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# Surface characteristics of a windblown soil altered by tillage intensity during summer fallow

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ABSTRACT

Winter wheat – summer fallow is the crop rotation used on more than 1.5 million ha in the Pacific Northwest United States. Land maintained using conventional summer fallow is susceptible to wind erosion because multiple tillage operations during the fallow period expose the soil to high winds. Alternative management strategies are needed that protect the soil surface from erosion during summer fallow. Surface characteristics were examined after subjecting the loessial soil to seven (conventional), five (reduced), three (minimum), and zero (no) tillage operations during the fallow period. Surface residue biomass and roughness and soil crust, aggregation, strength, and water content were measured after tillage and sowing operations. No tillage resulted in a more persistent and thicker soil crust and greater residue cover, silhouette area index (SAI), and penetration resistance than conventional and reduced tillage. For those treatments subject to tillage, minimum tillage resulted in a thicker soil crust and greater residue cover, SAI, ridge roughness, mean aggregate diameter, and penetration resistance as compared to conventional or reduced tillage after primary tillage. Near the end of the fallow period, minimum tillage resulted in 15% greater residue cover than conventional tillage. Soil loss from minimum tillage is expected to be 50% of conventional tillage based upon these differences in residue cover. This study suggests that minimum tillage is an alternative strategy to conventional tillage for reducing wind erosion in the wheat-fallow region of the Pacific Northwest.

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## 1. Introduction

Windblown dust is a major source of PM10 (particulate matter $\leqslant$10 µm in diameter) that degrades air quality within the Columbia Plateau region of the Pacific Northwest United States. In fact, 90% of the exceedances of the US Environmental Protection Agency national ambient air quality standard for PM10 in southeastern Washington are a result of windblown dust emissions from agricultural lands (Sharratt and Lauer, 2006). Wind erosion also degrades the soil resource as a result of removing the fertile topsoil, thereby potentially affecting the productivity of agricultural lands for future generations. Agricultural lands most susceptible to erosion during high wind events are typically managed in a winter wheat – summer fallow rotation; this rotation is employed on 1.5 million ha in the drier part (annual precipitation <300 mm) of the Columbia Plateau (Schillinger and Papendick, 2008). The summer fallow phase of the rotation is most susceptible to wind erosion but is essential for reducing risks associated with crop failures in this Mediterranean climate region where precipitation occurs mainly during winter and is suboptimal for grain production (Schillinger and Young, 2004). Summer fallow provides temporal stability in wheat production as a result of conserving soil water, thereby enabling winter wheat to be sown into moist soil at the end of summer fallow in late summer (Schillinger et al., 2006). Adequate soil water for seed germination at the end of the fallow phase is possible only as a result of maximizing the storage of precipitation over winter and suppressing soil evaporation during summer. Soil evaporation is suppressed by maintaining a thick and friable soil mulch (Schillinger and Papendick, 1997).

Conventional summer fallow within the Columbia Plateau generally entails multiple tillage operations during the 13-month fallow period. Conventional tillage includes the use of sweeps, disks, or cultivators after wheat harvest in late summer and again the following spring and then rodweeding the soil to control weeds prior to sowing winter wheat in late summer (Schillinger, 2001). Conventional tillage practices are very effective in conserving soil water during the fallow period; however, soils are very susceptible to erosion during summer fallow because multiple tillage operations degrade soil aggregates and bury crop residue. In fact, Sharratt

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et al. (2007) reported a loss of over 2300 kg ha$^{-1}$ of topsoil and over 210 kg ha$^{-1}$ of PM10 from conventional summer fallow during a single 14-hour high wind event in eastern Washington. Fine soil particles in suspension constituted most of the sediment mass in transport above the soil surface; from 50% to 65% of the sediment trapped at 0.1–1.5 m above the surface was smaller than 45 μm in diameter. Wind speeds in excess of 17 m s$^{-1}$ and a smooth, bare, dry, and loose (no crust) soil during the high wind event contributed to this soil loss (Feng and Sharratt, 2007).

Tillage practices during the summer fallow phase of a crop-fallow rotation or after harvest of annual crops can influence wind erosion. For example, Sharratt et al. (2010) found that sediment and PM10 flux from an agricultural field in the summer fallow phase of a wheat-fallow rotation was highest for conventional tillage and lowest for no tillage. Reduced or minimum tillage during fallow resulted in an intermediate flux as compared to conventional and no tillage. They also noted an increase in windblown sediment and PM10 flux after each tillage operation, with the largest increase occurring after breaking a soil crust by a tillage operation. Other soil properties can also affect sediment and PM10 emissions. Mendez and Buschiazzo (2010) found that no tillage could reduce the risk of wind erosion during the fallow period in Argentina because no tillage resulted in 50% greater residue cover than conventional and vertical tillage. In assessing the risk of wind erosion, residue cover was apparently more important than non-erodible aggregates because conventional and vertical tillage had a greater percentage of non-erodible aggregates on the soil surface than no tillage. Lopez et al. (1998) compared surface characteristics of a loam soil after either chisel plow or moldboard plow in the windy and semi-arid region of Aragon, Spain. They observed lower suspended sediment flux from chisel plow due to the rougher surface and greater coverage of non-erodible aggregates and residue than moldboard plow. For the wheat-fallow region of North Dakota, Merrill et al. (1999) found an increased risk of wind erosion with tillage intensity during the fallow phase of the rotation. Although no differences in aggregate size distribution were reported among tillage treatments, they found no tillage resulted in a smoother surface and greater residue cover and silhouette area than conventional and minimum tillage.

