Aeolian Research 10 (2013) 43–51

Contents lists available at SciVerse ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Soil property effects on wind erosion of organic soils

Ted M. Zobeck [a,*], Matthew Baddock [a,d], R. Scott Van Pelt [b], John Tatarko [c], Veronica Acosta-Martinez [a]

[a] USDA–Agricultural Research Service, Wind Erosion & Water Conservation Research Unit, Lubbock, TX, USA
[b] USDA–Agricultural Research Service, Wind Erosion & Water Conservation Research Unit, Big Spring, TX, USA
[c] USDA–Agricultural Research Service, Engineering & Wind Erosion Research Unit, Manhattan, KS, USA
[d] Griffith School of Environment, Griffith University, Brisbane, Australia

ARTICLE INFO

Article history:
Available online 15 November 2012

Keywords:
Wind erosion
Organic soils
Dust emissions
Air quality
Saltation

ABSTRACT

Histosols (also known as organic soils, mucks, or peats) are soils that are dominated by organic matter (OM > 20%) in half or more of the upper 80 cm. Forty two states have a total of 21 million ha of Histosols in the United States. These soils, when intensively cropped, are subject to wind erosion resulting in loss of crop productivity and degradation of soil, air, and water quality. Estimating wind erosion on Histosols has been determined by USDA–Natural Resources Conservation Service (NRCS) as a critical need for the Wind Erosion Prediction System (WEPS) model. WEPS has been developed to simulate wind erosion on agricultural land in the US, including soils with organic soil material surfaces. However, additional field measurements are needed to understand how soil properties vary among organic soils and to calibrate and validate estimates of wind erosion of organic soils using WEPS. Soil properties and sediment flux were measured in six soils with high organic contents located in Michigan and Florida, USA. Soil properties observed included organic matter content, particle density, dry mechanical stability, dry clod stability, wind erodible material, and geometric mean diameter of the surface aggregate distribution. A field portable wind tunnel was used to generate suspended sediment and dust from agricultural surfaces for soils ranging from 17% to 67% organic matter. The soils were tilled and rolled to provide a consolidated, friable surface. Dust emissions and saltation were measured using an isokinetic vertical slot sampler aspirated by a regulated suction source. Suspended dust was sampled using a Grimm optical particle size analyzer. Particle density of the saltation-sized material (>106 μm) was inversely related to OM content and varied from 2.41 g cm^{-3} for the soil with the lowest OM content to 1.61 g cm^{-3} for the soil with highest OM content. Wind erodible material and the geometric mean diameter of the surface soil were inversely related to dry clod stability. The effect of soil properties on sediment flux varied among flux types. Saltation flux was adequately predicted with simple linear regression models. Dry mechanical stability was the best single soil property linearly related to saltation flux. Simple linear models with soil properties as independent variables were not well correlated with PM_{10} E values (mass flux). A second order polynomial equation with OM as the independent variable was found to be most highly correlated with PM_{10} E values. These results demonstrate that variations in sediment and dust emissions can be linked to soil properties using simple models based on one or more soil properties to estimate saltation mass flux and PM_{10} E values from organic and organic-rich soils.

1. Introduction

The United States Department of Agriculture, Natural Resources Conservation Service estimates that erosion due to wind on non-federal cropland in the US in 2007 was approximately 0.7 billion Mg yr^{-1} (an average of 4.7 Mg ha^{-1} yr^{-1}) (USDA–NRCS, 2007). In the US, there are approximately 21 million ha of organic soils occurring in 42 states (Lucas, 1982). Wind erosion can be a serious problem in these soils (Lucas, 1982; Parent et al., 1982; Parent and Ilnicki, 2003; Kohake et al., 2010), causing severe soil losses resulting in crop loss and environmental degradation. Losses of 2.5 cm of soil and complete filling in of an agricultural drainage ditch from one storm have been observed (Lucas, 1982). In addition, organic soils are often used in the production of high-value vegetable crops and for a given mass loss, the offsite impacts from organic soils may be greater than mineral soils due to the increased soil volume and lower density of organic soils (Kohake et al., 2010).

The factors that affect wind erosion of organic soils are similar to those that affect mineral soils. Kohake et al. (2010) investigated

* Corresponding author. Address: USDA–Agricultural Research Service, Wind Erosion & Water Conservation Research Unit, 3810 4th St., Lubbock, TX 79415, USA. Tel.: +1 806 749 5560; fax: +1 806 723 5272.

E-mail addresses: ted.zobeck@ars.usda.gov (T.M. Zobeck), m.baddock@griffith.edu.au (M. Baddock), scott.vanpelt@ars.usda.gov (R. Scott Van Pelt), john.tatarko@ars.usda.gov (J. Tatarko), veronica.acosta-martinez@ars.usda.gov (V. Acosta-Martinez).

1875-9637/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.aeolia.2012.10.005

the wind erodibility of organic soils and suggested the most important soil factors are dry aggregate stability (DAS), dry aggregate size distribution (ASD), aggregate density (AD), surface moisture content, crusting and loose erodible material on the crust surface. In addition, the state of the soil structure, such as size, shape, and density of erodible and non-erodible fractions have been listed by Chepil and Woodruff (1963) as some of the most important soil conditions that influence wind erosion.

The DAS is a measure of the ability of soil aggregates to resist breakdown under physical forces. Wind erosion has been related to DAS, as measured by the energy needed to crush an aggregate to a specified end point, called the crushing energy (CE)(Skidmore and Layton, 1992; Hagen et al., 1995) and the amount of aggregate breakdown after repeated sieving in a rotary sieve (Chepil, 1962), called the mechanical stability (Chepil, 1951). In a study of four organic muck soils, Kohake et al. (2010) found the mean CE values to range from 2.73 to 4.12 $\ln(\mathrm{J\,kg^{-1}})$.

The ASD is a description of the distribution of soil aggregates or clods on the soil surface (Zobeck, 1991b; Zobeck et al., 2003a). A rotary sieve is used to determine ASD and the wind erodible material (WEM) of soil, defined as the percent of soil <0.84 mm diameter (Chepil, 1958). The WEM has long been used in conservation planning to estimate wind erosion using the Wind Erosion Equation (Woodruff and Siddoway, 1965). The geometric mean diameter (GMD) and geometric standard deviation are commonly used to describe the ASD (Zobeck, 1991b). In a study of the ASD of three organic (muck) soils in Michigan, the GMD varied throughout the year and ranged from 1.1 to 20.5 mm (Mokma, 1992). The GMD ranged from 1.1 to 8.8 mm in the Kohake et al. (2010) study. Zobeck et al. (2003a) reported the mean GMD of three organic soils in Michigan to vary from 2.3 to 6.6 mm. The mean WEM of the same study varied from 7% to 34%. The WEM observed for nine organic soils from the Midwest US ranged from 22% to 64% (Woodruff, 1970).

