Soil wind erosion influenced by clay amendment in the inland Pacific Northwest, USA

huawei Pi[1], David Huggins[2], and Brenton Sharratt[2]

[1]Washington State University
[2]USDA-ARS

May 5, 2020

Abstract

Soil clay content is one of the primary intrinsic soil properties affecting soil erodibility, but few studies have tested the effects of clay amendment on soil wind erosion. The objective of this study was therefore to evaluate the effect of progressive clay amendment on soil wind erosion in the inland Pacific Northwest (iPNW), where there is a high soil erodibility risk due to the arid and semi-arid environment. Clay amendment significantly increased crust crushing energy when physical soil crusts formed after simulated rainfall. Crusts were then subject to simulated tillage to create an erodible soil surface before determining wind erosion in a wind tunnel. Soil loss significantly decreased with increasing clay amendment, even for low clay amendments (2%). In addition, the rate of change in erosion decreased with increasing amounts of clay amendment. Clay amendment was more effective in decreasing soil loss for two sandy loams or soil types with lower clay content. Clay amendment decreased soil loss primarily due to its impact on increasing aggregate geometric mean diameter (GMD), but aggregate crushing energy is also important in decreasing soil loss in terms of decreasing abrasion flux. Clay amendment is thus an effective way to restrain land deterioration in terms of increasing crust crushing energy, aggregate GMD, and decreasing abrasion flux.

Introduction

Wind erosion is a serious problem in arid and semiarid regions where soil is loose and dry and not well protected by vegetation cover. Wind erosion is a process involving the detachment, transport, and deposition of soil particles by wind. Wind erosion not only causes soil loss from the soil surface, but also land degeneration or desertification. Land degradation may result from removing fertile top soil, namely, the clays and organic matter, and leaving the infertile and coarse soil. In addition, fine suspended particulates due to wind erosion is always a concern for air quality for cities located in or around arid and semiarid regions (Sharratt and Lauer, 2006; Chen et al., 2017). Moreover, severe and sustained wind erosion events have resulted in regional dust storms, which threatened aircraft, road transportation, and health of humans and animals (Hudson and Cary, 1999; Nel, 2005).

The inland Pacific Northwest region (iPNW) of the Unites States is surrounded by a series of tall Mountains, which intercept the flow of moist and relatively mild air from the Pacific Ocean, thus resulting in a semi-arid environment. The PM10 concentration caused by wind erosion events has exceeded National Ambient Air Quality Standard (NAAQS) several times per year at Kennewick, WA (Sharratt and Lauer, 2006). An estimated 98 Mg ha^{-1} soil and 2.7 Mg ha^{-1} PM10 are eroded each year from the agro-ecological classes of the iPNW (Pi et al., 2019a).

Wind erosion is influenced by a series of plant, soil and wind parameters. For example, plants reduce wind erosion as a result of directly intercepting saltating particle. Soil crusts also reduce wind erosion by binding soil particles together into a cohesive structure, thereby minimizing the availability of loose particles susceptible to transport by wind. Wind speed determines the energy imparted to soil particles and thus the transport capacity of wind erosion. Some wind erosion parameters are nearly static and change very slowly through time. For example, intrinsic soil properties such as clay and organic matter content change slowly with time. In contrast, some wind erosion parameters change very rapidly in response to management or weather. Aggregate and crust properties can be altered by tillage or rainfall events thus are called temporal or external soil properties (Zobeck, 1991a). Temporal soil properties appear to be relevant in controlling daily soil wind erosion whereas intrinsic soil properties largely control long-term soil wind erosion, the latter of which is called soil wind erosion potential (Zobeck, 1991a). Intrinsic or temporal soil properties do not simultaneously influence wind erosion because intrinsic soil properties more or less influence the temporal soil properties. For instance, soil clay content is one of the primary intrinsic soil properties affecting wind erodibility, but it rarely influences wind erosion other than through its impact on crust or aggregate crushing energy (Zobeck, 1991a). Temporal soil properties influencing wind erosion include random roughness, soil water content, as well as aggregate and crust properties (USDA, 2016).

Soil crusting is one of the most important factors influencing wind erosion. Crust crushing energy is highly dependent on clay and organic matter content which are the cohesive forces acting on particles. Crust crushing energy influences wind erosion in terms of its impact on controlling the amount of flaking (Gillette et al., 1982) and abrading (Hagen et al., 1992), Flaking and abrading contribute to the particle load which can be transported by wind, especially for weak crusts with lower crust crushing energy. In addition, crust crushing energy influence wind erosion through its impact on controlling threshold friction velocity (u_{*t}) . Gillette et al. (2001) indicated that hard crusts with greater crust crushing energy tended to show almost no change in u_{*t} with time whereas weak crusts with lower crust crushing energy resulted in a rapid decrease in u_{*t} with time.

Tillage is the primary factor influencing crust degradation on agricultural lands. Other crust properties influencing wind erosion include crust type (Belnap, 2003), crust hardness (Gillette et al., 2001), crust micro-topography (Gillette et al., 2001), crust thickness (Sharratt and Vaddella., 2014), progressive development of a crust cover (Pi and Sharratt, 2019), and loose material on the crust surface.

Aggregation is another essential factor influencing soil wind erosion. The Agricultural Policy /Environmental eXtender (APEX) model considers the aggregate size distribution (ASD) as the sole factor determining soil erodibility (Williams et al., 2015). Aggregate size distribution can influence soil wind erosion because ASD influences (1) the amount of available creep (0.84 to 2.0 mm), saltation (0.10 to 0.84 mm), suspension (<0.1 mm), and PM10 (<0.01 mm) components (USDA, 2016); (2) aggregate stability (Hevia et al., 2007); (3) threshold friction velocity (Gillette et al., 1980); (4) source of abrasion (Mirzamostafa et al., 1998); (5) random roughness (USDA, 2016); (6) the amount of nonerodible components transported by wind (> 2 mm) (Zobeck, 1991b). Kheirabadi et al. (2018) examined the effect of soil bed length, wind velocity and ASD on sediment flux. They found finer aggregates (D_{2mm}) at the surface are more susceptible to transport by wind while soil containing coarser aggregates exhibited less sediment flux. Mirzamostafa et al. (1998) examined the effect of soil aggregate and texture on suspension emission. They found suspension emission was directly related to soil texture (r^2= 0.87), whereas abraded emission was directly related to clay content (r^2= 0.69). Other aggregate properties influencing wind erosion include aggregate density and stability and minimum and maximum aggregate sizes (USDA, 2016).

The impact of random roughness in controlling wind erosion has been studied by Zobeck and Onstad (1987), Hagen and Armbrust (1992), and Gillette et al. (2001). They found wind erosion increased logarithmically with random roughness. Random roughness is associate with soil surface microrelief which can impact surface aerodynamic roughness and shear stress (Shao, 2008; Okin, 2008). Surface microrelief is greatly influenced by maximum aggregate size and crust rough (Zobeck, 1991a).

