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PM2.5 and PM10 emissions from agricultural soils by wind erosion ☆

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ABSTRACT

Soil tillage and wind erosion are two major emission sources of particulate matter less than 2.5 and 10 μm in size (PM2.5 and PM10) from cultivated soils. Samples from fifteen cultivated soils from five states of the US, both crushed (<2.0 mm) and uncrushed (natural aggregation), were tested for PM2.5 and PM10 emissions in a wind tunnel, at 8, 10, and 13 m s^{-1} wind velocities. In addition, 10 soils were paired as conventional vs. no-till. Results showed that: (1) PM2.5 and PM10 emissions of crushed and uncrushed samples increased with wind speed, with a more rapid and greater emissions trend for crushed samples; after three wind speeds, mean PM2.5 and PM10 emissions from crushed soils were 1.3–8.5 and 1.9–10 times that of uncrushed soils; (2) PM2.5/PM10 ratios of crushed and uncrushed samples were, respectively, 0.11–0.45 and 0.13–0.46, and the mean PM2.5/PM10 ratio of uncrushed samples was higher; (3) PM2.5 and PM10 emissions of tested soils showed a significant negative power function relationship with clay content and PM2.5 and PM10 fractions of the dispersed soil samples, whereas the sand content and <0.42-mm aggregate content of the samples showed a significant linear positive correlation with emissions; and (4) although not significant, no-till soils had consistently lower PM2.5 and PM10 emissions than paired conventional tilled soils for uncrushed samples.

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1. Introduction

Fugitive windblown dust has been recognized as a serious health and environmental issue associated with reduced air quality and visibility (Chepil and Woodruff, 1957; Hagen and Skidmore, 1977; Gillette, 1986; Carvacho et al., 2001), soil nutrient and productivity loss (Zobeck and Fryrear, 1986; Larney et al., 1998), and soil degradation due to nutrient/chemical loading on regional ecological systems (Leys, 1999; Leys and McTainsh, 1999). Fine particles, especially particulate matter of mean aerodynamic diameter 10 μm and less (PM10 and PM2.5), are hazardous to human health because they can penetrate pulmonary defenses and lodge deep in the lungs (Ostro et al., 1999; Kjelgaard et al., 2004b). The larger particles in this range (PM10–PM2.5) tend to be deposited in the upper airways of the respiratory tract, whereas PM2.5 can reach and be deposited in the smallest airways in the lungs. Smaller particles are considered more hazardous to health than larger particles (Pope et al., 1995; Schwartz et al., 1996; Klemm et al., 2000), but the larger particles (i.e., PM10) remain subject to regulation (Carvacho et al., 2001). The United States Environmental Protection Agency (US EPA, 1999a) set regulations for PM10 in 1987 and later regulated the mass concentration of PM2.5 (US EPA, 1996). In 2012, the US EPA revised the standard for PM2.5 as 35 μg m^{-3} for 24 h (US Federal Register, 2013).

Pace (2005) listed major sources of fugitive dust emissions as including traffic on paved and unpaved roads, construction, agricultural operations, mineral industries, and wind erosion from both agricultural and nonagricultural lands. Many studies have reported PM10 from paved and unpaved roads, but limited field data are available for other categories. PM10 emission rates from wind erosion are related to dust suspension (Roney and White, 2006). Several studies have evaluated PM10 from agricultural operations (Ashbaugh and Eldred, 2004; Kjelgaard et al., 2004a; Pace, 2005), but few research results have been reported for emissions from cultivated agricultural soil surfaces, especially for PM2.5 emission. The potential of various soils to contribute to the PM10 component of suspension was investigated by Hagen (2004a) and Carvacho et al. (2001, 2004). Mirzamostafa et al. (1998) proposed three major processes as possible sources of fine particulates from soils. These processes are direct entrainment (emission) of loose particles by the wind, abrasion of immobile aggregates and crusts by saltation impacts, and breakage of mobile saltation and creep-sized aggregates and particles into suspension

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Table 1
Description of soils sampled. "ID" refers to the sample site designation. Note that site 6 was used for preliminary testing and is not included in the data presented.

ID	Location	Latitude longitude	Texture	Series name	Classification	Management
1	Manhattan, KS	39 12.671N 96 35.749W	Silt loam	Ivan	Fine-silty, mixed, mesic Cumulic Hapludolls	Conventional till fallow winter wheat stubble
2		39 12.686N 96 35.750W	Silt loam			No-till corn (20 + yrs)
3		39 12.942N 96 35.870W	Silt loam	Smolan	Fine, smectitic, mesic Pachic Argiustolls	Conventional till fallow winter wheat stubble
4		39 12.946N 96 35.825W	Silt loam			No-till winter wheat-sorghum-soybean (15 yrs)
5		39 13.787N 96 34.803W	Silty clay loam	Chase	Fine, smectitic, mesic Aquertic Argiudolls	Conventional till continuous winter wheat
7		39 8.733N 96 38.031W	Loamy fine sand	Stonehouse	Sandy, mixed, mesic Typic Udifluvents	Soybean fallow conventional tillage
8		39 8.732N 96 37.903W	Loamy fine sand			Soybean stubble conventional tillage
9	Pullman, WA	46 46.713N	Silt loam	Palouse	Fine-silty, mixed, mesic Pachic Ultic Haploxerolls	No-till winter wheat-spring wheat-garbonzo
10		117 4.953W	Silt loam			Conventional winter wheat-spring wheat-garbonzo
11	Bushland, TX	35 10.837N 102 5.581W	Clay loam	Pullman	Fine, mixed, thermic Torrertic Paleustolls	Conventional tilled wheat-sorghum-fallow (30 yrs)
12		35 10.846N 102 5.611W	Clay loam			No-till wheat-sorghum-fallow (30 yrs)
13	Belle Glade, FL	26 39.387N 80 37.882W	Muck	Pahokee	Euic, hyperthermic Lithic Haplosaprists	Lettuce
14	Canal Point, FL	26 52.008N 80 37.405W	Muck	Torry	Euic, hyperthermic Typic Haplosaprists	Sugar cane
15	Pierre, SD	44 3.025N 100 8.557W	Clay	Promise	Very-fine, smetitic, mesic Typic Haplustert	Conventional (20 + yrs); most recently winter wheat
16		44 3.794N 100 9.740W	Clay	Promise		No-till (20 + yrs); most recently sunflower

size. The contribution of PM2.5 to the suspension component has had limited study (Feng et al., 2011; Hagen, 2004a; Pace, 2005).

A number of researchers have explored a variety of methods to estimate potential PM2.5 and PM10 emissions from both dispersed and non-dispersed soils, ranging from ambient measurements, laser diffraction of soils, and fluid bed to breakage of aggregates in a rotating chamber. These studies were summarized by Feng et al. (2011), who reported PM2.5/PM10 ratios of 0.03–0.55. Feng et al. (2011) is the only study that tested PM2.5 and PM10 emissions using a wind tunnel, but the soils used were hand-sieved to pass through a 2-mm sieve rather than naturally aggregated soils as found in the field.

The Wind Erosion Prediction System (WEPS) developed by the USDA Agricultural Research Service simulates emission of soil from cultivated agricultural fields for conservation planning and environmental assessments. (Wagner, 2013). It simulates hydrology, plant growth and decomposition, land management, and soil surface erodibility to simulate soil wind erosion loss as affected by stochastically simulated local weather (Hagen, 2004b). The WEPS model partitions soil loss into size classes that include saltation + creep (0.1–2.0 mm), suspension (<0.1 mm), and PM10 (<0.01 mm) and is therefore suited for environmental air quality assessments from wind erosion. A better understanding of the PM2.5/PM10 ratio of soils is needed to expand the capability of WEPS to simulate the emissions of PM2.5 as affected by climate, soils, and management.

The objective of this study was to determine PM2.5 emissions of loose erodible particulates in the surface soil at different wind speeds for a variety of soil textures. A secondary objective was to observe differences in fine particulate emissions as affected by management (i.e., conventional vs. no-till). The broader research goal is to support the development of WEPS and other technology to simulate fine particulate emissions from agricultural lands.

2. Materials and methods

2.1. Soil sample collection and pretreatment

Soil samples were collected from 15 sites within the United States to provide a variety of primary particle size distributions (i.e., soil textures) as mapped by USDA Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/; see Table 1). In addition, 10 of these sites were sampled as pairs on the same soil but with differing management, no-till (NT) vs. conventional (CV) tillage. Eight of these paired 10 paired sites were within 30 m of each other and within the same map unit delineation (i.e., sites 1 & 2, 3 & 4, 9 & 10, 11 & 12). The two other paired sites (sites 15 & 16) were mapped as the same soil but were approximately 2 km apart. The soil types also included two organic-dominated soils (Histosols). Samples were collected in the early spring to represent a highly erodible aggregate state. All samples were collected with a flat-bottomed shovel from the 0 to 5 cm depth. The soils were dried on plastic in a greenhouse, and roots and crop residues were hand-removed without destroying the soil structure.

