Aeolian Research 42 (2020) 100559

Contents lists available at ScienceDirect

Aeolian Research

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

Comparison of soil-aggregate crushing-energy meters

Huawei Pi[a,*], David R. Huggins[b,*], Nicholas P. Webb[c], Brenton Sharratt[d]

[a] *Washington State University, Department of Crop and Soil Sciences, Pullman, WA, USA*
[b] *USDA-ARS, 215 Johnson Hall, Washington State University, Pullman, WA, USA*
[c] *USDA-ARS, Jornada Experimental Range, MSC 3 JER, NMSU, Las Cruces, NM, USA*
[d] *USDA-ARS, 215 Johnson Hall, Washington State University, Pullman, WA, USA*

ARTICLE INFO

Keywords:
Wind erosion
Dust emission
Dry aggregate stability
Particle cohesion
Binding energy
Abrasion

ABSTRACT

Dry aggregate stability (DAS) is an important factor influencing soil wind erosion, dust emission and crop production. Historically and to the present, DAS has been determined using a horizontal- or vertical-plate crushing meter (Soil-Aggregate Crushing-Energy Meter, hereafter SACEM). The intent of this paper was to compare the performance of horizontal-plate SACEM with a commercial penetrometer (Mohr Digi-Test, hereafter MDT). The performance of both instruments was tested on aggregates collected from various soil types, crop rotations, soil amendments, and tillage systems across the inland Pacific Northwest United States (iPNW). Results indicated no consistently significant difference in DAS measured by the MDT and SACEM. However, there was evidence that SACEM under-estimated or MDT over-estimated DAS by 74 to 368% in measuring the stability of strong aggregates (DAS $> 3\,\mathrm{J\,kg^{-1}}$). Both instruments measured higher DAS for no-tillage summer fallow, winter wheat-summer fallow (WW-SF) rotations, and no green manure treatments compared with other tillage practices, oilseed rotations, and green manure treatments. The SACEM that has historically been used in measuring soil DAS can be replaced by the commercial penetrometer (MDT). Nonetheless, differences in the performance of instruments in measuring the stability of strong aggregates poses risks.

1. Introduction

Soil aggregate stability is a dynamic soil property that moderates soil susceptibility to wind erosion and dust emission potential (Zobeck and Popham, 1990). The stability of dry soil aggregates, termed dry aggregate stability (DAS), strongly influences the resistance of soils to abrasion and disaggregation under saltation bombardment, and the release of fine dust particles to the atmosphere (Shao, 2004; Kok et al., 2014). Soil DAS is controlled by the magnitude of cohesive forces between soil particles as determined by flocculation (e.g., due to electrostatic forces and Van der Waals forces) and cementation (Amézketa, 1999). The coefficient of abrasion or abrasive erosion (g $\mathrm{kg^{-1}}$) of soils varies exponentially as a function of DAS and is a critical parameter determining the fragmentation of soil aggregates and vertical dust flux (Shao, 2008). Large, weak aggregates tend to degrade into small aggregates which are more susceptible to erosion by wind. Aggregates smaller than 0.84 mm in diameter (Chepil, 1953) are particularly susceptible to wind erosion and so spatial and temporal change in soil DAS can have a profound effect on the spatiotemporal dynamics of wind erosion and dust emission (Tatarko et al., 2001). Soil DAS has been shown to respond dramatically to climate variability and disturbances such as cultivation and trampling by livestock (Webb and Strong, 2011). Accurately measuring soil DAS is therefore critical for understanding the impact of this dynamic soil property on wind erosion and dust emission and parameterizing its effects in predictive models.

A number of approaches have been used to measure soil aggregate stability at different scales and through different mechanisms (Amézketa, 1999). Early methods used to measure DAS, such as the drop shatter technique (Farrell et al., 1967) and sieving (Chepil, 1953; Toogood, 1978; Colazo and Buschiazzo, 2010), were time consuming (Boyd et al., 1983) and the units of these methods could not be incorporated consistently into wind erosion models. For example, the Wind Erosion Prediction System (WEPS) or Single-event Wind Erosion Evaluation Program (SWEEP) model uses the DAS in units of J $\mathrm{kg^{-1}}$ to simulate soil and PM_{10} loss, rather than dispersion degree measured by drop shatter technique or aggregate size percentage measured by sieving (Hagen, 1997). Colazo and Buschiazzo (2010) and Hevia et al. (2007) assessed DAS by measuring the mechanical stability of aggregates which entailed repeated dry sieving of each aggregate size. Their method defines DAS as:

---

[*] Corresponding authors at: USDA-ARS, 213A Johnson Hall, Washington State University, Pullman, WA 99164, USA.
E-mail addresses: huawei.pi@wsu.edu (H. Pi), dhuggins@wsu.edu (D.R. Huggins).

https://doi.org/10.1016/j.aeolia.2019.100559
Received 5 July 2019; Received in revised form 6 October 2019; Accepted 18 October 2019

$$\mathrm{DAS} = \left[1\frac{\mathrm{W} < 0.84}{\mathrm{W} > 0.84}\right] \times 100 \tag{1}$$

where W < 0.84 is the weight (g) of aggregates that passed though the 0.84 mm sieve after a second sieving and W > 0.84 is the weight (g) of aggregates retained on the 0.84 mm sieve after the first sieving. This method, however, is not in the true sense the measured aggregate stability. Boyd et al. (1983) suggested aggregate stability be defined as the energy required to alter an aggregate. The energy imparted to the aggregate is determined by the force applied to the aggregate and displacement. The energy or work (*W* with unit of *J*) can be described as:

$$W = \int_a^b F(x) \tag{2}$$

where *F (x)* is the force imparted to the aggregate and × (m) is the distance over which the force was imparted to the aggregate (displacement) from a (m) to b (m). The force imparted to the aggregate is termed the crushing force which is defined by the initial break force and final force. As force is slowly imparted to an aggregate, it usually remains rigid until the point of fracture. The force being applied to the aggregate at the time of fracture is called the initial break force (Skidmore and Layton, 1992). The final force required to fragment soil aggregates has been defined as the crushing force to thoroughly crush the aggregate (Boyd et al., 1983). The typical initial break force, final force, and crushing energy are illustrated in Fig. 1. The final force has been quantified as the crushing force at 1.5 times the initial break force (Hagen et al., 1995). Soil DAS can be calculated from the work required to crush each aggregate divided by the mass of the aggregate being crushed. Obtaining accurate force-based measurements of soil DAS is important for parameterizing saltation-induced aggregate disintegration to predict dust emission (Shao, 2004; Kok et al., 2014). There is a dearth of force-based data on soil DAS (Shao, 2008) and so indentifying instruments and methods to measure soil DAS in an accurate and repeatable way could facilitate improved representation of this dynamic soil property in wind erosion and dust emission models (Kok et al., 2012).