Few studies have considered the effect of tillage on a suite of soil properties and surface characteristics that govern wind erosion. Tillage practices, however, must be developed to minimize the risk of eroding the soil resource during summer fallow within the Columbia Plateau. Although tillage is vital for suppressing soil evaporation during the summer, we examine possible alternatives to conventional tillage that will protect the soil surface from the forces of wind within the Columbia Plateau. The purpose of this study was to compare soil properties of various tillage systems that govern wind erosion and dust emissions in the wheat-fallow region of the Columbia Plateau.

## 2. Materials and methods

This study was conducted at the Washington State University Dryland Research Station near Lind, Washington (47°00′N, 118°34′W). Agriculture is the primary industry of the community with the rural landscape predominately in a winter wheat – summer fallow rotation. The Station receives 240 mm of annual precipitation.

### 2.1. Tillage treatments

The experimental plots at the Dryland Research Station were located on a Ritzville silt loam (Andic Aridic Haplustoll) comprised of 1.5% organic matter, 13% clay, 60% silt, and 27% sand and with a mean primary particle diameter of 24 μm. The site was in a winter wheat – summer fallow rotation when the fallow phase of the rotation began after harvest of wheat in July 2004. The experimental design was a randomized complete block with four replications. Tillage treatments imposed after wheat harvest included: (1) conventional tillage. Plots were cultivated to a depth of 0.10 m using overlapping 0.36-m wide V-blades on 11 August 2004, chiseled to a depth of 0.30 m in October 2004, cultivated twice to a depth of 0.10 m using overlapping 0.20-m wide V-blades on 2 May 2005, and rodweeded to a depth of 0.10 m on 13 June, 11 July, and 9 August 2005; (2) reduced tillage. Plots were undercut to a depth of 0.10 m using overlapping 0.80-m wide V-blades on 11 August 2004 and 2 May 2005 and then rodweeded to a depth of 0.10 m on 13 June, 11 July and 9 August 2005; (3) minimum tillage. Plots were undercut to a depth of 0.10 m using overlapping 0.80-m wide V-blades on 2 May 2005 and then rodweeded to a depth of 0.10 m on 11 July and 9 August 2005; and (4) no tillage in which plots remained undisturbed throughout the fallow period. Weeds in no tillage plots were controlled with application of glyphosate herbicide in April and July 2005. The rodweeder used to control weeds in the conventional, reduced, and minimum tillage plots was equipped with a horizontal 25-mm square steel bar that rotated opposite to the direction of travel below the soil surface. Experimental plots were either 9 or 18 m wide and 30 m long. Plots subject to conventional, reduced, and minimum tillage were sown to winter wheat with a deep furrow drill on 31 August 2005. No-tillage plots were not sown to wheat until the arrival of autumn rains in October.

### 2.2. Soil characteristics

Soil surface characteristics of tillage treatments were typically assessed prior to a precipitation or high wind event after each tillage, rodweeding, and sowing operation. Unfortunately, intermittent precipitation events and high winds delayed ascertaining soil properties for 24 days after tillage in May 2005. Precipitation occurred on 12 days (totaling 24 mm) while sustained winds sufficient to cause erosion occurred on three additional days prior to assessing soil properties on 26 May 2005. Intermittent precipitation events and high winds also prevented measuring soil properties from tillage treatments after the June 2005 rodweeding operation. Precipitation (totaling 15 mm) and sustained winds sufficient to cause erosion occurred on 16 days between the 13 June and 11 July rodweeding operations. Herbicide application also prevented measuring soil properties in the no tillage treatment in July 2005.