For dispersed particle-size distribution, the clay was determined by pipette, sand fractions by sieving, and silt by difference according to the method of Gee and Dani (2002). Pipette sampling also was performed to determine dispersed PM10 and PM2.5. An approximately 2-kg sub-sample was taken for aggregate size distribution (ASD). The ASD was determined by dry-sieving with a rotary sieve using 0.42, 0.84, 2.00, 6.35, 19.05, 44.45, and 76.20-mm sieve sizes (Lyles et al., 1970). These aggregate size fractions were used to compute geometric mean diameter (GMD) and geometric standard deviation (GSD) of dry aggregates using the mesh size of each sieve and the amount of aggregates within each fraction (Nimmo and Perkins, 2002). Wind-erodible fraction (WEF), which is the percentage of air-dried aggregates <0.84 mm in

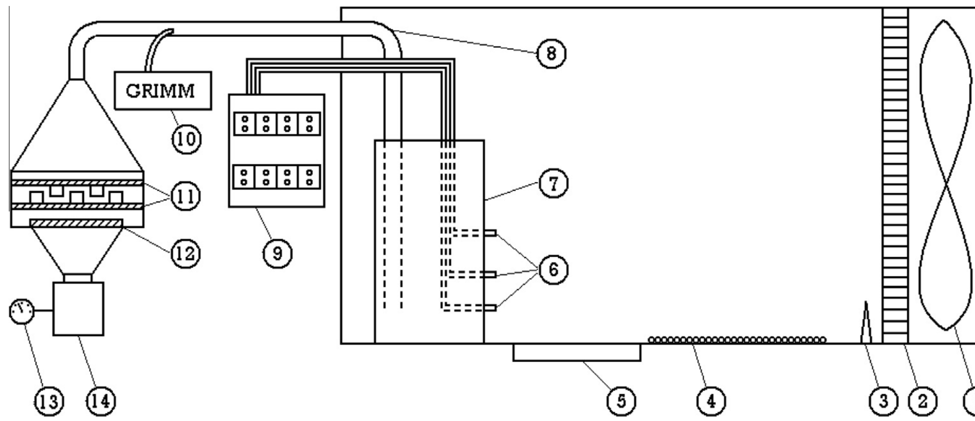

Fig. 1. Diagram of wind tunnel components and instrumentation for the tests (not drawn to scale). Components shown are: (1) fan, (2) honeycomb, (3) spires, (4) gravel bed, (5) soil test tray, (6) static pressure pitot tubes, (7) particle sampler inlet, (8) dust sampling duct tube (63.5 mm ID), (9) pressure transducers, (10) Grimm particle sampler, (11) cascade impactor plates, (12) PM10 filter, (13) pressure gauge, and (14) flow controller blower. Components 6–9 represent the isokinetic slot sampler components.

diameter, was computed from the dry aggregate size distribution. Wind-erodible fraction is the most common parameter used to evaluate soil susceptibility to wind erosion (Hagen et al., 1999).

Organic matter (O.M.) and calcium carbonate equivalent ($CaCO_3$) of the <2.0-mm fraction of each soil was determined by the Kansas State University Soil Testing Laboratory. O.M. was determined by loss on ignition at 400 °C (Schulte and Hopkins, 1996) and $CaCO_3$ by the method of Leo (1963).

Previous research on fine particle emissions using wind tunnels has been performed on both naturally aggregated soils (Mirzamostafa et al., 1998) as well as soils in which the ASD was controlled by passing soil through a 2.0-mm sieve (Feng et al., 2011). Feng et al. (2011) preformed emission tests on soils less than 2 mm. Therefore, soil samples for this study were prepared for wind tunnel tests by dividing them into two portions for comparison. One portion was crushed using a rubber mallet and sieved through a 2-mm sieve, and the other was kept in the original aggregated state. Each soil condition (crushed and uncrushed) was placed in wind tunnel test trays (inner dimension in meters: 1.18 L × 0.2 W × 0.03 D) in three replicates. The crushed sample trays were leveled with a straight edge to form a smooth, erodible surface, whereas the uncrushed soils were placed in the trays to mimic the original aggregated surface.

2.2. Wind tunnel and measurement system

Wind-tunnel tests were conducted at the USDA-ARS Engineering and Wind Erosion Research Unit (EWERU) Laboratory located in Manhattan, KS, using a push-type wind tunnel (13 L × 1.20 W × 1.47 H m) with a working section length of 12.2 m and a maximum possible free stream wind speed of 14 m s^{-1} with the current tunnel configuration. Screens were placed over the entire tunnel cross-section immediately downwind of the fan (Fig. 1, No. 1) to promote flow uniformity and decrease longitudinal turbulence. A honeycomb (Fig. 1, No. 2) after the screens was used to decrease lateral turbulence, and spires (Fig. 1, No. 3) were placed at the upwind end of the tunnel floor to increase the initial boundary-layer depth. The tunnel floor was lined with pea-sized gravel (5–7 mm in size; Fig. 1, No. 4) to simulate a surface roughness similar to the soil trays and promote an equilibrium boundary layer with the desired turbulence intensity. The roughness provided boundary-layer conditions within the air stream that better replicate those found in actual field conditions (Roney and White, 2006). Kohake et al. (2010), using the EWERU laboratory wind tunnel, showed that all loose erodible material was successfully removed from a soil surface when subjected to 13 m s^{-1} wind for 5 min; accordingly, three velocity gradients were chosen as 8, 10, and 13 m s^{-1}. Trays (Fig. 1, No. 5) filled with air-dried soils were placed even with the wind tunnel floor directly upwind of the slot-style sampler (Fig. 1, No. 7).

During wind tunnel testing, humidity and temperature were measured in real time with a temperature/humidity sensor (Model HMP 110, Vaisala). Humidity and temperature were measured at 1-s intervals throughout each test. Barometric pressure was measured with a barometric sensor (Electronic barometer, Model PTB-110, Vaisala). The humidity, temperature, and barometric pressure were used in determining air density, which was subsequently used in calculating wind velocity within the tunnel. A pitot tube was used to monitor the wind velocity of the wind tunnel located 75 cm above the tunnel floor on the central line upwind of the slot sampler and above the testing tray. Pressure was monitored with a variable voltage differential pressure transducer (Model 264, Setra Systems, Inc.).

2.3. Particulate sampling

A slot-style isokinetic sampler system (Fig. 1, Nos. 6–9) (Mirzamostafa et al., 1998; Van Pelt et al., 2010) collected dust emissions in the suspension size range (<100 μm). Emissions enter the system through a 3.6-mm-wide vertical slot. Inside the sampler, a cyclone separator separates saltation-sized particles from suspension-sized particles and deposits the saltation-sized particles into a catch pan under the sampler (not shown). Suspension-sized particles then travel into the 63.5-mm ID duct at the top of the sampler (Fig. 1, No. 8). Isokinetic sampling conditions were maintained by adjusting the slot length of the sampler slot from the top.

To capture the full height gradient of the emissions plume, the minimal allowed slot length was a 15° angle from the front of the sample tray. Volumetric flux across the sample area of slot sampler was maintained at 1.13 m^3 min^{-1}. Length of the slot was calculated as 520, 440, and 365 mm for the nominal wind speeds of 8, 10, and 13 m s^{-1}. To ensure isokinetic conditions, the static pressure difference between the inside and outside along the sampler intake was monitored in real time using a computer and pressure transducers (Fig. 1, No. 9).

Suspension-sized particles were measured with a Grimm portable aerosol spectrometer dust monitor (Model 1.108, Grimm Aerosol Technik GmbH & Co, Ainring, Germany) (Fig. 1, No. 10). The Grimm sample tube inlet was fixed in the middle of the duct (Fig. 1, No. 8) and perpendicular to the upwind direction. The inlet to the Grimm sample tube had an inner diameter of 1.85 mm to maintain isokinetic conditions. The sampling tube was positioned eight times the diameter of the duct ($63.5 \times 8 = 508$ mm) downwind of any changes in airflow direction and upwind one times the diameter of changes in airflow direction. This Grimm spectrometer drew air at a volume-controlled 1.2 L min^{-1} past a light-scattering laser diode source and divided particulate concentration into 15 distinct size classes from 0.23 to 20 μm. The spectrometer was used throughout wind tunnel testing to determine the particulate concentration resulting from emissions of the tray samples. It allowed for a real-time view of the particulate concentrations during testing and partitioning of emissions at each wind speed.

