Simultaneous Wind Erosion and PM_{10} Fluxes

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Introduction

With the advent of the 1990 Clean Air Act came the responsibility to monitor and control particulates less than 10 micron aerodynamic diameter (PM_{10}). The basis for this legislation was research findings which indicate that exposure to high aerosol 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, with several of these occasions occurring on days of obvious regional agricultural wind erosion. 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 dust emissions. Thus, the Columbia Plateau was chosen as a primary region to study relationships between PM_{10} particulate pollution and agricultural field erosion.

Historically, wind erosion prediction technology has been based on empirically derived relationships between the major factors found to cause or control wind erosion. The wind erosion equation (WEQ) based on the work of Chepil (Woodruff and Siddoway, 1965), 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. 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}-sized.

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. To dovetail prediction efforts with existing urban PM_{10} measurements, erosion and dust emission predictions were to be made on an event basis. To achieve this objective, a two-step model was developed. The model was derived to first predict the horizontal flux of eroded soil from factors known to cause and control wind erosion, then subsequently calculate a corresponding vertical flux of PM_{10} for the erosion event.

An empirical equation was first developed to predict Q_t, the streamwise (horizontal) flux of eroded soil on an event basis. Similar in form to the WEQ (Woodruff and Siddoway, 1965), the calculated flux was based on the major conditions known to control an erosion event:

$$Q_t = \mathrm{f}(W, EI, SC, K, WC) \tag{1}$$

where

Q_t = eroded soil
W = erosive wind energy
EI = soil erodibility
SC = surface cover
K = surface roughness
WC = soil moisture and crusting

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

$$F = - K_A \, r \frac{\partial c}{\partial z} \tag{2}$$

where

F = vertical aerosol flux, $\mu gm^{-2}s^{-1}$
K_A= aerosol exchange coefficient
r = air density
c = particle concentration, μgm^{-3}
z = height, m

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

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

where

F = vertical dust flux, $\mu gm^{-2}s^{-1}$
C_d = drag coefficient
U_1 and U_2 = mean wind velocities at heights 1 and 2, (ms^{-1})
M_1 and M_2 = mean dust concentrations at height of U_1 and U_2 (gm^{-3})

The drag coefficient is defined as (Priestly, 1959):

$$C_d = \left({}^{u_*}\!/\!_{U_1} \right)^2 \tag{4}$$

which when substituted into equation 3 to yields:

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

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

$$U_z = \frac{u_*}{\mathrm{k}} \, ln \frac{z}{z_0} \tag{6}$$

where

U_z = wind velocity
z = height above surface
k = dimensionless Von Karman constant of 0.4
z_0 = aerodynamic roughness height of zero average velocity

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

$$F = \frac{-k\,u_*(M_2 - M_1)}{ln\left({}^{z_2}\!/\!{}_{z_1}\right)} \tag{7}$$

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

Materials and Methods

Independent experiments were conducted to develop separate relationships which describe the effect of each of the above variables on the total dust emission from a given soil type and farming practice. One set of experiments was conducted in situ to assess the effect of naturally occurring windstorms on erosion for soil conditions representative of farming practices common to the Columbia Plateau. A second set of experiments was conducted using a portable wind tunnel designed to define a) the effect of surface residue and soil surface roughness on wind erosion and b) the range of erodibility for the soils encountered on the Columbia Plateau. Overlap between the in situ sites and the wind tunnel sites allowed for calibration of the erodibility factors from the broad range of soils investigated using the portable wind tunnel to those found for the stationary in situ sites. Additional soil analyses were conducted in the laboratory to determine the dustiness, or freely available PM_{10} content, of the common soil types found on the Columbia Plateau.