Aggregate density is a measure of the mass of soil aggregates per unit volume. Other factors being equal, wind of a given strength can move larger aggregates that are less dense compared with aggregates that are more dense (Kohake et al., 2010). The density of organic soil aggregates will depend upon the type of organic material, level of organic matter decomposition, and the amount and type of mineral matter present. In addition, the density of aggregates tends to decrease with increasing aggregate (or sample) size. For example, the bulk density of large samples of organic soils is often quite low. The surface soil bulk density of Florida organic soils was observed to vary from 0.26 to 0.73 $\mathrm{Mg\,m^{-3}}$ (Zelany and Carlisle, 1974). The surface soil of a cultivated Houghton muck soil in Michigan had a bulk density of 0.30 $\mathrm{Mg\,m^{-3}}$ (Lucas, 1982). In more recent work, the bulk density of organic soil surfaces ranged from 0.19 to 0.64 $\mathrm{Mg\,m^{-3}}$ while the density of 20 mm diameter clods of organic soils ranged in density from 0.58 to 1.11 $\mathrm{Mg\,m^{-3}}$ (Mokma, 1992). In the Kohake et al. (2010) study of four muck soils, the mean density of five different aggregate size classes, ranging in diameter from approximately 1–19 mm, varied from 0.93 to 1.13 $\mathrm{Mg\,m^{-3}}$. The density of smaller organic soil aggregates and particles may be even greater. The mean densities of 0.29–2.00 mm diameter particles and aggregates from nine organic soils from the Midwest US ranged from 1.57 to 1.70 $\mathrm{Mg\,m^{-3}}$ (Woodruff, 1970). The density of the smaller particles was likely related to the amount of organic matter (OM), relative to mineral matter, contained in each sample. The density of organic soil aggregates increases with increasing sand to OM ratio due to the much greater density of mineral grains relative to OM.

Although Kohake et al. (2010) also noted the importance of soil moisture and crust properties to wind erosion of organic soils. In our study, we used air-dried, tilled and leveled soils to maintain similar moisture and surface conditions for each site.

Relative to mineral-dominated soils, few studies have focused on the wind erosion of organic soils. Portable wind tunnel studies of organic soils in Ohio and Wisconsin and laboratory tests of samples from Michigan and Minnesota suggested organic soils react differently to wind action than mineral soils (Woodruff, 1970). Results from sieving with a rotary sieve suggested that organic soils were less erodible than highly erodible sands and sandy loams. However, wind tunnel tests and incidence of erosion under natural conditions indicated they are highly erodible under certain conditions (Woodruff, 1970). In a laboratory wind tunnel study, Zobeck (1991a) found that the soil loss rate for a sieved organic soil could be an order of magnitude greater than that of mineral soils, with the exception of a loamy sand soil. Under the lowest abrasion feed rate tested in the study, the organic soil loss rate was 2.7 times that of the loamy sand soil.

The Wind Erosion Prediction System (WEPS) developed by scientists at the USDA–ARS is a process-based, daily time-step model that incorporates the latest wind erosion science and technology, and was designed to be a replacement for the USDA–ARS Wind Erosion Equation (Hagen, 1991; Wagner, 1996; USDA–ARS, 2008). The structure of WEPS is modular and includes sub-models that simulate daily weather, hydrology, tillage and crop management, crop growth, soil surface conditions, decomposition, and erosion. The model includes five databases for climate, soils, management, barriers, crop growth, and residue decomposition. A user interface provides a way for the user to enter initial conditions such as field dimensions and orientation, barriers, locations of barriers, management operations, and soil type for the desired simulation region (USDA–ARS, 2008). Given the information provided by the user, the interface accesses the databases for the detailed information needed for simulation. Specific soil-related data needed by WEPS include surface micro-relief (roughness) properties such as ridge height and spacing and random roughness, soil sand and clay content, organic matter and calcium carbonate content, and crust and aggregate properties including aggregate size distribution, dry stability, and density. Further detailed descriptions of the many inputs needed for WEPS are beyond the scope of this paper and have been described elsewhere (Hagen, 1991; Zobeck, 1991b; Wagner, 1996; USDA–ARS, 2008).

WEPS outputs include average and total number of erosion events over the simulation period, soil loss per erosion event, and average creep and saltation material, suspension, and PM_{10} (particulate matter less than 10 μm) leaving the field. WEPS has been field tested and validated for a wide variety of mineral soils (Funk et al., 2004; Hagen, 2004; Feng and Sharratt, 2007) but no similar field studies have been made on organic soils. However, since so little information is available for organic soils, WEPS and other physically-based erosion models need additional data relating wind erosion of organic soils to soil properties. The objective of this study was to determine the effects of organic matter content, aggregate density, stability, and erodible fraction on wind erosion of organic soils to provide further information needed in the development of WEPS.

2. Materials and methods

2.1. Study sites

Soils with a range of surface soil organic matter (OM) contents were identified in Palm Beach Co., Florida and Newaygo Co., Michigan (Fig. 1). Three sites in Michigan were all mapped as Adrian muck (sandy or sandy-skeletal, mixed, euic, mesic Terric Haplosaprists) and were designated as high (MH, 57.5% OM), medium (MM, 40.9% OM), and low (ML, 16.7% OM) organic matter contents (Table 1). Three sites were also identified in Florida and were mapped as

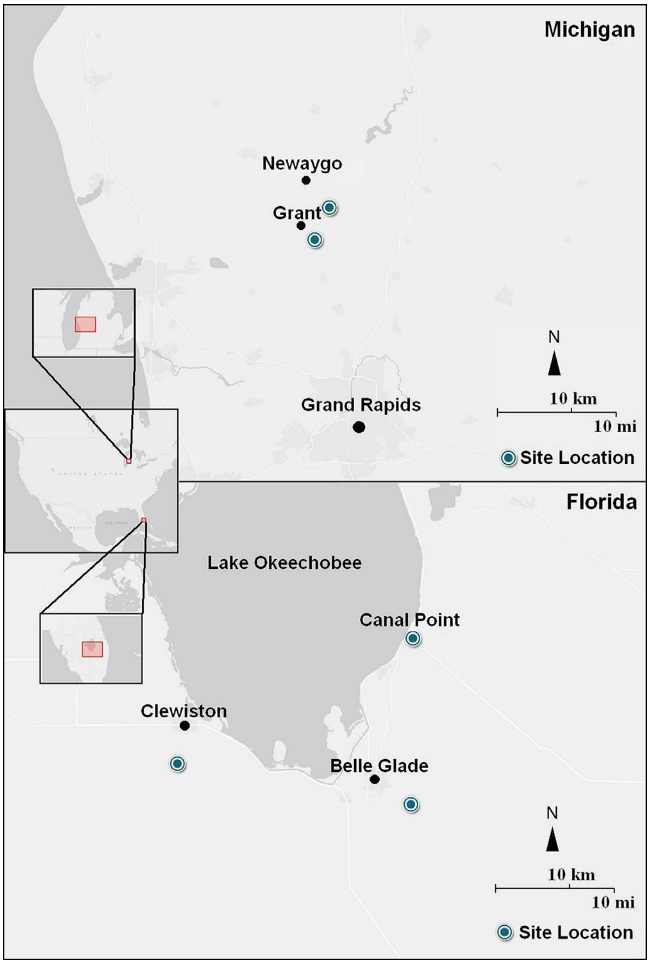

Fig. 1. Location of the study sites in Michigan and Florida.