A PM10 High-Volume (Hi-Vol) Sampler (EPA reference method: RFPS-1287-063; Graseby Andersen/GMW Model 1200 High-Volume Air Sampler) was used to separate and collect PM10 size particles (Fig. 1, Nos. 11–14). As ambient air is drawn into the inlet, it is evacuated from the buffer chamber through nine acceleration nozzles into the impaction chamber, where particles >10 μm impact on greased collection plates. The air containing the PM10 particle fraction is then channeled through an additional 16 vent tubes and collected on a glass fiber filter.

PM10 as measured by the aerosol spectrometer dust monitor was found to be highly correlated with that collected on the Hi-Vol filter (Fig. 2). The Hi-Vol sampling system is an EPA-approved PM10 sampling method (US EPA, 1999b); however, the high correlation between the two methods demonstrates that the dust monitor in this study also provided a good measure of PM10. Because the Grimm provided an additional separation of PM2.5 as well as real-time monitoring, we present only PM2.5 and PM10 loss as calculated from the Grimm in this paper.

2.4. Wind tunnel experimental procedure

The trays were placed even with the wind tunnel floor directly upwind of the slot sampler. Prior to a wind tunnel run, the pump of the sampler was run 1 min to stabilize the system. The wind speeds were then adjusted at discrete free stream velocities of 8, 10, and 13 m s^{-1} for each tray. This velocity was maintained for 5 min during emission testing for uncrushed samples and 2 min for crushed samples at each wind speed. There was a 1-min interval of no wind between the speed changes during which the system walls were knocked with a wooden dowel to dislodge particulates attached to the interior of the system. During the test, the Grimm records particle concentration in 6-s intervals. After the test was finished, the pump was run for 1 min to evacuate particles from the system. The system was cleaned with compressed air between soil trays.

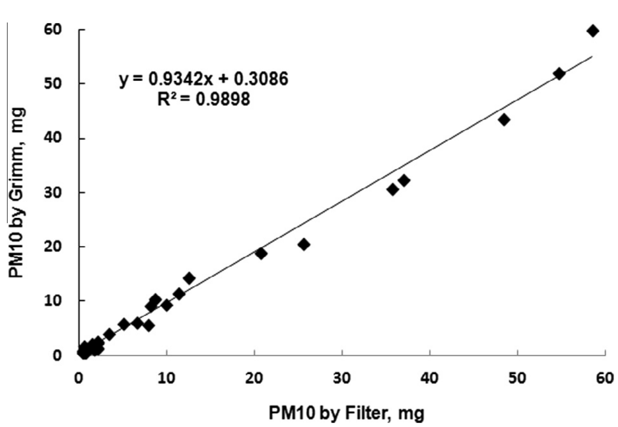

Fig. 2. Comparison of total PM10 as measured by Grimm vs. Hi-Vol sampler for all data.

Results from the Grimm were expressed in total PM2.5 or PM10 emissions loss per effective area. This was calculated using the following formula:

$$E = \frac{1}{A} * k\sum_{i=1}^{n}(C_i * Q * \Delta t)$$

where

E = emission loss per area (g m^{-2});
A = effective area of tray = 0.00425 m^2 (1.181 m tray length $\times$ 0.0036 m slot width);
k = unit conversion factor (1/60,000,000 g min s^{-1} μg^{-1});
n = number of 6-s iterations
C_i = 6-s sliding average PM concentration as measured by the Grimm (μg m^{-3});
Q = flow rate of PM10 Hi-Vol sampler (m^3 min^{-1})
Δt = time interval (6 s).

Because the 8, 10, and 13 m s^{-1} tests ran in succession on the same tray, the emission loss per area at each wind speed was the summation of the loss at lower wind speed. This summation method is less than optimal as it masks the emission loss at each individual wind speed. The summation was done however to expedite the wind tunnel testing process, minimize the time for processing Hi-Vol filters, and avoid completely cleaning the system between changes of wind speed for each run.

2.5. Ambient atmospheric dust monitoring

Atmospheric dust concentration in the study is the background ambient dust in the air that is drawn into the wind tunnel. Particle concentration of the background environment (PM10 and PM2.5) was measured by a MiniVol Tactical Air Sampler (Airmetrics model: TAS-5.0) that was positioned approximately 5 m from the intake of the wind tunnel fan. The sampler was located in an unobstructed area. The PM contents of the atmosphere were calculated from the weight change of the mini-filters, flow rate, and run-time.

The average background concentrations of PM10 and PM 2.5 were 0.022 and 0.0019 μg m^{-3} during research ($p = 0.858$ for PM2.5, $p = 0.893$ for PM10), respectively. Difference analysis shows no significant differences ($p > 0.05$) in atmospheric dust concentration of each interval during the test. All samples were tested under the same background conditions, and test values were comparable; therefore, the difference in particle concentration obtained by the Grimm dust monitor was assumed to result from differences in soil emissions within the tunnel.

3. Results and discussion

3.1. Physical and chemical properties of tested soils

The general physical and chemical properties of each soil are presented in Table 2. Clay contents ranged from 1.6% to 82.7%, sand ranged from 1.6% to 66.6%, and silt varied from 15.7% to 86.7%. Fine and very fine sand are often used to estimate the amount of abrader sand on erodible soils, so they are reported here. Organic matter content ranged from 0.7% to 5.1% for mineral-dominated soils and 25.3–64.0 % for organic-dominated soils (Nos. 13 and 14). The dry aggregate size distribution (DASD) parameters are presented for crushed and uncrushed soils in Table 3. Erodible faction (EF) ranged from 15.2% to 89.8%. EF is the percentage of air-dried aggregates with <0.84-mm diameter and is the parameter found to be most sensitive to a soil's susceptibility to wind erosion (Hagen et al., 1999). The <0.42-mm percentage ranged from 11.7% to 87.7% and was found in this study to be positively correlated with measured PM2.5 and PM10 concentrations (discussed later).

Table 2
Physical and chemical characteristics of the study soils. Note that no dispersed PM was measured for the soil with high organic content (13 and 14).

ID	Dispersed particle size								
	PM2.5 %	PM10	PM2.5/PM10	Clay %	Silt	Sand	Fine Sand	Very Fine Sand	Organic Matter
1	21.3	30.9	0.690	20.6	58.7	20.6	0.4	4.5	3.0
2	13.3	18.6	0.714	13.0	73.9	13.0	1.2	9.5	3.8
3	31.2	38.1	0.819	30.5	38.9	30.5	0.5	4.8	2.9
4	28.0	35.5	0.790	27.5	45.0	27.5	0.5	3.7	4.1
5	26.9	36.4	0.740	26.4	47.2	26.4	0.2	2.3	2.8
7	4.5	5.3	0.842	4.4	29.1	66.6	10.7	54.0	0.7
8	7.3	9.4	0.780	7.1	56.8	36.1	5.0	28.9	1.7
9	21.1	32.3	0.655	20.0	73.7	6.3	0.7	4.9	5.1
10	20.8	31.9	0.654	20.0	73.0	7.0	0.6	5.9	3.8
11	34.7	42.8	0.810	33.9	51.7	14.4	1.8	12.4	2.0
12	32.2	40.2	0.801	31.5	54.1	14.4	1.7	12.6	2.3
13	–	–	–	18.9	63.3	17.8	5.8	8.4	64.0
14	–	–	–	82.7	15.7	1.6	0.8	0.6	25.3
15	51.0	61.5	0.829	48.4	49.5	2.1	0.2	1.6	4.8
16	54.7	66.3	0.826	52.2	45.8	2.0	0.3	1.1	4.4

Table 3
Dry aggregate size distribution for crushed and uncrushed soils, where WEF is the wind-erodible fraction <0.84 mm, GMD is the geometric mean diameter, and GSD is the geometric standard deviation.