Soil aggregate stability is an important factor influencing soil wind erosion and dust emission potential. However, soil DAS effects are generally omitted from wind erosion models such as the Agricultural Policy /Environmental eXtender (APEX), Revised Wind Erosion Equation (RWEQ), Texas Tech Erosion Analysis Model (TEAM), or Wind Erosion on European Light Soils (WEELS) model and/or have been parameterized from limited measurements or their values tuned to reproduce measured dust fluxes (Shao et al., 2011; Kok et al., 2014). The lack of DAS data to support wind erosion and dust modeling is in large part due to the lack of a universal measuring method that produces a quantitative and force-based measure of DAS.

Variations in the performance of DAS instruments are expected based upon different technologies utilized in measuring the forces and displacement. The Soil-Aggregate Crushing-Energy Meter (SACEM), developed by Boyd et al. (1983), uses a crushing vise with 6.35 mm (1/4 in) aluminum plate to measure the forces and displacement. The performance of the SACEM was shown to be excellent based on the coefficient of determination (r^2) of 0.999 between the energy measured by the SACEM and an Instron Universal Testing Instrument (Instron, Norwood, MA). However, Boyd et al. (1983) found that the break force was sometimes absent in the aggregate crushing process, particularly for the weak soil aggregates for which the force will directly crush aggregates without initial break force. To overcome this issue, Hagen et al. (1995) developed a vertical soil crushing-energy meter (VSCEM) that did not require an initial break force. They found that DAS measured with VSCEM agreed closely with measurements from the SACEM. The SACEM and VSCEM have become the standard instruments used to measure soil DAS for wind erosion applications (Zobeck et al., 2003), the VSCEM is appropriate to measure the weak soil aggregates. However, as both the SACEM and VSCEM were developed several decades ago, and purpose built for measuring soil DAS, neither enable data visualization, are portable, or accessible at low cost and are very time consuming to use.

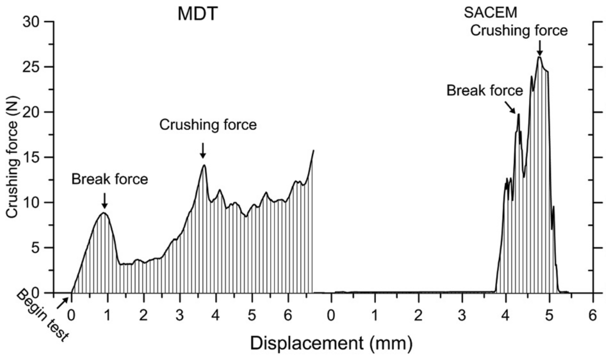

Fig. 1. Typical force (N) versus displacement (mm) curves during crushing of Shano silt loam aggregates at Othello, WA by the MDT and SACEM.

To address this issue, Pi et al. (2018) tested the application of a commercial penetrometer (Mohr Digi-Test, MDT), Mohr and Associates, Inc. Richland, WA) to determine soil DAS. However, they did not compare DAS measured by the MDT to the SACEM or VSCEM. The MDT was developed for the fruit industry in testing firmness and quality of fruit. The sensitivity and commercial availability of the instrument provides an opportunity for soil scientists and aeolian researchers to more broadly characterize the stability of soil aggregates. Few studies have been undertaken to compare DAS instrument performance. The objective of this paper is to compare the performance of DAS instruments that have been used in scientific research and commerce. These instruments include the SACEM and MDT monitor. This information will provide scientists with an understanding of inherent differences in the performance of DAS instruments used in the laboratory and especially in measuring DAS from different soil types and land management practices (crop rotation, soil amendments, and tillage) that influence soil erodibility dynamics and dust emission.

2. Materials and methods

Soil aggregates used to compare the SACEM and MDT in determining DAS were collected from crop rotation, fertilizer, green manure, and tillage treatments at various sites across the inland Pacific Northwest (iPNW) (Fig. 2). Table 1 shows the characteristics of the sites used to assess DAS measurements across soil types under different management practices. The sand contents of soils in this study ranged from 30% to 56%, while the clay contents ranged from 9% to 14%

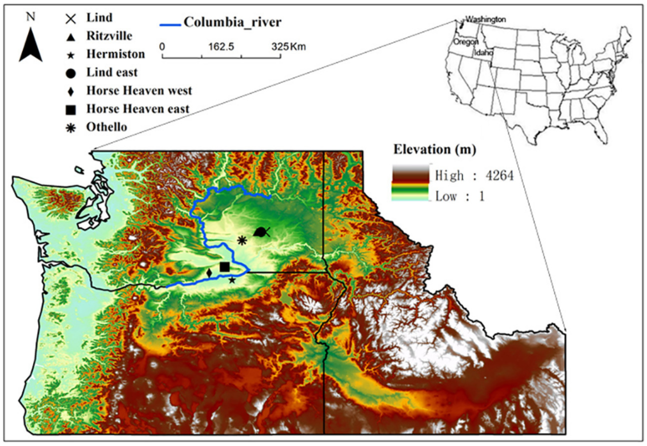

Fig. 2. Location of sites where soil was collected to assess dry aggregate stability in the inland Pacific Northwest.

Table 1
Aggregates were collected from various fertilizer, green manure, crop rotation, and tillage practices and used to compare the performance of MDT and SACEM in measuring DAS.

Characteristic	Management practices						
	Tillage		Crop rotation		Green manure		Fertilizer
Location	Horse Heaven east	Horse Heaven west	Lind	Ritzville	Hermiston	Othello	Lind east
Coordinates	46°08′N, 119°28′W	45°59′N, 119°51′W	47°00′N, 118°34′W	47°09′N, 118°28′W	45°49′N, 119°17′W	46°48′N, 119°02′W	47°0′N, 118°34′W
Annual precipitation (mm)	211	153	242	292	265	215	242
Elevation (m)	440	240	510	570	190	365	500
Primary tillage treatments[1]	UT, DT, NT	UT, DT, NT	UT	UT	rototilled and packed	rototilled and packed	UT, DT
Crop rotation[2]	WW-SF	WW-SF	WW-SF, WW-C-SF	WW-SF, WW-S-SF	SW-P	SB-P	WW-SF
Fertilizer	synthetic	Synthetic	synthetic	synthetic	green manure, no green manure	green manure, no green manure	synthetic, biosolids
Crop water source	rainfed	rainfed	rainfed	rainfed	irrigated	irrigated	rainfed
Soil type	Ritzville silt loam	Warden silt loam	Shano silt loam	Ritzville silt loam	Adkins very fine sandy loam	Shano silt loam	Shano silt loam
Mean particle size (μm)	46	59	31	26	68	43	31
Clay (%)	13	14	9	11	9	9	9
Silt (%)	54	50	56	59	35	51	56
Sand (%)	33	36	35	30	56	40	35
Organic matter (%)	0.9	0.6	1.0	1.0	0.7	0.8	0.7
Mean particle surface area[3] (m^2)	0.0066	0.0109	0.0031	0.0021	0.0145	0.0058	0.0030
Geometric mean aggregate diameter[4] (mm)	9.40	152.78	1.10	1.01	0.99	1.68	0.63
EF[5]	0.473	0.482	0.483	0.470	0.530	0.500	0.491
Data sources	Sharratt and Schillinger (2018)		Sharratt and Schillinger (2016)		Sharratt et al. (2018)		Pi et al. (2018)

[1] NT is no-tillage, DT is disk tillage, and UT is undercutter-tillage.

