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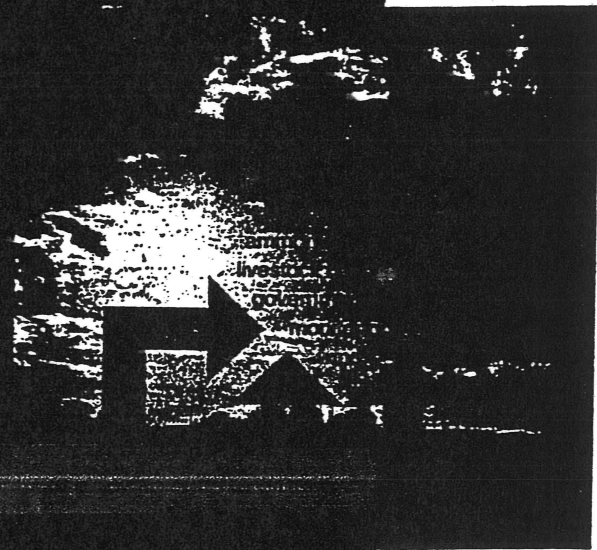
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PM-10 GENERATION BY WIND EROSION

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Abstract

The objectives of this study were to quantify individual sources of PM-10 generated by wind erosion and then to simulate the PM-10 generation capabilities of a range of Kansas soils. Three sources of PM-10 were identified: splash-emission of loose PM-10 by saltating aggregates, PM-10 abraded from clods/crust by saltating aggregates, and PM-10 from breakage of saltating aggregates. Parameters to quantify each of these PM-10 sources were proposed and then measured in field or laboratory experiments.

Measurements of fractions of loose, PM-10 mass in the tillage layer were made each fall and spring for 2 or 3 years in 11 Kansas soils. Mean loose, PM-10 ranged from 0.04 to 0.3 percent of soil mass. A wind tunnel and sampling train were used to test four soils to determine PM-10 generated from abrasion of clods by washed sand. Next, saltation-size aggregates from the same four soils were repeatedly cycled down the wind tunnel for a total of 300 m. Breakdown rate of the saltating aggregates and PM-10 generation were measured.

Finally, the measured parameters were used to simulate PM-10 generation capabilities of the tested soils. Maximum values for the ratio of vertical PM-10 flux to horizontal saltation transport capacity were: 0.000232 m^{-1}, Carr sandy loam; 0.000235 m^{-1}, Haynie silt loam; 0.000104 m^{-1}, Keith silt loam; and 0.000173 m^{-1}, Wymore silty clay. The PM-10 vertical flux increased downwind. The largest source of PM-10 on a simulated, large, bare field was the abrasion of clods.

Introduction

Dust generated by wind erosion often depletes soil productivity when emitted, degrades air quality in transit, and may contribute to a range of additional problems upon deposition (Pye, 1987). The finest portion of the dust, particles with an aerodynamic diameter of less than 10 microns (PM-10), is regulated as a health hazard in the United States.

Some areas of the western U.S. currently cannot meet National Ambient Air Quality Standards because of PM-10 caused by wind erosion. Hence, it is important to identify both the areas where significant dust storms occur and the PM-10 contributions from individual soils, so that optimum control measures can be designed. Areas where frequent dust storms occur have been identified using the meteorological records (Hagen and Woodruff, 1973; Orgill and Sehmel, 1976; Wheaton and Chakravarti, 1990).

Two main methodologies have been used to estimate PM-10 generation by wind erosion. One has involved using the USDA Wind Erosion Equation (WEQ) (Woodruff and Siddoway, 1965) to estimate total soil loss and then assigning a fraction of the loss as PM-10 (State of California Air Resources Board, 1991). A second approach has included assigning an aerodynamic roughness and threshold friction velocity to various surfaces and then relating dust (Gillette and Passi, 1988) or PM-10 generation (Barnard and Stewart, 1991) to calculated friction velocities.

