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Windblown soil crust formation under light rainfall in a semiarid region

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ABSTRACT

Many soils in arid and semi-arid regions of the world are affected by crusting, a process by which a compact layer or thin mantle of consolidated material is formed at the soil surface. Crusts can increase the resiliency of the soil to wind erosion, but characterization of soil crust formation to light precipitation events common to the Columbia Plateau region of the Inland Pacific Northwest is unknown. Our objective was to evaluate the effect of light rainfall events on crust formation of five soil types prominent in the Columbia Plateau. The five soils were Athena silt loam, Palouse silt loam, Ritzville silt loam, Walla Walla silt loam, and Warden sandy loam. Soil crusts were formed in the laboratory using a rainfall simulator that applied water at a rate of 2.5 mm h^{-1} for various durations to achieve a total rainfall application of 0, 0.15, 0.30, 0.60 and 1.0 mm. Crust strength was measured by a penetrometer while crust thickness was measured by a ruler. Silt and clay content of the five soils ranged from 23 to 66% and from 9 to 17%, respectively. An increase in crust thickness and strength was observed with an increase in rainfall for all soils. Crust thickness was similar among the soils whereas crust strength varied among soils at any given level of rainfall. For example, crust strength of soils when subject to 0.15–0.60 mm of rainfall decreased in order of Walla Walla > Athena and Palouse > Ritzville and Warden. These results are consistent with a decreasing order of clay and silt contents. The strongest crust was formed on Palouse silt loam under the highest rainfall amount. A logarithm relationship adequately described the relationship between crust thickness and rainfall for the five soils (r^2 = 1.00). This relationship over-predicted crust thickness based upon observations in the field, but performed better than the algorithm used by the Wind Erosion Prediction System.

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1. Introduction

Surface crusting is a phenomenon that is common to many soils around the world. Crusting is the process that begins with aggregate breakdown and clay dispersion when soils are wetted or exposed to rainfall. As a result of clay dispersion and as the soil dries, a thin seal or skin forms that is less permeable than the underlying soil. This process of crust formation when soils are exposed to rain is described by Chen et al. (1980). The soil crust includes both the skin of fine material on the immediate surface of the soil as well as the consolidated material immediately beneath the skin (Hagen et al., 1995).

Surface crusts play a critical role in conserving the soil resource base. Soil crusts are characterized by an interlocking network of particles that reduce the susceptibility of the soil to erosion when exposed to wind (Zobeck, 1991a; Zobeck and Popham, 1992; Reynolds et al., 2001; Chepil, 1958). This is particularly important in arid and semi-arid regions where vegetative cover may be insufficient to protect the soil from erosion. Wind tunnel and field studies have demonstrated that crusted soils erode at a rate of one-fortieth (Zobeck, 1991b) to one-sixth (Chepil et al., 1955; Chepil, 1958) the rate of non-crusted soils. Models such as the Wind Erosion Prediction System (WEPS) that simulate erosion processes require information on soil crustal properties such as thickness, stability, and percent cover. Crust thickness and stability are important for determining crust longevity when subject to abrasion while percent cover defines the non-erodible area of a soil surface.

Crust formation is influenced by soil physical and chemical properties as well as rainfall quantity, rate, intensity, duration, and energy. Physical and chemical properties that affect crust formation have been respectively reviewed by Bradford and Huang (1992) and Shainberg (1992). Zobeck (1991a) also summarized the physical and chemical properties of soils that affect the wind erodibility of soil crusts. Although observations have been reported on the effect of rainfall characteristics on soil crust formation (Farres, 1978; Morrison et al., 1985), wind erosion models suggest a significant