[2] WW-SF is winter wheat-summer fallow; WW-C-SF is winter wheat-camelina-summer fallow; WW-S-SF is winter wheat-safflower-summer fallow; SW-P is spring wheat-potato; and SB-P is spring barley-potato.

[3] Mean particle surface area estimated as surface area = $4\pi r^2$ where r is mean particle radius.

[4] Soil aggregate geometric mean diameter of the modified log-normal distribution.

[5] EF is soil erodible fraction in Revised Wind Erosion Equation (RWEQ) to assess soil erodibility.

(Table 1).

2.1. Tillage, crop rotation, green manure, and fertilizer treatments

Aggregate stability was assessed for three tillage treatments. Tillage treatments were imposed in two fields that had been managed in a during a WW-SF rotation using traditional summer fallow tillage practices in the Horse Heaven Hills of south central Washington at Lind, WA. The fields were located 20 km apart; one in the west Horse Heaven Hills and the other in the east Horse Heaven Hills. Tillage treatments included 1) Disk tillage (DT) is a traditional practice, in which plots were disked to a depth of 0.1 m in spring 2007, fertilized with an applicator shank in early summer, and then rodweeded to a depth of 0.1 m in June and July 2007; 2) Undercutter tillage (UT) was applied to plots that were "undercut" using overlapping 0.8-m wide V-blades to a depth of 0.1 m in spring 2007, and then rodweeded to a depth of 0.1 m in June and July 2007; and 3) No-tillage (NT) treatment, weeds were controlled using the herbicide beginning in spring 2007 and plots remained undisturbed throughout the whole fallow period.

Crop rotation treatments were established at Lind and Ritzville, WA and included winter wheat-summer fallow (WW-SF) rotation and winter wheat-camelina-summer fallow (WW-C-SF) rotations at Lind and WW-SF and winter wheat-safflower-summer fallow (WW-S-SF) rotations at Ritzville. These rotations were implemented every year since 2009 at the two sites.

Green manure treatments were established in a wheat-potato rotation at Hermiston, OR and in a barley-potato rotation at Othello, WA and included green manure and no green manure treatments. The treatments were established in 2011 at both sites. Mustard was sown after harvest of wheat or barley and then chopped and incorporated into the soil as green manure in late autumn 2011.

Fertilizer treatments were established in a WW-SF rotation at Lind, WA and included the use of synthetic and biosolid fertilizer. Class B biosolids, obtained from the King County Wastewater Treatment Division, Seattle, Washington, were applied to experimental plots in the spring prior to disk or undercutter tillage while synthetic fertilizer was either surface applied prior to disk tillage or injected during undercutter tillage. The amount of biosolids applied was estimated to meet the crop nutrient requirements, and were applied at a rate for two crop years. Pi et al. (2019) provide a detailed description of the tillage, crop rotation, green manure, and fertilizer treatments for which we assessed soil DAS.

2.2. SACEM

The SACEM (Boyd et al., 1983) uses a crushing vise with 6.35 mm (1/4 in) aluminium plates to measure the force and displacement (Fig. 3). The crushing vise allows for 18 revolutions along a drive shaft, with a total travel distance of 25.4 mm. Crushing force is measured using an SSM 100 load cell with a force capacity of 445 N (100 Ib). A Hewlett-Packard 7D-CDT1000 displacement transducer was used to measure the displacement of the crushing plate. The SACEM has been widely used in the measurement of soil DAS (Skidmore and Powers, 1982; Boyd et al., 1983; Skidmore and Layton, 1992; Layton et al., 1993). The SACEM is characterized by low sensitivity (0.0001 N), no electronic screen, and heavy body (Table 2).

2.3. MDT

The MDT is a portable computer-controlled penetrometer which provides digital output, calculates statistics, and facilitates data tracking. The instrument allows data visualization and export of data to

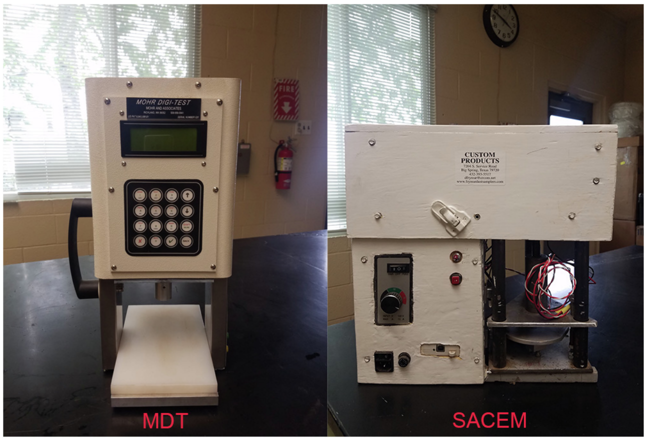

Fig. 3. Photograph of Mohr Digi-Test (MDT) and soil-aggregate crushing-energy meter (SACEM).

Table 2
The instrument parameters for the MDT and SACEM.

Parameters	MDT	SACEM
Force sensitivity (N)	0.00005	0.0001
Force range (N)	0–294	0–445
Displacement sensitivity (mm)	0.001	0.01
Displacement range (mm)	0–7.3	0–2.54
Probe velocity (mm/s)	0–100	0.8
Probe diameter (mm)	25	120
AC power (VAC)	110/220	110/220
Weight (kg)	4.5	16.7

Table 3
Dry aggregate stability (DAS), as measured by the MDT and SACEM, influenced by fertilizer, green manure, crop rotation, and tillage treatments across the inland Northwestern United States.