Soil surface characteristics were assessed at three random locations within each experimental plot. Care was taken to avoid measuring soil characteristics in wheel tracks caused by tractors or implements. Silhouette area index was determined from standing stubble characteristics within a 0.25 m$^2$ area according to:

$$SAI = \left(\sum dh\right) \Big/ A \quad (1)$$

where $A$ is soil surface area (m$^2$), $d$ is stem diameter (m), $h$ is stem height (m), and the summation is evaluated for all standing stems located within the measurement area. Biomass of prostrate wheat residue and standing wheat stubble was then assessed by collecting, drying, and weighing the above-ground residue components within the same 0.25 m$^2$ area. Crop residue cover, soil crust cover, and soil surface random roughness was measured using a pin (roughness) meter. The pin meter was comprised of 40 equidistant aluminum pins that protruded and moved vertically through holes in a steel frame mounted above the soil surface. Residue and crust cover were calculated as the percent of pins lying on prostrate residue elements and soil crust after lowering the pins to the surface. A washer (6.4 mm diameter) was secured to the bottom of each pin to keep the foot of the pin suspended on the friable and fine-grained soil surface. A residue element or underlying crust touching a predetermined position on the perimeter of the foot of the pin added to percent cover. The pins were then raised and residue removed from the soil surface before once again lowering the pins to the surface to assess roughness. Random roughness was determined as the standard deviation among pin elevations after correcting for slope (Currence and Lovely, 1970).

Aggregate size distribution was determined on soil samples collected in the upper 0.03 m of the soil profile. A flat-bladed shovel was used to collect and place an approximate 1-kg sample on a tray. The samples were air-dried and then processed through a compact rotary sieve (Chepil, 1962) equipped with sieves having 0.42, 0.84, 2.0, 6.4, and 19.0 mm openings. A sonic sieve was used to determine the size distribution for the <0.42 mm size fraction.

Soil surface water content was determined by inserting a 76-mm diameter steel ring assembly into the soil. The assembly consisted of two separate rings, the upper ring being 5 mm tall and the lower ring 30 mm tall. Steel tabs welded on the outside of the upper ring provided stability to the assembly. The assembly was inserted such that the top of the assembly was nearly level with the soil surface. A knife was used as a screed to level the soil across the surface of the ring. The assembly was extracted from the soil after which the upper ring was removed from the assembly. The 5 mm thick layer of the soil protruding above the lower assembly was then placed into a sealed container. Soil water content and water potential of the 5-mm sample was determined by gravimetric analysis and a water activity meter (WP4-T, Decagon Devices, Pullman, WA), respectively. Soil protruding below the bottom of the lower ring was removed to create a planar surface across the surface of the ring. Volumetric water content and bulk density was determined using the soil remaining in the lower sample ring. The soil was placed inside a sealed container, weighed, and dried at 100 °C to obtain the dry weight of the sample.

Surface penetration resistance was determined using a pocket penetrometer. The standard 6.5-mm diameter foot of the penetrometer was interchanged with larger diameter feet so as to increase the sensitivity of the penetrometer over a range of soil surface conditions. Oriented or ridge roughness was only apparent prior to primary tillage and after sowing wheat; ridges created by the deep furrow drill were characterized by roughness according to Zingg and Woodruff (1951). Ridge roughness (RidgR) is defined by ridge height and spacing as:

$$\text{RidgR} = (4^{*}H^{2})/D \qquad (2)$$

where $H$ is ridge height (mm) and $D$ is ridge spacing (mm).

## 3. Results and discussion

Soil properties were assessed immediately after most tillage and sowing operations. However, intermittent precipitation and high wind events precluded taking measurements after rodweeding in June 2005. In addition, frequent precipitation events occurring after tillage in May 2005 postponed our assessment of soil properties for 24 days. A total of 24 mm of precipitation between spring tillage (2 May) and our assessment of soil properties (26 May) resulted in a 10-mm crust in treatments subject to tillage on 2 May (Table 1). At the time soil properties were assessed in May 2005, no differences were apparent in crust thickness among the conventional, reduced, and minimum tillage treatments. In contrast, a 57-mm crust was apparent in the no-tillage treatment. Although differences were apparent in crust cover in May 2005 (Table 1), these differences were due to differences in crop residue cover (Table 2) since residue and crust constituted 100% of cover of the loessial soil. For example, no-tillage resulted in the lowest crust cover (55%) and highest residue cover (45%) while conventional tillage resulted in the highest crust cover (83%) and lowest residue cover (17%). Although conventional tillage resulted in the highest crust cover, sediment flux under conditions of copious saltation was highest for conventional tillage in May 2005 (Sharratt et al., 2010). This suggests that crop residue is more important than soil crust in protecting the soil surface from saltating particles.

Crop residue cover appeared to diminish during the fallow phase of the rotation in all tillage treatments except the no-tillage treatment; residue cover in no-tillage remained between 40% and 45% over the duration of this study (Table 2). The decline in residue cover was more apparent in conventional tillage than in minimum tillage. Thus, more intense tillage resulted in lower residue cover at the time of sowing. There was not a consistent difference in residue cover between the conventional and reduced tillage treatments despite the conventional tillage treatment being subject to two additional tillage operations. Differences in residue cover, however, were more consistent between the conventional and minimum tillage treatments with conventional tillage resulting in lower residue cover. Conventional tillage was subject to three additional tillage and one additional rodweeding operations as compared with minimum tillage.