In some of the above procedures, it was assumed that the PM-10 generation for similar erosive losses did not vary among soils. But earlier field measurements showed that, with similar saltation discharges, vertical flux of fine dust varied widely among soils (Gillette, 1977). However, the ratio of vertical dust flux to horizontal saltation discharge was nearly independent of friction velocity.

Improving estimates of PM-10 generation by wind erosion involves two major challenges. The first includes adequately simulating the weather and field conditions, to provide reasonable estimates of the saltation discharge. The recently developed Wind Erosion Prediction System (WEPS) (Hagen et al., 1995) provides the necessary databases and submodels to simulate the saltation discharge. The second is to determine the variation in potential for PM-10 generation among the various soils and the basis for these variations.

The individual sources of PM-10 generated by wind erosion are difficult to identify in field studies. However, basic knowledge about the various sources of PM-10 is needed to understand PM-10 generation processes, to aid in assessing the PM-10 production potential of various soils, and to simulate the effects of various PM-10 control strategies.

The objectives of this study were to determine the magnitude of individual sources of PM-10 generated during wind erosion and then to simulate the PM-10 generation capabilities of typical Kansas soils exhibiting a range in texture.

Theory

Except under extremely high wind speeds, wind erosion begins only when loose, erodible aggregates are present on the soil surface. Two variations of the soil condition are envisioned -- a thick layer of aggregates with varying sizes, such as occurs after tillage, or a thin layer of

sparse aggregates on a crusted surface, such as occurs after rainfall. During wind erosion, both of these surfaces generally produce a vertical flux of PM-10 particles.

There are three probable sources for the PM-10 generated during wind erosion. The first is emission of loose, PM-10 particles present in the surface soil. Saltation-size particles have a much lower threshold wind speed than PM-10 particles (Greeley and Iverson, 1985). Thus, the main mechanism for generation of airborne PM-10 from loose PM-10 is splash-emission caused by impacts of saltating particles as demonstrated by Shao et al. (1993). The loose, PM-10 particles generally are interspersed among larger aggregates and perhaps weakly bonded to them. Hence, they likely become exposed and emitted into the air in proportion to the emission rate of saltation and creep-size aggregates. For a simple field, the emission flux of loose soil is (Stout, 1990)

$$G_{en} = C_{en}(q_{cp} - q), \quad q \leq q_{cp} \quad (1)$$

where

G_{en} = vertical emission flux of loose soil (kg m^{-2} s^{-1}),

C_{en} = coefficient of emission (m^{-1}),

q_{cp} = transport capacity of saltation/creep (kg m^{-1} s^{-1}), and

q = saltation/creep at distance x from field edge (kg m^{-1} s^{-1}).

Subdividing the total emission gives

$$G10_{en} = SF10_{en}SFSS_{en}G_{en} \quad (2)$$

where

$G10_{en}$ = vertical emission flux of loose PM-10 (kg m^{-2} s^{-1}),

$SF10_{en}$ = soil fraction of PM-10 in the suspension-size soil, and

$SFSS_{en}$ = soil fraction of suspension-size in the emitted soil.

The preceding soil fractions can be estimated from the aggregate size distribution at the soil surface as

$$SF10_{en} = \frac{(F \leq 0.01 \ mm)(CF_{den})}{(F \leq 0.1 \ mm)} \quad (3)$$

$$SFSS_{en} = \frac{(F \leq 0.1 \ mm)}{(F \leq 0.84 \ mm)} \quad (4)$$

where

CF_{den} = correction factor when particle density not equal 1 Mgm^{-3}.

A second source of PM-10 is abrasion of surface clods and crust by saltation impacts that create and eject particles. The vertical flux from abrasion can be described as (Hagen, 1984, 1991):

$$G_{an} = (\sum_{i=1}^{2} F_i C_{ani})q \quad (5)$$

where

G_{an} = vertical flux of aggregates abraded from clods and crust (kg m^{-2} s^{-1}),

F_i = fraction of saltation impacting ith targets (clods or crust)

C_{ani} = coefficient of abrasion of the ith target (clods or crust) (m^{-1}).