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rainfall is required before soil erodibility is affected by the formation of a soil crust. The Revised Wind Erosion Equation, for example, simulates the impact of a soil crust on wind erosion only when a soil is exposed to >12.5 mm of rainfall since the last soil disturbance (Fryrear et al., 2000). Surface crusting does not therefore affect wind erosion processes when soils are exposed to <12.5 mm of rainfall. Similarly, WEPS requires >10 mm of accumulated precipitation to form a soil crust (Hagen et al., 1995). The relationship between soil crust cover and precipitation in WEPS was based upon data of highly erodible sandy soils (Zobeck and Popham, 1992). In contrast, Sharratt et al. (2007) observed that a thin and patchy soil crust suppressed particulate emissions from an eroding loessial soil of the Columbia Plateau after a 3-mm rainfall event. Sundram et al. (2004) developed a multi-scale model to simulate the transport and dispersion of windblown sediment across the Columbia Plateau. While they acknowledged the importance of soil crusting in estimating particulate emissions, no attempt was made to describe the spatial and temporal variation in soil crusting across the domain. Thus, a need exists for estimating soil crusting based upon rainfall characteristics inherent to the Columbia Plateau.

Knowledge of crust formation is important for evaluating management strategies aimed at mitigating wind erosion. The prediction of crust formation and strength based upon cumulative precipitation is very useful in simulating wind erosion processes, but there is a lack of information on crust formation of loessial soils in response to light rainfall events that are characteristic of the Columbia Plateau. The objective of this study was to evaluate the effect of rainfall quantity on surface crust formation and to determine the relationship between rainfall amount and crust thickness and strength for five loessial soils of the Columbia Plateau.

2. Materials and methods

Five soil types found across the Columbia Plateau region of the Inland Pacific Northwest of the USA were utilized in this study. These soils are vulnerable to crusting, but vary in susceptibility to wind erosion (Feng et al., 2011) and prominence across the landscape. Collectively, the five soils cover about 20% of the area of the Columbia Plateau. The soils are from the Athena soil series (Fine-silty, mixed, superactive, mesic Pachic Haploxerolls), Palouse soil series (Fine-silty, mixed, superactive, Palouse mesic Pachic Ultic Haploxerolls), Ritzville soil series (Coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls), Walla Walla soil series (Coarse-silty, mixed, superactive, mesic Typic Haploxerolls), and Warden soil series (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids). The Ritzville series is the most common series and covers 8% of the 65,000 km^2 Columbia Plateau region. The Athena, Palouse and Warden soil series each cover 3% and the Walla Walla soil series covers 5% of the region.

Samples from the five soil series were collected from across the Columbia Plateau (Fig. 1) as follows: (1) Warden soil was collected during the summer fallow phase of a winter wheat–summer fallow rotation near Paterson, WA (46.0192°N, 119.6247°W). Winter wheat–summer fallow is used on 1.5 million ha and is particularly vulnerable to wind erosion during the 13-month summer fallow period. The soil is tilled on multiple occasions during the fallow period, resulting in little vegetative cover and roughness (Sharratt and Feng, 2009), (2) Ritzville soil was collected during the summer fallow phase of a winter wheat–summer fallow rotation near Ritzville, WA (47.1383°N, 118.4706°W), (3) Palouse soil was collected from a continuous cereal rotation near Pullman, WA (46.7606°N, 117.2003°W), (4) Athena soil was collected during the chemical fallow phase of a no-tillage winter wheat–spring wheat–chemical fallow rotation near Colfax, WA (46.7903°N, 117.4564°W), and (5) Walla Walla soil was collected during the summer fallow phase of a winter wheat–spring wheat–summer fallow rotation near Waitsburg, WA (46.2497°N, 118.1642°W). Soil samples were collected from the upper 30 mm of the soil profile, air-dried, and hand sieved through a 2-mm sieve to remove plant residue and acquire the wind erodible fraction. Large aggregates were broken by hand to facilitate passage through the 2-mm sieve.