Management practice	Location	Sample time	Treatments[1]	MDT	SACEM
				(J kg^{-1})	
Tillage	Horse Heaven Hills east	April 2007	DT	3.47	–
			NT	5.81	–
			UT	4.06	–
		August 2007	DT	5.42a[2]	2.17bα[3]
			NT	10.93a	2.56bα
			UT	5.74a	2.42bα
	Horse Heaven Hills west	April 2007	DT	2.5a	0.99bα
			NT	5.35a	1.48bα
			UT	3.9a	1.26bα
		August 2007	DT	3.58a	1.87aα
			NT	6.73a	2.34bα
			UT	5.41a	2.11bα
Crop rotation	Lind	September 2011	WW-SF	3.53a	1.99aα
			WW-C-SF	3.52a	1.76aα
		August 2012	WW-SF	2.60a	3.84aα
			WW-C-SF	1.97a	3.10aα
	Ritzville	September 2011	WW-SF	4.50a	1.73bα
			WW-S-SF	2.91a	1.51aα
		September 2012	WW-SF	2.77a	2.92aα
			WW-S-SF	2.26a	2.53aα
Green manure	Hermiston	2012	Manure	2.36a	1.95aα
			No manure	2.33a	2.06aα
	Othello	2012	Manure	3.26a	1.98aα
			No manure	4.01a	3.03aα
Fertilizer	Lind east	2015	DT	4 a	1.77aα
			UT	4.04a	1.40bα
		2016	DT	1.14 a	1.09aα
			UT	3.22a	1.97aß
		2015	Synthetic	4.91a	1.54bα
			Biosolid	2.88a	1.56aα
		2016	Synthetic	1.64a	1.57aα
			Biosolid	2.72a	1.59aα

[1] NT is no-tillage, DT is disk tillage, UT is undercutter-tillage, WW-SF is winter wheat-summer fallow, WW-C-SF is WW-camelina-SF, and WW-S-SF is WW-safflower-SF.

[2] Treatment means followed by same English letter indicates no significant difference between dry aggregate stability measured by MDT and SACEM at $P \leq 0.05$.

[3] Means followed by same Greek letter within a column for the same sample time and location are not significantly different at $P \leq 0.05$.

a spreadsheet format (Fig. 3). The MDT has sophisticated control electronics that measure trajectory of displacement, velocity, and acceleration from which the force is measured by a test plunger. The MDT has standard plunger probes with diameters of 4.7, 8, and 11 mm. The displacement and load cell sensitivity of the penetrometer are respectively 0.001 mm and 5 mg (1×10^5 Ibs) (Table 2). The MDT uses a constant rate of displacement.

2.4. Measurement of aggregate strength using the SACEM and MDT monitor

Soil aggregate samples were collected using a flat-bladed shovel from the upper 30 mm of the soil profile at three random locations in four replicated treatment plots in spring, summer, or autumn at the field sites. Soil aggregate samples were transported to a greenhouse to air-dry prior to processing through a rotary sieve equipped with 0.42, 0.84, 2.0, 6.4, and 19.2 mm openings (Chepil, 1962). The size distribution of aggregates used in the study was reported by Sharratt and Schillinger (2018) for the tillage treatments, Sharratt and Schillinger (2016) for the crop rotation treatments, Sharratt et al. (2018) for the green manure amendment treatments, and Pi et al. (2018) for the fertilizer treatments. Aggregates were gently hand sieved to obtain aggregates 12.7–19.0 mm in diameter to determine aggregate stability, which was the diameter recommended for DAS measurement by Hagen et al. (1995). The sieved aggregates were stored at 25 °C until processed for stability measurement in Spring 2018. The sieved aggregates then were randomly divided into two groups, with one group processed using the SACEM and the other group processed using the MDT.

Soil DAS was determined by the crushing energy imparted to the sieved aggregates and the mass of the aggregates being crushed. The crushing energy is the integral of the product of the force on the aggregate and the displacement of the crushing probe. The crushing probe of the MDT is a cylindrical aluminum plate with a diameter of 2.5 cm, while the crushing probe of SACEM is an aluminium disk with diameter of 12 cm. After measuring the mass of an aggregate, the force on the sample and the displacement of the crushing plate were measured using the SACEM and MDT monitor during the crushing process. At least five replications of each treatment were processed for assessing DAS.

2.5. Statistical analyses

One-way analysis variance (ANOVA) was used to examine the effect of crop rotation, fertilizer, green manure amendment, or tillage treatments on aggregate stability. Normality tests were conducted prior to the ANOVA tests. Regression analysis, Nash–Sutcliffe model efficiency coefficient (NSE), root-mean-square error (RMSE), and model performance index of agreement (d) were used to compare the DAS measured by SACEM and MDT monitor in this study. The NSE (Nash and Sutcliffe, 1970) was defined as:

$$\mathrm{NSE} = 1.0 - \left[\frac{\sum_{i=1}^{N}(Pi - Oi)^2}{\sum_{i=1}^{N}(Oi - \bar{O})^2}\right] \tag{3}$$

with NSE ranging from $-\infty$ to 1. The closer the NSE value was to 1, the closer of the DAS measured by both monitors. The RMSE (Ma et al., 2012) was defined as:

Table 4
Regression of dry aggregate stability (DAS)[1], as measured by the MDT and SACEM, versus selected intrinsic soil properties from experimental sites in the iPNW.

Intrinsic soil property	MDT				SACEM			
	Regression model[2] and Coefficients				Regression model and Coefficients			
	a	b	c	R^2	a	b	c	R^2
Geometric mean aggregate diameter, mm	2.7826	0.3586	−0.0023	0.93	2.1346	0.0353	−0.0003	0.31
Particle surface area, $m^2\,g^{-1}$	0.6376	1069.9	−63616	0.75	2.09	51.443	−4739	0.12
Clay content	−1.997	0.6086	−0.0068	0.65	−0.22	51.96	−274.47	0.37
EF[3]	41.309	− 126.96	102.57	0.19	17.401	−58.412	55.56	0.02

[1] DAS used in the regression analysis were the average values of each soil type.
[2] Regression model: $DAS = a + bX + cX^2$, where X is value of the soil property
[3] EF is soil erodible factor in Revised Wind Erosion Equation (RWEQ) to assess soil erodibility.

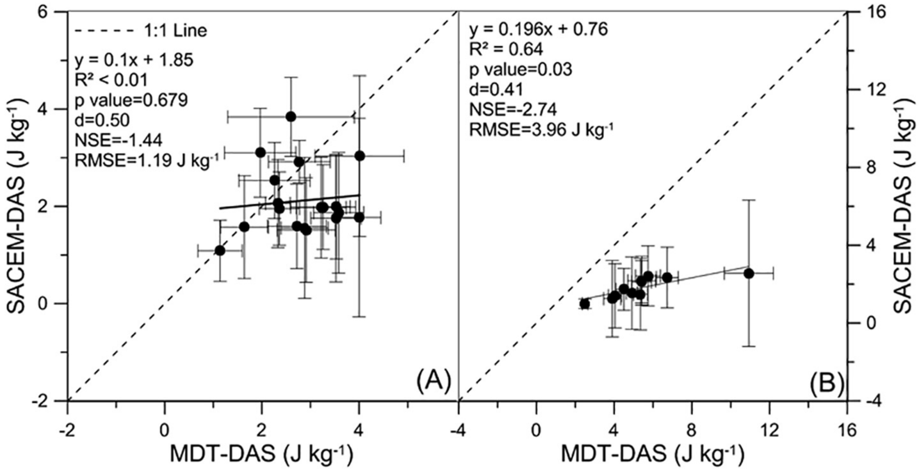

Fig. 4. Relationship between dry aggregate stability measured by MDT and SACEM across various treatments at the seven sites in this study. Illustrated is the relationship for 18 of the 29 cases, which no significant differences of DAS measured by both instruments according to ANOVA (A) and for 11 of the 29 cases, which significant differences of DAS measured by both instruments according to ANOVA (B). Vertical and horizontal bars are the standard deviation in measured DAS.