Bilbro and Fryrear (1994) describe a relationship between soil loss ratio (SLR) and crop residue cover. SLR is the ratio of soil loss from a treated soil to soil loss from a smooth, friable, and bare soil. According to their relationship, a SLR of 0.65 would be expected for conventional tillage as a result of maintaining 10% residue cover toward the end of the fallow phase. In contrast, a SLR of 0.35 is expected for minimum tillage as a result of maintaining 25% residue cover at the end of the fallow phase. Thus, soil loss from conventional tillage is expected to be twice that of minimum tillage when considering only differences in residue cover between treatments. This difference compares favorably with observation made by Sharratt et al. (2010) who reported sediment flux under conditions of limited or copious saltation was 30–230% higher from conventional than minimum tillage at the end of the fallow period.

Above-ground crop residue biomass in all tillage treatments declined during the fallow phase of the rotation (Table 2). The decline in residue biomass was a result of loss of both prostrate and standing residue biomass. Loss of standing biomass was most apparent after tillage in autumn, 2004 or spring, 2005 and over winter in the no-tillage treatment (data not shown). Standing biomass in conventional and reduced tillage was similar across nearly all sample dates. However, minimum tillage consistently resulted in more standing biomass than conventional tillage prior to sowing wheat in September 2005. The importance of standing residue in controlling wind erosion has been emphasized by Bilbro and Fryrear (1994) who found that standing residue is nine times more effective in controlling wind erosion than prostrate residue. Thus, SAI (the projected area of standing stems into the wind) is a critical parameter in assessing wind erosion. Differences in SAI were apparent among the tillage treatments (Table 2). Tillage after wheat harvest in 2004 resulted in a reduction in SAI with no-tillage and minimum tillage resulting in a higher SAI than conventional and reduced tillage. The SAI of no-tillage decreased overwinter, likely as a result of decomposition of the stem leading to breakage (Stott et al., 1990; Tanaka, 1986). The SAI of the minimum tillage treatment remained higher than the reduced tillage treatment prior to the last rodweeding in the summer of 2005. At the time of the last rodweeding in August and sowing in September 2005, no differences were apparent in SAI among the conventional, minimum, and reduced tillage treatments. Differences in SAI after tillage in the spring of 2005 suggest that the soil subject to conventional and reduced tillage is more erodible than the soil subject to minimum tillage. Bilbro and Fryrear (1994) established

**Table 1**
Soil crust characteristics affected by tillage during the fallow phase of a wheat-fallow rotation in eastern Washington. The summer fallow phase of the rotation began after wheat harvest in August 2004 and ended with sowing wheat in September 2005.

| Crust characteristic | Tillage treatment | Date of sampling | | | | |
|---|---|---|---|---|---|---|
| | | 2004 | 2005 | | | |
| | | 16 Aug | 26 May | 12 Jul | 10 Aug | 8 Sep |
| Crust cover (%) | Conventional | 0b[α] | 83a | 0 | 0b | 0b |
| | Reduced | 0b | 73b | 0 | 0b | 0b |
| | Minimum | 63a | 75b | 0 | 0b | 0b |
| | No till | 58a | 55c | ND[β] | 58a | 60a |
| Crust thickness (mm) | Conventional | 0b | 9b | 0 | 0b | 0b |
| | Reduced | 0b | 12b | 0 | 0b | 0b |
| | Minimum | 34a | 11b | 0 | 0b | 0b |
| | No till | 30a | 57a | ND | 58a | 60a |

[α] Tillage treatments followed by same letter indicates no significant difference in crust characteristic on the date of sampling.
[β] ND indicates no data.

**Table 2**
Crop residue biomass characteristics affected by tillage during the fallow phase of a wheat-fallow rotation in eastern Washington. The summer fallow phase of the rotation began after wheat harvest in August 2004 and ended with sowing wheat in September 2005.

| Residue characteristic | Tillage treatment | Date of sampling | | | | |
|---|---|---|---|---|---|---|
| | | 2004 | 2005 | | | |
| | | 16 Aug | 26 May | 12 Jul | 10 Aug | 8 Sep |
| Residue biomass ($g\ m^{-2}$) | Conventional | 216b[α] | 60c | 33b | 29c | 28b |
| | Reduced | 276b | 115b | 54b | 48c | 50b |
| | Minimum | 369a | 151b | 113a | 86b | 56b |
| | No till | 439a | 329a | ND[β] | 253a | 260a |
| Prostrate residue cover (%) | Conventional | 33bc | 17c | 8c | 10c | 8c |
| | Reduced | 26c | 27b | 14b | 10c | 18bc |
| | Minimum | 37ab | 25b | 21a | 29b | 22b |
| | No till | 42a | 45a | ND | 42a | 40a |
| Silhouette area index ($m^2\ m^{-2}$) | Conventional | .105b | .005c | .003c | .004b | .006b |
| | Reduced | .116b | .003c | .006b | .006b | .007b |
| | Minimum | .196a | .014b | .014a | .007b | .009b |
| | No till | .205a | .073a | ND | .060a | .058a |