Field Erosion: The in situ wind erosion sites were located in the Horse Heaven Hills near Prosser, WA (HHH); at the T-16 Ranch near Lind, WA (T-16); and near Ritzville, WA (Ritz) on silt loam soil developed from loess, some containing abundant volcanic ash. HHH and T-16 were located on a Shano series very fine sand and silt loam soils (Xerollic Camborthids). Ritz was set on a Ritzville series silt loam soils (Andic Aridic Hapllustolls). The on-site meteorology was recorded by three-cup anemometers located at heights of 0.1, 0.75, 1.5, 3.0 and 5.0m, thermocouples at 0.1, 2.0 and 5.0m and a tipping-bucket raingauge at 1.5m. Data were continuously recorded as 15 minute averages, then increased to one minute when the average wind speed at 3.0 m height exceeded 6.4 m/s, the potential initiation of wind erosion. This threshold for initiation of saltation was calculated assuming an average grain size sand of 0.50 mm diameter from the equation developed by Bagnold (1941):

$$u_{*t} = \mathrm{A}\left(\frac{s\ -\ r}{r}\,\mathrm{g}d\right)^{0.5} \tag{8}$$

where

$u_{*t} =$ threshold friction velocity

A = empirical coefficient of turbulence approximately equal to 0.1 for particle friction Reynolds number > 3.5

s = particle density, 2.65 gcm^{-3} for quartz grains

r = air density, 1.22×10^{-3} gcm^{-3}

g = acceleration due to gravity, 980 cms^{-2}

d = mean particle diameter, 0.05 cm

then utilizing equation 6 to solve for U at z=300 cm and a typical z_0= 0.12 cm. Once the initiation threshold was exceeded, the data was logged as one-min averages until the 15 min average wind speed at 3.0 m dropped below an arbitrary cessation threshold of 5.75 m/s.

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 x 54 m rectangular grid at heights of 0.1, 0.2, 0.5, 1.0, and 1.5 m. To ensure measuring the maximum carrying capacity of the streamwise flux of eroded soil, 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 also deployed within the BSNE arrays to collect sediment traveling at heights of 0.0, 5.0 and 7.5 mm. Sample collection ranged from weekly to monthly, depending on weather and field conditions. Samples were air dried only if the BSNEs had collected water during the sampling period. A mean sample mass was calculated for each collection height. The vertical distribution of mean sample mass was fit by a double exponential equation of the form:

$$m(z)=\mathrm{A}e^{-\mathrm{B}z} + \mathrm{C}e^{-\mathrm{D}z} \tag{9}$$

where

$m(z)$=sample mass collected at height z
z = sample height, m
A, B, C and D= constants of regression

The streamwise mass flux, q_{int} , representing the total 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:

$$q_{int} = \int_0^{1.5} \mathrm{Ae}^{-\mathrm{B}z} + \mathrm{Ce}^{-\mathrm{D}z} dz \tag{10}$$

Simultaneous sampling of PM_{10} for the duration of each windstorm was conducted using high-volume constant flow samplers[1] (hi-vols) with PM_{10}-cut inlet heads at 1.5m and 2.5 m above the soil surface. The hi-vols were powered by portable generators triggered to operate between the 3.0 m wind velocity initiation and cessation thresholds. High volume filters were replaced at the same times as the BSNEs were emptied and desiccated for 48 hours 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 susceptibility to erosion of a wide variety of soils and the effect of flat residue and random roughness levels. Relative erodibility trials were conducted for five replications on thirty 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. Eroded material was collected using a vertically integrating (modified Bagnold) slot sampler connected in series with a high efficiency cyclone and vacuum. The average mass of soil collected from each site was divided by that from a representative very erosive site to yield the site erodibility ratio, R.

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[1] General Metal Works, Village of Cleves, OH. Use of commercial names is only for the need of scientific documentation and implies no endorsement or preference.