Soil clay content is a primary soil component due to its various influences for soil ecological processes. Soil clay amendment can impact soil ecosystems as a result of modifying enzyme activity (Abd-elgwad, 2019), hydraulic conductivity (Frenkel et al., 1978), soil-water retention curves (Gupta and Larson, 1979), soil moisture distribution and water use efficiency (Ismail and Ozawa, 2007; Mi et al., 2017), evaporation (Zayani et al., 1996), soil fertility (Mi et al., 2017), and crop yield (Mojid et al., 2012). Although Diouf et al. (1990) reported soil clay amendment impacted wind erosion as a result of influencing aggregate stability, little information is available that documents the effect of clay amendment on other soil properties such soil wind erosion.

We are not aware of any studies that have measured the change in wind erosion of clay-amended soils, which is a primary soil component that binds individual particles together resulting in changes to aggregate and crust properties. Therefore, the objective of this study was to: (1) identify the impact of clay amendment (Wyoming bentonite) on wind erosion from disturbed crusts of four major loessial soils in the inland Pacific Northwest, USA; (2) test the effect of clay amendment on crust crushing energy; and (3) evaluate the effect of clay amendment on surface characteristics affecting wind erosion such as random roughness, aggregate crushing energy, and ASD.

Methods and Materials

Soil loss influenced by clay amendment was assessed for four soil series commonly found across the inland Pacific Northwest (iPNW) of the northwestern United States (Figure 1). The soil of the iPNW developed from eolian deposition of loess eroded from Rocky Mountain outwash deposits, as well as the loess and volcanic deposits (Chandler et al., 2004; Zobeck et al., 2011). The four soils were obtained from four locations in Washington State. Two silt loam soils (Athena silt loam, Walla Walla silt loam) were collected from a humid continental climate area which receives an average annual precipitation > 499 mm. The two sandy loam (Warden sandy loam, and Farrell sandy loam) were collected from a semi-arid area which receives an average annual precipitation < 341 mm. Soil texture is the primary soil property affecting wind erodibility (Zobeck, 1991a). Both sandy loams have larger sand content resulting in higher erodibility than the silt loam soils, nonetheless the latter is characterized by greater PM10 emission potential (Table 1). All sites were in a winter wheat (*Triticum aestivum*)-summer fallow rotation (WW-SF) except the Colfax, WA site which was in a winter wheat-safflower-summer fallow rotation. Lands in fallow are typically at greater risk for wind erosion due to limited vegetative cover, little surface roughness, and poor aggregation. More details of the soils used in this study are given in the Table 1.

Samples of the four soil types were collected from the upper profile (30 mm) at the field sites during the fallow phase of a WW-SF or WW-SW-SF rotation or after sowing in late spring. Warden sandy loam and both silt loams were previously used to assess wind erodibility characteristics in the region (Sharratt and Vaddella, 2012; 2014), Sharratt et al. (2013), and Pi and Sharratt (2019).

Crust cover preparation

After soil samples were obtained from the field, they were transported to a laboratory located at the Palouse Conservation Field Station (PCFS), Washington State University, Pullman, WA. The samples were processed to remove plant residue by hand. Samples were then placed in a

greenhouse to dry for a few weeks; dry soil samples were then sieved using a 2 mm screen to remove large non-erodible materials.

Dry crust or aggregate stability increases with the clay content or organic matter within certain limits (Skidmore and Layton, 1992). In this study, we added Wyoming bentonite clay to the four soil series. Wyoming bentonite clay is an industrial product from Wyoming where 70 percent of the world's known deposits are located and exploited for industrial clay for more than 125 years. Wyoming bentonite clay has been added to Tivoli sand from Kansas to reduce wind erosion erodibility and found to be several times more effective than kaolinite in reducing wind erosion (Diouf et al., 1990). Wyoming bentonite clay was mixed into our four soils to achieve 2, 4, 8%, and 16% higher clay content compared with the soil without the clay amendment. Mixing of the clay into the soil was accomplished by hand after which the mixed soil was placed in trays. The trays (0.015 m deep, 0.2 m wide, and 1.0 m long) were filled with the mixed soil layer-by-layer until overfilled. The irregular surface was then leveled with a metallic screed to create a flat and uniform surface. This method of filling trays resulted in a bulk density of about 1.1 kg m^{-3}. A backpack sprayer was used to wet the soil surface of each tray. Approximately 1 L of water was applied to the surface to create a uniform 10-mm thick crust. The sprayer was equipped with a nozzle 1 cm in diameter to evenly spray water. The nozzle applied 0.5-mm diameter water drops which is representative of the largest natural raindrops in the region (McCool et al., 2009). After applying water drops to the soil surface of each tray, the tray was placed in an oven and dried at 60°C for >24 h to achieve a 10-mm thick complete crust cover. The presence of a soil surface crust is typically disturbed by tillage on agricultural lands (Usón and Poch, 2000). In our study, we created a soil tillage simulator to mimic tillage in the field. A tandem disk plough with blades spaced 25 cm apart is typically used for tillage of fallow lands in the iPNW. The blades are typically inserted into the soil to a depth of 10 cm. The tillage simulator was created based on a tillage depth to spacing ratio of 1:3 in the field. The tillage simulator was made by uniformly spacing nails along a board which was mounted on a frame above the soil tray. As the nails were manually pulled through the soil at a depth of 1 cm in the tray, ridges were created that were 0.8 cm high at 3 cm spacing. The tillage simulator maintained consistent disturbance for the soil surface. The orientation of tillage was parallel to the long axis of the trays or wind direction. Hagen and Armbrust (1992) demonstrated that ridge orientation and wind direction affected soil erosion. In our experiment, tillage was performed with our simulator to avoid any overlap. Four replications of each treatment were prepared for assessing soil loss using the wind tunnel.

Wind Tunnel Assessment

After simulated tillage, the soil trays were kept in an oven until we could assess wind erosion. The trays were then transported to a portable wind tunnel which was located inside a non-regulated climate building. The tunnel was powered by a 33-kW engine and had a working section of 7.3 m long, 1.0 m wide, and 1.2 m tall. A complete description of the design and aerodynamic characteristics of the wind tunnel are given by Pietersma et al. (1996).

Wind speed above the experimental trays during the wind tunnel test was measured using Pitot tubes, which were attached to differential pressure transmitters (616W-5 102280-45 differential pressure transmitter, Dwyer Instruments, Michigan City, IN). The inlets (1 cm in diameter) of pitot tubes were mounted at heights of 0.005, 0.01, 0.02, 0.04, 0.06, and 0.10 m above the soil surface immediately downwind of the soil tray inside the tunnel. Data of pressure transmitters were recorded every 1 s by a data logger. Relative humidity, atmospheric pressure, and air temperature were also monitored near the entrance of the wind tunnel to ensure that experiments were run under consistent atmospheric conditions. A Sensit (Model H11-LIN, Sensit Company, Portland, North Dakota) was used to measure saltation activity at a height of 5 cm downwind of the tray.