The abrasion flux also can be partitioned based on its aggregate size distribution to give

$$G10_{an} = SF10_{an}SFSS_{an}G_{an} \quad (6)$$

where

$G10_{an}$ = vertical flux of PM-10 abraded from clods and crust (kg m^{-2} s^{-1}),

$SF10_{an}$ = soil fraction of PM-10 in suspension-size aggregates created during abrasion of clods and crust, and

$SFSS_{an}$ = soil fraction of suspension-size aggregates created during abrasion of clods and crust.

A third source of PM-10 is the breakdown of the saltating aggregates upon impact at the surface or collisions with each other. This phenomenon can be simulated as

$$G10_{ss} = SF10_{bk}C_{bk}(1 - F_{san})q \quad (7)$$

where

$G10_{ss}$ = vertical flux of PM-10 from breakdown of saltation and creep to suspension-size aggregates (kg m^{-2} s^{-1}),

$SF10_{bk}$ = soil fraction of PM-10 in suspension-size aggregates broken from saltation and creep,

C_{bk} = coefficient of breakage (m^{-1}), and

F_{san} = fraction sand in the soil.

Equation 7 represents only an approximation of field conditions, because as saltation and creep are converted to suspension, new saltation and creep aggregates

are added to the air stream. Hence. at any downwind point, the saltation and creep consist of a mixture of aggregates that have been subjected to a wide range of breakage energy. To simplify this complex problem. we propose that the breakage coefficient is approximately constant (i.e.. that breakdown of the saltation discharge with distance occurs at nearly a constant rate). and further. the breakdown of individual saltating aggregates asymptotically approaches a minimum which is approximately the sand content of the soil aggregates at the beginning of saltation. For saltation over a noneroding surface. this process can be described as

$$\frac{d(q/q_0)}{dx} = -C_{bk}(q/q_0 - F_{san})$$ (8)

where

q_0 = saltation discharge at distance x equal zero $(kg\ m^{-1}s^{-1})$,

x = distance downwind (m), and

F_{san} = soil fraction sand at x equal zero.

Finally. the overall vertical flux of PM-10 is the sum of the individual components:

$$G10 = G10_{en} + G10_{an} + G10_{ss}$$ (9)

On a uniform field, the variation in saltation and creep discharge with distance often can be approximated by

$$q = q_{cp}[1 - \exp(-x/s)]$$ (10)

where

x = distance along wind direction from field boundary (m), and

s = distance for q to reach 0.63 q_{cp} (m).

Now. the relative variation with field length of the various PM-10 sources can be illustrated by dividing equation 9 by q_{cp} and then substituting the r.h.s. of equation 10 for q to give:

$$\frac{G10}{q_{cp}} = SF10_{en}SFSS_{en}C_{er}\left[\exp\left(\frac{-x}{s}\right)\right] +$$
$$\left[SF10_{an}SFSS_{an}(\sum_{i=1}^{2} F_iC_{an}) - SF10_{bk}C_{bk}(1-F_{san})\right]$$ (11)
$$\left[1-\exp\left(\frac{-x}{s}\right)\right]$$

Equation 11 also was used to compare the relative PM-10 production potential among soils with the same total erosion.

Experimental Methods

To obtain estimates of loose PM-10. surface soils from 11 Kansas soils were sampled each spring and fall for 2 or 3 years. Soil samples were obtained from three different moisture regimes; these were the udic. ustic. and aridic. Samples were 10 kg composites from five locations in each field. A small. representative. subsample then was sieved on micromesh sieves to determine the fine end of the aggregate size distribution. The remainder of the sample was sieved through a rotary sieve to determine the coarse end of the distribution (Lyles et al., 1970).

Particle aerodynamic diameter varies as the square root of particle density. and typical density of fine crustal materials is about 2 Mg m^{-3} . Hence. an approximate correction factor for density was developed for the sieve data. The factor was obtained by linear extrapolation of the cumulative mass fraction against ln particle diameter to give PM-10 as 0.85 times the sieve fraction smaller than 10 microns.