Roughness and residue trials were conducted on 68 plots at field locations near Lind, WA and south of Prosser, WA (Horning, 1998). The data for each plot consisted 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 (*K*, cm std. dev.) was estimated by visually comparing test plots with photographs of well-documented random roughness conditions as described by McCool et al. (1996) and were converted from units of inches to centimeters for use in this analysis. Residue cover was estimated by visual comparisons with documented photos published by the Soil Conservation Service (USDA-SCS, 1992) and soil moisture content was determined by gravimetric sampling. The eroded material collected in the slot sampler system for each of three one-minute tests (5, 12, and 18 ms^{-1} at 3.0 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-minute flux rate from a test plot by the flux rate of the standard surface for that soil type:

$$SLR = \frac{F_{Treat}}{F_{Std}} \tag{11}$$

where SLR = soil loss ratio
F_{treat} = flux from a treated plot (gm^{-1} 3-min^{-1})
F_{std} = flux from a smooth, bare surface plot (gm^{-1} 3-min^{-1})

Soil Dustiness Index: It is the smallest and lightest fraction of the soil that most commonly is 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, the amount of PM_{10} available for suspension from a soil, or soil dustiness, *D*, was estimated by laboratory procedure. Soil samples taken at the wind tunnel erodibility trial sites were used to determine the percentage of free PM_{10} particles available for suspension. Samples of each soil class were passed through a 2 mm sieve to remove all residue and larger aggregates. Sub-samples of 0.50 g were injected into a sampling bell by a small, uniform blast of air. The air was aspirated from the bell through a PM_{10} control head and the re-suspended dust was continuously weighed by an electronic balance[2] until all suspended particles were removed. The dustiness index of the sample, *D*, was calculated as:

$$D = \frac{m_{sp}}{m_s} * 100 \tag{12}$$

where

D = dustiness index
m_{sp} = mass of suspended particles collected by TEOM
m_s = mass of soil sample <2 mm suspended

Average *D* values for the regional soil classes are shown in Table 1. Because much less energy is required to entrain a loose particle of soil than to detach that particle from a larger aggregate, only the "free" particles are considered in this current measure of dustiness because sandblasting abrasion of larger aggregates by saltating particles was not included in the analysis method. This addition will likely be more important to application of the model to soils beyond

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[2] TEOM, Rupprecht and Patashnick, Co Inc. Albany, NY.

those of the Columbia Plateau, where higher clay and organic matter content results in significant aggregation.

Results

The several sets of data 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 desired predictions should represent any given period of definition. This is important because simulations operate on an hourly time step of input data and flux calculations. First, the several variables required to define the horizontal erosion flux (eq. 1) was analyzed, then connecting relationships to the vertical dust flux (eq. 7) were defined.

Wind Erosion Flux

The several variables related to a minimal definition of wind erosion flux with 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 roughness (*K*) were found to exert a synergistic control on wind erosion, in agreement with the results of Fryrear (1985). The correlation equation (Horning, 1998) developed from the wind-tunnel trials to estimate the effectiveness of residue cover and random roughness was:

$$SLR = e^{-0.05*SC} * e^{-0.52*K} \tag{13}$$

where

SLR = Soil Loss Ratio
SC = flat residue cover (%)
K = random roughness (cm, std. dev.)

This relationship shows that maintaining surface plant residue is a very effective and practical method to control wind erosion (Woodruff et al., 1977). However, significant decreases of wind erosion from tilled soils can also be achieved with increases in either random roughness (clods) or 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, as summarized by Greely and Iverson (1985). Following the form of Lettau and Lettau (1978), we calculated event wind energy for the duration of wind velocities above threshold from a one-minute average wind speed as:

$$W_t = r\sum_{0}^{t} U^2\left(U - U_t\right)\Delta t \tag{14}$$

where

W_t = event wind energy
r = air density (gm^{-3})
U = one-minute average wind speed at 3m height (ms^{-1})
U_t = the threshold one-minute average wind speed at 3 m height (ms^{-1})
t = number of measurement intervals for which $U \geq U_t$
$D\,t$ = time interval of measurement (s)

The choice of a longer average velocity time interval will reduce the maximum average wind speed calculated for any period (Stetler, this issue) and will affect not only the calculated wind energy for any period, but the selection of U_t. Thus, a distinction must be made between wind energy calculated from one-minute average wind speed, W_t, and wind energy calculated from the more commonly available one-hour average wind speeds, W_{hr}:

$$W_{hr} = 3600\, r\, \overline{U}^2 (\overline{U} - \overline{U}_t) \tag{15}$$

where

W_{hr} = hourly wind energy
$\overline{U}$ = one-hour average wind speed at 3 m height (ms^{-1})
$\overline{U}_t$ = the threshold one-hour average wind speed at 3 m height (ms^{-1})