Horizontal soil loss was measured over two separate. The first sampling period of each test represented limited saltation conditions (no abrader was added to the air stream) while the second period of the test represented with copious saltation conditions. During the second sampling period, abrader (sand 250-500 µm in diameter) was fed into the air steam at the leading edge of the working section of the tunnel; The abrader flux inside the tunnel was maintained at 0.5 g m^{-1} s^{-1} which typifies the flux of soil during high winds across the iPNW (Sharratt et al., 2010). During the first sampling period of each test, freestream wind speed was systematically increased inside the tunnel from 2 to 7.5 m s^{-1} at a rate of 0.6 m s^{-1} every 15 s. Freestream wind velocity was then abruptly increased to 12 m s^{-1} and remained at that wind speed for 180 s so as to enhance soil loss. During the second sampling period, freestream wind velocity was maintained at 12 m s^{-1} for 180 s to generate soil loss with abrader. Horizontal soil loss was measured using a modified Bagnold type slot sampler (Stetler et al., 1997) which trapped sediment in saltation and suspension to a height of 0.75 m (0.225 cm wide) above the soil surface. A collector, made in-house, was attached to the leeside of the tray to trap particulates creeping along the soil surface. After a completed wind tunnel test, the floor and pitot tubes were cleaned to eliminate the influence of residual dust on the next observation prior to placement of the new experimental soil tray.

Aggregate size distribution in the upper 10 mm of the soil profile was determined on 500g soil samples collected from the tray after each test. After the representative samples were air-dried in a green house, samples were processed through a compact rotary sieve (Chepil,1962) equipped with sieves having 0.045, 0.09, 0.42, 0.85, 2.0, 6.3, and 12.0 mm openings. Aggregates, ranging from 12.7–19.0mm size in diameter, were used to determine the aggregate crushing energy (Hagen et al., 1992). Aggregates crushing energy was determined by the mass of the aggregate being crushed and crushing energy imparted to the aggregate, which recently has been measured by a commercial penetrometer (Mohr Digi-Test, hereafter MDT, Mohr and Associates, Inc. Richland, WA) (Pi et al., 2020a). The energy imparted to the aggregate was determined by the force applied to the aggregate and displacement of the force. The energy or work (W with unit of J) can be described as:

$W = \int_a^b F(x)$ (1)

where *F (x)* is the force imparted to the aggregate and x(m) is the distance over which the force was imparted to the aggregate (displacement) from point a to b. The force imparted to the aggregate was distinguished as initial break force and final force. The force being applied to the crust at the time of fracturing is called the initial break force while the force being applied to crush the crust is called the final force or crushing force (Skidmore and Layton, 1992). However, the final force is often difficult to detect, especially for some weak aggregates (Pi et al., 2019b). The force at 1.5 times the initial break force has been empirically used to estimate final force (Hagen et al.,1995). The typical initial break force and final force as a function of displacement is illustrated in Figure 2, which shows the typical force (N) versus displacement (mm) curves during crushing of aggregates with 4% and 8% clay amendment for four soil types. The average aggregate crushing energy of each treatment was determined for a minimum of 10 aggregates. Crust stability and aggregate stability are equal according to Hagen et al. (1992), because both are controlled by the magnitude of cohesive forces between soil particles (Amézketa,1999; Saleh, 1993).

Soil surface water content and random roughness are key factors that influences soil loss and were assumed to vary across treatments. Both parameters were measured after each wind tunnel test. Soil water content was calculated by the reduction in weight of a soil sample after drying. A portable pin-type profile meter (Allmaras et al., 1966) was used to measure the random roughness. The meter was comprised of a rigid frame with 1 m long and 40 pins that moved vertically through holes in the frame. Forty surface elevations were measured during each test. Random roughness was thus determined based on the standard deviation of height elevations after adjust for surface slope (Zobeck, 2001).

Statistical analysis

A one-way ANOVA was used to examine the effect of clay amendment on soil loss using commercial software (SPSS Statistics 20.0; the SPSS Inc., Chicago, IL). Normality tests were conducted prior to the ANOVA tests. Regression analysis was used to examine the relationship among clay amendment, crust crushing energy, random roughness**,** aggregate GMD and crushing energy, and soil loss.

Results and discussion

Intrinsic soil properties impact wind erosion within limits, but indirectly impact erosion by influencing temporal or external soil properties. We hypothesized that clay amendment would influence wind erosion within limits for a dry and loose soil surface. However, clay amendment may considerably affect crust crushing energy when generating natural physical crusts. After an erodible soil surface is created by tilling a crusted surface using a tillage simulator, erosion may be influenced by temporal wind erosion factors such as random roughness, aggregate GMD as well as aggregate crushing energy and density. A flow diagram of the wind tunnel study in evaluating the effect of progressive clay amendment on soil wind erosion in the inland Pacific Northwest is shown in Figure 3.

Impact of clay on wind erosion for a dry and loose soil surface

We did not measure soil loss for the dry mixed soil in the absence of a soil crust because we hypothesized that clay amendment impacts wind erosion within limits for a dry and loose soil surface. This can be verified by wind erosion models. We used the Revised Wind Erosion Equation (RWEQ) model to quantify the impact of clay amendment for a dry and loose soil surface. RWEQ estimates soil loss influenced by clay content in terms of soil erodible factor (EF):

$Q_R = EF * Qs$ (2)

$$\mathrm{EF} = \frac{29.09+0.31sa+0.17si+\frac{0.33sa}{\mathrm{cl}}-2.59OM-0.95CaCO}{100} \quad (3)$$

where *sa, si, cl, OM* , and *CaCO* are respectively the percentage of sand, silt, clay, organic material and $CaCO_3$ in the soil, $\frac{\mathrm{sa}}{\mathrm{cl}}$ is the sand to clay ratio (range =1.2 to 53) (Fryrear et al., 1998). Where Q_R is the soil loss in the presence of clay amendments, whereas Q_S is the soil loss for the original soil. Soil losses simulated by RWEQ as a function of clay amendment for the four soil types are shown in the Figure 4. However, regression analysis between clay amendment and soil loss indicated that both clay amendment and soil loss are not statistically related ($p<0.1$). Simulated soil loss decreased with the increasing clay amendment. RWEQ simulated soil loss was reduced by 36%, 37%, 47% and 71% for Athena, Walla Walla, Warden, and Farrell soil in the presence of 16% clay amendment. Nonetheless, the rate of change in wind erosion was far less than those caused by clay amendment within the disturbed crust surface through crust and aggregate properties (discussed in section 3.4 and 3.5). The results indicated clay amendment impacts wind erosion within limits for the dry and loose soil surface.

Impact of clay on crust crushing energy

Significant differences in crust crushing energy were found between 0 and 2% clay amendment treatments for the four soil series according to ANOVA (Table 2). However, no statistical significant differences in crust crushing energy were found between 2 and 4% clay amendment treatments for two silt loams and between 4 and 8% and 8 and 16% clay amendment treatments for the four soil series except Athena silt loam. This suggests that the effectiveness in increasing crust crushing energy diminished with progressive increase in clay amendment.