Pahokee muck (hyperthermic Lithic Haplosaprists), Torry muck (euic, hyperthermic Typic Haplosaprists), and Plantation muck (sandy, siliceous, hyperthermic Histic Humaquepts). The Pahokee muck was designated as high OM (FH, 66.6%), the Torry muck had medium OM (FM, 28.2%), and the Plantation muck had low OM (FL, 12.6%) (Table 1).

Three plots were prepared and tested in the same manner on each site. Each plot was approximately 2 m wide and 10 m long and was air-dried, roto-tilled, raked, and finally rolled flat using a 25 kg turf roller to ensure surface roughness was as similar as possible (Fig. 1).

2.2. Wind tunnel

A portable (field) wind tunnel was used to estimate the erodibility of each soil surface by measuring fluxes of saltation and suspended PM_{10} dust (Fig. 2). The wind tunnel system employed here has been described in detail by Van Pelt et al. (2010) and has been successfully deployed in other wind erosion investigations (Baddock et al., 2011). Airflow was generated by a 1 m diameter push-type fan. The tunnel was 1 m high with a 6 m × 0.5 m open-floor testing length in which the bare soil surface was exposed to the fan-induced air flow. Sediment transport in the wind tunnel was sampled using a 1 m high slot sampler with a 3 mm wide slot (0.003 m cross section) which vertically integrated over the entire height of the tunnel at the center of the tunnel exit. The sampler was aspirated by suction fans at a rate to achieve isokinetic flow with the airflow of the wind tunnel when at its final steady velocity. Sediment was captured by the slot sampler moving in suspension as well as that material moving near or at the bed as saltation and surface creep (Van Pelt et al., 2010). Having been collected at the end of each run, the bed-transported material deposited in a pan in the bottom of the slot sampler was later sieved to retain the portion 106–2000 μm. This was to remove the finer fraction (<0.106 μm) for further analysis as well as any larger non-sand particles (>2 mm) and other material in order to provide the fraction transported as saltation and creep flux. This mass was converted to a (saltation-dominated) horizontal mass flux, q ($g\ m^{-2}\ s^{-1}$), based on the duration of each run, the area in front of the sampler subjected to abrasion ($0.018\ m^{-2}$) after adjusting for the sampler trap efficiency (73%, Van Pelt et al., 2010).

A small portion of the air aspirated through the slot sample was also tested by an optical particle size analyzer. The analyzer was a GRIMM 1.108 optical particle counter (Grimm Aerosol Technik GmbH & Co., KG, Germany), which uses a laser to determine the number and size of particles (for 15 size bins < 25 μm) per liter of air per minute, returning a count every 6 s. The number of particles by volume per unit time was converted to a mass value for the particles <10 μm (PM_{10}) in each sample interval using the particle density measured for each site determined with a Micromeritics AccuPyc 1330 helium pycnometer (Micromeritics Instrument Corp., Norcross, GA, USA) from sieved bulk samples as described in the next section. The vertically integrated mass of PM_{10} per unit time was divided by the tunnel floor area ($3\ m^2$) to obtain the mass per unit area per unit time and called the E value ($\mu g\ m^{-2}\ s^{-1}$), (see also Houser and Nickling, 2001).

Following rolling (Fig. 2), tests were initiated when the relative humidity was <60% and the ambient wind speeds were $<5\ m\ s^{-1}$. Each plot was subjected to three wind tunnel runs when the surface soil was in an air-dry condition. The first run was an initial blow-off when flow was accelerated from zero to the target velocity of $12.6\ m\ s^{-1}$ at a height of 0.5 m in the center of the tunnel. The wind tunnel was calibrated to this velocity, which represents an erosive condition from field studies of erosion events, and this height-velocity sets up a known flow profile for the tunnel (Van Pelt et al., 2010). It took up to 3 min to achieve the target velocity and the total period of this run was approximately 5 min. By the end of the initial run, the most readily eroded material had been blown from the study plots. The sediment trap in the bottom of the slot sampler was emptied and replaced at this point, but tunnel air flow was not terminated after the first run. Flow velocity therefore remained constant at the target value ($\pm 0.5\ m\ s^{-1}$) for the start of the subsequent run. This following run was conducted for 20 min and in this run sand was introduced into the flow in order to bombard the surface throughout the entire run. The sand was added to the flow near the ground surface and was distributed evenly across the tunnel width via chutes leading down from a hopper atop the tunnel. The abrader sand was introduced steadily, at a known rate, to simulate sandblasting, a process essential in driving prolonged emission from most natural surfaces (Shao et al., 1993). The added material was geologically clean, well-sorted fine sand (86.6% of mass between 106 and 500 μm diameter) and was largely dust free (0.03% < 10 μm). Its input rate was equivalent to $14.5\ g\ m^{-1}\ s^{-1}$, a rate comparable to that used in several laboratory-based wind tunnel abrasion studies (e.g., Zobeck, 1991a; McKenna Neuman et al., 2005). The use of a blow-off run followed by an abrader run in this manner was based on previous studies that had successfully characterized both saltation and dust emission fluxes from different soil surfaces (e.g., Baddock et al., 2011).

During the 20 min abrasion test (Run 1), a representative velocity profile was determined for the steady flow run by recording time-averaged wind speeds at six known heights above the surface. This was performed by moving a single hotwire anemometer

Table 1
Amount of wind erodible soil and soil stability values by site.

Site ID	State	LOI organic matter content [%][†]	Organic carbon content [%]	Particle density > 106 μm diameter [Mg m^{-3}]	Particle density < 106 μm diameter [Mg m^{-3}]	Wind erodible material [%]	Dry mechanical stability [%]	Dry clod stability [LN(CE)] [†]	Geometric mean diameter [mm]
FH	Florida	66.6a[††]	38.8a	1.61e	1.60d	38.4b[††]	90.8a	7.50a	1.67ab
FM	Florida	28.2d	17.3d	1.97b	2.01a	37.5b	94.3a	7.58a	1.93a
FL	Florida	12.6e	9.6e	2.41a	1.91bc	50.9b	73.0ab	4.81b	1.06b
MH	Michigan	57.5b	29.3b	1.75d	1.63d	36.0b	76.9ab	6.48a	1.89ab
MM	Michigan	40.9c	25.0c	1.87c	1.82c	42.6b	89.3a	6.70a	1.50ab
ML	Michigan	16.7e	10.9e	2.38a	1.97ab	73.5a	59.9b	2.85c	0.20c

[†] LOI – Loss on ignition; LN(CE) – natural log of the crushing energy in J kg^{-1}.
[††] Values with the same letter, within columns, are not significantly different at the 5% level of significance.

Fig. 2. Prepared wind tunnel plot and inset view of wind tunnel.

between different heights and sampling the mean velocity at each interval for 30 s. Surface roughness length (z_0) was then calculated using the established method of fitting the Prandtl–von Karman logarithmic law to the measured wind speed profile. Detail on the general application of this law to wind erosion studies is reviewed fully by Zobeck et al. (2003b). The average aerodynamic roughness (and standard deviation) over all tests was 0.0015 m (0.0011 m) and the average friction velocity (and standard deviation) was 0.88 m s^{-1} (0.12 m s^{-1}). The 20 min run was followed by a final 10 min run (Run 2) during which abrader was again added throughout the entire run.