Sand, silt, and clay fractions of primary particles in each soil also were determined by sieving the sand fraction and pipetting the clay fraction. according to the method of Gee and Bauder (1986) (Table 1).

To obtain estimates of potential PM-10 generation from the other two sources, large samples of four soils were brought to the laboratory. The samples were air-dried and sieved to separate the saltation-size from the larger soil clods.

Tests were conducted using a push-type wind tunnel and particulate sampling train as denoted by numbers in parenthesis and illustrated in Figure 1. The tunnel was powered by a gasoline engine driving a constant-pitch fan (1). A short convergence section and a honeycomb after the fan were connected to a working section 12.2 m in length and 0.92 X 0.92 m in cross-section. Beyond the working section, an open-top bin collected the saltation and creep-size aggregates, while the suspension-size exited the top of the bin to the atmosphere.

A hopper (2) to feed saltation-size abrader was placed on top of the tunnel, and feed tubes (3) extended from the hopper to 0.04 m above the floor. The feed rate to the tubes was regulated by varying the size of adjustable openings (4) at the bottom of the hopper.

A subsample of all soil moving down the tunnel was collected by a 3.8 mm-wide vertical slot sampler (7) mounted at the tunnel outlet. A variable-speed blower (12) was adjusted to obtain isokinetic flow at the slot sampler inlet (8) as indicated by four paired, interior and exterior, static pressure ports (10). Coarse particles were collected in the sampler pan (9), while fine particles moved upward through the outlet. Next, an isokinetic subsample ranging from 30 to 35 percent of the slot sampler outlet flow was
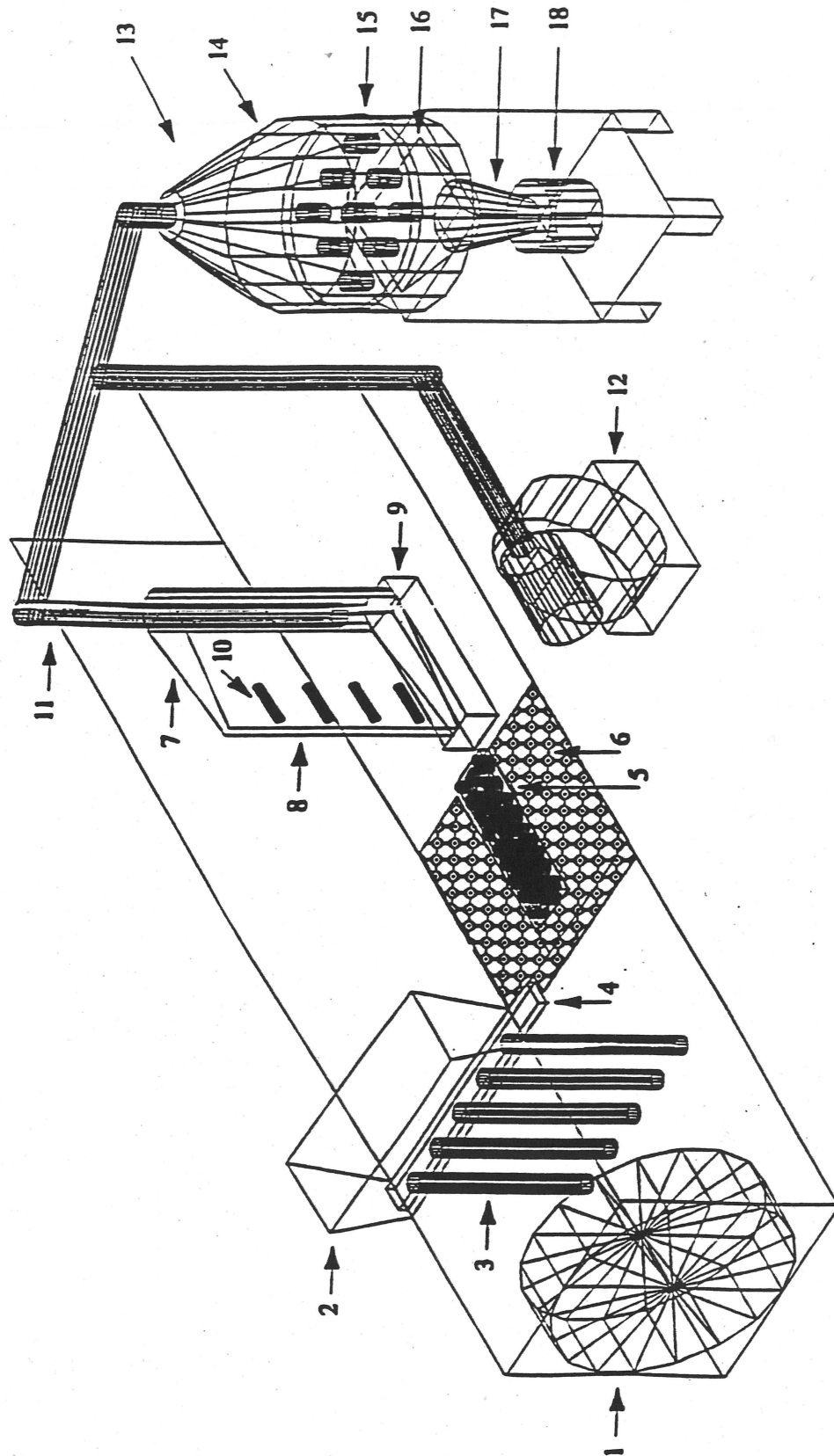
Figure 1. Diagram of wind tunnel and sampling train in configuration used for clod abrasion tests.