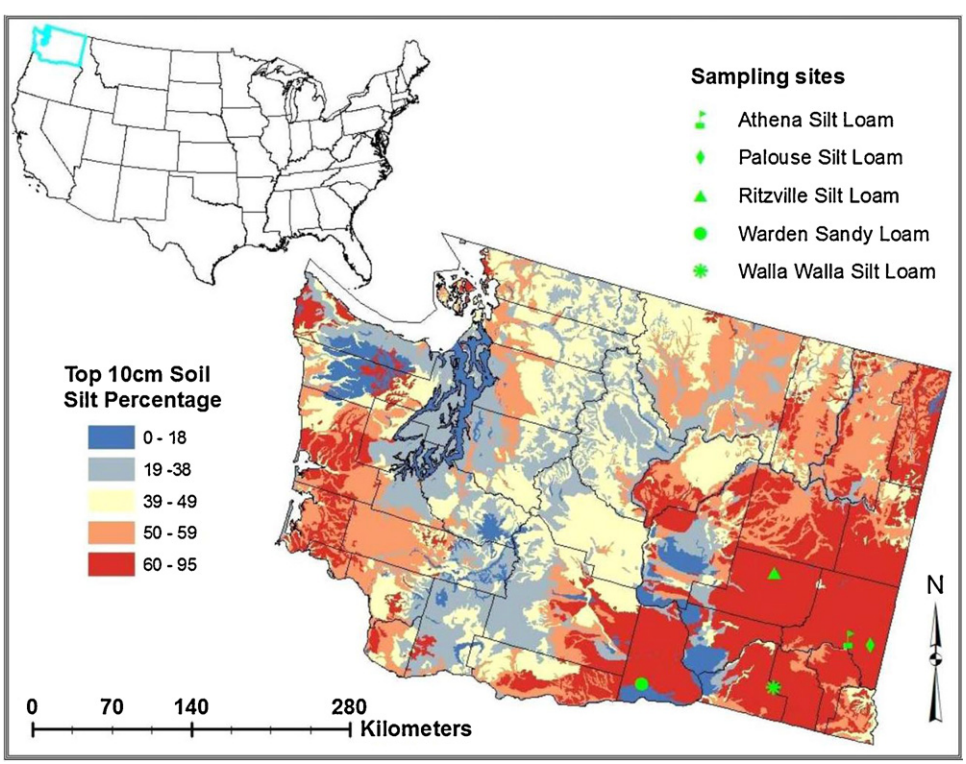

Fig. 1. Sample locations of the five soils and silt content of soils in the state of Washington.

Soil passing through the 2-mm sieve was used to assess basic physical and chemical properties and crust formation in this study.

Basic physical and chemical characteristics of the five soils assessed included particle size, pH, organic carbon, exchangeable Ca and Na, and $CaCO_3$. Dispersed particle size of the five soils was measured using a Malvern Mastersizer S laser diffractometer (Malvern Instrument, Malvern, England). Samples were pretreated prior to particle size analysis using sodium acetate to dissolve carbonates and hydrogen peroxide to oxidize organic matter. Samples were rinsed with deionized water, centrifuged, and excess supernatant was decanted. Each sample was dispersed with sodium hexametaphosphate by agitation for 16 h and analyzed in a de-ionized water suspension with no sonication. Soil pH was measured on a 1:1 soil–water suspension using an electronic pH meter while organic carbon content was determined by high temperature combustion of a 0.3-g soil sample in a furnace (LECO Corporation, St. Joseph, MO.). Exchangeable Ca and Na were determined by analyzing the extract of a soil–ammonium acetate mixture on an atomic absorption spectrophotometer. Percent $CaCO_3$ was determined using a soil–HCl mixture and titrating with NaOH.

Soil crusts were formed using a rainfall simulator (Bubenzer et al., 1985) to simulate low-intensity, small drop-size rains that are typical of the Columbia Plateau (McCool et al., 2009). The simulator was equipped with a rotating head having a wide angle, full jet nozzle (model 4.3w, Spraying Systems Co., Wheaton, IL) that delivers rainfall at 2.5 mm h^{-1}. The nozzles were positioned 1.5 m above the soil and sprayed vertically downward at 100 kPa pressure to generate drop size and drop velocity similar to naturally occurring, low-intensity rainfall common in the region. Median raindrop size diameter was about 1 mm which is common for the region (McCool et al., 2009). The kinetic energy of the raindrops, e, was calculated with the equation of Brown and Foster (1987)

$$e = 0.29[1 - 0.72\exp(-0.05i)] \quad (1)$$

where i is rainfall intensity (mm h^{-1}). Thus, the kinetic energy of the rainfall was 10.57 J m^{-2} mm^{-1}. We examined the effect of 0, 0.15, 0.3, 0.6 and 1 mm of cumulative rainfall on soil crust properties. These quantities of rainfall were chosen because dramatic changes in soil erodibility have been observed under small quantities of precipitation in the Columbia Plateau (Sharratt et al., 2007). Rainfall was characterized by an electrical conductivity of 0.0325 S m^{-1}.