2.3. Soil analysis

Following the plot-preparation rolling, a 5 kg bulk soil sample was collected from the surface 5 cm of each plot to determine the dry ASD using a compact rotary sieve (Chepil, 1962). The WEM was measured as the percent mass of soil <0.89 mm diameter after sieving. The ASD was estimated as the geometric mean diameter (GMD) and determined by assuming a logarithmic-normal aggregate distribution and regressing percent mass undersize on the logarithm of the aggregate diameter as described by Gardner (1956) and Zobeck et al. (2003a) The dry mechanical stability of each plot was determined with the rotary sieve by resieving the >0.89 mm diameter fraction as described by Chepil (1958). The dry stability of each plot was also evaluated by determining the energy required to crush 15–20 mm diameter clods to a known endpoint (called the crushing energy). Approximately 25 clods were collected from the soil surface immediately following rolling and air-dried prior to determining the crushing energy (J kg^{-1}) using a Vertical Aggregate Crushing Energy Meter (VSA-CEM) as described by Hagen et al. (1995). Bulk soil samples of the surface 5 cm were also collected to determine other soil properties.

Soil samples used to determine organic C content were ground to pass a 150 μm screen using a roller mill and analyzed for organic C content using an Elementar Vario Max C–N analyzer (Elementar Americas Inc., Mt. Laurel, New Jersey). Total soil OM content of the soil surface <2 mm diameter also was determined by loss on ignition (LOI) at 400 °C as described in USDA–NRCS (1996). This combustion method was also used because a muffle furnace used for dry combustion at 400 °C is more readily available in standard soils laboratories. Subsamples of the bulk surface soil (<2 mm) were air-dried, sieved with a 106 μm (No. 140) sieve and the particle density of each size fraction (2 mm to 106 μm and the portion < 106 μm) was determined with the Micromeritics AccuPyc 1330 helium pycnometer.

Statistical analyses were performed using JMP 9.0 (SAS Institute, 2010). One way analysis of variance was used to determine differences among sites using the Tukey–Kramer HSD (honestly significant differences) test (Tukey, 1953; Kramer,

Table 2
Restricted maximum likelihood correlation coefficients of selected soil properties.

Source	LOI organic matter content	Organic carbon content	Particle density > 106 μm	Particle density < 106 μm	Dry mechanical stability	Wind erodible material	Dry clod stability	Geometric mean diameter
LOI organic matter content (%)	1	0.98***	−0.96***	−0.90***	0.45	−0.65**	0.66**	0.61*
Organic carbon content (%)		1	−0.95***	−0.87***	0.51	−061*	0.69**	0.58*
Particle density > 106 μm (Mg m^{-3})			1	0.77***	−0.62**	0.74**	−0.82***	−0.73**
Particle density < 106 μm (Mg m^{-3})				1	−0.24	0.50*	−0.42	−0.43
Dry mechanical stability (%)					1	−0.94***	0.83***	0.56*
Wind erodible material (%)						1	−0.93***	−0.98***
Dry clod stability (LN(crushing energy, J kg^{-1}))							1	0.86***
Geometric mean diameter (mm)								1

* Significant at the 0.05 level.
** Significant at the 0.001 level.
*** Significant at the 0.0001 level.

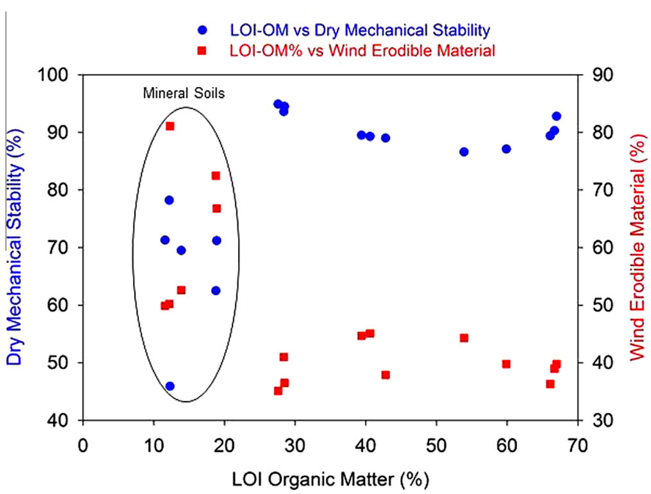

Fig. 3. Effect of LOI organic matter on dry mechanical stability and wind erodible material.

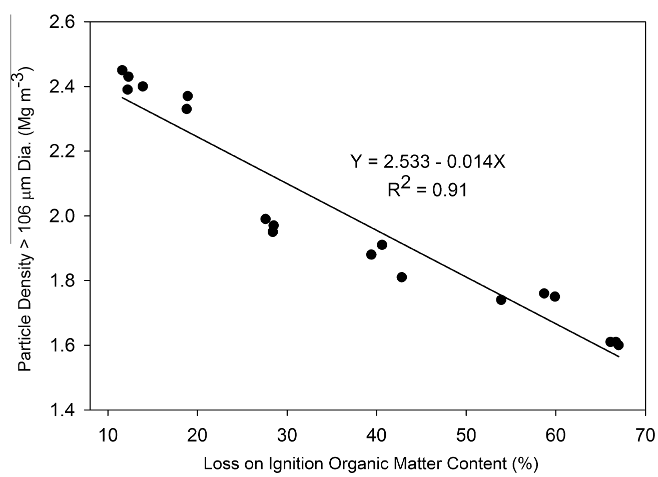

Fig. 4. Effect of organic matter content on particle density.

1956). The restricted maximum likelihood method was used to perform correlations to evaluate the interactions of selected soil properties and stepwise regression was used to relate soil properties and dust emissions.

3. Results and discussion

3.1. Soil property differences among sites

Not all of the soil surfaces tested were organic soil material as defined in the USDA Soil Taxonomy (Soil Survey Staff, 1999). Organic soil material has an organic carbon content, by weight, of over 18% (30% OM as measured by LOI) if the mineral fraction contains 60% or more clay; or more than 12% (20% OM as measured by LOI) if the mineral fraction contains no clay; or more than 12% plus the clay percentage multiplied by 0.1 if the mineral fraction contains less than 60% clay. Although all sites were originally mapped as organic soils, according to these criteria soils FL and ML had high levels of organic matter but too little to qualify as organic soil material (Table 1). Since the sites have been in production agriculture for several decades, the lower organic matter levels now observed may be attributed to losses due to soil erosion and/or oxidation of the organic matter upon draining (Lucas, 1982). All study soils classified as having medium and high OM levels had high enough OM to be classified as organic soil material.

Organic matter was measured as organic carbon using an instrument that combusts the organic carbon and determines the carbon content using gas analysis (Vario-Max) and as organic matter by simple combustion using a muffle furnace. The Vario-Max is more precise but requires special equipment not available in all labs. The muffle furnace is a common and relatively inexpensive laboratory instrument. The organic carbon (%), as measured by the gas analysis in the Vario-Max (Y) was highly correlated (Table 2) with the LOI OM content (%) measured by combustion in the muffle furnace (X):

$$Y = 2.98 + 0.51X \; (R^2 = 0.96) \tag{1}$$

In general, the OM content measured by the muffle furnace was about 1.6 times the organic carbon content measured by gas analysis. The standard deviation of this comparison was 0.2%. The LOI OM content will be used in future comparisons for this manuscript.