ID	Crushed				Uncrushed			
	WEF	<0.42 mm	GMD	GSD	WEF	<0.42 mm	GMD	GSD
	%		mm		%		mm	
1	79.6	46.9	0.14	6.5	65.4	35.0	0.30	8.5
2	76.0	50.2	0.13	6.8	31.1	14.7	1.70	9.2
3	80.2	43.6	0.16	6.4	60.2	25.5	0.41	6.9
4	74.1	41.7	0.17	6.5	29.3	11.7	1.78	7.9
5	82.2	43.7	0.15	6.3	64.9	28.6	0.42	8.8
7	96.6	93.9	0.02	2.5	89.8	87.7	0.04	5.8
8	97.0	90.0	0.03	3.0	72.1	65.0	0.13	14.3
9	70.0	48.7	0.14	7.1	15.2	8.2	4.90	8.7
10	71.9	52.0	0.13	7.1	19.3	11.0	4.11	11.5
11	78.8	45.6	0.15	6.5	58.4	31.8	0.44	10.5
12	65.8	33.9	0.24	6.3	47.2	24.0	0.72	9.8
13	72.5	50.5	0.13	7.0	47.7	30.1	0.57	11.2
14	63.8	37.5	0.22	6.7	32.3	17.8	1.11	8.2
15	90.7	35.7	0.19	5.5	76.9	26.4	0.33	6.3
16	62.4	19.7	0.41	4.7	60.9	18.4	0.51	5.7

The GMD ranged from 0.04 to 4.90 mm, and the GSD ranged from 5.7 to 14.3. GMD and GSD are parameters used to evaluate the soil's susceptibility to wind erosion (Skidmore et al., 1994) and are inputs to the WEPS model.

3.2. PM2.5 loss from crushed and uncrushed soils

Results of PM2.5 loss of crushed and uncrushed soils at all wind speeds are shown in Table 4. As the wind speed increased, PM2.5 loss from crushed soil increased. At the initial wind speed (8 m s^{-1}), PM2.5 loss of soil No. 15 was the lowest (0.0082 g m^{-2}), whereas the highest loss was soil No. 8 (0.0781 g m^{-2}), which was 9.54 times the former. There were significant differences among the PM2.5 loss of crushed samples at 8 m s^{-1} wind ($F = 2.103$, $p = 0.043$). Duncan's multiple comparison analysis ($F = 4.287$, $p < 0.001$) showed significant difference among Nos. 7, 8, and 15 ($p < 0.05$), but the soils did not differ among the other 12 samples. There were also significant differences among crushed samples at 10 m s^{-1} and 13 m s^{-1} ($F = 29.6006$, $p < 0.001$and $F = 61.075$, $p < 0.001$). Feng et al. (2011) tested five crushed soils for 5 min at 18 m s^{-1} in a laboratory wind tunnel and reported losses ranging from 0.1 to 6.0 g m^{-2}.

The PM2.5 losses from uncrushed samples have trends similar to crushed samples after wind speed increases, but the loss is less than that of crushed samples. At 8 m s^{-1}, the PM2.5 loss of No. 14 was the least (0.0095 g m^{-2}), whereas the greatest was No. 10 (0.0455 g m^{-2}), which is 4.8 times the former. A significant difference in PM2.5 loss of uncrushed soils was observed at 8 and 10 m s^{-1} wind speeds ($F = 3.239$, $p = 0.003$ & $F = 5.210$, $p < 0.001$). Duncan's multiple comparison analysis of loss from the uncrushed soils also shows differences ($p < 0.05$). At 13 m s^{-1} wind speed, PM2.5 losses of three samples (Nos. 7–9) are significantly different from the other 12 samples, but no difference was found among the other 12 samples.

The change in loss of crushed and uncrushed soils as wind speed increased showed PM2.5 loss from crushed soils increases rapidly with increases in wind speed, averaging 3.7 times more loss when the wind speed changed from 8 to 10 m s^{-1}. When the wind speed increased to 13 m s^{-1}, PM2.5 loss increased to an average 23.6 times the loss at 8 m s^{-1}. Among them, loss from 7 samples (Nos. 1, 2, 9, 10, 12–14) increased more than the mean. Results reported by Feng et al. (2011) are in agreement with our test, where crushed PM10 and PM2.5 loss from each soil increased with wind speed. Loss for uncrushed soils at 10 m s^{-1} wind averaged 1.95 times higher than 8 m s^{-1} wind, whereas average PM2.5 loss at 13 m s^{-1} was 2.6 times the emission at 8 m s^{-1} wind.

As a whole, PM2.5 loss from uncrushed soils was less than that from crushed samples. The average values of crushed soils are 1.3, 2.5, and 8.5 times those of uncrushed soils at 8, 10, and 13 m s^{-1}; moreover, their difference is significant (statistics not shown), which reflects the effects of soil structure on PM2.5 loss. When the soil structure is crushed, PM2.5 release increases rapidly with the increase of wind speed.

3.3. PM10 loss from crushed and uncrushed soils

Results of PM10 loss of crushed and uncrushed soils at all wind speeds are presented in Table 5. The PM10 loss of crushed samples shows No. 16 had the least (0.0330 g m^{-2}) of all samples and No. 8 had the most (0.7100 g m^{-2}, or 21.5 times the former) at 8 m s^{-1}. Significant difference in PM10 loss from crushed soils also was observed ($F = 2.964$, $p < 0.006$). Duncan's multiple comparison analysis ($F = 5.304$, $p < 0.001$) shows sample Nos. 7 and 8 (with high sand content) did not differ from Nos. 10, 13, and 16, but they were significantly different from the other 10 samples, which exhibited no difference at 8 m s^{-1} wind.

Table 4
PM2.5 loss for each soil as measured by the Grimm for crushed and uncrushed samples at three wind speeds.

ID	8 m s^{-1}		10 m s^{-1}		13 m s^{-1}	
	Crushed	Uncrushed	Crushed	Uncrushed	Crushed	Uncrushed
	g m^{-2}					
1	0.0237abc	0.0194abcd	0.1277b	0.0387ab	0.8365c	0.0674abc
2	0.0136ab	0.0155ab	0.0829ab	0.0320ab	0.8011c	0.0494ab
3	0.0162ab	0.0168abc	0.0375ab	0.0334ab	0.2274ab	0.0502ab
4	0.0455abcd	0.0134a	0.0666ab	0.0249abc	0.3252ab	0.0411a
5	0.0374abcd	0.0295abcde	0.0505ab	0.0506abcde	0.2479ab	0.0754abc
7	0.0711cd	0.0409de	0.2340c	0.0848f	0.7335c	0.2028f
8	0.0781d	0.0380cde	0.3113c	0.0870f	1.4380de	0.1866ef
9	0.0233abc	0.0284abcde	0.0532ab	0.0575bcdef	1.2905d	0.0923abcd
10	0.0528abcd	0.0455e	0.1266b	0.0823ef	1.6372e	0.1320cde
11	0.0216abc	0.0403de	0.0379ab	0.0691cdef	0.3797b	0.1061bcd
12	0.0161ab	0.0275abcde	0.0549ab	0.0456abcd	0.4621b	0.0877abc
13	0.0648bcd	0.0371bcde	0.5900d	0.0747def	2.6953f	0.1544def
14	0.0225abc	0.0095a	0.0356ab	0.0170a	0.7443c	0.0282a
15	0.0082a	0.0122a	0.0195a	0.0323ab	0.0837a	0.0841abc
16	0.0113ab	0.0150ab	0.0230a	0.0292ab	0.0442a	0.0536ab
Means	0.0337aA	0.0259aB	0.1234bA	0.0506aB	0.7964cA	0.0941aB

Note: Significance level = $p < 0.05$. Loss values for each soil within a column followed by the same letter are not significantly different. For the row of means, values followed by lowercase letter are not significantly different between the three wind speeds for crushed or uncrushed soil samples. Similarly for the row of means, values followed by uppercase letter are not significantly different between crushed and uncrushed samples at the same wind speed.

Table 5
PM10 loss for each soil as measured by the Grimm for crushed and uncrushed samples at three wind speeds.

ID	8 m s^{-1}		10 m s^{-1}		13 m s^{-1}	
	Crushed	Uncrushed	Crushed	Uncrushed	Crushed	Uncrushed
	g m^{-2}					
1	0.1174a	0.0517a	0.9536bc	0.11591a	5.2886gh	0.2809ab
2	0.1599a	0.1392ab	0.5451ab	0.2216ab	3.8040def	0.2984ab
3	0.0726a	0.1401ab	0.2047a	0.2171ab	1.4194abc	0.2850ab
4	0.0286a	0.1058ab	0.4100ab	0.1459a	2.0272abcd	0.2128ab
5	0.1373a	0.0772a	0.2821ab	0.1327a	2.1705abcd	0.2081ab
7	0.7051b	0.4036c	1.8423de	0.6598c	4.7657fg	1.3420c
8	0.7100b	0.2491abc	2.3975ef	0.5683bc	10.1360i	1.2922c
9	0.2037a	0.1127ab	0.3635ab	0.1890a	7.5177h	0.2954ab
10	0.3992ab	0.1612bc	1.2478cd	0.5523bc	12.2134ij	0.8582bc
11	0.1319a	0.17996abc	0.2042a	0.3181abc	2.4321bcd	0.5092ab
12	0.1383a	0.0805a	0.3954ab	0.1569a	3.1472cde	0.3901ab
13	0.4004ab	0.1423ab	2.8590f	0.2690ab	14.0533j	0.5981ab
14	0.1408a	0.0513a	0.2059a	0.0863a	2.6824abcd	0.1356a
15	0.0518a	0.0396a	0.1667a	0.1167a	0.5430ab	0.3698ab
16	0.0330b	0.0375a	0.0564a	0.0659a	0.1442a	0.1607ab
Means	0.2458aB	0.1315aA	0.8089bB	0.2544bA	4.8230cB	0.4824cA

Note: Significance level = $p < 0.05$. Loss values for each soil within a column followed by the same letter are not significantly different. For the row of means, lowercase letters followed by the same letter are not significantly different between the wind speeds for crushed or uncrushed samples. Similarly for the row of means, values followed by the same uppercase letter are not significantly different between crushed and uncrushed samples at the same wind speed.