[α] Tillage treatments followed by same letter indicates no significant difference in residue biomass characteristic on the date of sampling.
[β] ND indicates no data.

a relationship between SLR and SAI and found that the relationship was dependent upon wind speed. For a range of wind speeds from 10 to 20 $m\ s^{-1}$, a SLR of 0.27–0.78 would be expected in conventional and reduced tillage as a result of maintaining a SAI of 0.005 $m^2\ m^{-2}$ after spring tillage. In contrast, a SLR of 0.07–0.61 is expected in minimum tillage as a result of maintaining a SAI of 0.014 $m^2\ m^{-2}$ after spring tillage. Thus, soil loss from conventional and reduced tillage is expected to be 25–285% higher than minimum tillage when considering only differences in SAI between treatments. Standing residue in no tillage appeared sufficient to control erosion over the range of wind speeds since a SLR of 0.0006–0.25 is expected in no-tillage as a result of maintaining a SAI of 0.073 $m^2\ m^{-2}$ in May 2005.

Tillage after wheat harvest enhanced random roughness, thus conventional and reduced tillage had greater random roughness compared to minimum and no tillage in August 2004 (Table 3). Minimum and no tillage, however, retained the structure of ridges that were created during the sowing operation the previous year (2003) and had greater ridge roughness as compared to reduced and conventional tillage. Ridge height in the minimum and no tillage treatments in August 2004 was about 45 mm (data not shown). Random roughness after spring tillage was similar and tended to decrease with additional tillage and sowing operations for the conventional, reduced, and minimum tillage treatments. Random roughness of no tillage decreased by 50% over winter; this was likely due to breakdown of surface aggregates from weather-related processes (e.g. raindrop impact, freeze-thaw). Random roughness of no tillage changed little after May 2005, likely a result of a lack of precipitation during the summer months in the Mediterranean climate of eastern Washington. Horning et al. (1998) found that the SLR was dependent upon residue cover and random roughness for soils of eastern Washington. Based upon their equation and our observations of residue cover and random roughness after spring tillage, the SLR was lowest for no tillage and highest for conventional tillage. The SLR ranged from 0.083 to 0.106 for no tillage and from 0.166 to 0.405 for conventional tillage across the four sample dates in 2005. Differences in the SLR suggest that soil loss from conventional tillage would be 2–4 times higher than from no tillage. However, the measured soil and PM10 loss from conventional tillage was, respectively 6–12 times and 2–18 times higher than from no tillage across the four sample dates in 2005 (Sharratt et al., 2010). Our observations of differences in soil loss between conventional and no tillage may be greater than estimates based upon Horning et al. due to the presence of a soil crust in no tillage. In the absence of a soil crust, estimates of the SLR based upon Horning et al. (1998) suggest that soil loss from conventional tillage would be 2–3 times that from minimum tillage after the two rodweedings and sowing operation in 2005. Similarly, the measured soil loss from conventional tillage after the rodweedings and sowing operation was about twice that from minimum tillage (Sharratt et al., 2010).

Soil aggregate size has a profound influence on wind erosion and dust emissions since larger aggregates are less erodible at a given wind speed. We found that more intense tillage operations

**Table 3**
Soil surface roughness characteristics affected by tillage during the fallow phase of a wheat-fallow rotation in eastern Washington. The summer fallow phase of the rotation began after wheat harvest in August 2004 and ended with sowing wheat in September 2005.

| Roughness characteristic | Tillage treatment | Date of sampling | | | | |
|---|---|---|---|---|---|---|
| | | 2004 | 2005 | | | |
| | | 16 Aug | 26 May | 12 Jul | 10 Aug | 8 Sep |
| Ridge roughness (mm) | Conventional | 0b[α] | 0b | 0a | 0b | 69a |
| | Reduced | 0b | 0b | 0a | 0b | 65a |
| | Minimum | 30a | 0b | 0a | 0b | 76a |
| | No till | 28a | 23a | ND[β] | 22a | 20b |
| Random roughness (mm) | Conventional | 26.1a | 18.2a | 14.4a | 10.5a | 9.7a |
| | Reduced | 17.0b | 14.8b | 14.4a | 13.1a | 10.1a |
| | Minimum | 7.4c | 14.1b | 16.4a | 12.4a | 10.6a |
| | No till | 9.4c | 4.7c | ND | 4.6b | 4.7b |

[α] Tillage treatments followed by same letter indicates no significant difference in roughness characteristic on the date of sampling.
[β] ND indicates no data.

tended to result in smaller mean aggregate sizes (Table 4). The geometric mean diameter of aggregates of reduced and conventional tillage was similar throughout much of the summer fallow period. Minimum tillage resulted in larger aggregates as compared with conventional tillage during the early fallow period. However, after the final rodweeding and sowing operation, all tillage treatments except no tillage resulted in a similar mean aggregate size.

