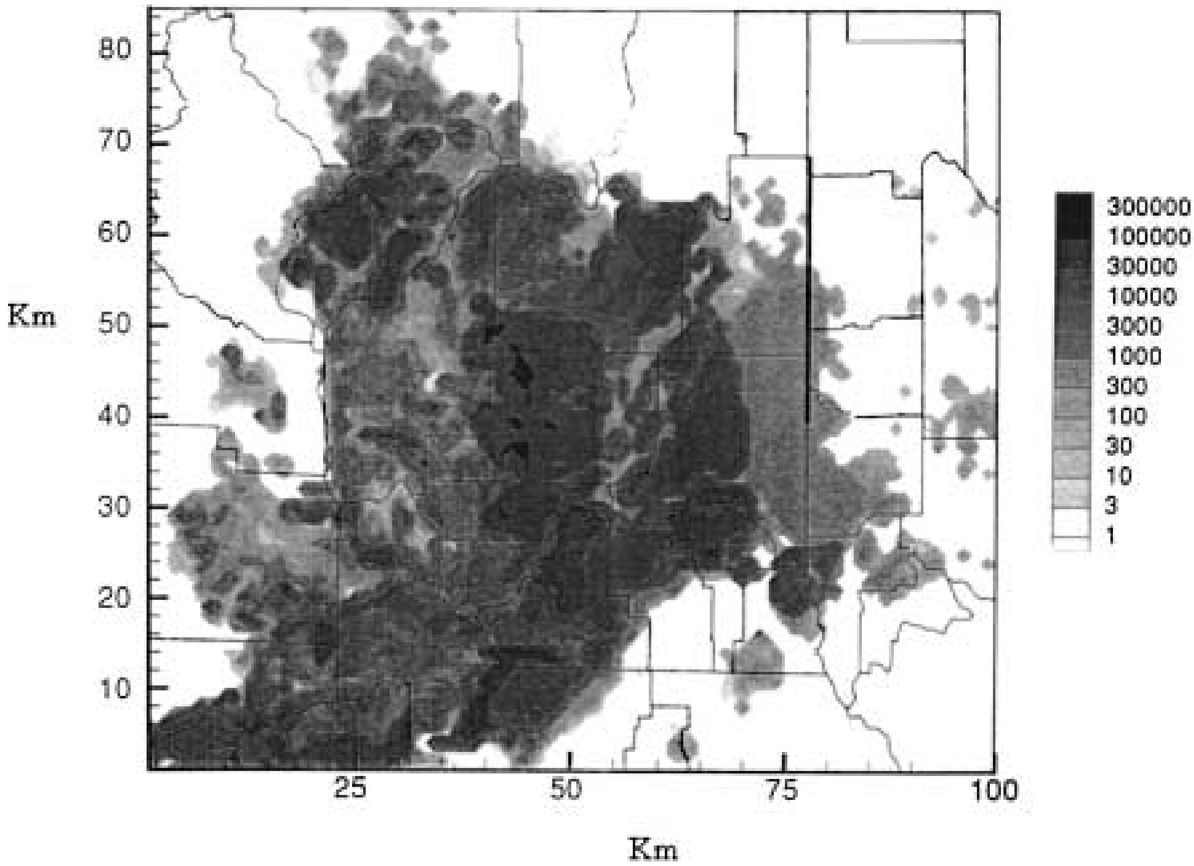

Figure 5–Spatial patterns of 1-h PM_{10} dust emissions (g km^{-2} s^{-1}) over the Columbia Plateau study region from a uniform wind of 20 m s^{-1} for mid September conditions.

The combined emission and transport-dispersion model has been applied to characterize the nature of regional dust storms using historical data and to evaluate the effectiveness of potential control strategies to reduce ambient PM concentrations. Hourly particulate concentrations for each dust storm event were estimated for a 4 km × 4 km grid (based on mean of 1 km^2 emission estimates) throughout the Columbia Plateau. The downwind dust concentrations were compared with measured values by PM_{10} monitors. An example temporal dust concentration computed and observed for Spokane, Washington, is shown in figure 6 with a scaling coefficient for magnitude but not the time distribution (Lee, 1998).