In the same way, PM10 loss from uncrushed soils increased with the wind speed as shown in Table 5. At 8 m s^{-1} wind, the least loss was No. 16 (0.0375 g m^{-2}), whereas No. 7 had the most (0.4036 g m^{-2}) at 10.7 times the former. The analysis of variance shows PM10 emission differs significantly among soils at wind speeds of 8, 10, and 13 m s^{-1} ($p < 0.035$, 0.007 and 0.002). Loss at 10 m s^{-1} is 1.3–3.4 times that of 8 m s^{-1} (mean value is 1.9 times), and emission at 13 m s^{-1} is 2.0–9.3 times that of 8 m s^{-1} winds (mean value is 3.7 times).

PM10 loss showed similar magnitudes of increase with wind speed. PM10 at 10 m s^{-1} resulted in an average increase of 3.3 times the loss compared to 8 m s^{-1}. When the wind speed increased to 13 m s^{-1}, PM10 loss from all crushed soils increased to 19.6 times the loss at 8 m s^{-1}. Among them, loss from six samples (Nos. 1, 2, 7, 8, 12, and 13) increased by more than the mean.

As was found for crushed soils, PM10 loss of uncrushed soils was less than that of crushed samples, and stronger wind let do greater differences between uncrushed and crushed soils. The average values of crushed soils were 1.9, 3.2, and 10 times those of uncrushed soils at 8, 10, and 13 m s^{-1} and their difference was significant (statistics not shown).

3.4. Comparisons of PM2.5 and PM10 loss between crushed and uncrushed samples

As a whole, the PM2.5 loss of uncrushed soils was less than that of crushed soils. This is likely the result of the higher erodible fraction of crushed soils. The means of the crushed soils were 1.30, 2.44, and 8.46 times the values of the former at 8, 10, and 13 m s^{-1} (Table 6). PM10 exhibited a similar trend; in general, PM10 emission of uncrushed soils was less than that crushed samples, and stronger wind led to a greater difference between uncrushed and crushed soils. PM loss increased sharply with wind velocity. The mean PM10 losses of crushed soils were 1.9, 3.2, and 10 times those of uncrushed soils at 8 m s^{-1}, 10 m s^{-1}, and 13 m s^{-1} (Table 6), and the means were highly significant between

Table 6
Comparisons of crushed and uncrushed soil loss ratios at three wind speeds.

ID	PM2.5 (crushed/uncrushed)			PM10 (crushed/uncrushed)		
	8 m s^{-1}	10 m s^{-1}	13 m s^{-1}	8 m s^{-1}	10 m s^{-1}	13 m s^{-1}
1	1.22	3.30	12.41	2.27	8.23	18.83
2	0.88	2.59	16.22	1.15	2.46	12.75
3	0.96	1.12	4.53	0.52	0.94	4.98
4	3.41	2.67	7.91	2.71	2.81	9.52
5	1.27	1.00	3.29	1.78	2.13	10.43
7	1.74	2.76	3.62	1.75	2.79	3.55
8	2.06	3.58	7.71	2.85	4.22	7.84
9	0.82	0.93	13.98	1.81	1.92	25.45
10	1.16	1.54	12.40	2.48	2.26	14.23
11	0.54	0.55	3.58	0.73	0.64	4.78
12	0.59	1.20	5.27	1.72	2.52	8.07
13	0.67	0.60	1.00	1.31	1.43	1.47
14	0.75	0.79	0.83	0.88	0.86	0.90
15	1.74	7.89	17.45	2.81	10.63	23.50
16	2.36	2.10	26.37	2.74	2.39	19.79
Means	1.30a	2.44a	8.46b	1.87a	3.18a	10.00b

Note: Significance level = $p < 0.05$. Values within the row of means followed by the same letter are not significantly different.

13 m s^{-1} and the other wind speeds (Table 6). This finding suggests that the changed soil aggregation (i.e., crushing soil) increased PM2.5 and PM10 losses.

3.5. The ratio of PM2.5/PM10

Because PM2.5 is a component of PM10, a good approximation of PM2.5 can be obtained by treating PM2.5 as a fixed weight fraction of PM10 (Feng et al., 2011; Hagen, 2004a). The PM2.5/PM10 emission ratio has been used by many for the evaluation of different surface soils to release PM2.5 (Cowherd and Kuykendal, 1997; Chandler et al., 2002; Ashbaugh et al., 2003; Carvacho et al., 2004; Feng et al., 2011). Greater values express PM2.5 particle emission from soil and more serious harm to the human body and environment.

Table 7 contains the PM2.5/PM10 ratio from crushed and uncrushed samples as the wind speed varied. Overall, PM2.5/PM10 ratio of crushed samples ranged from 0.11 to 0.45, and the means of crushed soils were 0.19, 0.18, and 0.18, respectively, at the 8, 10, and 13 m s^{-1} wind speeds. The PM2.5/PM10 ratio for uncrushed soils ranged from 0.13 to 0.46, and the means were 0.27, 0.27, and 0.24, respectively, at 8, 10, and 13 m s^{-1}. Under the action of wind erosion and abrasion, this study shows PM10 and PM2.5 losses of uncrushed soils were lower than those of crushed samples, but PM2.5 losses constituted a larger proportion of PM10 in crushed soils. Comparing values among the three wind speeds, the ratios of PM2.5/PM10 are listed in descending order: 8 m s^{-1} < 10 m s^{-1} < 13 m s^{-1}. This indicates that PM10 emission increased faster than PM2.5 as the wind speed increased.

The PM2.5/PM10 ratio of crushed soil was in the range of 0.11–0.45, which is similar to the results of others. Pace (2005) reported PM2.5/PM10 ratios of 0.2 for agricultural soil. Cowherd and Kuykendal (1997) reported that the PM2.5/PM10 ratios varied from 0.15 to 0.25 for various fugitive dust categories and noted an average multiplier of about 0.17. Ashbaugh and Eldred (2004) reported the ratio of PM2.5/PM10 to be 0.12 for an agricultural field in the San Joaquin Valley of California. Ono (2005) found the ratio of PM2.5/PM10 to be "around or less than 0.10" for windblown dust from the Owens dry lake bed, with the average ratio of PM2.5/PM10 for the source categories found to be 0.10. The PM2.5/PM10 ratios of crushed and uncrushed samples for our study are 0.1–0.45 and 0.13–0.46, respectively, which are lower than the results of Chandler et al. (2002), who reported values of 0.33–0.55. This difference may be associated with the tests being done using a wind tunnel in our study compared with the chamber method of Chandler et al. (2002).

Of the 15 soils studied, the PM2.5/PM10 ratios at 3 wind speeds ranged from 0.11 to 0.45 and had a wider range than the five soils tested by Feng et al. (2011), who found ratios from 0.11 to 0.33 at 15 m s^{-1}. This result could be attributed to the wider range of soils and management practices in the present study.

Table 7
The PM2.5/PM10 loss ratio for each crushed and uncrushed soil at three wind speeds.

ID	8 m s^{-1}		10 m s^{-1}		13 m s^{-1}	
	Crushed	Uncrushed	Crushed	Uncrushed	Crushed	Uncrushed
1	0.21a	0.39bc	0.14a	0.33bcd	0.16abc	0.26abc
2	0.18a	0.19a	0.16a	0.24ab	0.21c	0.26abc
3	0.22a	0.18a	0.18a	0.17ab	0.16abc	0.19a
4	0.17a	0.23ab	0.18a	0.24ab	0.16abc	0.23ab
5	0.26ab	0.43c	0.19a	0.41cd	0.11a	0.38c
7	0.12a	0.13a	0.14a	0.15a	0.16abc	0.17a
8	0.12a	0.18a	0.13a	0.19ab	0.14ab	0.17a
9	0.17a	0.29abc	0.18a	0.32abc	0.17abc	0.32abc
10	0.13a	0.20a	0.11a	0.20abc	0.14ab	0.19a
11	0.19a	0.27abc	0.19a	0.25ab	0.16abc	0.22ab
12	0.14a	0.33abc	0.14a	0.28ab	0.15abc	0.22ab
13	0.17a	0.26abc	0.21a	0.28ab	0.19bc	0.27ab
14	0.17a	0.19a	0.18a	0.21ab	0.27d	0.21ab
15	0.18a	0.32abc	0.12a	0.30ab	0.16abc	0.22ab
16	0.41b	0.42abc	0.45b	0.46d	0.30d	0.34bc

Note: Significance level = $p < 0.05$. Values within a column followed by the same letter are not significantly different.