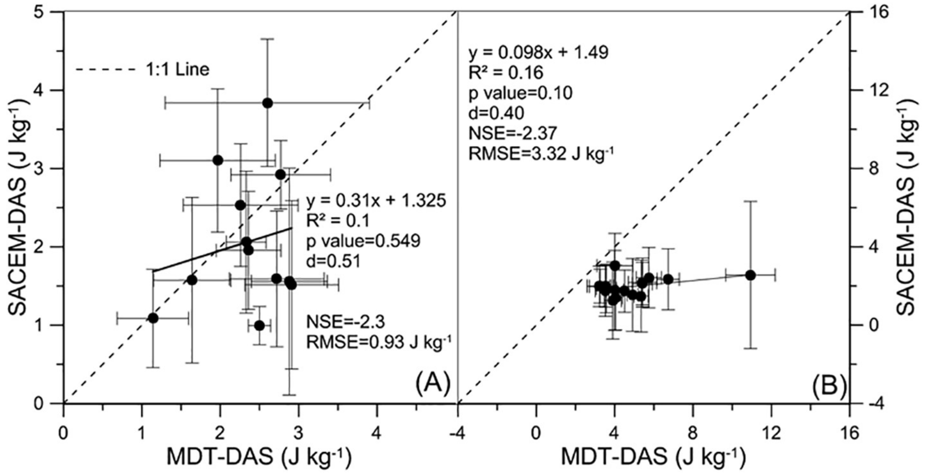

Fig. 5. Relationship between dry aggregate stability measured by MDT and SACEM across various treatments at the seven sites in this study. Illustrated is the relationship for minor DAS ($DAS < 3\,J\,kg^{-1}$) (A) and major DAS ($DAS > 3\,J\,kg^{-1}$) (B). Vertical and horizontal bars are the standard deviation in measured DAS.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Pi - Oi)^2}{N}} \tag{4}$$

The model performance index of agreement, d was determined according to:

$$d = 1.0 - \left[\frac{\sum_{i=1}^{N}(Pi - Oi)^2}{\sum_{i=1}^{N}(|Pi - \bar{O}| + |Oi - \bar{O}|)^2}\right] \tag{5}$$

with d ranging from 0 to 1.0 (Willmott, 1981) and where Pi was the DAS value measured by MDT monitor, Oi was the DAS value measured by SACEM monitor, N was the number of comparisons, and $\bar{O}$ was the average value measured by SACEM monitor. Higher values of d indicate the closer of the DAS measured by both monitors.

3. Results and discussion

3.1. Effect of crop rotation, fertilizer, green manure, and tillage treatments on soil DAS

Significant differences in DAS, as measured by the MDT (hereafter MDT-DAS), were found between tillage treatments at all the sites (Table 3). DAS was 24 to 114% higher for no-tillage summer fallow

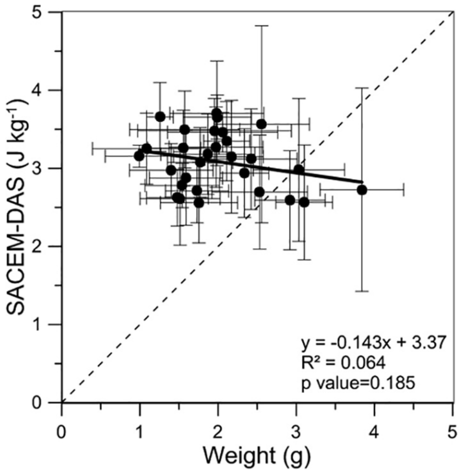

Fig. 6. Relationship between dry aggregate stability measured by SACEM and weight across various treatments at the seven sites in this study. Vertical and horizontal bars are the standard deviation in measured DAS and weight.

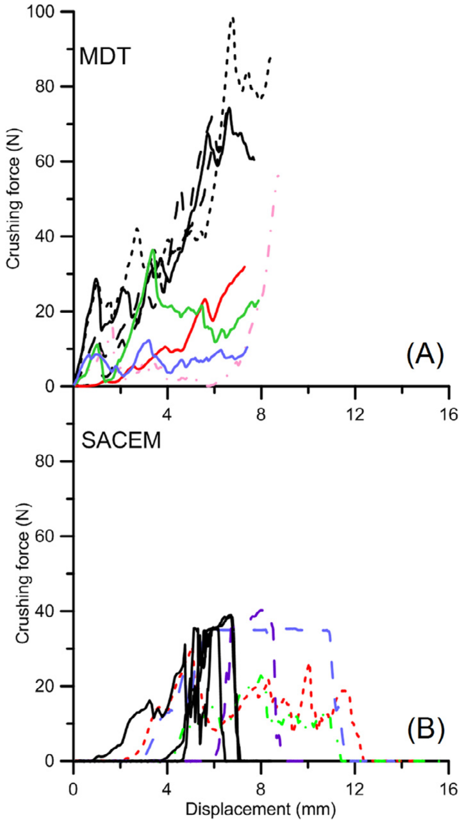

Fig. 7. Force (N) versus displacement (mm) curves during crushing of Palouse silt loam aggregates by MDT and SACEM.

than tillage-based summer fallow treatments. In contrast, significant differences in DAS, as measured by the SACEM (hereafter SACEM-DAS), were only found between DT and UT tillage treatments at the Lind east site in 2016. No significant differences in DAS were found between crop rotations at the two sites in central Washington, or between fertilizer treatments for both instruments.