Aluminum trays (1 m long, 0.2 m wide, and 0.02 m deep) were filled with air-dried soil (<2-mm size fraction at a gravimetric water content of about 2%) in layers. After the addition of each soil layer, the sides of the trays were tapped to ensure even settling. Following the addition of the last layer, the trays were overfilled with soil and then leveled with a screed. The resulting bulk density was about 1.1 kg m^{-3}. The trays were placed under the rainfall simulator (after stabilizing water pressure to the nozzles) for an appointed time to ensure a cumulative rainfall of 0, 0.15, 0.3, 0.6 and 1 mm.

Each rainfall treatment was replicated four times. At the conclusion of the simulated rainfall, the soil tray was placed inside a glasshouse for >48 h to dry the soil. Maximum and minimum daily air temperature inside the glasshouse respectively averaged 50 and 15 °C.

Following drying of the soil, the tray was removed from the glasshouse and equilibrated at ambient temperature (25 °C) in the laboratory. Soil water potential in the upper 5 mm of the profile was measured concurrently with crust strength and thickness. Water potential was measured with a dewpoint potentiometer (Model WP-4, Decagon Devices, Inc., Pullman, WA) and was no higher than −100 MPa across all treatments and replications. Soil surface strength has been used as an index of the degree of seal and crust formation (Norton, 1987; Luk and Cai, 1990). In our study, a handheld penetrometer (Model FDN 32, Wagner Instruments, Greenwich, CT) with a 15-mm diameter foot was used to determine the soil surface crust strength. The penetrometer was inserted 6 mm into the soil at a rate of 2 mm s^{-1}. The maximum resistance (resolution of 0.1 kPa) was recorded during insertion of the penetrometer. Crust strength can be ascertained from the maximum resistance required to penetrate the soil. In this study, the difference in penetration resistance between a soil with and without a crust was assumed to be the force required to penetrate the soil crust. Penetration resistance of the mineral soil was about one-half of the resistance of the soil with the thinnest crust, thus ensuring detection of any higher resistance to penetrate a soil crust. The thickness of the crust was measured by first exposing a cross section of the soil. This was done by vertically slicing through the soil profile with a knife and then inserting the knife horizontally along the bottom of the tray (bottom of soil profile). The knife was gently lifted to fracture the crust and expose a cross-section of the crust. The cross-section of the crust was gently tilted on end and the thickness measured with a ruler. Penetration resistance and crust thickness were measured at three random locations across the top of each tray.

The experimental design was a randomized complete block with statistical analyses being performed on the data using a mixed-model ANOVA in SAS (SAS 8.2, Institute, Inc., Cary, NC). A one-way ANOVA was conducted to examine the effect of soil type on crust strength at any given rainfall amount. Multiple pairwise comparisons were made using Tukey's adjustment. All results are reported at $\alpha = 0.05$ level of significance. Normality of the distributions was examined by the Shapiro–Wilk test before performing any statistical analysis. Residuals from the mixed model of crust penetration resistance at 0, 0.15 and 0.3 mm of rainfall were not distributed normally, therefore an exponential transformation was performed on the data to satisfy the normality assumption necessary for the ANOVA.

3. Results and discussion

The textural class of all tested soils was silt loam with one exception; the Warden soil was a sandy loam (Table 1). The four silt loams had a silt content that ranged from 58 to 66% and clay

Table 1
Soil particle size and chemical properties of five soils found within the Columbia Plateau.