drawn into a Hi-vol[2] sampler (13) fitted with a cone-shaped inlet (14). Fine particles larger than PM-10 were collected on a lubricated impaction shim (15) and PM-10 particles on a filter (16). Filters were dried and weighed before and after collection runs of 10 to 20 minutes. Constant flow to the sampler was ensured by a flow controller (17) attached to the blower (18).

Two test procedures were used in the wind tunnel. In the first procedure, soil clods (5) ranging from 15 to 25 mm in diameter were placed on a 0.3 X 2.0 m wire mesh, which was centered on the tunnel floor ahead of the sampler. The clods were surrounded by similar-size non-abradable aggregates (6). Quartz sand, 0.29 to 0.42 mm diameter, was washed, dried, and then fed down the tunnel to abrade the soil clods using a 15 m s^{-1} freestream wind speed.

Abrasion coefficients with units (m^{-1}) were calculated for clods from each soil by dividing kg m^{-2} of abrasion soil loss from clods by kg m^{-1} width of sand abrader discharge. Size distribution of the abraded soil was determined from the subsample in the sampler pan and the mass collected on the shim and filter of the Hi-vol sampler. Breakdown of the quartz sand was assumed to be negligible. Tests were conducted only when wind direction moved the suspended particles downwind from the tunnel outlet.

In the second test procedure, soil abrader samples 0.15 to 0.42 mm in diameter were fed down a bare plywood tunnel floor. Preliminary particle rebound tests showed that the rebound from plywood was similar to that from large aggregates or crust. The saltation-size aggregates were collected on a tarp in the outlet bin, weighed, and then recycled down the tunnel at 13 m s^{-1} freestream wind speed. This process was repeated until the abrader had traveled about 300 m down the tunnel. A mean coefficient of breakage for each soil was calculated as a least squares fit of the solution of equation 8 to the data for each run. Size distribution and PM-10 generated were subsampled with the sampling train.

Results and Discussion

The mean fraction of loose soil particles less than 0.01 mm in sieve diameter in the tillage layer of 11 Kansas soils was relatively low, ranging from 0.04 to 0.3 percent of the soil mass . Based on an approximate correction for particle density, we estimated that 85 percent of the mass less than 0.01 mm was PM-10.