Erodibility Index: The soil erodibility index, *EI*, 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 would show that *EI* may be calculated as the ratio of the measured erosion during a windstorm, Q_t, to the total wind energy, W_t, during that erosive period:

$$EI = \frac{Q_t}{W_t(SC, K, WC)} \tag{16}$$

As shown by figure 1, EI was calculated as the slope of the line of Q_t vs. W_t from 11 wind erosion events which occurred during periods in 1994 and 1996 characterized by dry soil conditions and no crust, thus *WC* was approximately 1.0. Events which followed significant rainfall were observed to have decreased erosion due to wetness and/or crusting (as shown in figure 1) and were not used to calculate *EI* because a method for estimating the *WC* term was not yet available. For each event, Q_t was calculated by adjusting q_{int} for observed surface roughness and residue conditions for the site at the time of the event. Thus:

$$Q_t = {q_{int}} \Big/ {e^{-0.05*SC} e^{-0.52*K}} \tag{17}$$

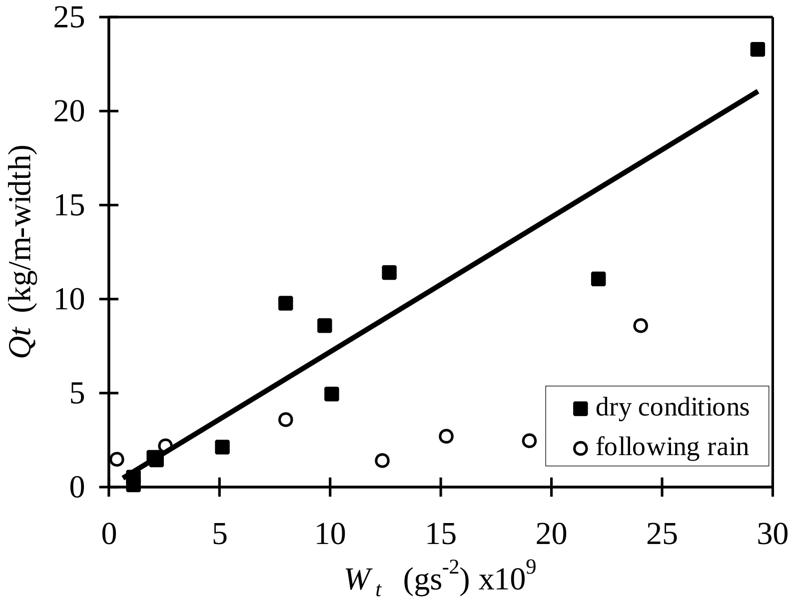

Figure 1: Erodibility Index (*EI*), calculated as the line slope for in situ site T-16 for wind storms which occurred during periods when the soil surface was both dry and non-crusted. Events which occurred following significant rain are shown for comparison.

Choice of threshold wind speed for initiation of erosion, U_t, may have a large effect on W_t, and thus on *EI*. To select an appropriate U_t for dry, non-crusted conditions, W_t was calculated for a range from 5.0 to 8.0 m/s for each event for U_t values (Figure. 2). The intercept of the Q_t vs. W_t line generally was most near the origin for U_t=6.0 m/s, representing no wind erosion and no effective wind energy. U_t=6.0 m/s was selected as a representative value for our three in situ sites for the calculation of *EI*. Similarly, we found equivalent values of W_{hr} and W_t for the model calibration events by setting $\overline{U}_t$ =5.5 m/s when U_t=6.0 m/s.