SACEM failed to measure any significant differences in DAS among crop rotation, fertilizer, green manure, and tillage treatments except DT and UT tillage treatments at Lind east in 2016. Nonetheless, the SACEM-DAS appeared consistently higher for NT summer fallow (2.13 ± 0.23 J kg^{-1}; mean ± standard deviation) than tillage-based summer fallow treatments (1.71 ± 0.23 J kg^{-1}). SACEM-DAS for the WW-SF rotation (2.62 ± 0.42 J kg^{-1}) was consistently higher than WW-C-SF or WW-S-SF rotations (2.23 ± 0.32 J kg^{-1}). SACEM-DAS for the no green manure treatment (2.55 ± 0.24 J kg^{-1}) was higher than the green manure treatments at Othello, WA (1.97 ± 0.01 J kg^{-1}). We found SACEM-DAS were higher for NT summer fallow, WW-SF rotations and no green manure treatments compared with other treatments, which were in accord with those measured by the MDT (Pi et al., 2019).

Soil type greatly affects DAS directly through inherent soil properties, such as the geometric mean diameter of primary particles, mean particle surface area, water content at −1500 J kg^{-1} matric potential, and clay content, sand and silt fraction (Skidmore and Layton, 1992). Our regression of mean DAS, as measured by both instruments, to geometric mean aggregate diameter, mean particle surface area, and clay content are shown in Table 4. DAS, as measured by the both instruments, were more strongly correlated with aggregate clay content compared with other soil properties. This result is consistent with previous studies; for example, Skidmore and Layton (1992) found regression of DAS as a function of clay content had the highest coefficient of determination ($R^2 = 0.97$) of tested soil properties. The coefficients of determination of regression between DAS and soil properties and in our study were generally lower than those reported by Skidmore and Layton (1992) for both the MDT and SACEM. Nonetheless, Skidmore and Layton (1992) only considered soil property effects and did not address the influence of extrinsic factors. Our results suggest that, in addition to intrinsic soil properties, extrinsic factors such as fertilizer, green manure, crop rotation, and tillage treatments, and the interactions among them, can significantly influence DAS.

3.2. DAS comparison between MDT and SACEM

We found no significant differences in DAS measured by the MDT and SACEM for 18 of the 29 cases examined in this study according to ANOVA (Table 3). For these 18 cases, regression analysis between DAS measured by the MDT and SACEM ($y = 0.1x + 1.85$, $R^2 < 0.01$) with $p > 0.1$ indicated that both SACEM-DAS and MDT-DAS are not statistically significant (10% level). These points distributed two sides of 1:1 line suggested no consistent positive and negative difference between SACEM-DAS and MDT-DAS (Fig. 4-A). However, relatively small RMSE (1.19 J kg^{-1}) and difference of mean (0.69 J kg^{-1}), p value = 0.679 (ANOVA), and d value of 0.5 suggested the DAS measured by MDT were close to those of the SACEM in the 18 cases. Feng and Sharratt (2009) reported that d value of 0.5 is acceptable condition in evaluating the difference between measurement and simulation. We found significant differences in DAS between MDT-DAS and SACEM-DAS for 11 of the 29 cases (table 3). For these 11 cases, relatively big RMSE = 3.96 J kg^{-1} and a positive difference of mean (3.59 J kg^{-1}), p value = 0.03 (ANOVA), and d value of 0.41 suggested that the SACEM under-estimated or MDT over-estimated DAS. Regression analysis between DAS measured by the MDT and SACEM ($y = 0.196x + 0.76$, $R^2 = 0.64$) with $p < 0.1$ indicated that both SACEM-DAS and MDT-DAS are statistically significant (10% level), which further suggested the SACEM under-estimated or MDT over-estimated DAS by 73 to 252% of the range in measured DAS (Fig. 4-B). In addition DAS measured by the MDT ranged from 1.14 to 10.93 J kg^{-1}, while DAS measured by the SACEM had a smaller range from 1.09 to 3.84 J kg^{-1}. Dry aggregate stability measured by the SACEM was therefore much narrower in range that DAS measured by the MDT. This suggests that the MDT had a higher sensitivity than the SACEM for measuring DAS in this study. We presume that the SACEM under-estimated DAS of strong aggregates (MDT-DAS > 3 J kg^{-1}) based upon the low d value of 0.4, big RMSE (3.32 J kg^{-1}) (Fig. 5-B) and all the points distributed down sides of 1:1 lines (Fig. 5-B). Regression analysis between MDT-DAS and SACEM-DAS ($y = 0.098\times + 1.49$, $R^2 = 0.16$) and p value = 0.1 suggested SACEM under-estimated or MDT over-estimated DAS by 78 to 326%. In contrast, for weaker aggregates with DAS of < 3 J kg^{-1}, these points

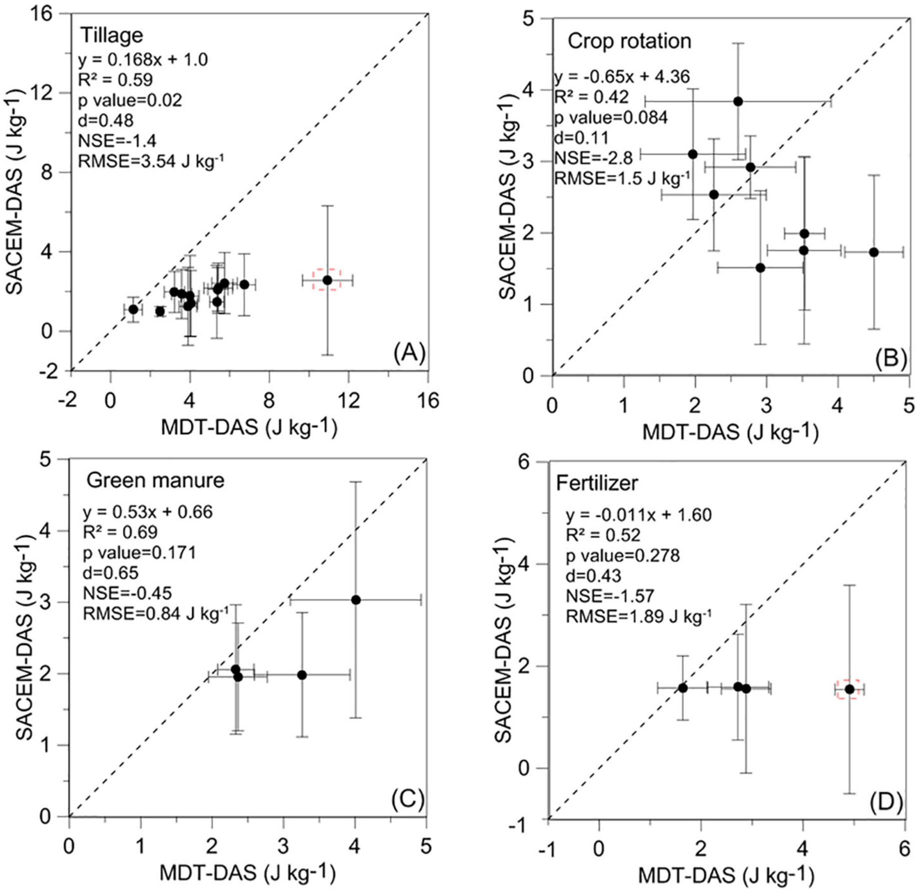

Fig. 8. Relationship between dry aggregate stability measured by MDT and SACEM for fertilizer, green manure, crop rotation, and tillage treatments.

distributed two sides of 1:1 lines suggested no consistent positive and negative difference between SACEM-DAS and MDT-DAS (Fig. 5-A). However, relatively small RMSE (0.93 J kg^{-1}), p value = 0.549 (ANOVA), and d value of 0.51 suggested the DAS measured by MDT were close to those of the SACEM. This is not surprising because the MDT has a more sensitive probe than the SACEM irrespective of force or displacement (Table 2).