In this study, the mineral soils (FL and ML) had relatively high OM contents but produced relatively clear differences in certain soil properties in comparison to the organic soils. For example, the dry mechanical stability, dry clod stability and GMD of the mineral soils were lower than most of the organic soils (Fig. 3 and Table 1). The wind erodible material content had a similar but inverse relationship. The effect of OM on the particle density of the saltation and creep-size particles (>106 μm diameter) had a similar trend but not as distinct. The particle density of the saltation and creep-size particles of the mineral soils was greater than the organic soils but the difference was in line with the OM content of the organic soils as shown in Fig. 4. In fact, the correlation of OM with particle density was among the highest among all soil properties compared (Table 2).

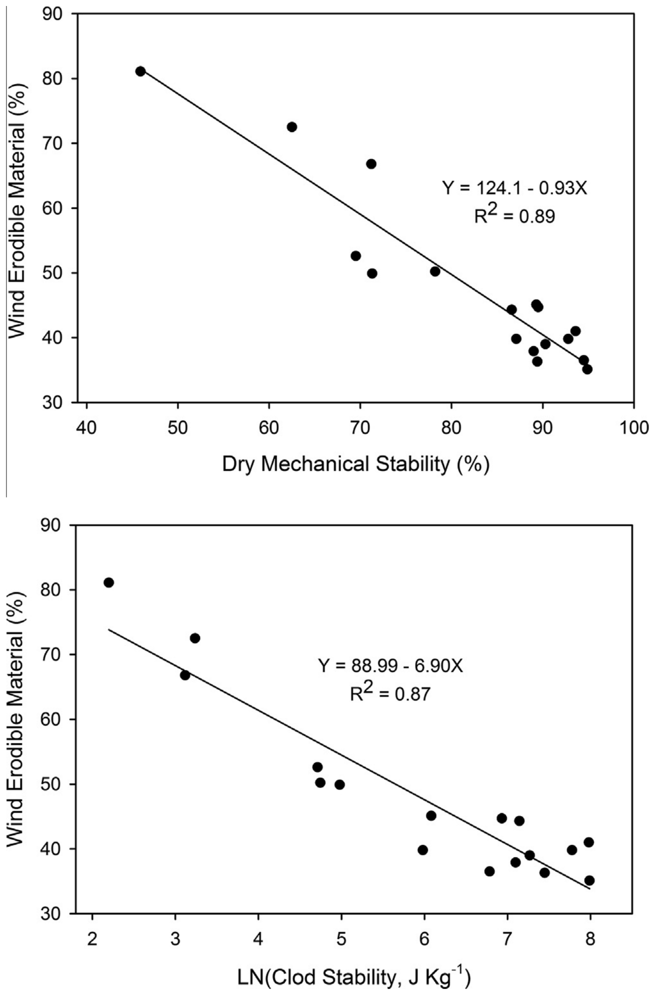

Fig. 5. Relationship of wind erodible material and dry mechanical stability (top) and dry clod stability (bottom).

More detailed examination of the particle density data and its effect on soil properties revealed some variation in density levels by particle size and OM level. Among both size classes tested (<106 μm and >106 μm diameter), the particle density was highly but inversely related to the OM content. Soils with the highest level of OM had the lowest density, varying from 1.6 to 1.75 Mg m^{-3}, and the soils with the lowest level of OM had the greatest density, varying from 1.91 to 2.38 Mg m^{-3} (Table 1). Particle density did not vary greatly by size for the high and medium level OM soils. However, for the soils with the lowest level of OM, the density of the larger saltation-sized particles (>106 μm diameter) was considerably greater than the density of the small suspension-sized particles (Table 1). The density of the particles >106 μm diameter was much more highly correlated (negatively) with dry mechanical stability, clod stability, and GMD than the <106 μm diameter particle density. In addition, the density of the particles >106 μm diameter was much more positively correlated with the amount of wind erodible material than the <106 μm diameter particle density. These correlation results imply that as the density of the material >106 μm diameter increased, likely reflecting increasing soil sand content, the dry soil stability and size decreased and the amount of erodible soil material increased.

Most of the soils tested had similar amounts of wind erodible material as measured with the rotary sieve (Table 1). Only the ML site had a significantly greater amount of wind erodible material than the other soils. Since all sites were thoroughly tilled in the same manner, the reason for the difference in amount of wind erodible material is suggested to lie in the strength of the soil aggregates. The ML site had the lowest dry clod stability among all sites (Table 1).

Dry clod stability and dry mechanical stability were positively and highly correlated (Table 2) and would be expected to have the same effect on soil erodibility. The effects of dry mechanical stability and dry clod stability on soil erodibility are shown by comparing each property to wind erodible material content, resulting in similar regression trends and negative R^2, indicating an inverse relationship (Fig. 5). Dry clod stability was also highly positively correlated with GMD and GMD had one of the highest (negative) correlations with wind erodible material among all comparisons of selected soil properties (Table 2). Thus, as these measures of soil stability and ASD decreased, the amount of erodible material available for transport by erosive winds increased.

3.2. Soil property effects on saltation mass flux

The saltation mass flux values observed for each run and site are shown in Table 3. Run 0 saltation mass flux values are represented as g m^{-2} for the entire initial blow period. The durations of the initial blow periods varied somewhat for each rep, but were approximately 5 min. The Run 0 plots were blown until saltation ceased, so precise emission rates per second are not shown. One-way ANOVA indicated considerable overlap in saltation mass flux values among sites that does not appear to be clearly associated with organic matter levels (Table 3). For example, although the soil with one of the lowest OM levels (ML) had the highest saltation mass flux, as expected, the soil with the second highest OM level (MH) had the second highest saltation mass flux (Table 3). Unfortunately, the saltation data for the site with the lowest OM content, FL, was not available for analysis. However, although the soil with the highest organic matter content, FH, had one of the lowest saltation mass flux values, it was similar to both sites with medium levels of OM. This weak association of Run 0 saltation mass flux and OM content is supported by a non-significant pair-wise correlation of OM content with Run 0 saltation flux (Table 4). The saltation mass flux values for Runs 1 and 2 were more highly correlated with OM content, although the correlations were somewhat low compared to comparisons with other soil properties. Runs 1 and 2 saltation mass flux values were much more highly correlated

Table 3
Saltation mass flux and PM_{10} *E* values (mass flux) by site and run number.

Site ID	Saltation mass flux			PM_{10} *E* values		
	Run 0 [g m^{-2}]	Run 1 [g m^{-2} s^{-1}]	Run 2 [g m^{-2} s^{-1}]	Run 0 [μg m^{-2} s^{-1}]	Run 1 [μg m^{-2} s^{-1}]	Run 2 [μg m^{-2} s^{-1}]
FH	254.47c[†]	2.56b	2.50b	51.1b	196.3ab	194.7ab
FM	81.58c	2.16b	2.13b	55.3b	140.8bc	142.8bc
FL	ND	ND	ND	55.5b	249.9a	277.6a
MH	904.56b	2.82b	2.29b	178.9ab	101.0c	85.8c
MM	325.22bc	2.70b	2.62b	60.5b	100.4c	85.8c
ML	2063.48a	5.37a	4.14a	635.4a	235.0a	201.6ab

[†] Values with the same letter, within columns, are not significantly different at the 5% level of significance; ND - Not determined.