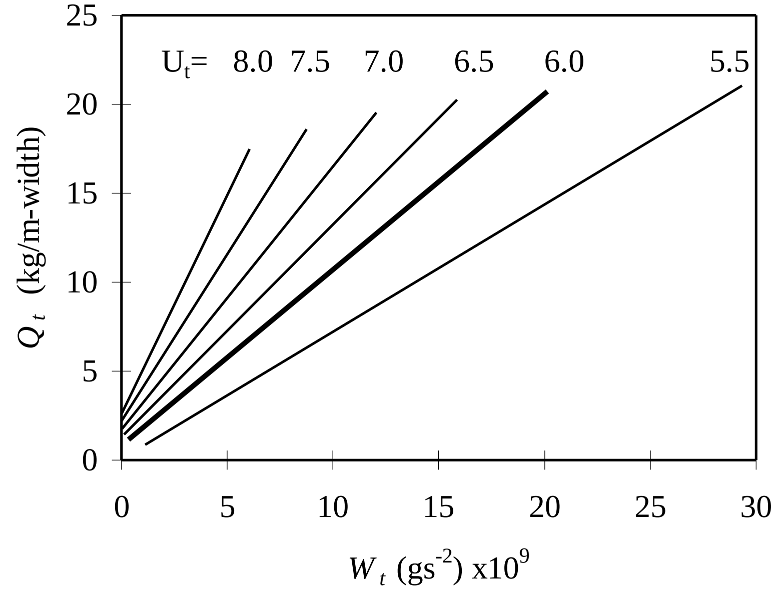

Figure 2: The effect of threshold wind speed, *Ut*, the slope and intercept of the line defining *EI*.

To provide an estimate of soil erodibility for all of the regional soil classes tested with the wind tunnel, a relationship was determined between the *EI* found under natural conditions at the three in situ sites and the values of relative soil loss, *R*, for wind tunnel runs at those sites (Figure. 3). The developed equation (forced through the origin):

$$EI = 8.2\text{x}10^{-7}\, R^{0.5} \tag{18}$$

which was then used to calculate the *EI* 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 wetness and crusting term (*WC*) reduces the predicted dust emissions depending on the antecedent history of rainfall and cultivation. For field conditions which are wet or crusted, the value of this term varies from 0.0 to 1.0, with the higher values assigned for more disturbed and drier non-crusted soils. The model was developed for events judged to be independent from wetness or crusting effects. Additional measured events not included in the analyses which had wetness or crusting did have substantially reduced erosion (Fig. 1). A predictive capability for this term more accurate than rational judgment has yet to be fully developed for Columbia Plateau soil conditions.

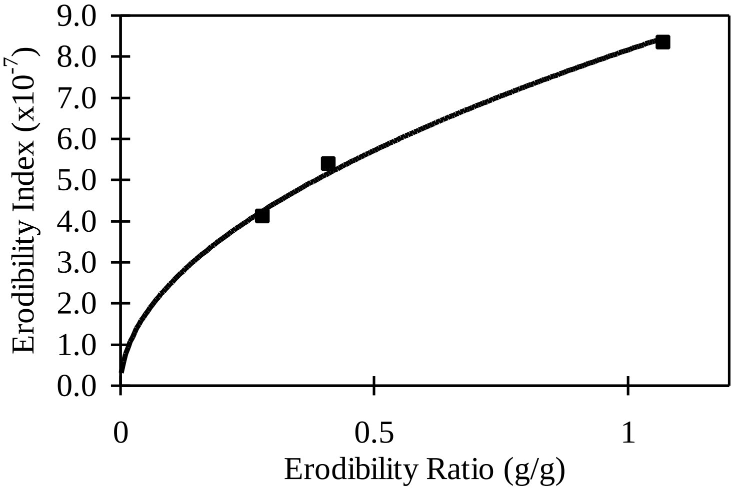

Figure 3: Correlation of the Erodibility Index (*EI*) at the in situ sites with the Relative Erodibility Ratio, R, from wind tunnel data at the sites.