During measurement, the MDT crushing probe will come down and touch the test object, then retract. Alternatively, the SACEM crushing system is composed by two 6.35 mm (thick) aluminum plates with diameter of 12 cm. The upper plate, as the crushing probe of SACEM, will come down, touch and crush the test aggregate sample, which has been already placed on the lower plate. The lower plate supported by an Interface SSM100 load cell, which used to read the force from the crushing aggregate (Boyd et al., 1983). The upper aluminum plate is not able to retract automatically but will continue to crush an aggregate until stopped by an operator. The instrument specifications for the MDT and SACEM are shown in Table 2. Force sensitivity (numerical precision) are respectively 0.00005 and 0.0001 N for the MDT and SACEM and the mean displacement was about 10 mm in this study. Therefore, differences in sensitivity will result in a standard deviation of 0.0005 and 0.001 J kg^{-1} for respectively MDT and SACEM. In addition, the MDT emphasizes the importance of penetrating because the area of the plunger probe was smaller than the test object in most cases. However, the SACEM emphasizes the importance of crushing as the area of the crushing plate was greater than the test object in most cases. The difference between the area of the plunger or crushing plate and frontal area of an aggregate may be one factor that influences DAS.

The aggregates used in the study ranged from 12.7 to 19.0 mm in diameter. Aggregate weights depended on aggregate size for aggregates with the same density. We found no evidence that DAS was related to aggregate size (weight) on the basis of the low coefficient of regression ($y = -0.399\times + 4.99$, $R^2 = 0.02$, p value = 0.46) for aggregates with diameter 12.7–19.0 mm (Fig. 6). Although we found no influence of aggregate size (weight) on DAS, both instruments measured significant DAS variation (indicated by the standard deviations of DAS for both instruments in Figs. 5 and 8). Fig. 7 is an example of DAS variation based on the typical force (N) versus displacement (mm) during crushing of Palouse silt loam aggregates. Fig. 7-A show the Palouse silt loam DAS measured by the MDT varied during 10 replications of the measurement. Fig. 7-B show the DAS measured by the SACEM varied during 10 replications of the measurement.

Amézketa (1999) reported that measured DAS may have large variability, even within a soil sample site. Potential reasons for variations in DAS may include environmental conditions to which aggregates were exposed within the surface soil profile, the characteristics of individual samples (aggregates) subjected to a test, the time of shaking the sample during sieving (Amézketa, 1999), We hypothesize that the large variability in DAS in our results is due to the aggregate shape or surface area and its relative placement on the crushing plate. During measurement, we observed round, rectangular, cylindrical or rhomboidal aggregates may be found to have different DAS depending on the angle at which the instrument crushing points contact an aggregate during the crushing process. Furthermore, soil aggregates are not solid, but are pore-filled. The pore size, distribution, and orientation inside soil aggregates combined with the relative placement of aggregates on the crushing plate are likely to have directly impacted the initial break force. Aggregate break forces are likely to be larger or smaller depending on pore orientation when forces were applied top-down.

DAS measured by both instruments appeared to be similar for the green manure treatment based on $d > 0.6$ and $R^2 > 0.5$, NSE = 0.63, and small RMSE (0.84 J kg^{-1}) (Fig. 8-C), whereas greater differences between instruments were found in crop rotation treatments based on $d = 0.11$ and $R^2 < 0.5$, $NSE = -1.4$, and big RMSE ($3.6\,J\,kg^{-1}$) (Fig. 8-B). Similarly, greater differences between instruments were found in tillage and fertilizer treatments based on the low d value, and big RMSE (Fig. 8-A and D). This greater differences partly due to the SACEM under-estimated or MDT over-estimated strong aggregates. DAS measured by both instruments appeared to be similar for the tillage and fertilizer treatments treatments based on d value = 0.5, and small RMSE (2.77 and $1.0\,J\,kg^{-1}$) when a single strong aggregates (was circled by rectangle dash line in Fig. 8-A and D) was removed. The maximum DAS, measured by the MDT, occurred for a Ritzville silt loam under NT fallow in HHH, while the maximum DAS, measured by SACEM, occurred for a Shano silt loam under a WW-SF crop rotation at Lind. This suggested strong aggregates potentially resulted in the greater differences between instruments. The greater differences between instruments in measuring strong DAS may be further due to the greater standard deviation of DAS. Fig. 5-B show the bars of standard deviation were close to or across the 1:1 lines (represents the SACEM-DAS = MDT-DAS) for most strong aggregates. This indicated SACEM-DAS was potentially close to the MDT-DAS for these strong aggregates.

Fast and universal method in measuring DAS will beneficial to the model comparing and calibration. Both MDT and SACEM provide a universal measuring methods that produce a quantitative and force-based measure of DAS. The tested instruments provide generally comparable measurements and so the MDT could useful for evaluating soil DAS to better parameterize wind erosion and dust models.

4. Conclusions

A horizontal-plate crushing meter (SACEM) historically used to measure soil DAS was compared with a commercial penetrometer (MDT) on aggregates collected from various crop rotations, soil amendments, and tillage systems across the iPNW. No significant difference in DAS was measured between the MDT and SACEM for most of the cases. However, there was evidence that SACEM under-estimated or MDT over-estimated DAS of strong aggregates ($DAS > 3\,J\,kg^{-1}$). In general, DAS measured by the MDT was consistent with that measured with the SACEM. For example, both instruments measured higher DAS for no-tillage compared with tillage-based summer fallow, WW-SF compared with oilseed rotations, and no green manure versus green manure treatments. The MDT can be used instead of the SACEM for measuring DAS. A future objective is to capture the range of uncertainty in random aggregate shape in influencing DAS.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the project “Regional Approaches to Climate Change for Pacific Northwest Agriculture,” funded through award #2011-68002-30191 from the USDA-National Institute for Food and Agriculture and Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20030102).

References

Amézketa, E., 1999. Soil aggregate stability: a review. J. Sustainable Agric. 14, 83–151. https://doi.org/10.1300/J064v14n02_08.