Table 4
Restricted maximum likelihood pairwise correlations of selected properties with saltation mass flux and PM_{10} E values.

Source	Saltation mass flux			PM_{10} E values		
	Run 0	Run 1	Run 2	Run 0	Run 1	Run 2
LOI organic matter content (%)	−0.49	−0.58*	−0.53*	−0.33	−0.51*	−0.47
Particle density > 106 μm (Mg m^{-3})	0.73*	0.80**	0.77**	0.42	0.64*	0.58*
Dry mechanical stability (%)	−0.83***	−0.79**	0.67*	−0.65*	−0.53*	−0.21
Wind erodible material (%)	0.86***	0.95***	0.91***	0.76**	0.59*	0.50
Dry clod stability (LN(crushing energy, J kg^{-1}))	−0.93***	−0.96***	−0.91***	−0.71**	−0.60*	−0.44
Geometric mean diameter (mm)	−0.81**	−0.91***	−0.88***	−0.66*	−0.60*	−0.52*

* Significant at the 0.05 level.
** Significant at the 0.001 level.
*** Significant at the 0.0001 level.

Table 5
Selected regression parameter estimates relating Run 1 saltation mass flux with selected soil properties.

Source	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (5)	Eq. (6)	Eq. (7)	Eq. (8)
Intercept	4.67	−3.71	10.44	−0.69	7.10	5.59	−1.47	10.47
LOI organic matter content (%)	−0.04						0.01	0.001
Particle density > 106 um (Mg m^{-3})		3.58						
Dry mechanical stability (%)			−0.09					−0.09
Wind erodible material (%)				0.08			0.09	
Dry clod stability (LN(crushing energy, J kg^{-1}))					−0.63			
Geometric mean diameter (mm)						−1.78		
Coefficient of determination (R^2)	0.31	0.63	0.97	0.94	0.94	0.90	0.96	0.97

with soil stability, density, and size parameters than with OM content (Table 4).

Since abrader material was introduced into the wind tunnel during Runs 1 and 2, the saltation results reflect the mass captured at the end of the wind tunnel after abrasion of the surface and sediment trapping that may have occurred. We did not attempt to estimate the amount of trapping so interpretations of the saltation mass flux data are best considered relative in nature. The Run 1 and Run 2 saltation mass flux values for all sites were the same (Table 3), with the exception of the ML site, which was significantly higher ($P < 0.05$).

3.3. Soil property effects on PM_{10} mass flux E values

The PM_{10} E values observed for each run and site are shown in Table 3. These values represent the average of the last 3 min of each run. The initial blow-off created during Run 0 emitted more loosely, readily entrained dust available on the soil surface. The dust created during Runs 1 and 2 was caused by the abrasion process. Unfortunately, we were unable to collect data for Run 2 for rep 3 of FH and for reps 2 and 3 for FS. Since data from all reps were available for Runs 0 and 1, comparisons of PM_{10} E values were made using Run 0 and Run 1. For comparisons of Run 1 data, the average PM_{10} E values ranged from a high of 635.4 μm m^{-2} s^{-1} for site ML, to a low of 51.1 μm m^{-2} s^{-1} for site FH. The PM_{10} E values for Runs 1 and 2 had a narrower range, from a high of 277.6 μm m^{-2} s^{-1} for site FL to a low of 85.8 μm m^{-2} s^{-1} for sites MH and MM.

The general trends of the ANOVA of the dust data were similar to that of the saltation data, with some exceptions (Table 3). Unlike the saltation data, the PM_{10} E values for Run 0 were not considerably higher than Runs 1 and 2, with the exception of sites ML and MH. The Run 0 PM_{10} E values of ML were about three times that Runs 1 and 2 and the Run 0 PM_{10} E values of MH were about twice that of Runs 1 and 2. However, as with the saltation flux data, site ML had a significantly higher PM_{10} E values (about two to seven times) for Run 0 than the other sites. In addition, all of the Run 0 PM_{10} E values for the Florida sites were the same. The general trends for PM_{10} E values for Runs 1 and 2 were similar to the trends found for the saltation mass flux values. Generally, the sites with low OM levels (FL and ML) had significantly greater PM_{10} E values than the other sites, which were statistically the same.

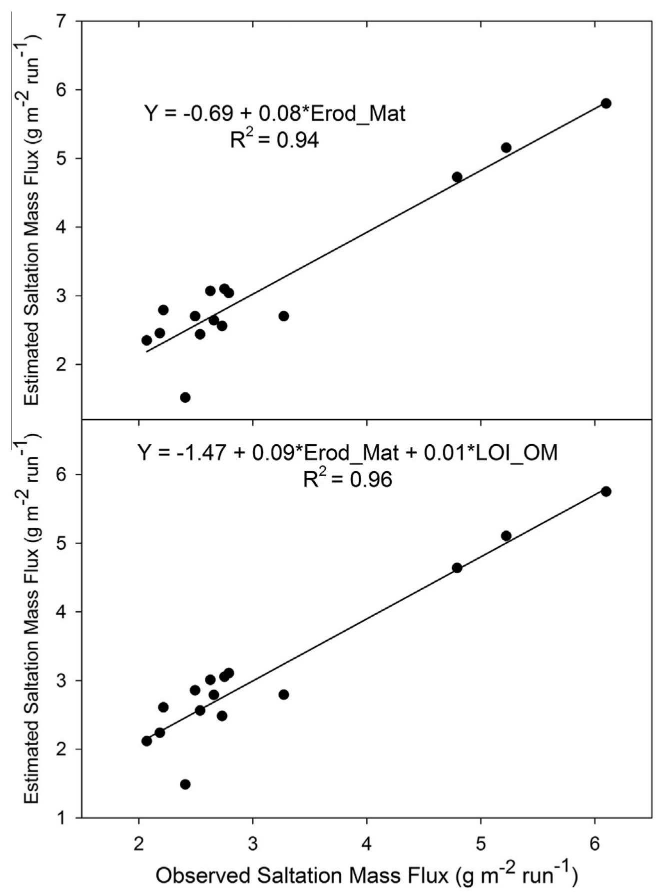

Fig. 6. Estimation of saltation mass flux for Run 1 using Eq. (4) (top) and Eq. (7) (bottom), Table 5, with wind erodible material (Erod_Mat) and LOI OM (LOI_OM) content as independent variables.

Table 6
Selected regression parameter estimates relating Run 1 PM_{10} E values (mass flux) with selected soil properties.