The relationship between clay amendment and crust crushing energy for the four soil types examined in this study is illustrated in Figure 5a. The relationship between clay amendment and crust crushing energy appeared to be nearly a binomial function for all soil types. This binomial trend was consistent with previous studies for a variety of soil types (e.g., Diouf et al., 1990; Hagen, 1995; Pi et al., 2019b). Clay particles play an important function in cementing sand grains together which then can cause considerable change in crust strength. Crust crushing energy increased with increasing clay content. However, Skidmore and Layton (1992) reported crust crushing energy steadily increased with the increasing clay content until clay content reached 33%. In this study, the clay content for all the soil types was much less than 33%, thus we did not find a decrease in crust crushing energy with increasing clay amendment.

Regression analysis revealed similar trends with ANOVA in that the rate of change in crust crushing energy diminished with progressive increase in clay amendment. Crust crushing energy increased by 226, 357, 306 and 7473% for Athena, Walla Walla, Warden and Farrell when clay amendment increased from 0 to 2%. Nonetheless, crust crushing energy increased by only 69, 41, 218 and 144 % for the four soil types when clay amendment increased from 2 to 4%.

The rate of change in crust crushing energy with progressive increase in clay amendment varied among soil types based on regression coefficients. The relationships between clay amendment and rate of change in crust crushing energy for the four soil types examined in this study is illustrated in Figure 5b. The relationship appeared to be nearly a linear function for all soil types. The higher regression coefficients suggest the rate of change in crust crushing energy with progressive increase in clay amendment was higher for Farrell sandy loam than Warden sandy loam, followed by Athena silt loam, and Walla Walla silt loam. Clay amendment was more effective in increasing crust crushing energy for Farrell sandy loam than other soil types. Actually, clay amendment was more effective in increasing crust crushing energy for two sandy loams than two silt loams. For example, crust crushing energy increased by 30 and 17 fold for Athena silt loam and Walla Walla silt loam and by 32 and 229 fold for Warden sandy loam and Farrell sandy loam in the presence of 16% clay amendment. This was expected because of lower clay content for sandy loam than silt loam.

Impact of clay on soil erodibility through crust crushing energy

Clay was used to amend the original four soils in terms of increasing crust crushing energy. After an erodible soil surface is created by tilling a crusted surface, soil loss can influence temporal wind erosion factors such as random roughness, aggregate GMD as well as aggregate crushing energy and density within the erodible soil surface environment.

No statistical relationships were found between crust crushing energy and soil water content, random roughness, and aggregate density for the four soil types according to the p-value (>0.1) (Figure 6) except the aggregate geometric mean diameter (GMD) and crushing energy. Crust crushing energy appeared to increase logarithmically with GMD for all soil types (Figure 7a). As the disruptive force is imparted to a crust surface by tillage, the crust fractures into aggregates. Crusts with low stability may fracture into smaller sizes due to their limited cohesive forces. Aggregate size distributions are highly correlated with aggregate stability, which is also called aggregate crushing energy (Kemper and Rosenau, 1986). Colazo and Buschiazzo (2010) and Hevia et al. (2007) used aggregate size distributions to determine aggregate stability. Aggregate stability increased with aggregate size for aggregates > 0.84 mm. In this study, we assumed that crust crushing energy was equal to aggregate crushing energy because both are controlled by the magnitude of cohesive forces between soil particles (Amézketa,1999, Saleh, 1993; USDA, 2016). This therefore is not surprising that aggregate GMD increased with increasing crust crushing energy as well as aggregate crushing energy. These results indicated that crust crushing energy also was an important factor affecting ASD for a disturbed crust surface. As clay amendment increased, the crust surface was more difficult to disturb even though the crust could be broken into greater aggregate sizes. However, as the crust crushing energy exceeds a certain value, the crust will not break down into aggregate but rather into clods (often called secondary aggregates, Zobeck, 1991a) due to their considerable cohesive forces. Not only does tillage practices affect dry ASD (Hevia et al., 2007), but aggregate crushing energy also appears to impact ASD.

Gillette et al. (2001) found crust hardness correlated with rough crusts, the latter of which may influence microrelief. Large aggregates associated with high crushing energy may be more prone to result in high random roughness. However, we found no statistical relationships between crust crushing energy and random roughness in this study (Table 2). This was not surprising because random roughness usually associates with tillage intensity (Hagen, 1991), rainfall amount and kinetic energy, and runoff (Zobeck and Onstad, 1987). These parameters was assumed not to change due to the application of standard tillage and rainfall simulator. Similarly, no consistent increase or decrease in soil water content was found with increasing crust crushing energy. In addition, soil water content varied little and was much less than the wilting point water content, thus water content and random roughness were expected to have little effect on soil loss in this study.

Impact of aggregate GMD on soil loss

Only aggregate GMD and crushing energy appeared to increase with increasing crust crushing energy for the four soil types. The relationship between aggregate GMD and soil loss for the four soil types examined in this study is illustrated in Figure 7b. Soil loss appeared to decrease linearly with increasing aggregate GMD. Actually, soil loss is directly related to the amount of aggregates >0.84 mm in diameter, which are considered nonerodible aggregates (Zobeck et al., 2011). However, the impact of aggregate GMD on soil loss varied among soil types based on regression coefficients and ANOVA. We found that the impact of aggregate GMD on soil loss was higher for Farrell sandy loam and Warden sandy loam than Walla Walla silt loam and Athena silt loam based on the regression coefficients (Figure 7b).

Aggregate size distribution not only determines the amount of wind erosion due to the amount of erodible size aggregates present on the soil surface, but also impacts other key wind erosion factors such as the threshold friction velocity, PM10 or suspension potential (Zobeck,1991b). The impact of aggregate crushing energy on wind erosion will be discussed in section 3.6.

Impact of clay on wind erosion for an erodible soil crust surface

In this study, we found the crust crushing energy increased binomially with increasing clay amendment (Figure 5a). These results are consistent with previous studies (e.g., Diouf et al., 1990; Hagen, 1995; Pi et al., 2019b). However, the rate of change in crust crushing energy decreased linearly with increasing clay amendment (Figure 5b). The rate of change in crust crushing energy was higher for the two sandy loams than two silt loams. In addition, soil loss significantly decreased with the increasing aggregate GMD. Soil loss was higher for the two sandy loams than two silt loams. Both trends appeared consistent and indicated that decreased soil loss was directly associated with increasing clay amendment, crust crushing energy and aggregate GMD.