3.6. Relationship between soil particle and aggregate size distribution and particulate loss

Chepil (1955) verified that sand particles have little or no cohesiveness and are readily loosened by the force of wind and that coarse particles are easily moved by the wind. Silt and clay have good cohesive properties and form wind-resistant clods that enhance resistance to wind erosion and add substantial resistance to abrasion by wind-blown materials. The sand contents of Nos. 7 and 8 are 66.6% and 36.1%, whereas the clay plus silt contents of other samples is greater than 80%, so the cohesiveness of Nos. 7 and 8 is weak, as is their ability to resist wind erosion. Thus, PM2.5 and PM10 loss of both sandy samples are higher than the others, even though their dispersed PM2.5 and PM10 are quite low (<10%).

The correlation of different soil properties with PM2.5 and PM10 emission of both crushed and uncrushed samples at 8 m s^{-1} are shown in Fig. 3, and the regressions, correlation coefficients, and significance of soil properties and their PM losses are summarized in Table 8. They show a significant negative correlation of both PM2.5 and PM10 loss from crushed samples at 8 m s^{-1}, with dispersed PM2.5, PM10, and clay content in the soil samples, and a power function relationship (Fig. 3a–f). There are significant negative correlations between the dispersed PM2.5, PM10 and clay content in the soils and PM10 loss from uncrushed soils, but only clay content is very significantly negative correlated with PM10 loss. In addition, no obvious relationship exists between PM2.5 loss and the dispersed PM2.5, PM10, and clay for uncrushed soil. According to the fitted equation, when PM2.5, PM10, and clay content in the soil increase to 10%, PM2.5 and PM10 emissions decrease sharply. When clay contents reach 20%, PM2.5 and PM10 emissions are stabilized.

PM2.5 and PM10 loss from all soils shows a linear negative relationship with silt content in the samples (Fig. 3g and h). Fig. 3i shows a significant linear positive correlation of sand with particle losses of all samples, except PM2.5 loss of uncrushed samples has no linear correlation to sand content. The <0.42-mm aggregates are

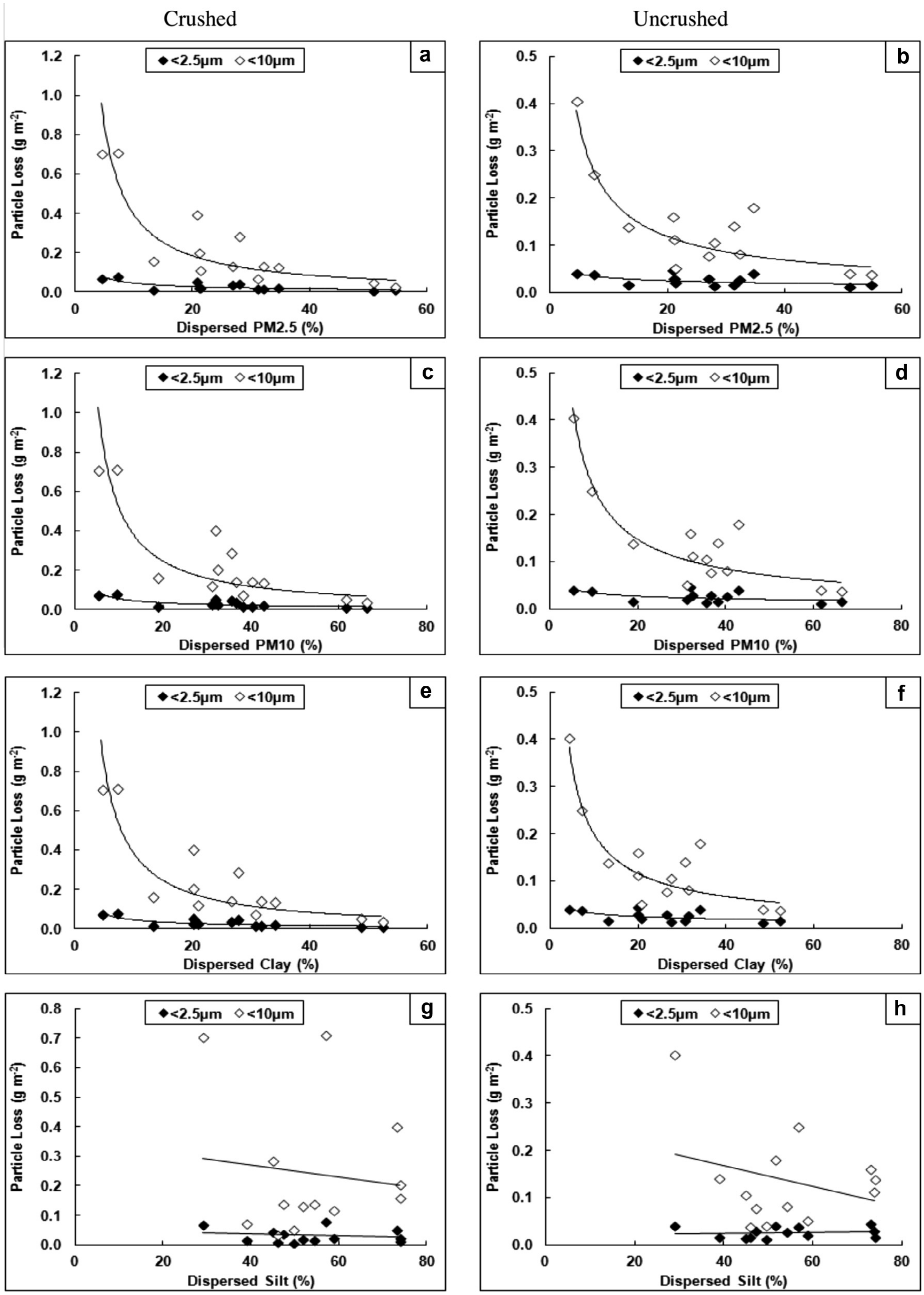

Fig. 3. The relationship between soil properties and particulate loss of crushed (left) and uncrushed (right) soil at 8 m s^{-1} wind speed. (a and b): relationship of dispersed soil PM2.5 (%) with particulate loss; (c and d): relationship of soil dispersed soil PM10 (%) with particulate loss; (e and f): relationship of soil clay with particulate loss; (g and h): relationship of soil silt with particulate loss; (i and j): relationship of soil sand with particulate loss; (k and l): relationship of soil aggregates <0.42 mm (%) with particulate loss; (m and n): relationship of soil aggregates <0.84 mm (%) with particulate loss.

linearly positively correlated but are significant only for crushed samples (Fig. 3k and l); in other words, the higher the sand or <0.42 aggregate content, the more PM2.5 and PM10 are lost. There is a linear positive relationship with <0.84 particle content (Fig. 3m and n), but these correlations are not significant ($p > 0.05$). As a whole, the correlations of uncrushed samples are