Soil series	Sand (%)	Silt (%)	Clay (%)	Diameter[a] (μm)	pH	Na[b] (cmol kg^{-1})	Ca[b] (cmol kg^{-1})	Organic carbon (%)	$CaCO_3$ (%)	CEC[c] (cmol kg^{-1})
Warden	67.5	23.3	9.2	98.29	8	0.36	4.5	0.4	4.5	12
Athena	17.3	65.7	17.0	30.66	4.8	<0.09	5.9	3.1	<0.5	21
Palouse	23.4	62.2	14.4	42.71	4.8	0.21	5.9	2.9	<0.5	18
Ritzville	30.5	58.1	11.4	44.87	5.7	0.15	4.3	1.3	<0.5	12
Walla Walla	19.6	63.8	16.6	31.63	6.9	0.1	12	1.2	0.7	18

[a] Mean diameter of dispersed soil particles
[b] Exchangeable Na and Ca
[c] CEC is cation exchange capacity

content that ranged from 11 to 17%. The mean particle diameter of the silt loams varied from 31 to 45 μm and of the sandy loam was 98 μm. The silt loams were acidic to near neutral (pH varied from 4.8 to 6.9) with <1% $CaCO_3$ while the sandy loam was basic (pH was 8.0) with 4.5% $CaCO_3$. Some variation exists in organic carbon content and cation exchange capacity (CEC) of the soils; soil (Warden sandy loam) from the drier areas (200 mm of annual precipitation) of the Columbia Plateau had 0.4% organic carbon content and a CEC of 12 cmol kg^{-1} while soils (Athena silt loam and Palouse silt loam) from the wetter areas (>490 mm of annual precipitation) of the Columbia Plateau had 2.9–3.1% organic carbon content and a CEC of 18–21 cmol kg^{-1}. Organic carbon aids in stabilizing soil aggregates (Robinson and Woodun, 2008), thus soils with higher organic carbon should be less susceptible to aggregate breakdown from raindrop impact and to surface sealing and crust formation.

Rainfall plays a key role in crust formation, which was observed for the five soils considered in this study (Table 2). Previous studies also suggest that cumulative rainfall is the dormant force affecting crust formation (Freebairn et al., 1991; Fan et al., 2008). A positive relationship was found between crust thickness and penetration resistance (Fig. 2). Crust thickness and penetration resistance increased as soils were subject to greater rainfall (Table 2). The greatest crust thickness and strength was found after the soils were exposed to the highest amount of rainfall in this study (1 mm). Although crust thickness was similar among soils, soils varied in penetration resistance at any given level of rainfall. Relative differences in penetration resistance among soils, however, did not persist across all rainfall treatments. For example, in the absence of rainfall, Athena silt loam and Palouse silt loam had the highest resistance and Walla Walla silt loam the lowest resistance. After being exposed to 1 mm of rainfall, Palouse silt loam had the highest resistance and Athena silt loam and Ritzville silt loam the lowest resistance. Differences in penetration resistance appeared to be relatively consistent when soils were subject to 0.15–0.6 mm of rainfall. For these rainfall treatments, crust penetration resistance decreased in order of Walla Walla silt loam > Athena silt loam and Palouse silt loam > Ritzville silt loam and Warden sandy loam. Differences among soils in crust strength observed across the 0.15–0.6-mm rainfall treatments are consistent with differences among soils in silt and clay content. For example, the soil with the highest crust strength (Walla Walla silt loam) also had the highest silt and clay contents while soils with the lowest crust strength (Ritzville silt loam and Warden sandy loam) had lowest silt and clay contents. These findings validate conclusions of Evans and Buol (1968) and Gary and Evans (1974) that high silt content weakens soil structure and aggregates and results in a high density crust. Onofiok (1985) explained that the effect of clay and silt content on soil crust strength is attributed to the reactivity of the large surface area and the corresponding increase in the magnitude of inter-particle cohesion in silt and clay. While Warden sandy loam has relatively low silt and clay contents and thus relatively weak crust compared to the other soils subject to 0.15 to 0.6 mm of rainfall (Table 2), other characteristics inherent to the Warden sandy loam may contribute to the development of a strong crust. For example, Warden sandy loam has a greater exchangeable Na, calcium carbonate, and pH compared to the four silt loams (Table 1). These attributes tend to weaken and disperse soil aggregates, potentially resulting in a strong soil crust which was evident after being exposed to a 1-mm rainfall. The role of the physicochemical mechanism in crust formation has been widely studied (Shainberg and Letey, 1984; Shainberg et al., 1992; Mermut et al., 1995) and found to be mainly controlled by exchangeable Na percentage (Shainberg et al., 1992) and calcium carbonate content of the soil (Robinson and Woodun, 2008). Nevertheless, the low silt and clay contents of Warden sandy loam were likely the dominate factors in forming a weaker soil crust when exposed to 0.15–0.6 mm of rainfall as compared to the silt loams.