Boyd, D.W., Skidmore, E.L., Thompson, J.G., 1983. A soil-aggregate crushing-energy meter 1. Soil Sci. Soc. Am. J. 47, 313–316. https://doi.org/10.2136/sssaj1983.03615995004700020028x.

Chepil, W.S., 1953. Field structure of cultivated soils with special reference to erodibility by wind. Soil Science Society Proceedings 185, 190.

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

Colazo, J.C., Buschiazzo, D.E., 2010. Soil dry aggregate stability and wind erodible fraction in a semiarid environment of Argentina. Geoderma 159, 228–236. https://doi.org/10.1016/j.geoderma.2010.07.016.

Farrell, D.A., Greacen, E.L., Larson, W.E., 1967. The effect of water content on axial strain in a loam soil under tension and compression 1. Soil Sci. Soc. Am. J. 31 (4), 445–450.

Feng, G., Sharratt, B., 2009. Evaluation of the SWEEP model during high winds on the Columbia Plateau. Earth Surf. Proc. Land. 34, 1461–1468.

Hagen, L.J., Schroeder, B., Skidmore, E.L., 1995. A vertical soil crushing-energy meter. Trans. ASAE 38, 711–715. https://doi.org/10.13031/2013.27884.

Hagen, L.J., 1997. Wind erosion prediction system: erosion submodel. In: Skidmore, E.L., Tatarko, J., (Eds.), Wind Erosion – Proceedings of an International Symposium/Workshop, 3–5 June 1997, Manhattan, Kansas. USDA-Agricultural Research Service, Wind Erosion Research Unit and Kansas State University. https://infosys.ars.usda.gov/WindErosion/symposium/abstracts/hagen.htm > .

Hevia, G.G., Mendez, M., Buschiazzo, D.E., 2007. Tillage affects soil aggregation parameters linked with wind erosion. Geoderma 140, 90–96. https://doi.org/10.1016/j.geoderma.2007.03.001.

Kok, J.F., Mahowald, N.M., Fratini, G., et al., 2014. An improved dust emission model–Part 1: model description and comparison against measurements. Atmos. Chem. Phys. 14 (23), 13023–13041.

Kok, J.F., Parteli, E.J., Michaels, T.I., Karam, D.B., 2012. The physics of wind-blown sand and dust. Rep. Prog. Phys. 75 (10), 106901.

Layton, J.B., Skidmore, E.L., Thompson, C.A., 1993. Winter-associated changes in dry-soil aggregation as influenced by management. Soil Sci. Soc. Am. J. 57, 1568–1572. https://doi.org/10.2136/sssaj1993.03615995005700060029x.

Ma, L., Ahuja, L.R., Nolan, B.T., Malone, R.W., Trout, T.J., Qi, Z., 2012. Root Zone Water Quality Model (RZWQM2): Model Use, Calibration, and Validation. Trans. ASABE 55, 1425–1446. https://doi.org/10.13031/2013.42252.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I-a discussion of principles. J. Hydrol. 10, 282–290 https://doi.org/10.1016/0022-1694(70)90255-6.

Pi, H., Huggins, D., Sharratt, B., 2019. Dry aggregate stability influenced by soil type, crop rotation, soil amendment, and tillage in the Columbia Plateau. Aeolian Res. 40, 65–73. https://doi.org/10.1016/j.aeolia.2019.07.001.

Pi, H., Sharratt, B., Schillinger, W.F., Bary, A.I., Cogger, C.G., 2018. Wind erosion potential of a winter wheat–summer fallow rotation after land application of biosolids. Aeolian Res. 32, 53–59. https://doi.org/10.1016/j.aeolia.2018.01.009.

Shao, Y., 2004. Simplification of a dust emission scheme and comparison with data. J. Geophys. Res.: Atmos. 109 (D10).

Shao, Y., 2008. Physics and Modelling of Wind Erosion. Springer Science & Business Media.

Sharratt, B., Schillinger, W.F., 2018. Soil properties influenced by summer fallow management in the Horse Heaven Hills of south central Washington. J. Soil Water Conserv. 73, 452–460. https://doi.org/10.2489/jswc.73.4.452.

Sharratt, B., Schillinger, W.F., 2016. Soil characteristics and wind erosion potential of wheat–oilseed–fallow cropping systems. Soil Sci. Soc. Am. J. 80, 704–710. https://doi.org/10.2136/sssaj2015.12.0427.

Sharratt, B.S., McGuire, A., Horneck, D., 2018. Early-season wind erosion influenced by soil-incorporated green manure in the pacific northwest. Soil Sci. Soc. Am. J. 82, 678–684. https://doi.org/10.2136/sssaj2018.01.0018.

Shao, Y., Wyrwoll, K.-H., Chappell, A., Huang, J., Lin, Z., McTainsh, G.H., Mikami, M., Tanaka, T.Y., Wang, X., Yoon, S., 2011. Dust cycle: An emerging core theme in Earth system science. Aeolian Res. 2, 181–204. https://doi.org/10.1016/j.aeolia.2011.02.001.

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. https://doi.org/10.2136/sssaj1992.03615995005600020034x.

Skidmore, E.L., Powers, D.H., 1982. Dry soil-aggregate stability: energy-based index 1. Soil Sci. Soc. Am. J. 46, 1274–1279. https://doi.org/10.2136/sssaj1982.03615995004600060031x.

Tatarko J., Wagner L.E., Boyce C.A., 2001. Effects of Overwinter Processes on Stability of Dry Soil Aggregates, in: Soil Erosion. Presented at the Soil Erosion, American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/2013.4576.

Toogood, J.A., 1978. Relation of aggregate stability to properties of Alberta soils. In: Emerson, W.W., Bond, R.D., Dexter, A.R. (Eds.), Modification of Soil Structure.Wiley, Chichester, UK, pp. 211–215.

Webb, N.P., Strong, C.L., 2011. Soil erodibility dynamics and its representation for wind erosion and dust emission models. Aeolian Res. 3, 165–179. https://doi.org/10.1016/j.aeolia.2011.03.002.

Willmott, C.J., 1981. On the validation of models. Phys. Geogr. 2, 184–194. https://doi.org/10.1080/02723646.1981.10642213.

Zobeck, T.M., Popham, T.W., 1990. Dry aggregate size distribution of sandy soils as influenced by tillage and precipitation. Soil Sci. Soc. Am. J. 54, 198–204. https://doi.org/10.2136/sssaj1990.03615995005400010031x.

Zobeck, T.M., Sterk, G., Funk, R., Rajot, J.L., Stout, J.E., Pelt, R.S.V., 2003. Measurement and data analysis methods for field-scale wind erosion studies and model validation. Earth Surf. Proc. Land. 28, 1163–1188. https://doi.org/10.1002/esp.1033.