We observed a weak linear trend, R^2= 0.64, for the mass fraction less than 0.01 mm to increase with the silt/clay ratio in the 0 to 20 mm surface soil layer (Figure 2). The mean fractions less than 0.01 mm were 0.00137

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and 0.00075 in the 0 to 0.20 mm and the 20 to 200 mm layers, respectively. The means were significantly different at P = 0.10 level. However, significant variation occurred between observations, and the average coefficient of variation about the means for the loose PM-10 in the 11 soils was 0.80.

Some preliminary measurements of aggregate size distributions in soils from other semi-arid regions show that PM-10 contents can reach 4 percent of soil mass. Hence, the loose PM-10 results for Kansas soils may not be widely
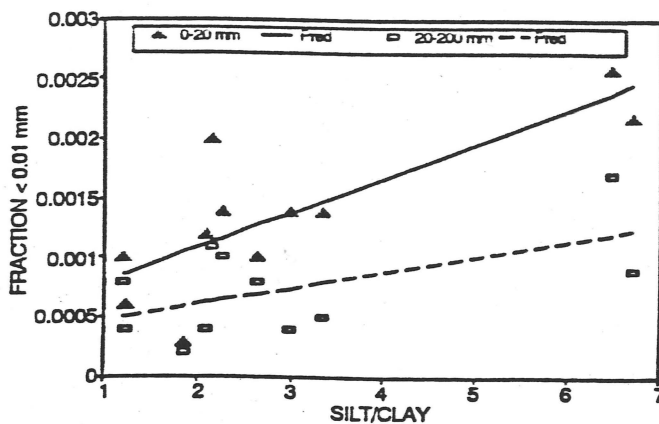

Figure 2. Mean soil fractions smaller than 0.01 mm in two soil layers. Upper prediction line R^2 = 0.64, lower line R^2 = 0.34.

applicable to other regions.

In the theory section, splash-emission of loose PM-10, abrasion from clods and crust, and breakage of saltating aggregates were suggested as sources of the PM-10 generated during wind erosion. The parameters to describe each of these sources were measured, and mean values for four soils are shown in Table 2. The Carr and Haynie soils had higher fractions of both emission-size soil and loose, PM-10 than Keith and Wymore.

During abrasion, the weak aggregate structure of the Carr and Haynie soils had a marked influence. For example, their abrasion coefficients, and consequently abrasion losses, exceeded those of Keith and Wymore by 13 to 58 times. However, PM-10 content in the soil removed by abrasion was highest in the Keith and Wymore.

Using a constant breakage coefficient provided good fits to the measured breakage data with R^2 > 0.95 for all the tested soils. Distinct differences also occurred in