Significant differences in soil loss were found between 0 and 2% clay amendment treatments for Warden sandy loam and Farrell sandy loam according to ANOVA (Table 3). The relationship between clay amendment and soil loss is illustrated in Figure 8. Regression analysis revealed similar trends with ANOVA. The relationship between clay amendment and soil loss appeared to be nearly an exponential function for all soil types. Clay particles are important in cementing sand grains together and thereby changing crust strength and soil loss. In fact, we found soil loss decreased with the increasing clay content for the erodible soil crust surface. This trend was consistent with previous studies for a variety of soil types where soil loss was inversely related to clay content (e.g., Zobeck, 1991b; Hagen et al., 1992; Pi et al., 2020b). No statistical differences in soil loss were found with increasing clay amendment for Athena silt loam and Walla Walla silt loam until clay amendment reached 16 and 8% respectively. No significant differences in soil loss were found between 8% and 16% clay amendment for all the soil types except for the Athena silt loam. Regression analysis also suggested that the rate of change in erosion decreased with increasing amounts of clay amendment. For example, soil loss decreased by 3.33, 4.31, 6.32, and 94.1 g m^{-2} for Athena silt loam, Walla Walla silt loam, Warden sandy loam and Farrell sandy loam when amended clay content increased from 0 to 2%. Nonetheless, soil loss decreased by only 1.66, 1.75, 2.86 and 3.17 g m^{-2} for the four respective soil types when amended clay content increased from 14 to 16%. Soil loss was thus sensitive to the low clay amendment treatment; this trend was consistent with the effect of clay amendment on crust crushing energy.

Our results indicate that clay amendment protects the soil surface from erosion for the soil types used in this study, at least until the clay amendment exceeded a certain value in which case the protective effect of clay amendment may have reached a peak. For example, strong crust due to greater clay amendment may be more prone to break down into greater aggregate or cloud when undergoing a disruptive tillage, the former of which may be very hard to be eroded. However, we assume soil loss will not decrease to zero because loose and small soil particles are present along the vertical cracks caused by tillage.

Based on the coefficients of linear regression (Figure 8), the effectiveness of clay amendments in decreasing soil loss varied among soil types. The higher regression coefficients suggest the rate of change in soil loss with progressive increase in clay amendment was higher for Farrell sandy loam than Warden sandy loam, followed by Athena silt loam, and Walla Walla silt loam. For example, soil loss decreased by 56 and 66% for Athena silt loam and Walla Walla silt loam and by 82 and 99% for Warden sandy loam and Warden sandy loam in the presence of 16% clay amendment. This was expected because of greater wind soil erodibility and lower clay content for two sandy loams than two silt loams. Clay therefore appeared to influence soil wind erosion with greater sand content in this study. In fact, amending sandy soil using clay has been considered a sustainable and economical reclamation strategy for enhancing plant productivity and soil water retention in previous studies (Zayani et al., 2006; Ismail and Ozawa, 2006).

The impact of clay amendment on soil loss may be primarily due to the changes in aggregate GMD. Aggregates influence soil loss primarily through the amount of available saltation and suspension components which directly causes variations in soil loss. Nonetheless, the flux of abrading particles from aggregates is an additional available source of saltation and suspension. Aggregates with lower crushing energy can result in considerable flux of abrading particles (Hagen, 1991). Mirzamostafa et al. (1998) investigated fraction of the flux of abrading particles in suspension as influenced by clay content for four Kansas soils. They found abrasion flux decreased with clay content ranging from 0 to 17%. In this study, we assumed that aggregate crushing energy and aggregate GMD similarly impacted soil loss. Crust crushing energy has been considered to equal aggregate crushing energy according to the Single-event Wind Erosion Evaluation Program (SWEEP) user guide (USDA, 2016).

Impact of aggregate crushing energy on soil loss through abrasion flux

Soil wind erosion degrades aggregates as a result of abrading (Hagen et al., 1991). Abrasion influences particles potentially available for emissions and aides in the initiation of erosion. In the Jornada Desert of New Mexico, Webb et al. (2016) found that horizontal mass flux was controlled by the supply and abrasion efficiency of saltators.

The abrasion of aggregates is determined by aggregate crushing energy (Hagen et al., 1993). Weak aggregates can be eroded rapidly, especially by wind which carries suspended or blowing soil particles (Zobeck, 1991a), whereas strong aggregates are more resistant to erosion. We found soil loss was sensitive to clay amendment when aggregate crushing energy was low. Indeed, weak aggregates with low aggregate crushing energy may have greater abrading potential. With an increase in clay amendment, the abrading potential decreased until sufficient aggregate strength was achieved to resist an further abrasion. Hagen et al. (1993) found aggregate crushing energy determined aggregate abrasion coefficients and thus abrasion flux. In this study, we used the SWEEP to simulate abrasion flux in order to interpret the effect of clay amendment on aggregate crushing energy. The SWEEP wind erosion submodel was described in detail by USDA (2016) and simulates abrasion flux following:

$Q_{abrasion}=\sum_{i=1}^{m} Q*F_{ani}*C_{ani}$ *(4)*

where $Q_{abrasion}$ is simulated vertical abrasion flux (g m^{-2}); Q is saltation discharge (g m^{-2}), which was caused by wind speed at 12 m s^{-1} for 180 s within abrader environment (Table 3).F_{ani}, C_{ani} are respectively the fraction of saltation abrading surface with ith abrasion coefficient, and abrasion coefficient of ith surface (1/m). Hagen et al. (1993) recommended using a single target surface in wind tunnel tests. TheF_{ani} was calculated as:

$F_{ani}=[1-4B_f-2SV_{roc}(1-Bf)]*[1-(1-(\frac{SF_{84}-SF_{10}}{SF_{200}-SF_{10}}))\,e^{(\frac{-SFA_{12}}{20})}]$ *(5)*

where B_f is biomass fraction of flat cover,SV_{roc} is soil volume with rock (m^{-3} m^{-3}),SF_{10},SF_{84},$SF_{200}$are the aggregate fraction less than 0.1, 0.84, and 2 mm,SFA_{12} is soil surface fraction with shelter angles greater than 12 degrees. B_f , $SV_{roc,}$ and SFA_{12} are consistent zero for all the treatments. The C_{ani} was calculated as:

$C_{ani}= e^{(-2.07-0.077X^{2.5}+Ln(x))}$

(6)

where X is Ln [crushing energy (J kg^{-1})] with lower limit 0.1.

The abrasion coefficient of aggregates and vertical abrasion flux simulated by SWEEP as a function of aggregate crushing energy for the four soil types are shown in Figure 9a and b. Both relationships appeared to be nearly logarithmic. However, a linear function provided a good fit to the data. The abrasion coefficient of aggregates and vertical abrasion flux decreased with increasing aggregate crushing energy. This trend was consistent with previous studies for a range of crushing energies (e.g., Hagen et al,1993; Zobeck, 1991b). Nonetheless, different regression coefficients suggest that the rate of change in abrasion coefficient and abrasion flux with an increase in crushing energy varied among soil types. The rate of change in simulated abrasion coefficients and abrasion fluxes with crushing energy was higher for the two sandy loams than two silt loams. These effects were consistent with measured soil loss.

The abrasion coefficient of aggregates and vertical abrasion flux simulated by SWEEP as a function of clay amendment for the four soil types are shown in Figure 10a and b. Both relationships appeared to be statistically significant except the relationship between vertical abrasion flux and clay amendment for Farrell sandy loam (Figure 10b). The SWEEP simulated abrasion flux for the four soil types was reduced at least 29% relative to a surface devoid of clay amendment.