The erodible fraction, or fraction of soil mass with aggregates <0.84 mm in diameter, is an important parameter in quantifying wind erosion because aggregates $\geqslant$0.84 mm are not subject to erosion by wind (Chepil, 1942). The erodible fraction was similar for the conventional, reduced, and minimum tillage treatments during the fallow period. After the July rodweeding, the erodible fraction of these tillage treatments tended to be $\geqslant$0.4. Conventional tillage appeared to be the only tillage treatment potentially at risk to wind erosion; the erodible fraction of conventional tillage approached 0.6 after sowing, suggesting that this treatment poses a serious risk to wind erosion (Campbell et al., 1993). In contrast, the erodible fraction of no tillage was $\leqslant$0.3 and lower than other tillage treatments throughout much of the fallow period.

Soil strength, as reflected in penetration resistance, was greatly affected by tillage treatments (Table 4). Tillage after wheat harvest in August 2004 reduced soil strength such that strength was greater for minimum and no tillage as compared to conventional and reduced tillage. For treatments subject to tillage, tillage intensity appeared to have no influence on soil strength. This is supported by the similarity in strength for conventional, reduced, and minimum tillage after spring tillage. Soil strength in no tillage appeared to increase overwinter and then remained steadily high during the remainder of the fallow period. This increase in strength in no tillage may be due to an increase in crust thickness over winter. Soil strength is also influenced by bulk density and water content (Bradford, 1986), but bulk density and soil water content and potential did not appear to change appreciably in no tillage during this study (Table 5). In fact, bulk density, soil water content, and soil water potential did not vary across tillage treatments during this study. Soil water content was below 0.02 g $g^{-1}$ and water potential was below −200 MPa in all tillage treatments across all sample dates. Data of Bisal and Hsieh (1966) suggest that soil wetness has no effect on threshold friction velocity, and therefore on erosion since erosion is proportional to the difference between friction velocity and threshold friction velocity, of loam-textured soils at water contents below 0.035 g $g^{-1}$. Cornelis et al. (2004) observed little change in threshold friction velocity of loam-textured soils at water contents below 0.01–0.02 g $g^{-1}$ while Fecan et al. (1999) reported no change in threshold friction velocity of loam-textured soils in response to wetness at water contents below 0.02 g $g^{-1}$. Thus, variations in soil wetness across sample dates likely had little or no impact on soil erodibility in this study.

Differences in soil surface characteristics among tillage treatments were used to estimate relative differences in horizontal sediment transport according to the Revised Wind Erosion Equation (Fryrear et al., 2000). The equation is described by:

**Table 4**
Soil aggregation and penetration resistance characteristics affected by tillage during the fallow phase of a wheat-fallow rotation in eastern Washington. The summer fallow phase of the rotation began after wheat harvest in August 2004 and ended with sowing wheat in September 2005.

| Soil characteristic | Tillage treatment | Date of sampling | | | | |
|---|---|---|---|---|---|---|
| | | 2004 | 2005 | | | |
| | | 16 Aug | 26 May | 12 Jul | 10 Aug | 8 Sep |
| Geometric mean diameter (mm) | Conventional | 36.6b[α] | 12.1b | 1.6b | 1.5b | 0.7b |
| | Reduced | 69.5ab | 22.6ab | 14.5a | 2.9b | 2.0b |
| | Minimum | 78.5a | 49.1ab | 11.0a | 5.2b | 2.4b |
| | No till | 86.4a | 71.1a | ND[β] | 36.4a | 41.1a |
| Erodible fraction | Conventional | 0.13a | 0.30a | 0.48a | 0.46a | 0.59a |
| | Reduced | 0.10a | 0.31a | 0.39b | 0.45ab | 0.51a |
| | Minimum | 0.17a | 0.31a | 0.40ab | 0.40ab | 0.48a |
| | No till | 0.15a | 0.24b | ND | 0.32b | 0.30b |
| Penetration resistance (kPa) | Conventional | 7b | 18b | 2b | 6b | 6b |
| | Reduced | 14b | 21b | 3b | 7b | 8b |
| | Minimum | 514a | 26b | 2b | 8b | 8b |
| | No till | 558a | 1496a | ND | 1411a | 1400a |

[α] Tillage treatments followed by same letter indicates no significant difference in roughness characteristic on the date of sampling.
[β] ND indicates no data.