Carr Sandy Loam Soil

Haynie Silt Loam Soil

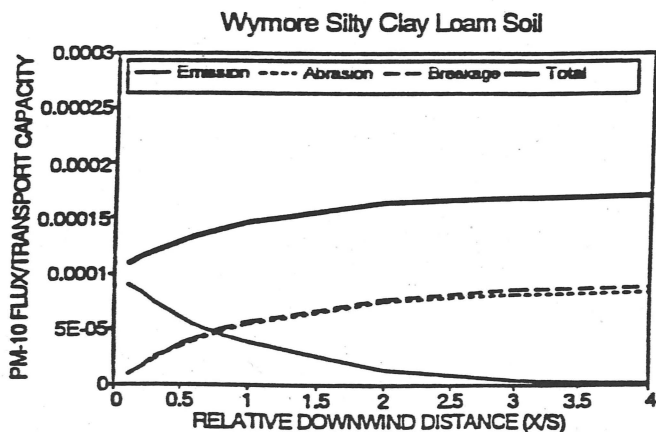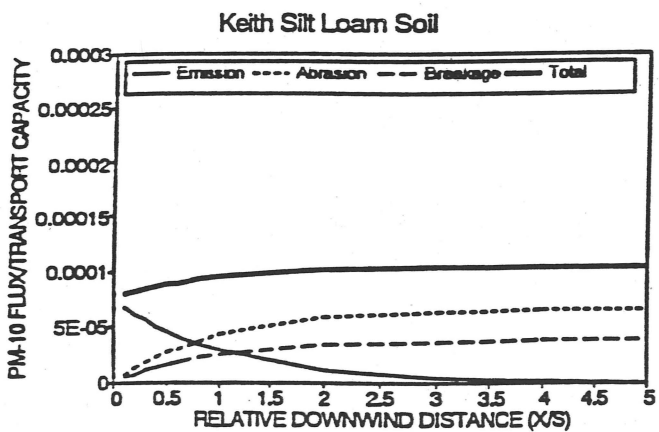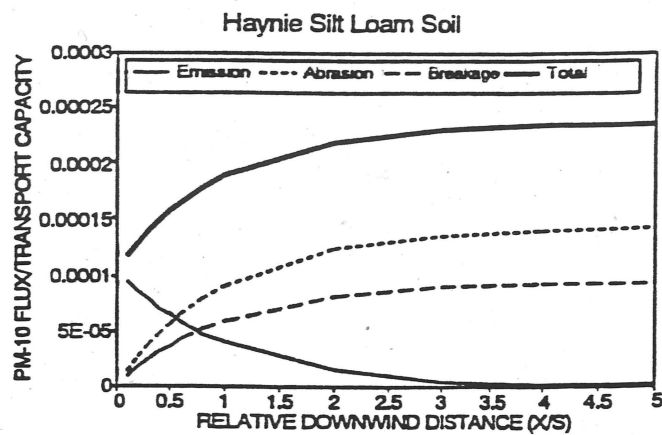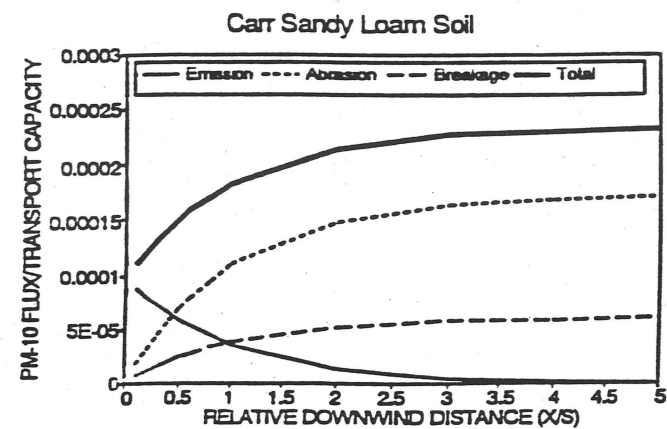## Keith Silt Loam Soil

Wymore Silty Clay Loam Soil

Figure 3. Comparison of Carr, Haynie, Keith, and Wymore soils for components and total PM-10 as a function of distance downwind, where S is the distance to 0.63 saltation transport capacity.

the breakage patterns among the soils. The saltating aggregates of Carr and Haynie resisted breakdown much better than the parent clods, so the breakage coefficients were 13 to 18 percent of the abrasion coefficients. In contrast, these coefficients were nearly equal in the Keith and Wymore soils.

The individual and combined effects of the three sources on PM-10 generation as a function of field length were simulated for each soil using equation 11 (Figure 3). A constant value of 0.04 m^{-1} was used for C_{en} in the simulations. Because the abscissa is a relative distance, selecting a different value of C_{en} would not change the relationships in Figure 3.

On the simulated fields, several common trends occurred. First, as saltation discharge approached transport capacity, the contribution of loose PM-10 from emission became small. This occurred because, at transport capacity, net removal of saltation-size aggregates at the soil surface was small. Hence, the relative contribution from each source to the total PM-10 depended somewhat on total field length. Clearly, on long fields abrasion and breakage are likely the dominant sources of PM-10.

Another trend was that the abrasion source generally exceeded the breakage source, except in the case of Wymore, where they were nearly equal. However, the results were for bare, cloddy surfaces. If the surface were armored with rocks or residues, the generation from abrasion would drop sharply, and breakage could become the dominant generation process.