Conclusions

Soil clay content is one of the primary intrinsic soil properties affecting wind erodibility. We found clay amendment significantly impacted crust crushing energy. Crust crushing energy increased with increasing clay amendment (over a range of 0 to 16%) for types found across iPNW. Soil loss from a disturbed crust surface significantly decreased with increasing clay amendment. This can be primarily due to the change in aggregate GMD, followed by aggregate crushing energy, the latter of which influence vertical abrasion flux. Vertical abrasion flux significantly decreased with increasing clay amendment and aggregate crushing energy. Clay amendment was more effective in decreasing vertical abrasion flux for two sandy loams than two silt loams. The rate of change in vertical abrasion flux was more sensitive for soil types with weak crusts. The change in vertical abrasion flux appears to the same pattern with the change of soil loss caused by clay amendment. Vertical abrasion flux from erodible aggregates is the important source of soil loss for soil surface in the presence of weak aggregates.

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.

Conflict of Interest Statement

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

References:

Allmaras RR, Burwell RE, , Larson WE, , Holt RF, 1966. Total porosity and random roughness of the inter-row zone as influenced by tillage. US Department of Agriculture Conservation Research Report 7 U. S. Department of Agriculture, Washington, D. C.

Abd-elgwad shebl. 2019. Effect of Microbial Inoculation and Bentonite Amendments on Growth, Enzyme activity and Yield of cowpea cultivated in sandy soil. *Environment, Biodiversity and Soil Security* **3** : 71–80. DOI: 10.21608/jenvbs.2019.9954.1055

Amézketa E. 1999. Soil Aggregate Stability: A Review. *Journal of Sustainable Agriculture* **14** : 83–151. DOI: 10.1300/J064v14n02_08

Belnap J. 2003. The world at your feet: desert biological soil crusts. *Frontiers in Ecology and the Environment* **1** : 181–189. DOI: 10.1890/1540-9295(2003)001[0181:TWAYFD]2.0.CO;2

Chandler D G, Saxton K E, Busacca A J. 2004. Predicting Wind Erodibility of Loessial Soils in the Pacific Northwest by Particle Sizing. *Arid Land Research and Management* **19** : 13–27. DOI: 10.1080/15324980590887074

Chepil WS. 1962. A Compact Rotary Sieve and the Importance of Dry Sieving in Physical Soil Analysis 1. *Soil Science Society of America Journal* **26** : 4–6. DOI: 10.2136/sssaj1962.03615995002600010002x

Chen L, Zhao H, Wang W, Bai Z, Wang Z, Sun F, Hou L, Liu G, Shi M, Miao Y. 2017. Effect of windblown dust from local and regional sources on the air quality of the central district in Jinan, China. *Atmospheric Research* **185** : 44–52. DOI: 10.1016/j.atmosres.2016.10.026

Colazo, J. C., & Buschiazzo, D. E. 2010. Soil dry aggregate stability and wind erodible fraction in a semiarid environment of Argentina. *Geoderma,* **159** (1–2): 228–236. https://doi.org/10.1016/j.geoderma.2010.07.016

Diouf B, Skidmore EL, Layton JB, Hagen LJ. 1990. Stabilizing fine sand by adding clay: Laboratory wind tunnel study. *Soil Technology* **3** : 21–31. DOI: 10.1016/S0933-3630(05)80014-5

Frenkel H, Goertzen JO, Rhoades JD. 1978. Effects of Clay Type and Content, Exchangeable Sodium Percentage, and Electrolyte Concentration on Clay Dispersion and Soil Hydraulic Conductivity. Soil Science Society of America Journal **42** : 32–39. DOI: 10.2136/sssaj1978.03615995004200010008x

Gillette DA, Adams J, Endo A, Smith D, Kihl R. 1980. Threshold velocities for input of soil particles into the air by desert soils.*Journal of Geophysical Research* **85** : 5621. DOI: 10.1029/JC085iC10p05621

Gillette DA, Adams J, Muhs D, Kihl. R. 1982. Threshold friction velocities and rupture moduli for crusted desert soils for the input of soil particles into the air. *Journal of Geophysical Research: Oceans* **87** : 9003–9015. DOI: 10.1029/JC087iC11p09003

Gillette DA, Niemeyer TC, Helm PJ. 2001. Supply-limited horizontal sand drift at an ephemerally crusted, unvegetated saline playa. *Journal of Geophysical Research: Atmospheres* **106** : 18085–18098. DOI: 10.1029/2000JD900324

Gupta SC, Larson WE. 1979. Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. Water Resources Research **15** : 1633–1635. DOI: 10.1029/WR015i006p01633

Hagen LJ, Armbrust DV. 1992. Aerodynamic Roughness and Saltation Trapping Efficiency of Tillage Ridges. *Transactions of the ASAE***35** : 1179–1184. DOI: 10.13031/2013.28717

Hagen LJ, Skidmore EL, Saleh A. 1992. Wind Erosion: Prediction of Aggregate Abrasion Coefficients. *Transactions of the ASAE***35** : 1847–1850. DOI: 10.13031/2013.28805

Hagen LJ, Schroeder B, Skidmore EL. 1995. A Vertical Soil Crushing-energy Meter. *Transactions of the ASAE* **38** : 711–715. DOI: 10.13031/2013.27884

Hevia GG, Mendez M, Buschiazzo DE. 2007. Tillage affects soil aggregation parameters linked with wind erosion. *Geoderma***140** : 90–96. DOI: 10.1016/j.geoderma.2007.03.001

Hudson T, Cary A. 1999. Dust storm causes deadly pileup on I-84.

Tri-City Herald

Ismail SM, Ozawa K. 2007. Improvement of crop yield, soil moisture distribution and water use efficiency in sandy soils by clay application. *Applied Clay Science* **37** : 81–89. DOI: 10.1016/j.clay.2006.12.005

Kemper, W. D., & Rosenau, R. C. 1986. Aggregate Stability and Size Distribution. In In: Methods of Soil Analysis, Part 1. *Physical and Mineralogical Methods (2nd Edition).* (Vol. No. 9., pp. 425–442). Agronomy Monograph.

Kheirabadi H, Mahmoodabadi M, Jalali V, Naghavi H. 2018. Sediment flux, wind erosion and net erosion influenced by soil bed length, wind velocity and aggregate size distribution. *Geoderma* **323** : 22–30. DOI: 10.1016/j.geoderma.2018.02.042

McCool DK, Williams JD, Morse JR. 2009. Raindrop Characteristics in the Pacific Northwest. *Transactions of the ASAE* 19

Mirzamostafa N, Stone LR, Hagen LJ, Skidmore EL. 1998. Soil Aggregate and Texture Effects on Suspension Components from Wind Erosion.*Soil Science Society of America Journal* **62** : 1351. DOI: 10.2136/sssaj1998.03615995006200050030x

Mi J, Gregorich EG, Xu S, McLaughlin NB, Ma B, Liu J. 2017. Effect of bentonite amendment on soil hydraulic parameters and millet crop performance in a semi-arid region. *Field Crops Research***212** : 107–114. DOI: 10.1016/j.fcr.2017.07.009

Mojid MA, Wyseure GCL, Mustafa SMT. 2012. Water Use Efficiency and Productivity of Wheat as a Function of Clay Amendment.*Environmental Control in Biology* **50** : 347–362. DOI: 10.2525/ecb.50.347

Nel A. 2005. Air Pollution-Related Illness: Effects of Particles.*Science* **308** : 804–806. DOI: 10.1126/science.1108752

Okin G S. 2008. A new model of wind erosion in the presence of vegetation. *Journal of Geophysical Research: Earth Surface* , 113(F2).