**Table 5**
Soil water content and potential at 0–5 mm depth and bulk density at 0–30 mm depth affected by tillage during the fallow phase of a wheat-fallow rotation in eastern Washington. The summer fallow phase of the rotation began after wheat harvest in August 2004 and ended with sowing wheat in September 2005.

| Soil characteristic | Tillage treatment | Date of sampling | | | | |
|---|---|---|---|---|---|---|
| | | 2004 | 2005 | | | |
| | | 16 Aug | 26 May | 12 Jul | 10 Aug | 8 Sep |
| Soil water content ($g\ g^{-1}$) | Conventional | 0.008a[α] | 0.016a | 0.017a | 0.018a | 0.017a |
| | Reduced | 0.008a | 0.015a | 0.016ab | 0.017a | 0.014a |
| | Minimum | 0.009a | 0.016a | 0.013b | 0.017a | 0.016a |
| | No till | 0.008a | 0.018a | ND[β] | 0.015a | 0.014a |
| Soil water potential (MPa) | Conventional | −295a | −225a | −236a | −248a | −234a |
| | Reduced | −300a | −220a | −220a | −259a | −244a |
| | Minimum | −289a | −226a | −258a | −259a | −220a |
| | No till | −302a | −212a | ND | −301a | −270a |
| Bulk density ($m^3\ m^{-3}$) | Conventional | 1.13a | 1.05a | 1.14a | 1.16a | 1.14a |
| | Reduced | 1.09a | 1.04a | 1.08b | 1.16a | 1.13a |
| | Minimum | 1.06a | 1.01a | 1.07b | 1.12a | 1.11a |
| | No till | 1.09a | 1.02a | ND | 1.13a | 1.12a |

[α] Tillage treatments followed by same letter indicates no significant difference in roughness characteristic on the date of sampling.
[β] ND indicates no data.

**Table 6**
Revised Wind Erosion Equation (RWEQ) parameters used to estimate maximum horizontal sediment flux from four tillage treatments in eastern Washington. Sediment flux was estimated on the day soil characteristics were measured during the fallow phase of a wheat-fallow rotation.

| Date | Tillage | RWEQ parameters[α] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | WF[β] ($kg\ m^{-1}$) | EF | SCF | $K$ | $SLR_f$ | $SLR_s$ | $Q_{max}$ ($kg\ m^{-1}$) |
| 16 Aug 2004 | Conventional | 0.1 | 0.13 | 1 | 0.82 | 0.25 | 0.06 | 0.016 |
| | Reduced | 0.1 | 0.10 | 1 | 0.86 | 0.33 | 0.04 | 0.014 |
| | Minimum | 0.1 | 0.17 | 0.46 | 0.92 | 0.20 | 0.02 | 0.003 |
| | No till | 0.1 | 0.15 | 0.46 | 0.91 | 0.17 | 0.01 | 0.001 |
| 26 May 2005 | Conventional | 0.3 | 0.30 | 0.46 | 0.86 | 0.49 | 0.65 | 1.259 |
| | Reduced | 0.3 | 0.31 | 0.46 | 0.88 | 0.31 | 0.75 | 0.982 |
| | Minimum | 0.3 | 0.31 | 0.46 | 0.88 | 0.34 | 0.45 | 0.631 |
| | No till | 0.3 | 0.24 | 0.46 | 0.94 | 0.14 | 0.10 | 0.047 |
| 12 Jul 2005 | Conventional | 0.1 | 0.48 | 1 | 0.88 | 0.71 | 0.75 | 2.468 |
| | Reduced | 0.1 | 0.39 | 1 | 0.88 | 0.55 | 0.65 | 1.341 |
| | Minimum | 0.1 | 0.40 | 1 | 0.87 | 0.40 | 0.45 | 0.683 |
| | No till | 0.1 | ND[γ] | ND | ND | ND | ND | ND |
| 10 Aug 2005 | Conventional | 0.1 | 0.46 | 1 | 0.90 | 0.65 | 0.72 | 2.120 |
| | Reduced | 0.1 | 0.45 | 1 | 0.89 | 0.64 | 0.63 | 1.781 |
| | Minimum | 0.1 | 0.40 | 1 | 0.89 | 0.32 | 0.60 | 0.760 |
| | No till | 0.1 | 0.32 | 0.46 | 0.94 | 0.08 | 0.10 | 0.013 |
| 8 Sep 2005 | Conventional | 0.2 | 0.59 | 1 | 0.91 | 0.72 | 0.64 | 5.415 |
| | Reduced | 0.2 | 0.51 | 1 | 0.90 | 0.47 | 0.61 | 2.899 |
| | Minimum | 0.2 | 0.48 | 1 | 0.90 | 0.43 | 0.55 | 2.251 |
| | No till | 0.2 | 0.30 | 0.46 | 0.94 | 0.07 | 0.09 | 0.017 |