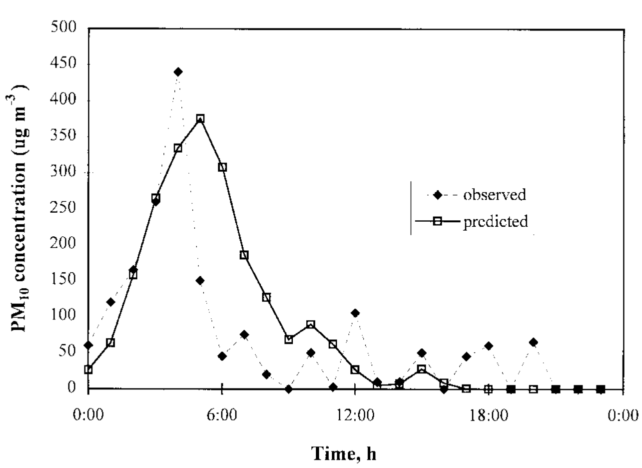

Figure 6–Predicted and observed PM_{10} dust concentrations for the event of 3 Nov. 1993, at about 10 m within Spokane, Washington, with calibrated magnitudes but no time adjustment.

Estimated concentrations 100 km downwind of the central emission area were within factors of about 0.5 to 2.0 of those measured (Saxton et al., 1997; Papendick and Saxton, 1997). This may be an accuracy within the expected limits given the number of variables, spatial variation and accuracy of definition of both the emission and transport-dispersion models to adequately represent the characteristics of the 134 000 km^2 study region. These results provided useful relative downwind urban air quality impacts by improved farming practices and guidance as to where these practices would be most cost effective.

SUMMARY

A combined empirical wind erosion and PM_{10} dust flux model was developed from extensive field data throughout the Columbia Plateau of eastern Washington State, northern Oregon, and the Idaho panhandle. This model was included as the emissions input to a regional GIS-based transport-dispersion prediction model, and preliminary trials show quite reasonable results when compared with downwind dust concentrations for several historic events. While needing further development and verification, this model provided dust emission estimates for a variety of regional landuse conditions and was used to evaluate potential control strategies with an accuracy useful for planning and policy decisions.

References

Bagnold, R. A. 1941. *The Physics of Blown Sand and Desert Dunes.* New York, N.Y.: William Morrow & Co.

Boling, M., B. Frazer, and A. Busacca. 1998. General soil map of Washington. Pullman, Wash.: Dept. of Crop and Soil Sciences Pub., Washington State University.

Chepil, W. S. 1941. Relation of wind erosion to the dry aggregate structure of a soil. *Scientific Agric.* 21: 488-507.

Chepil, W. S., and N. P. Woodruff. 1957. Sedimentary characteristics of dust storms: II. Visibility and dust concentrations. *Am. J. Sci.* 225: 104-114.

Claiborn, C., B. Lamb, A. Miller, J. Beseda, B. Clode, J. Vaughan, L. Kang, and C. Newvine. 1998. Regional measurements and modeling of windblown agricultural dust: The Columbia Plateau PM_{10} Program. *J. Geophysical Res.* 103(D16): 19,753-19,767.

Fryrear, D. W. 1984. Soil ridges—Clods and wind erosion. *Transactions of the ASAE* 27(2): 445-448.

_____. 1985. Soil cover and wind erosion. *Transactions of the ASAE* 28(3): 781-784.

_____. 1986. A field dust sampler. *J. Soil & Water Conserv.* 41(2): 117-120.

Gillette, D. A. 1977. Fine particulate emissions due to wind erosion. *Transactions of the ASAE* 20(5): 890-897.

Gillette, D. A., I. H. Blifford, and C. R. Fenster. 1972. Measurements of aerosol size distribution and vertical fluxes of aerosols on land subject to wind erosion. *J. Appl. Meteor.* 11: 977-987.

Gillette, D. A., I. H. Blifford, and D. W. Fryrear. 1974. The influence of wind velocity on the size distribution of aerosols generated by the wind erosion of soils. *J. Geophys. Res.* 79: 4068-4075.

Gillette, D. A., and R. Passi. 1988. Modeling dust emission caused by wind erosion. *J. Geophys. Res.* 93: 14,233-14,242.

Greely, R., and J. D. Iverson. 1985. Wind as a geological process. Cambridge, UK: Cambridge University Press.

Horning, L., L. Stetler, and K. E. Saxton. 1998. Surface residue and soil roughness for wind erosion protection. *Transactions of the ASAE* 41(4): 1061-1065.

Lee, Bu-Hyun. 1998. Regional air quality modeling of PM10 due to windblown dust on the Columbia Plateau. M.S. thesis. Pullman, Wash.: Washington State University, Dept. of Civil and Environmental Eng., December.

Lettau, K., and H. H. Lettau. 1978. Experimental and micro-meteorological field studies of dune migration. In *Exploring the World's Driest Climate*, eds. H. H. Lettau, and K. Letteau. University of Wisconsin-Madison, Institute for Environmental Studies, *IES Report* 101: 110-147.