Pi H, Huggins DR, Abatzoglou JT, Sharratt B. 2019a. Modeling soil wind erosion from agro-ecological classes of the Pacific Northwest in response to current climate. *Journal of Geophysical Research: Atmospheres* . DOI: 10.1029/2019JD031104

Pi H, Huggins DR, Sharratt B. 2019b. Dry aggregate stability of soils influenced by crop rotation, soil amendment, and tillage in the Columbia Plateau. *Aeolian Research* **40** : 65–73. DOI: 10.1016/j.aeolia.2019.07.001

Pi H, Sharratt B. 2019. Threshold Friction Velocity Influenced by the Crust Cover of Soils in the Columbia Plateau. *Soil Science Society of America Journal* **83** : 232. DOI: 10.2136/sssaj2018.06.0230

Pi H, Huggins DR, Webb NP, Sharratt B. 2020a. Comparison of soil-aggregate crushing-energy meters. *Aeolian Research***42** : 100559. DOI: 10.1016/j.aeolia.2019.100559

Pi H, Huggins DR, Webb NP, Sharratt B. 2020b. Influence of physical crust cover on the wind erodibility of soils in the inland Pacific Northwest, USA. *Geoderma* (under review).

Pietersma D, Stetler LD, Saxton KE. 1996. Design and aerodynamics of a portable wind tunnel for soil erosion and fugitive dust research.*Trans. ASAE* **39** : 2075–2083

Saleh A. 1993. Soil Aggregate and Crust Density Prediction. *Soil Science Society of America Journal* **57** : 524–526. DOI: 10.2136/sssaj1993.03615995005700020037x

Shao, Y. 2008. Physics and Modelling of Wind Erosion. *Springer Verlag,* 452p.

Sharratt BS, Lauer D. 2006. Particulate Matter Concentration and Air Quality Affected by Windblown Dust in the Columbia Plateau.*Journal of Environmental Quality* **35** : 2011–2016. DOI: 10.2134/jeq2006.0212

Sharratt BS, Vaddella V. 2014. Threshold friction velocity of crusted windblown soils in the Columbia Plateau. *Aeolian Research***15** : 227–234. DOI: 10.1016/j.aeolia.2014.08.002

Sharratt B, Wendling L, Feng G. 2010. Windblown dust affected by tillage intensity during summer fallow. *Aeolian Research* **2** : 129–134. DOI: 10.1016/j.aeolia.2010.03.003

Sharratt BS, Vaddella VK. 2012. Threshold friction velocity of soils within the Columbia Plateau. *Aeolian Research* **6** : 13–20. DOI: 10.1016/j.aeolia.2012.06.002

Sharratt BS, Vaddella VK, Feng G. 2013. Threshold friction velocity influenced by wetness of soils within the Columbia Plateau.*Aeolian Research* **9** : 175–182. DOI: 10.1016/j.aeolia.2013.01.002

Skidmore EL, Layton JB. 1992. Dry-Soil Aggregate Stability as Influenced by Selected Soil Properties. *Soil Science Society of America Journal* **56** : 557–561. DOI: 10.2136/sssaj1992.03615995005600020034x

Stetler L, Saxton KE, Horning L. 1997. Isokinetic sampling of eroded soil from a wind tunnel. *Transactions of the ASAE* 97–2031

USDA. 2016. WEPS 1.5 User Manual. USDA-ARS Agricultural Systems Research Unit Fort Collins, Colorado USA.

Usón A, Poch RM. 2000. Effects of tillage and management practices on soil crust morphology under a Mediterranean environment. *Soil and Tillage Research* **54** : 191–196. DOI: 10.1016/S0167-1987(99)00099-9

Webb, N. P., Galloza, M. S., Zobeck, T. M., & Herrick, J. E. 2016. Threshold wind velocity dynamics as a driver of aeolian sediment mass flux. *Aeolian Research* **20** : 45–58. https://doi.org/10.1016/j.aeolia.2015.11.006

Williams JR, Izaurralde RC, Williams C, Steglich EM. 2015. Theoretical Documentation.

Zayani K, Bousnina H, Mhiri A, Hartmann R, Cherif H. 1996. Evaporation in layered soils under different rates of clay amendment.*Agricultural Water Management* **30** : 143–154. DOI: 10.1016/0378-3774(95)01217-6

Zobeck TM. 1991a. Soil properties affecting wind erosion. *Journal of Soil and Water Conservation* **46** : 112–118

Zobeck, T. M. 1991b. Abrasion of Crusted Soils: Influence of Abrader Flux and Soil Properties. *Soil Science Society of America Journal***55** (4):1091–1097. https://doi.org/10.2136/sssaj1991.03615995005500040033x

Zobeck TM, Onstad CA. 1987. Tillage and rainfall effects on random roughness: A review. *Soil and Tillage Research* **9** : 1–20. DOI: 10.1016/0167-1987(87)90047-X

Zobeck TM, Popham TW. 2001. Cropping and tillage effects on soil roughness indexes. *Transactions of the ASAE* **44** : 1527–1536

Zobeck TM, Van Pelt RS, Hatfield JL, Sauer TJ. 2011. Wind Erosion.*ACSESS publications* . Soil Science Society of America. DOI: 10.2136/2011.soilmanagement.c14

Table 1. Characteristics of four soils used in this study.

Characteristic	Soil types	Soil types	Soil types	Soil types
	Athena silt loam	Walla Walla silt loam	Warden sandy loam	Farrell sandy loam
Location of field sites	Colfax, WA	Waitsburg,WA	Paterson, WA	Washtucna, WA
Coordinates	46°47'N, 117deg26'W	46°15'N, 118deg09'W	46°01'N, 119deg37'W	46°89'N, 118deg29'W
Annual precipitation (mm)	510	499	200	341
Annual average air temperature ()	9.0	12.3	12.1	9.9
Crop rotation[1]	WW-SW-SF	WW-SF	WW-SF	WW-SF
Crop water source	rainfed	rainfed	rainfed	rainfed
%PM10	38.7	38	17.3	15
% sand	17.2	20.2	67.2	78
% very fine sand	8.7	15.2	44.5	45
% silt	65.8	63.5	23.2	15
% clay	17	16.3	9.6	7
Mean particle (mm)	0.0171	0.0185	0.0771	0.09
Soil wilting point water content (g g^{-1})	0.1072	0.1042	0.0664	0.035

Table 2: Input parameters required by the SWEEP for model application. Parameters were measured in the soil tray used to assess the influence of crust cover on wind erosion potential of four soils found across the Columbia Plateau.