[α] WF is weather factor, EF is erodible fraction, SCF is soil crust factor, K is soil roughness factor, $SLR_f$ and $SLR_s$ are, respectively the soil loss ratio for flat and standing residue, and $Q_{max}$ is the maximum horizontal sediment flux.
[β] Values are for a 24 h period.
[γ] ND indicates no data.

$$Q_{max} = 109.8(WF^{*}EF^{*}SCF^{*}K^{*}SLR_f^{*}SLR_s) \qquad (3)$$

where $Q_{max}$ is the maximum horizontal flux of windblown sediment ($kg\ m^{-1}$), WF is the weather factor ($kg\ m^{-1}$), EF is the erodible fraction, SCF is the soil crust factor, $K$ is the soil roughness factor, and $SLR_f$ and $SLR_s$ are, respectively the SLR for flat and standing residue. The WF was derived from RWEQ using data from Moses Lake, Washington, which is nearest (within 50 km) of all weather stations in the RWEQ database to our experimental plots. The SCF was derived from clay and organic matter content and $K$ was determined from random roughness (Table 3) according to Fryrear et al. (1998a). $K$ also depends on ridge roughness, but we assumed that prevailing winds were parallel to ridges and thus did not affect sediment transport. The $SLR_f$ and $SLR_s$ were respectively determined from residue cover and SAI (Table 2) according to Fryrear et al. (1998a). $Q_{max}$ was greater for conventional tillage than other tillage treatments throughout the summer fallow period in this study. For example, $Q_{max}$ for conventional tillage was 15–85% greater than for reduced tillage (Table 6). In addition, $Q_{max}$ for conventional tillage was 100–435% greater than for minimum tillage with the largest difference occurring after tillage in August 2004. No tillage resulted in the lowest $Q_{max}$ after spring tillage and throughout the remainder of the summer fallow period. This is particularly evident after sowing in September 2005 when $Q_{max}$ for no tillage was, respectively 130, 170, and 320 times smaller than for minimum, reduced, and conventional tillage. These results suggest that differences in soil aggregation, surface roughness, and residue biomass among tillage treatments likely influence horizontal sediment transport during high winds. For those treatments subject to tillage in this study, our analysis of soil surface characteristics revealed that only residue cover consistently differed among treatments, particularly for the duration of the fallow period after spring tillage (Table 2). Most noteworthy is the higher residue cover in minimum tillage versus conventional tillage. Based upon the measured differences in residue cover of tillage treatments after spring tillage, and assuming no differences in other soil characteristics among treatments, we found that $Q_{max}$ of conventional tillage was 0–50% higher than reduced tillage and 65–100% higher than minimum tillage.

Horizontal sediment transport estimated for our loessial soil by RWEQ (Table 6) appears relatively small compared to transport estimated by RWEQ for other soil types. Fryrear et al. (1998b), for example, reported $Q_{max}$ of 5–1240 kg $m^{-1}$ at 10 locations representative of soils ranging in texture from fine sand to silt loam across the central and western United States. They report a $Q_{max}$ of 234 kg $m^{-1}$ for a fine sand near Mabton, Washington, which is large compared to $Q_{max}$ in this study. Sharratt et al. (2007) observed that sediment flux from eroding loessial soils of the Columbia Plateau was very small compared to other regions of the United States. The small sediment fluxes from eroding loessial soils within the Columbia Plateau may be a consequence of the small particles comprising airborne sediment. Indeed, Sharratt (2011) observed that >90% of sediment in transport was <100 μm in diameter and that airborne sediment was characterized by a geometric mean diameter of 25 μm.

## 4. Conclusions

Tillage intensity affects wind erosion and PM10 emissions of soils managed in a wheat-fallow rotation in eastern Washington. Sediment transport is generally greater from conventional tillage and least from no tillage. Tillage altered the physical characteristics of the soil surface with more intense tillage (conventional tillage) consistently resulting in lower residue cover than less intense tillage (minimum tillage). No other surface characteristics consistently differed among conventional, reduced, and minimum tillage after spring tillage to the end of the fallow period. Based upon residue cover measured toward the end of the fallow period, a SLR of 0.65 would be expected for conventional tillage as a result of maintaining 10% residue cover whereas a SLR of 0.35 is expected for minimum tillage as a result of maintaining 25% residue cover. Sediment transport estimated by RWEQ was at least 0.15, 2, and 15 times higher for conventional tillage than from respectively reduced, minimum, and no tillage. These results emphasize the importance of maintaining surface residue when subjecting soils to tillage during the summer fallow phase of a wheat-fallow rotation in the Columbia Plateau.

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