The simulation results demonstrate that, even with equal total erosion, PM-10 generation differs significantly among soils (Figure 4). The total PM-10 generation for the Carr and Haynie soils was more than twice that predicted for the Keith soil. This occurred primarily because of the large contributions from abrasion of clods, which also caused the sharp increase of PM-10 with field length. Obviously, PM-10 controls, such as residues and reduced field lengths, would be most effective if applied to these soils.
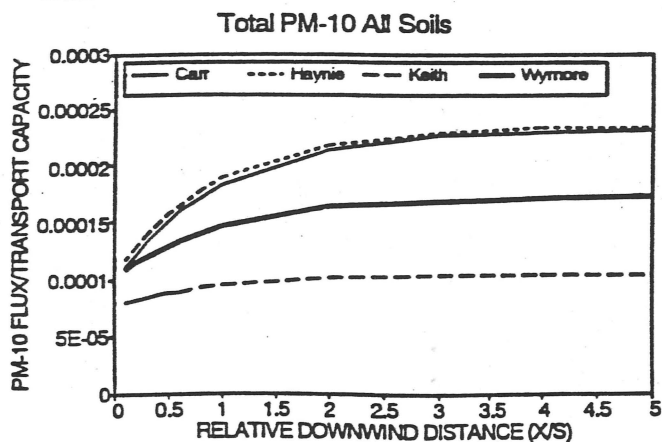

Total PM-10 All Soils

Figure 4. Comparison of total PM-10 from four soils calculated as a function of distance downwind, where S is the distance to 0.63 saltation transport capacity.

The simulation results in this study were somewhat less than PM-10 flux calculated for a highly erodible loam soil on a dry lakebed at Owens Lake, California (Gillette et al., 1995). The Owens Lake value of $G10/q_{cp} = 0.00045\ m^{-1}$ was based on field measurements of vertical gradients of PM-10 near the surface. Similar procedures were used to calculate values for vertical flux of particles less than 0.02 mm in diameter on several Texas soils (Gillette, 1977), and values both above and below those in the present study were reported.

Conclusions

Combined field sampling and wind tunnel studies can be used to quantify potential PM-10 generation by various soils. On large, bare, Kansas fields, the major sources of PM-10 are abrasion of clod/crusts and breakage of saltating aggregates. Among soils tested, Carr sandy loam and Haynie silt loam had the potential to produce most PM-10 during wind erosion.

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Table 1. Description of 11 Kansas soils tested for aggrgate size distribution and primary particle size.

Series	Particle Size (mm)		
	Sand	Silt	Clay
	>0.05	0.05-0.002	<0.002
	-----Percent-----		
Carr sandy loam	59.0	35.5	5.5
Eudora silt loam	29.1	54.5	16.4
Haynie silt loam	32.9	58.4	8.7
Harney silt loam	9.6	61.1	29.3
Inavale loamy sand	81.5	12.6	5.9
Keith silt loam	19.5	58.4	22.1
Kimo silty clay loam	20.0	44.0	36.0
New Cambria silty clay	14.3	46.6	39.1
Reading silt loam	6.3	70.1	23.6
Smolan silty clay	7.0	60.1	32.9
Wymore silty clay	7.8	63.8	28.4

Table 2. Measured average values of emission, abrasion and breakage factors of four Kansas soils.

Process	Soils			
	Carr	Haynie	Keith	Wymore
Emission:				
Fraction<0.01mm	0.0026	0.0022	0.0010	0.0014
$SF10_{em}$	0.0035	0.0040	0.0093	0.0112
$SFSS_{em}$	0.6924	0.6555	0.2025	0.2438
Abrasion:				
$SF10_{ab}$	0.0071	0.0204	0.1092	0.1732
$SFSS_{ab}$	0.2300	0.1378	0.1602	0.2704
F_iCan_i (m^{-1})	0.1060	0.0508	0.0038	0.0018
Breakage:				
Initial diameter				
0.15 to 0.42 mm				
$SF10_{bk}$	0.0105	0.0153	0.0162	0.0360
C_{bk} (m^{-1})	0.0139	0.0091	0.0029	0.0027