Table 1. Average Dust Index (*D*), Relative Erodibility (*R*) and estimated Soil Erodibility Index (EI) values for major soil classes on the Columbia Plateau

Regional Soil class	**Dust Index (D)**		**Relative Erodibility *(R)***		**Soil Erodibility Index (EI) x 10^{-7}**
	avg.	**st. dev.**	**avg.**	**st. dev.**	
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

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

$$Q_t = \left(W_t * EI * e^{-0.05*SC} * \mathrm{e}^{-0.52*K*2.54} * WC\right) \tag{19}$$

This equation allows predicting the soil mass transported horizontally in an open field for a width of 1.0 m and a height of 1.5 m on a time basis defined by the wind energy. This equation approximates the equilibrium dust transport by creep and saltation for the wind energy and field surface condition of the specified event.

Vertical Dust Flux

The second step of the model predicts the vertical flux of PM_{10} (F) emitted during an erosive period, based on the Q_t, the soil dustiness (D), and the wind velocity, (U):

$$F = f(Q_t, D, U). \tag{20}$$

Simultaneous measurement of PM_{10} concentrations and Q_t during wind erosion events were made to develop a relationship between vertical dust flux and wind erosion. The filter mass of PM_{10} measured at 1.5 and 2.5 m height ($m_{1.5}$, $m_{2.5}$) relate the amount of dust which is available within the horizontal transport near the soil surface to that suspended in the over-riding layers of air. A linear relationship was found as the best fit between $m_{1.5}$, and the PM_{10} fraction of the eroded soil, Q_t times D, as shown in (figure 4):

$$m_{1.5} = k_1 \, Q_t \frac{D}{100} \tag{21}$$

A strong relationship (r^2=0.92) (figure 5) was also found between $m_{1.5}$ and $m_{2.5}$:

$$m_{2.5} = k_2 m_{1.5} \tag{22}$$

where $k_1=7.7\text{x}10^{-2}$ and $k_2=9.2\text{x}10^{-1}$.

While the correlations between $m_{1.5}$, $m_{2.5}$ and Q_T were made between mass values collected over one or more wind episodes, we expect the same relationships to hold for any time period. Thus to accommodate time intervals in an event model, mean hourly concentrations of PM_{10} at 1.5 and 2.5 m, $M_{1.5}$ and $M_{2.5}$, were estimated by dividing $m_{1.5}$ and $m_{2.5}$ by the volume of air aspirated through the filter on an hourly basis, for example:

$$M_{1.5} = \frac{m_{1.5}}{R\,t} \tag{23}$$

where

R = flow rate through sampler inlet, m^3s^{-1}
t = duration of sampling period, s

or

$$M_{1.5} = {}^{m_{1.5}}\!/_{k_3} \quad \text{and} \quad M_{2.5} = {}^{m_{2.5}}\!/_{k_3} \tag{24}$$

where

k_3=68.0 m^3, the hourly flow volume of our sampler.

Substitution of equations 21, 22 and 23 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 and mass from a defined wind event, soil type and surface condition:

