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Windblown dust affected by tillage intensity during summer fallow

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ABSTRACT

Winter wheat–summer fallow is the conventional crop rotation used on more than 1.5 million ha of agricultural land in the low precipitation zone of the Columbia Plateau in the Pacific Northwest United States. This land is very susceptible to wind erosion during summer fallow because multiple tillage operations during fallow degrade and expose the soil to high winds. We examined possible alternatives to conventional tillage for reducing the emission of windblown PM10 (particulate matter $\leqslant$10 μm in aerodynamic diameter) during summer fallow. Soil was subject to seven (conventional), five (reduced), three (delayed-minimum), and zero (no) tillage operations between harvest in July 2004 and sowing in August 2005. Sediment catch and PM10 concentration and wind speed profiles were measured after each tillage operation and sowing under simulated high winds (using a portable wind tunnel) to estimate horizontal sediment and PM10 flux. Horizontal sediment and PM10 flux generally decreased with a decrease in number or intensity of tillage operations. No tillage resulted in the lowest sediment and PM10 flux after most tillage operations; no tillage, however, is not yet an economically viable management option for the region. Sediment and PM10 flux were typically lower for reduced and delayed-minimum tillage than for conventional tillage. Our study suggests that PM10 flux can be reduced from agricultural soils during the summer fallow phase of a wheat–fallow rotation by using reduced or delayed-minimum tillage practices. The reduction in PM10 flux from soils will improve air quality during high winds in the region.

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1. Introduction

Air quality within the Columbia Plateau region of the Pacific Northwest United States is impacted by the emission of fine particulates or dust from agricultural lands during high wind events. In fact, windblown dust emanating from agricultural lands has been the cause of vehicular accidents due to poor visibility (Graman, 2009; Hudson and Cary, 1999) and exceedance of the US Environmental Protection Agency ambient air quality standard for PM10 (particulate matter $\leqslant$10 μm in aerodynamic diameter) in the region (Sharratt and Lauer, 2006). Although PM10 is regulated to protect human health, the loss of soil particulates during high wind events is also of concern for the sustainability of the soil resource for the production of agricultural crops. The finer soil fraction suspended and transported in the atmosphere by high winds (e.g. <100 μm in diameter) is generally enriched with organic matter and nutrients and thus represents the most fertile part of the soil resource (Zhang et al., 2003).

Winter wheat–summer fallow is the conventional crop rotation used on more than 1.5 million ha of land in the low precipitation zone (annual precipitation <300 mm) of the Columbia Plateau. Conventional summer fallow typically includes cultivating the soil with sweeps, disks, or cultivators after wheat harvest in mid-summer and again the following spring and then rodweeding the soil to control weeds prior to sowing winter wheat in late summer (Schillinger, 2001). Summer fallow is vital to the stability of wheat production and farm profitability as compared to alternative management systems such as no-tillage annual cropping systems (Schillinger and Young, 2004). Enhanced stability in production is achieved by the successful establishment of winter wheat sown into moist soil in late summer (Schillinger et al., 2006). A moist soil layer at the depth of sowing (about 0.1 m) is made possible by maximizing the storage of precipitation during the preceding winter and then suppressing soil evaporation as precipitation diminishes from spring into late summer. Soil evaporation is suppressed by breaking capillary continuity in the upper soil profile via tillage (Schillinger and Papendick, 1997). Although conventional tillage practices are very effective in conserving soil water during the fallow phase of the rotation, soils are very susceptible to erosion during summer fallow because multiple tillage operations degrade soil aggregates and bury crop residue.

Few studies have measured the windblown loss of top soil or flux of dust or PM10 from agricultural lands managed under

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contrasting tillage systems. Gillette et al. (1972) measured wind-blown fine particulate (⩽6 μm in aerodynamic diameter) emissions from an eroding agricultural field in Nebraska, but contrasting experimental treatments (i.e. tillage) were not imposed upon the field. Sharratt and Feng (2009) compared soil loss and PM10 flux from adjacent fields, managed using conventional tillage (spring disk followed by rodweeding) and undercutter tillage (spring undercut followed by rodweeding) during the summer fallow phase of a wheat–fallow rotation, over a series of high wind events in the Columbia Plateau. They found undercutter tillage reduced soil loss and PM10 emissions by 15–75% across the high wind events as compared to conventional tillage. Although Merrill et al. (1999) did not measure the emission of windblown dust, they did ascertain by simulation that undercutter tillage has the potential to reduce dust emissions in the Northern Great Plains of the United States. Zobeck et al. (1989) found greater windblown soil emissions from a tilled field than from an abandoned field or burned/unburned rangeland in the Southern High Plains of the United States, but their study lacked the rigor to compare emissions from contrasting tillage systems.

Developing strategies to mitigate wind erosion and PM10 emissions is imperative to conserving the soil resource and improving air quality within the Columbia Plateau. Recognizing that tillage is vital for maintaining a soil layer (or soil mulch) that suppresses soil evaporation during the fallow phase of a wheat–fallow rotation, we examine possible alternatives to conventional tillage for minimizing the emission of windblown PM10 during summer fallow within 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; elevation 515 m). Lind is a small agricultural community (population ∼500) that is surrounded by land predominately in a winter wheat–summer fallow rotation. The Station receives 240 mm of annual precipitation and the soil at the study site was derived from loess, classified according to the United States Department of Agriculture National Cooperative Soil Survey as a Ritzville silt loam (coarse-silty, mixed, mesic Andic Aridic Haplustoll), and had a measured composition of 13% clay, 60% silt, and 27% sand with a mean particle diameter of 24 μm.