Source	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (5)	Eq. (6)	Eq. (7)
Intercept	232.75	−104.80	253.88	306.70	39.40	−692.68	−77.56
LOI organic matter content (%)	−1.68					3.60	
Particle density > 106 μm (Mg m^{-3})		137.87				365.39	94.42
Dry mechanical stability (%)							
Wind erodible material (%)					2.82		1.28
Dry clod stability (LN(crushing energy, J kg^{-1}))				−22.73			
Geometric mean diameter (mm)			−60.51				
Coefficient of determination (R^2)	0.29	0.40	0.36	0.36	0.35	0.51	0.44

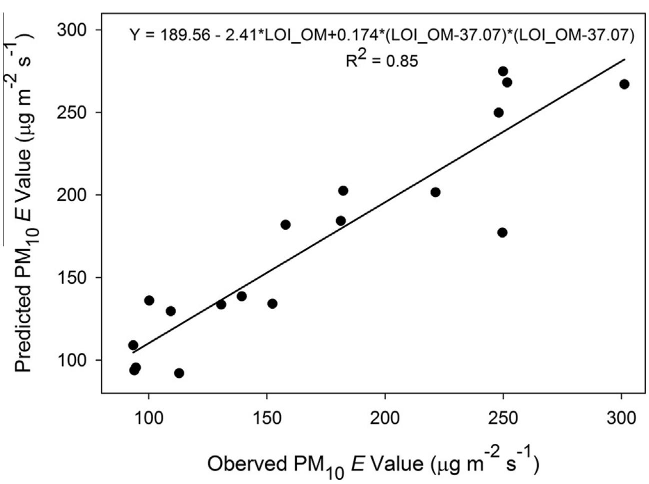

Fig. 7. Effect of OM on PM_{10} E value as represented by a second degree polynomial.

The pair-wise correlations of soils properties with PM_{10} by Run number are presented in Table 4. The correlations of the PM_{10} E values with soil properties were generally lower than to those found for the saltation mass flux values. For Run 0, the wind erodible material had the highest correlation with PM_{10} E values while the OM content and particle density were not significantly related to the PM_{10} E values. Organic matter content and the density of particles >106 μm diameter were more highly correlated in Runs 1 and 2, when abrader was added to the wind stream, than in the blow-off Run 0. The density of particles >106 μm diameter was the most highly correlated soil property for Run 1.

3.4. Simple mass flux prediction equations

Simple and multiple linear regressions were used to develop models relating saltation mass flux to soil properties (Table 5) for use in WEPS. Comparisons were made with data from Run 1 because this run included all reps. In comparisons of equations with only one independent variable, dry clod and mechanical stability, and wind erodible material, had similar high coefficients of determination (R^2) with saltation mass flux (Table 5, Eqs. (5), (3) and (4), respectively). The relationship of wind erodible material and saltation mass flux is illustrated in Fig. 6. The ASD parameter, GMD, had a slightly lower R^2 (Table 5, Eq. (6)). Adding another soil property to the predictive equation for saltation, such as OM (Table 5, Eqs. (7) and (8)), did not greatly improve the R^2.

Simple and multiple linear regressions also were used to develop simple models relating PM_{10} E values to soil properties (Table 6), similar to those developed to relate saltation mass flux to soil properties (Table 5). These regression equations demonstrate the poor correlation of simple linear models with only one independent variable (soil property) to predict PM_{10} E values. Adding a second independent variable to the model did not greatly improve the R^2 (Table 6, Eqs. (6) and (7)). The addition of a third independent variable to predictive equations provided no further improvement in R^2.

However, plots of the soil property data versus PM_{10} E values revealed that LOI OM and the density of particles >106 μm diameter seemed to have a second degree polynomial relationship with PM_{10} E values. Regression analysis revealed that LOI OM was the most highly related ($R^2 = 0.85$) with PM_{10} E values with this polynomial relationship as shown in Fig. 7. The second degree polynomial regression of the density of particles >106 μm diameter had $R^2 = 0.80$. Further analyses showed that second degree polynomial regressions relating PM_{10} E values with other soil properties produced much lower R^2.

Comparison of PM_{10} E values of the organic soils observed in this study were generally smaller than the PM_{10} E values observed in a similar study of a silt loam soil in Tribune, Kansas, described by Van Pelt et al. (2013). Mean PM_{10} E values observed at Tribune were 302 and 640 μm m^{-2} s^{-1} for Runs 1 and 2, respectively, compared with values of 171 and 148 μm m^{-2} s^{-1}, respectively, for Runs 1 and 2 observed in this study.

This result suggests that soil loss due to wind erosion of organic soils is comparable to that of mineral soils and may be lower, depending on the soils compared. This conclusion is based on a limited study of 6 organic soils. More information is needed to include other organic soils with wider range in soil properties.

4. Conclusions

The OM level of the surface soil had a clear effect on the soil properties and subsequent wind erosion in this study. For example, dry mechanical stability and dry clod stability decreased and the dry erodible material content increased as OM content decreased. The effect of OM on the particle density was similar, with soil particle density increasing with decreasing OM content. Particle density of the saltation-sized material (>106 μm) varied from 1.61 g cm^{-3} for the soil with highest OM content to 2.41 g cm^{-3} for the soil with the lowest OM content. Since all sites were thoroughly tilled in the same manner, most of the soils tested had similar amounts of wind erodible material (aggregates) as measured with the rotary sieve. Dry clod stability and dry mechanical stability were highly correlated and the differences in dry clod stability and dry mechanical stability among sites had the same pattern.

The soil properties had a decided effect upon the saltation and PM_{10} E values observed in this study. The soils with the highest fraction of wind-erodible material (51–74%) had distinctly higher dust emissions compared with the other soils. One-way ANOVA indicated considerable overlap in saltation mass flux values among sites that does not appear to be clearly associated with organic matter levels in Run 0. The saltation mass flux values for Runs 1 and 2 were more highly correlated with OM content, although the correlations were somewhat low compared to comparisons with other soil properties.

The Runs 1 and 2 saltation mass flux values were much more highly correlated with soil stability and density parameters than with OM content. Simple and multiple linear regressions used to develop models relating saltation mass flux to soil properties indicated the dry mechanical stability (Table 5, Eq. (3)), easily measured by sieving, was the best single soil property to predict saltation flux. Adding another soil property to the predictive equation for saltation, such as OM, did not greatly improve the estimate of R^2.

For comparisons of PM_{10} E values among sites, the sites with low OM levels (FL and ML) had significantly greater PM_{10} E values than the other sites, which were statistically the same. The correlations of the PM_{10} E values with selected soil properties were lower than those found for the saltation flux values. Organic matter content and the density of particles >106 μm diameter were more highly correlated in Runs 1 and 2, when abrader was added to the wind stream, than in the blow-off Run 0. Plots of the soil property data versus PM_{10} mass flux revealed that LOI OM and the density of particles >106 μm diameter seemed to have a second degree polynomial relation with PM_{10} E values. Regression analysis revealed that LOI OM was the most highly related ($R^2 = 0.85$) with PM_{10} E values with a second degree polynomial relationship. The regression of the density of particles >106 μm diameter had a polynomial relation with dust flux with a similar R^2 of 0.80. Polynomial equations relating PM_{10} E values with other soil properties had much lower R^2 values. These results demonstrate that variations in sediment and dust emissions can be linked to soil properties using simple models based on one or more soil properties to estimate saltation mass flux and PM_{10} E values from organic and organic-rich soils. The models are suggested to provide improvements of WEPS predictions for organic soils.

Disclaimer

Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by US Department of Agriculture. USDA is an equal opportunity provider and employer.