$$F = K\, \bar{u}_*\, Q_T D \tag{25}$$

where

$$K = \frac{-k\left(k_1 k_2 - k_1\right)}{k_3\, ln\, 2} \tag{26}$$

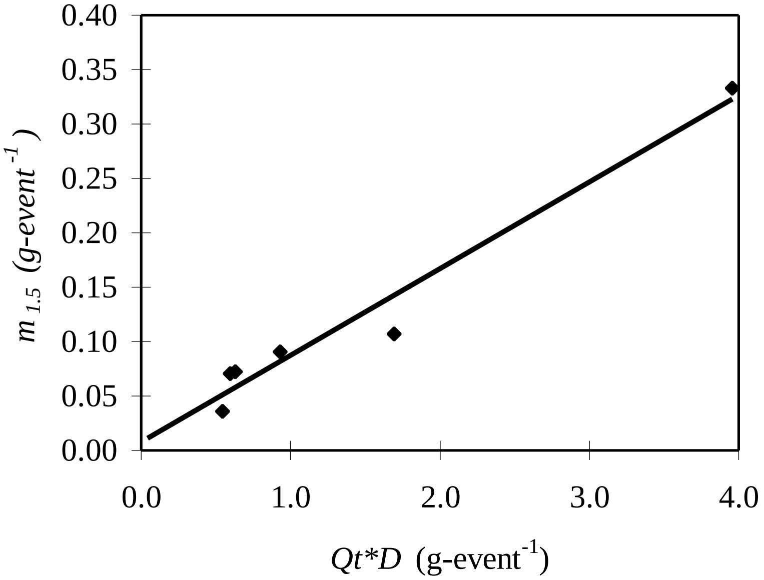

Figure 4: Correlation of PM10 filter mass at 1.5 m height (*m1.5*) with wind erosion (*Qt*) times dust coefficient (*D*).

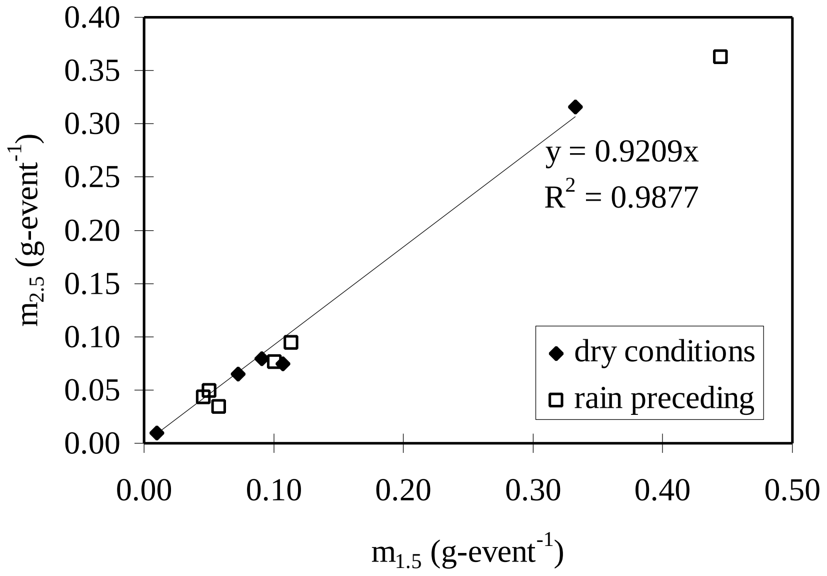

Figure 5: Correlation of filter mass for PM_{10} at 1.5 and 2.5 m heights for events.

While this model is based on actual field measurement and sound theory, it has not been accurately verified. We have applied the model as the input to a regional transport-dispersion equation for several selected events which caused regional particulate concentrations that exceeded 150 μgm^{-3}. While still in development, preliminary results show predicted concentrations of about 50 to 200% of those measured 100 km downwind of the central emission area (Papendick and Saxton, 1998). This is an accuracy likely within the expected limits given the number of variables, spatial variation and accuracy of definition of both the emission and transport-dispersion models.

Summary

Prediction of PM_{10} dust from a defined agricultural field during wind erosion events depends on factors which vary both spatially and temporally. Wind energy is the driving force for both wind erosion and dust suspension and may be calculated from wind speed above the threshold for erosion. Wind speed varies both seasonally and with topography. Both the threshold wind speed and the soil erodibility are dependent on soil type and condition. Similarly the wetness and crusting factor of a field is subject to the antecedent effects of rainfall (which develops the crust) and tillage (which breaks the crust). Thus the susceptibility of a particular field to wind erosion and dust emission depends greatly on the timing of field operations and the field condition. Predicting the dust emission from a domain larger than field scale requires knowledge of general regional time-dependent characteristics such as stage of crop growth and rainfall history and spatially-dependent characteristics such as soil type, farming systems and vegetative cover.

A PM_{10} dust flux model was developed from extensive field data throughout the Columbia Plateau of Eastern Washington State. This model was included as the input to a regional GIS-based prediction model and preliminary trials show quite reasonable results when compared with downwind dust concentrations for several historic events. Following further development and evaluations, this model will have the capability to estimate dust emissions from a variety of regional situations and potential control strategies with an accuracy suitable for planning and policy decisions.

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