Parameters	Soil type	Clay amendment	Clay amendment	Clay amendment	Clay amendment	Clay amendment
		0	2%	4%	8%	16%
Water content, (g g^{-1})	Athena silt loam	1.16a[1]	0.88a	1.05a	1.57a	1.19a
	Walla Walla silt loam	1.66a	1.74a	2.92b	1.49a	0.87a

Parameters	Soil type	Clay amendment	Clay amendment	Clay amendment	Clay amendment	Clay amendment
	Warden sandy loam	0.67a	0.67a	0.60a	1.69a	0.79a
	Farrell sandy loam	0.45a	1.48a	2.14b	0.65a	0.66a
Soil wilting point water content (g g^{-1})	Athena silt loam	0.107	0.107	0.107	0.107	0.107
	Walla Walla silt loam	0.104	0.104	0.104	0.104	0.104
	Warden sandy loam	0.066	0.066	0.066	0.066	0.066
	Farrell sandy loam	0.035	0.035	0.035	0.035	0.035
Crust crushing energy,(J kg^{-1})	Athena silt loam	0.700a	2.288b	3.874b	8.484c	21.622d
	Walla Walla silt loam	0.731a	3.348b	4.724bc	9.502cd	12.938d
	Warden sandy loam	0.326a	1.326b	4.209c	8.817cd	10.638d
	Farrell sandy loam	0.029a	2.214b	5.409c	5.622c	6.704c
Random Roughness, mm	Athena silt loam	3.80a	4.92a	4.72a	5.74a	5.05a
	Walla Walla silt loam	5.55a	4.35a	5.06a	5.42a	4.11b
	Warden sandy loam	3.55a	4.09a	3.74a	6.50b	4.67a
	Farrell sandy loam	5.54a	4.30a	4.52a	3.86b	4.56a
GMD of aggregate Size, mm	Athena silt loam	2.03a	5.40b	7.05b	9.30b	11.62b
	Walla Walla silt loam	3.05a	6.29a	5.23a	9.44b	10.72b
	Warden sandy loam	1.73a	5.98b	11.35c	12.65c	10.33c
	Farrell sandy loam	0.794a	3.84b	4.90b	6.82c	7.69c
Aggregate fraction less than 0.1mm (SF_{10}) (%)	Athena silt loam	2.36	0.15	0.15	1.34	0.90
	Walla Walla silt loam	1.04	0.18	1.87	0.34	0.33
	Warden sandy loam	1.76	0.14	0.08	0.42	0.49
	Farrell sandy loam	0.11	0.05	0.08	0.11	0.69

Parameters	Soil type	Clay amendment	Clay amendment	Clay amendment	Clay amendment	Clay amendment
Aggregate fraction less than 0.84 mm(SF_{84}) (%)	Athena silt loam	50.33	17.80	16.04	22.83	19.31
	Walla Walla silt loam	40.48	13.71	15.69	13.18	20.49
	Warden sandy loam	64.53	19.50	12.59	20.41	18.65
	Farrell sandy loam	94.81	29.89	19.81	21.17	42.08
Aggregate fraction less than 2.0 mm(SF_{200}) (%)	Athena silt loam	67.84	33.00	26.36	30.51	25.56
	Walla Walla silt loam	52.71	26.32	31.85	20.25	22.21
	Warden sandy loam	72.28	21.90	13.62	21.85	25.35
	Farrell sandy loam	99.89	33.86	22.96	23.66	46.26
Wind direction, degrees	All types	0	0	0	0	0
Wind speed, m s^{-1}	All types	Fig.2	Fig.2	Fig.2	Fig.2	Fig.2

[1] Parameters followed by the same letter for a given soil type are not significantly different at P [?] 0.1

Table 3. Soil loss (g m^{-2}) from Athena silt loam, Walla Walla silt loam, Warden sandy loam, and Farrell sandy loam after disturbing surface crusts created by amending the soil with clay inside a wind tunnel.

Soil type	Soil loss (g m^{-2}) without abrader	Soil loss (g m^{-2}) without abrader	Soil loss (g m^{-2}) without abrader	So
	Clay amendment 0%	Clay amendment 2%	Clay amendment 4%	Cl 8%
Athena	36.3a[1]	31.5a	27.9a	24
Walla Walla	37.8a	29.5a	27.8a	20
Warden	76.1a	50.3b	37.5b	17
Farrell	7031.9a	24.5b	15.1b	15
	Soil loss (g m^{-2}) with abrader	Soil loss (g m^{-2}) with abrader	Soil loss (g m^{-2}) with abrader	So
Athena	338.7a	320.4a	294.7b	29
Walla Walla	365.4a	256.9b	266.9b	28
Warden	845.4a	416.5b	328.9c	31
Farrell	7659.4a	324.5b	293.6b	26

[1] Clay amendment means followed by the same letter on a given soil type are not significantly different at P [?] 0.1.

Figure captions

Figure 1. Location of soil sample sites across the inland Pacific Northwest (iPNW).

Figure 2. The typical force (N) versus displacement (mm) curves during crushing of aggregates with 4% and 8% clay amendment for four soil types.

Figure 3. A flow diagram of the wind tunnel study in evaluating the effect of progressive clay amendment on soil wind erosion in the inland Pacific Northwest.

Figure 4. Soil loss simulated by the RWEQ model as a function of clay amendment at 12 m s^{-1} freestream wind speed within a dry and loose soil surface for four soil types found across inland Pacific Northwest.

Figure 5. Crust crushing energy (a) and their rates (b) as a function of clay amendment for four soil types found across inland Pacific Northwest (iPNW).

Figure 6**.** Soil water content (a), random roughness (b), and aggregate density (c) as a function of crust crushing energy for four soil types found across inland Pacific Northwest (iPNW). The p value >0.1 indicated the relationship was not statistically significant (10% level).

Figure 7. Aggregate GMD as a function of crust crushing energy (a) when crust break down by tillage, and soil loss as a function of aggregate GMD (b) for four soil types found across inland Pacific Northwest (iPNW).

Figure 8. Soil loss as a function of clay amendment for four soil types found across inland Pacific Northwest (iPNW).

Figure 9**.** The abrasion coefficient of aggregates (a) and vertical abrasion flux (b) simulated by SWEEP as a function of aggregate crushing energy for the four soil types found across inland Pacific Northwest (iPNW).

Figure 10. The abrasion coefficient of aggregates (a) and vertical abrasion flux (b) simulated by SWEEP as a function of clay amendment for the four soil types found across inland Pacific Northwest (iPNW).

Hosted file

`Figure 1.tif` available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

`Figure 2.tif` available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

`Figure 3.tif` available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

`Figure 4.tif` available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

`Figure 5.tif` available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

Figure 6.tif available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

Figure 7.tif available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

Figure 8.tif available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

Figure 9.tif available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa

Hosted file

Figure 10.tif available at https://authorea.com/users/303015/articles/433086-soil-wind-erosion-influenced-by-clay-amendment-in-the-inland-pacific-northwest-usa