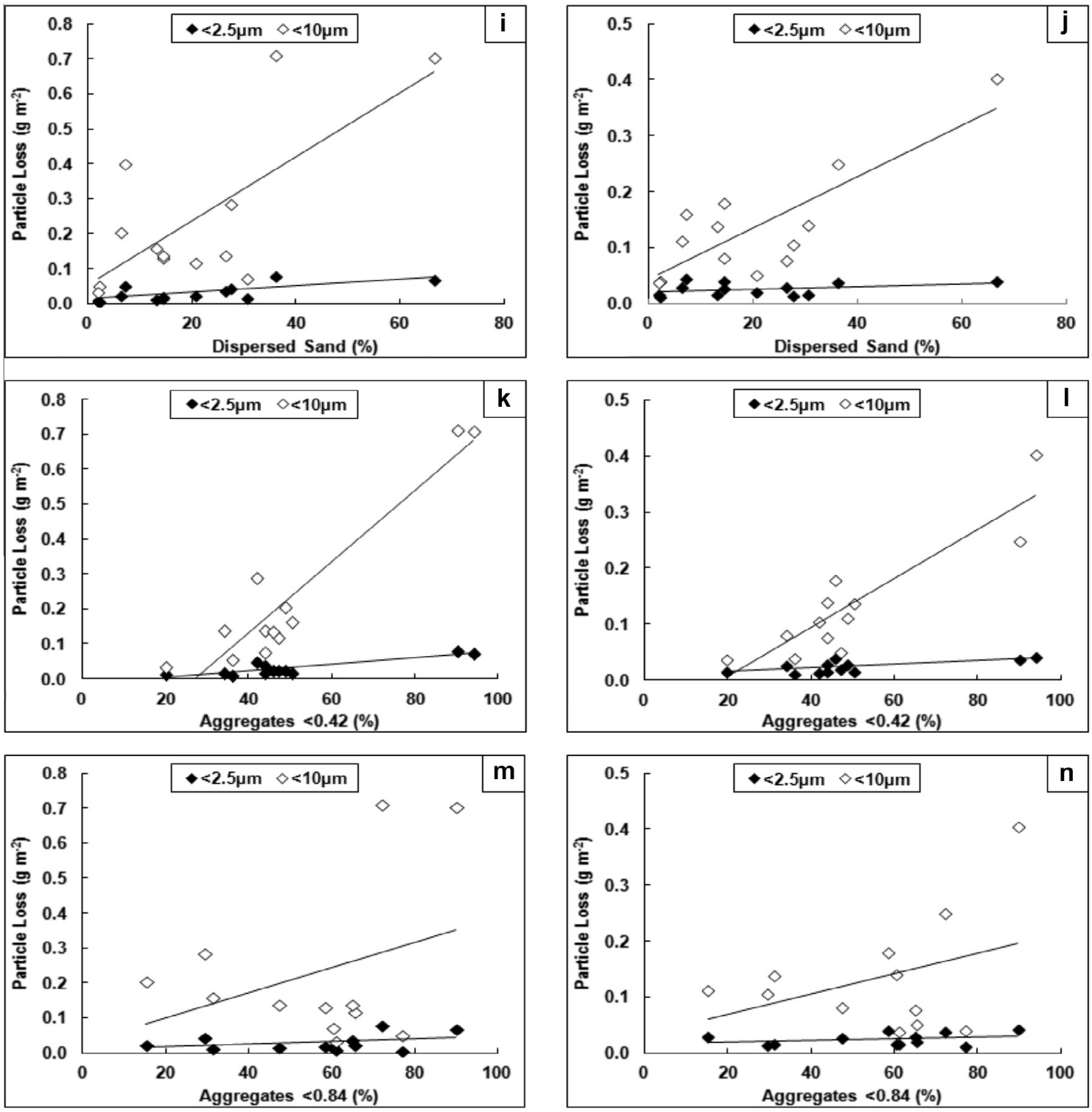

Fig. 3 (*continued*)

Table 8
Regression statistics for PM2.5 and PM10 loss at 8 m s^{-1} for dispersed particles and aggregate size of crushed and uncrushed soils.

Particle or aggregate size*		PM2.5			PM10		
		Regression equation	r^2	*p* value	Regression equation	r^2	*p* value
PM2.5	CU	$y_{2.5} = 0.2443x^{-0.73}$ $y_{2.5} = 0.0691x^{-0.344}$	0.5337 0.2729	<0.000 <0.007	$y_{10} = 5.0069x^{-1.102}$ $y_{10} = 1.2497x^{-0.787}$	0.7296 0.6475	<0.000 <0.001
PM10	CU	$y_{2.5} = 0.2837x^{-0.715}$ $y_{2.5} = 0.0719x^{-0.328}$	0.5071 0.2457	<0.000 <0.012	$y_{10} = 6.1821x^{-1.076}$ $y_{10} = 1.6076x^{-0.798}$	0.6877 0.6591	<0.000 <0.001
Clay	CU	$y_{2.5} = 0.2403x^{-0.732}$ $y_{2.5} = 0.0689x^{-0.346}$	0.5306 0.2739	<0.011 <0.028	$y_{10} = 4.915x^{-1.107}$ $y_{10} = 1.2229x^{-0.788}$	0.7280 0.6416	<0.003 <0.005
Silt	CU	$y_{2.5} = -0.0003x + 0.0477$ $y_{2.5} = 8E{-}05x + 0.0218$	0.0294 0.0095	<0.043 <0.282	$y_{10} = -0.002x + 0.3512$ $y_{10} = -0.0022x + 0.2456$	0.0148 0. 0893	<0.045 <0.073
Sand	CU	$y_{2.5} = 0.0009x + 0.0133$ $y_{2.5} = 0.0002x + 0.0216$	0.4971 0.1162	<0.000 <0.008	$y_{10} = 0.0092x + 0.0539$ $y_{10} = 0.0046x + 0.0425$	0.5021 0.6523	<0.000 <0.000
<0.42 mm	CU	$y = 0.0009x - 0.0162$ $y = 0.0002x + 0.0159$	0.7666 0.0987	<0.001 <0.048	$y = 0.0102x - 0.2763$ $y = 0.0018x + 0.0329$	0.8857 0.1409	<0.001 <0.008
<0.84 mm	CU	$y = 0.0004x - 0.094$ $y = 0.0002x + 0.0159$	0.1229 0.0987	<0.001 <0.048	$y = 0.0036x - 0.279$ $y = 0.0018x + 0.0329$	0.1103 0.1409	<0.001 <0.008

* C-crushed soil, U-uncrushed soil, r^2 is the square of correlation coefficient.

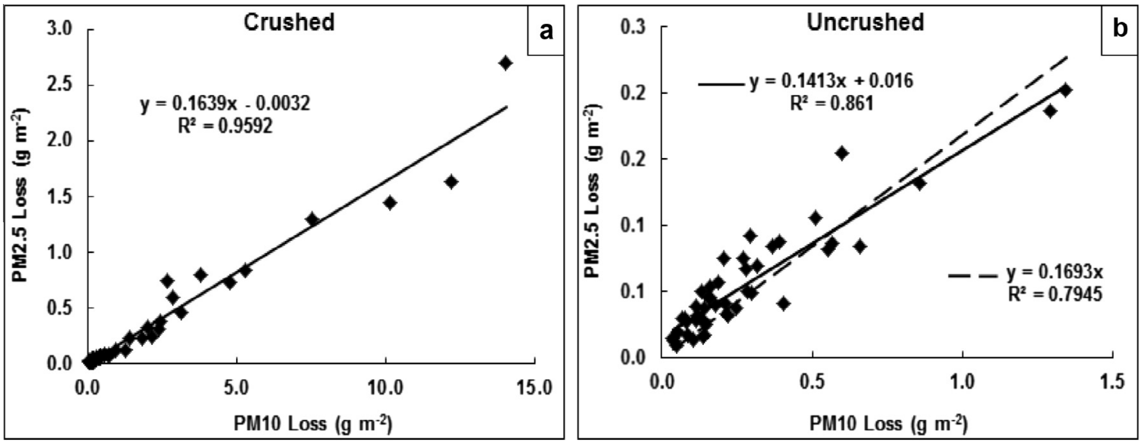

Fig. 4. The relationship of PM2.5 to PM10 loss from crushed (a) and uncrushed (b) samples at all three wind speeds. Dashed line in (b) represents line fitted with intercept set to 0.

Table 9
Comparison of PM2.5 and PM10 loss for conventional (CV) vs. no-till (NT) management at three wind speeds.