Crust thickness varied logarithmically with rainfall as portrayed in Fig. 3a. The logarithmic relationship implies that crust development in response to rainfall is initially large and then decreases with rainfall toward some equilibrium. A logarithmic function described well the trend in the laboratory data with a standard error of fit of 0.027 mm and also confirms previous work that a logarithmic relationship exists between crust thickness and rainfall (Assouline, 2004; Farres, 1978). Our interest in the utility of this function to describe crust formation

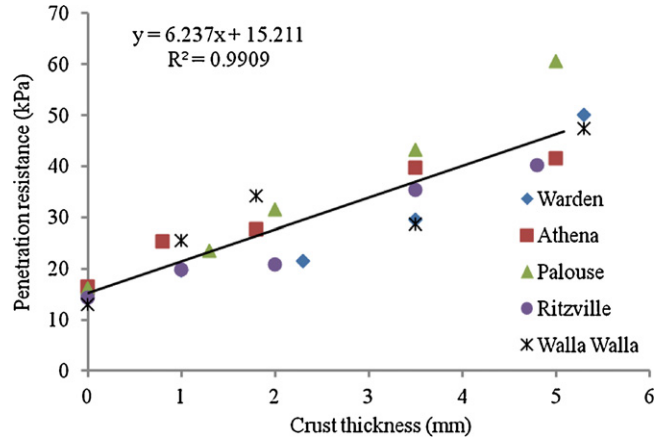

Fig. 2. Penetration resistance as a function of crust thickness based upon data from simulated rainfall experiment.

Table 2
Crust thickness and penetration resistance of five soils at five levels of rainfall.

Cumulative rainfall (mm)	Soil series	Crust thickness mm	Penetration resistance (kPa)
0	Warden	No crust	14.95b†
	Athena	No crust	16.50a
	Palouse	No crust	16.19a
	Ritzville	No crust	14.33b
	Walla Walla	No crust	13.09c
	P-Value†		<0.0001
0.15	Warden	1.0	19.75d
	Athena	0.8	25.33b
	Palouse	1.3	23.47c
	Ritzville	1.0	19.87d
	Walla Walla	1.0	25.57a
	P-Value†		<0.0001
0.30	Warden	2.3	21.46d
	Athena	1.8	27.74c
	Palouse	2.0	31.53b
	Ritzville	2.0	20.84d
	Walla Walla	1.8	34.17a
	P-Value†		<0.0001
0.60	Warden	3.5	29.59d
	Athena	3.5	39.74b
	Palouse	3.5	43.23a
	Ritzville	3.5	35.41c
	Walla Walla	3.5	44.24a
	P-Value†		<0.0001
1.00	Warden	5.3	50.13b
	Athena	5.0	41.53d
	Palouse	5.0	60.51a
	Ritzville	4.8	40.25d
	Walla Walla	5.3	47.38c
	P-Value†		<0.0001

† Values at same rainfall within a column followed by the same letter are not significantly different.