McCool, D. K., K. E. Saxton, and P. W. Mutch. 1996. Rapid method for estimating random roughness. ASAE Paper No. 96-2093. St. Joseph, Mich.: ASAE.

Nickling, W. G. 1978. Eolian sediment transport during dust storms: Slims River Valley, Yukon Territory. *Canadian J. Earth Sci.* 15: 1069-1084.

Nickling, W. G., and J. A. Gilles. 1989. Emission of fine-grained particulates from desert soil. In *Paleoclimatology & Paleometerology: Modern and Past Patterns of Global Atmospheric Transport,* eds. M. Leinen and M. Sarnthein, 133-165. New York, N.Y.: Kluwer Academic Pub.

Nickling, W. G., and J. A. Gilles. 1993. Dust emission and transport in Mali, W. Africa. *Sedimentology* 35: 499-511.

Papendick, R. I., and K. E. Saxton, ed. 1997. Northwest Columbia Plateau Wind Erosion Air Quality Project: An interim report, Best management practices for farming with the wind. Pub. MISC0195. Pullman, Wash.: College of Agriculture and Home Economics, Washington State University.

Pietersma, D., L. D. Stetler, and K. E. Saxton. 1996. Design and aerodynamics of a portable wind tunnel for soil erosion and fugitive dust research. *Transactions of the ASAE* 39(6): 2075-2083.

Priestly, C. H. B. 1959. *Turbulent Transfer in the Lower Atmosphere.* Chicago, Ill.: University of Chicago Press.

Saxton, K. E. 1995a. Wind erosion and its impact on off-site air quality in the Columbia Plateau—An integrated research plan. *Transactions of the ASAE* 38(4): 1031-1038.

_____. 1995b. The Columbia Plateau Wind Erosion and Air Quality Research Plan, Ch. 1. In *Northwest Columbia Plateau Wind Erosion and Air Quality Project.* Pub. MISC0182. Pullman, Wash.: College of Agriculture and Home Economics, Washington State University.

Saxton, K. E., L. D. Stetler, and L. B. Horning. 1996. Principles of Wind Erosion, Ch. 1. In *Northwest Columbia Plateau Wind Erosion and Air Quality Project*. Pub. MISC0184. Pullman, Wash.: Washington State University, College of Agriculture and Home Economics.

Saxton, K. E., L. D. Stetler, and D. Chandler. 1997. Simultaneous wind erosion and PM_{10} fluxes. In *Proc. Wind Erosion: An International Symposium/Workshop*, Manhattan, Kans., 3-5 June 1997. Manhattan, Kans.: USDA-ARS.

Stetler, L. D., and K. E. Saxton. 1995. Simultaneous wind erosion and PM-10 fluxes from agricultural lands on the Columbia Plateau. In *Proc. Annual Meeting AWMA*, 18-23 June 1995, San Antonio, Tex. Paper No 95-MP12. Pittsburg, Pa.: AWMA.

Stetler, L., and K. E. Saxton. 1996. Simultaneous wind erosion and PM-10 fluxes from agricultural lands on the Columbia Plateau, Ch. 3. In *Northwest Columbia Plateau Wind Erosion Air Quality Project—An Interim Report.* Pub. MISC0182. Pullman, Wash.: Washington State University, College of Agriculture and Home Economics.

Stetler, L. D., and K. E. Saxton. 1997. Analysis of wind data used for predicting soil erosion. In *Proc. Wind Erosion: An International Symposium/Workshop*, Manhattan, Kans., 3-5 June 1997. Manhattan, Kans.: USDA-ARS.

Stetler, L. K. E. Saxton, L. Horning. 1997. Isokinetic sampling of eroded soil from a wind tunnel. ASAE Paper No. 97-2031. St. Joseph, Mich.: ASAE.

Stout, J. E. 1998. Effect of averaging time on the apparent threshold for aeolian transport. *J. Arid Environ.* 39: 395-401.

USDA-SCS. 1992. Picture your residue. SCS-CRM-02. Washington, D.C.: USDA/NRCS.

Woodruff, N. P., and F. H. Siddoway. 1965. A wind erosion equation. *Soil Sci. Soc. Am. Proc.* 29(5): 602-608.

Woodruff, N. P., L. Lyles, and F. H. Siddoway. 1977. How to control wind erosion. Agricultural Information Bulletin No. 354. Washington, D.C.: U.S. Department of Agriculture.