State	Tillage:	$8\ m\ s^{-1}$		$10\ m\ s^{-1}$		$13\ m\ s^{-1}$	
		CV	NT	CV	NT	CV	NT
	ID	Soil Loss, $g\ m^{-2}$					
PM2.5 uncrushed							
KS	1 & 2	0.0194a	0.0155a	0.0387a	0.0320a	0.0674a	0.0494a
KS	3 & 4	0.0168a	0.0134a	0.0334a	0.0249a	0.0502a	0.0411a
WA	10 & 9	0.0455a	0.0284a	0.0823a	0.0575a	0.1320a	0.0923a
TX	11 & 12	0.0403a	0.0275a	0.0691a	0.0456a	0.1061a	0.0877a
SD	15 & 16	0.0122a	0.0150a	0.0323a	0.0292a	0.0841a	0.0536a
PM10 uncrushed							
KS	1 & 2	0.0517a	0.1392a	0.1159a	0.2216a	0.2809a	0.2984a
KS	3 & 4	0.1401a	0.1058a	0.2171a	0.1459a	0.2850a	0.2128a
WA	10 & 9	0.1612a	0.1127a	0.5523a	0.1890a	0.8582a	0.2954a
TX	11 & 12	0.1798a	0.0805a	0.3181a	0.1569a	0.5092a	0.3901a
SD	15 & 16	0.0396a	0.0375a	0.1167a	0.0659a	0.3698a	0.1607a
PM2.5/PM10 uncrushed							
KS	1 & 2	0.3934a	0.1891a	0.3332a	0.2423a	0.2625a	0.2628a
KS	3 & 4	0.1779a	0.2262a	0.1693a	0.2409a	0.1908a	0.2298a
WA	10 & 9	0.1976a	0.2858a	0.1960a	0.3160a	0.1882a	0.3157a
TX	11 & 12	0.2716a	0.3254a	0.2473a	0.2839a	0.2202a	0.2226a
SD	15 & 16	0.3169a	0.4157a	0.2972a	0.4600b	0.2237a	0.3396b
PM2.5 crushed							
KS	1 & 2	0.0237a	0.0136a	0.1277a	0.0829a	0.8365a	0.8011a
KS	3 & 4	0.0162a	0.0455a	0.0375a	0.0666a	0.2274a	0.3252a
WA	10 & 9	0.0528a	0.0233a	0.1266a	0.0532a	1.6372a	1.2905a
TX	11 & 12	0.0216a	0.0161a	0.0379a	0.0549a	0.3797a	0.4621a
SD	15 & 16	0.0082a	0.0113a	0.0195a	0.0230a	0.0837a	0.0442b
PM10 crushed							
KS	1 & 2	0.1174a	0.1599a	0.9536a	0.5451a	5.2886a	3.8040b
KS	3 & 4	0.0726a	0.2863b	0.2047a	0.4100a	1.4194a	2.0272a
WA	10 & 9	0.3992a	0.2037a	1.2478a	0.3635b	12.2134a	7.5177b
TX	11 & 12	0.1319a	0.1383a	0.2042a	0.3954a	2.4321a	3.1472a
SD	15 & 16	0.0518a	0.0330a	0.1667a	0.0564b	0.5430a	0.1442b
PM2.5/PM10 crushed							
KS	1 & 2	0.2055a	0.1792a	0.1416a	0.1647a	0.1583a	0.2126a
KS	3 & 4	0.2166a	0.1688a	0.1821a	0.1766a	0.1649a	0.1596a
WA	10 & 9	0.1317a	0.1706a	0.1052a	0.1783a	0.1352a	0.1749b
TX	11 & 12	0.1896a	0.1365a	0.1918a	0.1425a	0.1560a	0.1485a
SD	15 & 16	0.1780a	0.4065b	0.1212a	0.4543b	0.1564a	0.3005b

CV soils are Nos. 1, 3, 10, 11, and 15 and NT soils are Nos. 2, 4, 9, 12, and 16. Significance level = $p < 0.05$. Values within columns of the same wind speed followed by the same letter are not significantly different.

lower than those of crushed samples, and correlations are better between PM10 loss and the parameters of soil texture.

The different contents of particle size parameters in tested soils (dispersed PM2.5, PM10, clay, silt, and sand) led to great variation of fugitive dust loss among the samples. Under the same wind speed, sand-sized grains of 0.1–0.15 mm are most easily entrained and set into saltation, and as they return to the surface in the saltation trajectory, they "splash" into the bed, dislodging other grains to saltation and suspension (Bagnold, 1941; Anderson, 1987; Pye and Tsoar, 1990; Willetts and Rice, 1989); therefore, saltation causes increased PM emission and soil loss. On the other hand, the finer soil loss will be restrained because of the cohesion and interparticle forces of grains. In general, the higher content of clay and silt in the soil, the less dust released, so PM2.5 and PM10 concentration obviously decreased following the increase in dispersed PM2.5, PM10, clay, and silt content, and their relationship demonstrates a negative correlation. Positively correlated relationships were found between PM2.5 and PM10 emissions and sand and aggregate contents.

Fig. 4 shows the correlation between total PM2.5 and PM10 loss of crushed (a) and uncrushed (b) samples at all three wind speeds. The results show they are positively and highly correlated (solid lines, $R^2 = 0.9592$ and 0.861) and that PM10 loss increased as PM2.5 increased. The correlation for crushed samples was stronger. According to the fitted relationship of PM2.5 to PM10, PM2.5 can be estimated by the PM10 emission in wind erosion models such as WEPS. However, for prediction purposes in WEPS, the data were also fit to a linear relationship with the intercept set to 0 (dashed line, Fig. 4b). This was done because PM2.5 is a component of PM10. If the equation for uncrushed soils with intercept set to 0.016 (Fig. 4b) was used to predict PM2.5, a value of zero entered for PM10 would result in a positive PM2.5, which is meaningless. The slope of the equation (0.1693) is the overall PM2.5/PM10 ratio and is similar to the limited data published by others (Ashbaugh et al., 2003; Carvacho et al., 2004; Cowherd and Kuykendal, 1997; Feng et al., 2011).

3.7. Management influence on PM emissions

In this study, sample Nos. 2, 4, 9, 12, and 16 are under no-till (NT) management, whereas samples Nos. 1, 3, 10, 11, and 15 are under conventional (CV) management as paired samples from the same soil. Under both CV and NT, 8 m s^{-1} and 10 m s^{-1} wind showed PM2.5 and PM10 loss of uncrushed samples were more influenced by clay content. In other words, PM loss was low when soil has high clay content at the lower wind speeds, but when wind speed is higher (13 m s^{-1}), the loss was influenced more by tillage management. The PM2.5 and PM10 losses under CV were higher than for NT. Table 9 shows the difference in the PM losses of CV and NT management at 3 speeds. For NT soils, PM2.5 losses of uncrushed samples were lower than those of crushed samples at 8, 10, and 13 m s^{-1} wind speed, except No. 16 at 8 m s^{-1}. This result is likely due to the lower WEF (<0.84 mm) and larger GMD in NT soils (Table 3). Moreover, most of the PM2.5/PM10 loss ratios are higher for NT than for CV soils, which may be the result of less PM10 relative to PM2.5 because GMD is larger than PM2.5 in NT soils, indicating that NT management forms lager aggregates.

Although few significant differences were found, it is of interest to note that only one NT case out of 15 for uncrushed soils had higher PM2.5 loss than CV (Nos. 16 vs. 15 at 8 m s^{-1}). Similarly, NT PM10 losses on uncrushed soils were greater than CV in only 3 of 15 cases (Nos. 1 & 2 at 10 and 13 m s^{-1} and 15 & 16 at 8 m s^{-1}). These trends indicate that NT resulted in larger aggregate diameters than CV, which is supported by aggregate data in Table 3 and others (Eynard et al., 2004; Blanco-Canqui and Lal, 2008).

PM2.5/PM10 loss ratios were generally higher on CV uncrushed soils at 8 and 13 m s^{-1} wind speeds, whereas NT ratios were larger at 10 m s^{-1}. Considering crushed soils, PM2.5 and PM10 losses generally increased for both NT and CV soils as speeds increased. PM2.5 and PM10 did not show a pattern of NT higher than CV, except for one pair of samples (Nos. 10 and 9). No pattern is evident for PM2.5/PM10 ratios of crushed soils.

4. Conclusions

PM2.5 and PM10 losses from samples increased with wind speed no matter the treatment (crushed and uncrushed) or management (CV and NT), but a more rapid and greater trend was evident for crushed samples. Emissions of PM2.5 and PM10 from both crushed and uncrushed soils showed significant linear correlation. The PM2.5/PM10 ratio of crushed and uncrushed samples ranged from 0.11 to 0.45 and 0.13 to 0.46, and the PM2.5 proportion of PM10 is higher from uncrushed samples than from crushed ones. With increased wind speed, PM10 emission increase is more apparent than PM2.5 emission. Soil texture influenced PM emission, and the emissions from sandy samples (Nos. 7 and 8) were higher than from other samples. PM2.5 and PM10 emissions of tested soil and dispersed PM2.5, PM10, and clay content in the soil exhibited a significant negative correlation ($y = ax^b$). Sand and <0.42-mm aggregate content show a significant linear correlation. PM2.5 and PM10 emission were influenced by dispersed PM2.5, PM10, clay, and sand content of the soil, and the influence of clay content was especially significant. For uncrushed soil samples, PM2.5 and PM10 emissions at low wind speed were mainly affected by clay content. Emissions at high wind speeds were easily affected by NT. PM emissions from CV soils were higher than from NT soils. No-till management makes small particles form larger aggregates. The lack of significant differences found between NT vs. CV losses, while still showing definite and consistent trends, warrants further study of the effects of NT vs. CV on aggregate size distribution and subsequent wind erosion loss. The structural integrity of farmland surfaces should be supported as much as possible using NT and stubble farming measures that avoid frequent plowing to reduce soil wind erosion and PM2.5 and PM10 losses.

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