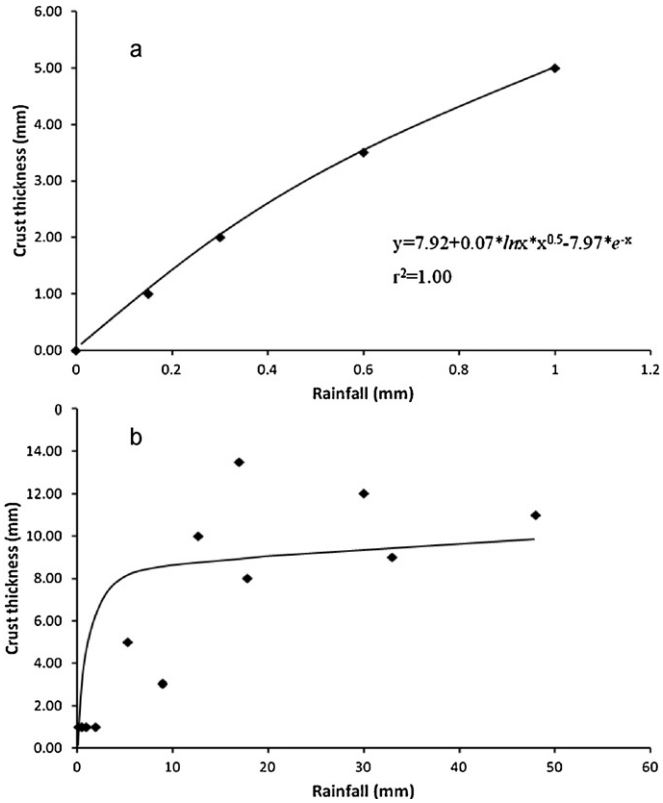

Fig. 3. Crust thickness as a function of rainfall based upon data from this laboratory study (a) and field locations within the Columbia Plateau (b). The equation was fit to laboratory data and is portrayed by the line for comparison with both laboratory and field.

beyond the laboratory led to testing the function on similar soil types in the field in the Columbia Plateau. Over the past decade, we have measured surface characteristics of wind erodible soils at various field locations across the region. These characteristics have aided in interpreting variations in windblown soil transport among crop and tillage systems and with time. For example, surface characteristics were measured during the summer fallow phase of a winter wheat–summer fallow rotation at a field site near Washtucna, WA in 2004. These characteristics aided in interpreting temporal trends in sediment transport as well as testing wind erosion models in the region (Feng and Sharratt, 2007). Field locations for which information was available on soil crust thickness are reported in Table 3. For the Lind and Ritzville locations, crust thickness was measured during the summer fallow phase of a winter wheat–summer fallow rotation. For the Paterson location, crust thickness was measured during the summer fallow phase of a winter wheat–summer fallow rotation (Warden sandy loam and Ritzville silt loam) or prior to sowing potato or corn in an irrigated potato–corn rotation (Quincy sandy loam). At the Hermiston and Othello locations, crust thickness was measured prior to sowing potato or wheat in an irrigated potato–wheat rotation. The soil type and clay content at these locations are reported in Table 3. Shano silt loam occurs in proximity to Ritzville silt loam while Quincy sandy loam and Adkins sandy loam occur in proximity to Warden sandy loam. Clay content was measured using a Malvern Mastersizer S laser diffractometer on soil samples collected from the upper 30 mm of the soil profile at each location. Crust thickness was measured using a ruler or caliber while precipitation was recorded by an automated rain gage at each location. Crust thickness and cumulative rainfall between the date of tillage and measurement of crust thickness at the various field locations are also reported in Table 3. The relationship between crust thickness and cumulative rainfall using data collected at all field locations appeared logarithmic and is portrayed in Fig. 3b.

Crust thickness observed at our field locations (Table 3) was estimated using the logarithmic function derived from our rainfall simulator and the algorithm in WEPS. Crust thickness in WEPS is estimated by

$$\mathrm{CT} = a \times P + b \times P^{0.5} \tag{2}$$

where CT is crust thickness (mm), P is cumulative precipitation (mm) and a and b are empirical coefficients. These coefficients are defined by

$$a = -0.072 + 0.2 \times \mathrm{CF} \tag{3}$$

$$b = 1.56 - 2.9 \times \mathrm{CF} \tag{4}$$

where CF is soil clay fraction. Based upon rainfall and clay fraction at the field locations, crust thickness was overestimated by our logarithmic function and underestimated by the WEPS algorithm (Table 3). Our logarithmic function appeared to perform better

Table 3
Crust thickness of soils as affected by rainfall at field locations across the Columbia Plateau.