Acknowledgements

The authors gratefully acknowledge the technical support provided by technicians Dean Holder, Joseph Wolf, Taylor Ward, Travis Brock and visiting scientist of the Chinese Academy of Sciences, Zhongling Guo. The authors appreciate the support of state office and field office USDA–Natural Resources Conservation Service personnel in locating sites and financial assistance provided by USDA–NRCS. We are grateful for the generous assistance provided by Alan Wright, Associate Professor of Soil and Water Science and other staff at the University of Florida, Everglades Research & Education Center, Belle Glade, FL; and Jack Comstock, Research Leader, USDA–ARS Sugarcane Field Station, Canal Point, FL. Finally, we are indebted to the anonymous farmers who allowed us access to their fields.

References

Baddock, M.C., Zobeck, T.M., Van Pelt, R.S., Fredrickson, E.L., 2011. Dust emissions from undisturbed and disturbed, crusted playa surfaces: cattle trampling effects. Aeolian Res. 3, 31–41.

Chepil, W.S., 1951. Properties of soil which influence wind erosion: V. Mechanical stability of structure. Soil Sci. 72, 465–478.

Chepil, W.S., 1958. Soil conditions that influence wind erosion. USDA–ARS, Tech. Bull. No. 1185, US Govt. Printing Off., Washington, DC.

Chepil, W.S., 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. Soil Sci. Soc. Am. J. 26, 4–6.

Chepil, W.S., Woodruff, N.P., 1963. The physics of wind erosion. Adv. Agron. 15, 211–302.

Feng, G., Sharratt, B.S., 2007. Validatino of WEPS for soil and PM10 loss from agricultural fields on the Columbia Plateau. Earth Surf. Proc. Landf. 32, 743–753.

Funk, R., Skidmore, E.L., Hagen, L.J., 2004. Comparison of wind erosion measurements in Germany with simulated soil losses by WEPS. Environ. Model. Software 19, 177–183.

Gardner, W.R., 1956. Representation of soil aggregate-size distributions by logarithmic-normal distribution. Soil Sci. Soc. Am. Proc. 20, 151–153.

Hagen, L.J., 1991. A wind erosion prediction system to meet user needs. J. Soil Water Conserv. 46, 106–111.

Hagen, L.J., Schroeder, B., Skidmore, E.L., 1995. A vertical soil crushing-energy meter. Trans. ASAE 38, 711–715.

Hagen, L.J., 2004. Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields. Environ. Model. Software 19, 171–176.

Houser, C.H., Nickling, W.G., 2001. The factors influencing the abrasion efficiency of saltating grains on a clay-crusted playa. Earth Surf. Proc. Landf. 26, 491–505.

Kohake, D.J., Hagen, L.J., Skidmore, E.L., 2010. Wind erodibility of organic soils. Soil Sci. Soc. Am. J. 74, 250–257.

Kramer, C.Y., 1956. Extension of multiple range tests to group means with unequal numbers of replications. Biometrics 12, 307–310.

Lucas, R.E., 1982. Organic soils (Histosols) formation, distribution, physical and chemical properties and management for crop production. In: Farm Science Research Report 435, Mich. State Univ. Agric. Exp. Sta., East Lansing, MI.

McKenna Neuman, C., Maxwell, C., Rutledge, C., 2005. Spatial and temporal analysis of crust deterioration under particle impact. J. Arid Environ. 60, 321–342.

Mokma, D.L., 1992. Effect of tillage and climate on temporal soil properties of wind-erodible organic and sandy soils in Michigan. In: Field Study Final Rept., Michigan State Univ., East Lansing, MI.

Parent, L.E., Ilnicki, P., 2003. Organic Soils and Peat Materials for Sustainable Agriculture. CRC Press, Boca Raton, FL.

Parent, L.E., Millette, J.A., Mehuys, G.R., 1982. Subsidence and erosion of a Histosol. Soil Sci. Soc. Am. J. 46, 404–408.

SAS Institute, 2010. JMP version 9.0.0 64-bit edition, Cary, NC. Available from: <www.jmp.com>.

Shao, Y., Raupach, M.R., Findlater, P.A., 1993. Effect of saltation bombardment on the entrainment of dust by wind. J. Geophys. Res. 98 (D7), 12719–12726.

Skidmore, E.L., Layton, J.B., 1992. Dry-soil aggregate stability as influenced by selected soil properties. Soil Sci. Soc. Am. J. 56, 557–561.

Soil Survey Staff, 1999. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys, 2nd ed. In: Agric. Handbook No. 436, US Department of Agriculture–Natural Resources Conservation Service, US Govt. Printing Off., Washington, DC.

Tukey, J.W., 1953. The problem of multiple comparisons. In: Braun, H.I. (Ed.), The Collected Works of John W. Tukey, vol. 8. Chapman & Hall, New York, p. 1994.

USDA–ARS, 2008. The Wind Erosion Predictin System: WEPS 1.0 User Manual. USDA–ARS Wind Erosion Research Unit, Manhattan, KS. <http://www.weru.ksu.edu/weps/wepshome.html> (accessed October 2012).

USDA–NRCS, 1996. Soil survey laboratory methods manual. Soil Survey Investigations, version 3.0. US Department of Agriculture–Natural Resources Conservation Service, Washington, DC.

USDA–NRCS, 2007, National Resources Inventory 2003. <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1041379.pdf> (accessed October 2012).

Van Pelt, R.S., Zobeck, T.M., Baddock, M.C., Cox, J.J., 2010. Design, construction, and calibration of a portable boundary layer wind tunnel for field use. Trans. ASAE 53, 1413–1422.

Van Pelt, R.S., Baddock, M.C., Zobeck, T.M., Acosta-Martinez, V., Schlegel, A.J., Vigil, M.F., 2013. Field wind tunnel testing of two silt loam soil on the North American Central High plains. Aeolian Res. 10, 53–59.

Wagner, L.E., 1996. An overview of the wind erosion prediction system. In: Proc. of International Conference on Air Pollution from Agricultural Operations, February 7–9, 1996, Kansas City, MO, pp. 73–75.

Woodruff, N.P., 1970. Annual Research Report. Soil Erosion Research, Manhattan, KS, pp. 6–8.

Woodruff, N.P., Siddoway, F.H., 1965. A wind erosion equation. Soil Sci. Soc. Am. J. 29, 602–608.

Zelany, L.W., Carlisle, W.H., 1974. Physical, chemical, elemental and oxygen-containing functional group analysis of selected Florida Histosols. In. Histosols (Chapter 6), Soil Sci. Soc. Am. Spec. Publ. No. 6, Madison, WI, pp. 63–78.

Zobeck, T.M., 1991a. Abrasion of crusted soils: influence of abrader flux and soil properties. Soil Sci. Soc. Am. J. 55, 1091–1097.

Zobeck, T.M., 1991b. Soil properties affecting wind erosion. J. Soil Water Conserv. 46, 112–118.

Zobeck, T.M., Popham, T.W., Skidmore, E.L., Lamb, J.A., Merrill, S.D., Lindstrom, M.J., Mokma, D.L., Yoder, Y.E., 2003a. Aggregates-mean diameter and wind-erodible soil predictions using dry aggregate-size distributions. Soil Sci. Soc. Am. J. 67, 425–436.

Zobeck, T.M., Sterk, G., Funk, R., Rajot, J.L., Stout, J.E., Van Pelt, R.S., 2003b. Measurement and data analysis methods for field-scale wind erosion studies and model validation. Earth Surf. Proc. Landf. 28, 1163–1188.