Location	Soil type	Clay fraction	Date[a] tillage/ measurement		Rainfall between dates[b] (mm)	Crust thickness (mm)	Predicted crust thickness[c] (mm)	WEPS predicted crust thickness (mm)
Lind, WA	Shano silt loam	0.098	5/10/2005	6/23/2005	18	8	11.2	4.5
	Shano silt loam	0.098	7/21/2005	8/24/2005	2	1	6.8	1.7
	Shano silt loam	0.098	8/31/2005	9/14/2005	0.2	1	1.3	0.6
Washtucna, WA	Ritzville silt loam	0.105	6/23/2004	8/06/2004	9	3	10.1	3.2
	Ritzville silt loam	0.128	6/02/2006	6/21/2006	30	12	11.9	5.1
	Ritzville silt loam	0.128	6/24/2006	7/19/2006	1	1	5.0	1.1
Paterson, WA	Warden sandy loam	0.142	4/11/2007	4/30/2007	5	5	8.9	2.4
	Warden sandy loam	0.142	8/23/2007	8/31/2007	0.5	1	3.2	0.8
	Ritzville silt loam	0.128	4/18/2007	4/23/2007	0.5	1	3.2	0.8
	Quincy sandy loam	0.078	4/30/2010	5/06/2010	1	1	5.0	1.3
Othello, WA	Shano silt loam	0.085	4/12/2011	4/20/2011	13	10	10.7	4.0
	Shano silt loam	0.085	3/12/2012	4/23/2012	33	9	12.0	5.7
Hermiston, OR	Adkins sandy loam	0.088	4/05/2011	4/18/2011	17	13	11.1	4.0
			3/09/2012	4/09/2012	48	11	12.4	6.4

[a] Date the soil was last tilled prior to the date of measuring crust thickness.
[b] Total rainfall between date soil was tilled and date of measuring crust thickness.
[c] Crust thickness calculated using equation in Fig. 3a.

than the algorithm used in WEPS to estimate crust thickness because the root mean square error of crust thickness was 3.2 mm for our logarithmic equation and 4.2 mm for the algorithm used in WEPS. Our logarithmic function overestimated crust thickness for all but two field observations reported in Table 3. Field observations reported in Table 3 were taken over a period of days and are influenced by the non-uniformity in the distribution of rainfall within and across days. For example, the 1-mm rainfall occurring between 24 June and 19 July 2006 at Ralston, WA consisted of a 0.8-mm rain on 7 July and a 0.2-mm rain 13 July. Subsequent rainfall events after soil drying may contribute little to crust development; this may be one reason for our logarithmic equation over-predicting crust thickness. In addition, raindrop size can dramatically influence crust formation. Although our rainfall simulator mimics low-intensity rains with small drop sizes, lower-intensity rains with smaller drop sizes in the field could result in thinner crusts than predicted by our logarithmic equation. Smaller rain drops have less energy and do not penetrate the soil as deep as larger drops, thus smaller drops do not alter the structure or compact the soil as deeply as larger drops (Belnap, 2001). Other factors may also contribute to the overestimation of our logarithmic function or under-estimation of the algorithm used in WEPS. Indeed, crust formation is a complex physiochemical process that is dependent upon factors other than rainfall and clay fraction (Onofiok, 1985; Zobeck and Popham, 1992).

4. Conclusions

Crust thickness and strength of five soil types found across the Columbia Plateau of eastern Washington increased as rainfall increased. Crust thickness did not appear to vary among the five soil types and the increase in crust thickness with rainfall was adequately described by a logarithmic function. This function appeared to overestimate crust thickness in the field, which could be due to non-uniform distribution in rainfall under natural conditions. Nevertheless, the logarithmic function appeared to better estimate crust thickness in the field than the algorithm used in WEPS. When soils were subject to 0.15–0.6 mm of rainfall, crust strength decreased in order of Walla Walla silt loam > Athena silt loam and Palouse silt loam > Ritzville silt loam and Warden sandy loam. Soils with higher sand contents or lower silt or clay contents (Ritzville silt loam and Warden sandy loam) may not disperse as readily as soils with lower sand contents or higher silt or clay contents and thus result in weaker crusts. The relationship between crust thickness and rainfall developed in this study may have application in models that simulate soil processes in the Columbia Plateau.

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