2.1. Tillage treatments

The study site at the Dryland Research Station was in a non-irrigated 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 during summer fallow included: (1) *conventional tillage*: Plots were cultivated to a depth of 0.1 m using overlapping 0.36-m wide V-blades in August 2004, chiseled to a depth of 0.3 m in October 2004, cultivated twice to a depth of 0.1 m using overlapping 0.2-m wide V-blades in May 2005, and rodweeded to a depth of 0.1 m in June, July, and August 2005; (2) *reduced tillage*: Plots were undercut to a depth of 0.1 m using overlapping 0.8-m wide V-blades in August 2004 and May 2005 and then rodweeded to a depth of 0.1 m in June, July, and August 2005; (3) *delayed-minimum tillage*: Plots were undercut to a depth of 0.1 m using overlapping 0.8-m wide V-blades in May 2005 and then rodweeded to a depth of 0.1 m in July and August 2005; and (4) *no tillage*: Plots remained undisturbed throughout the fallow period. Tillage operations occurring in the same month across treatments were performed on the same day of the month. Conventional tillage and delayed-minimum tillage, as described above, are practices used by many growers in the region (Schillinger et al., 2006).

Individual plots were either 9 or 18 m wide (depending on the width of tillage equipment) and 30 m long. Plots were sown to winter wheat with a deep furrow drill on 31 August 2005. Seed rows were spaced 0.4 m apart and oriented north-south.

2.2. Sediment and dust flux

Horizontal sediment and dust flux were typically assessed one day after tilling, rodweeding, and sowing plots using a portable wind tunnel. The portable wind tunnel is 13.4 m long and has a working section 7.3 m long, 1.2 m high, and 1.0 m wide. Winds are generated by a 1.4-m diameter fan and then conditioned by a diffuser and honeycomb-screen prior to passing through a non-uniform grid assembly to initiate the development of shear flow upon entry into the working section. Further details about the wind tunnel design and aerodynamic characteristics can be found in Pietersma et al. (1996) and Sharratt (2007). The wind tunnel required partial dismantling to facilitate moving between plots; the time required to set up the wind tunnel, measure emissions and soil characteristics, and partially dismantle the tunnel in each plot was about two hours. Soil characteristics measured during the course of this experiment are the subject of a forthcoming paper that describes the soil properties as influenced by tillage intensity. For the purpose of this paper, soil crust thickness was measured with a ruler or caliper. Crop residue cover was estimated by placing vertical rods (6 mm) equidistant along the soil surface and determining the percentage of pins that overly residue (versus mineral soil). Above-ground biomass was assessed by collecting, drying, and weighing crop residue from 0.25 m^2 areas within each plot.

Sediment catch and PM10 concentration were measured 5.4 m downwind of the leading edge of the wind tunnel working section. Horizontal sediment catch to a height of 0.75 m, resulting from saltation and suspension, was measured using a modified Bagnold type slot sampler (Stetler et al., 1997). The width of the slot sampler was adjustable for achieving isokinetic conditions across the face of the sampler over a range of wind velocities. The slot sampler was calibrated in the wind tunnel prior to the field experiment to ensure isokinetic conditions at a free stream velocity of 16 m s^{-1}. We chose to assess horizontal sediment and PM10 flux at this free stream velocity based upon a recurrence of at least once every two years for the region (Wantz and Sinclair, 1981). Horizontal sediment flux is the amount of entrainment sediment moving through a vertical plane over a period of time and is expressed as the ratio of sediment mass collected by the slot sampler to the sampling period (10 min as described below) and width of the sampler (∼0.003 m). PM10 concentration was optically measured at a frequency of 1 Hz using DustTrak aerosol monitors (TSI, St. Paul, MN) with monitor inlets mounted at heights of 0.05, 0.1, 0.2, and 0.3 m above the soil surface. Monitors were factory calibrated prior to this experiment and inlets were constructed of stainless steel tubing and attached to the monitors using tygon tubing. The diameter of the stainless steel tubing and monitor flow rate were adjusted to achieve a known face velocity across the inlet. A single face velocity was used to achieve isokinetic conditions at 0.2 m height within the boundary layer. Aerosol monitors at greater heights in the boundary layer would under sample PM10 while monitors at lower heights would over sample PM10. No adjustments were made to PM10 concentrations despite these differences in sampling efficiency with height. Background PM10 concentration was also measured at the leading edge of the tunnel working section.

Following deployment of the wind tunnel (parallel to stubble rows of no tillage plots and seed rows after sowing plots to winter wheat), sediment catch and PM10 concentrations were measured over two separate, but consecutive, 10 min sampling periods in each plot. The first sampling period typified field conditions with limited saltation (no abrader was added to the air stream) while the second period typified field conditions with copious saltation. During the second sampling period, abrader (quartz sand 250-500 μm in diameter) was introduced into the air steam at the leading edge of the tunnel working section at a rate of about 0.5 g m^{-1} s^{-1}; this rate typifies the flux of soil during high winds across the Columbia Plateau.

Horizontal PM10 flux from the working section of the wind tunnel was calculated as:

$$PM10_{flux} = \int_0^{z_b} Cu dz \quad (1)$$

where $PM10_{flux}$ is horizontal flux of PM10 expressed in units of g m^{-2} s^{-1}, z_b is height at which PM10 concentrations reached background concentrations (m), C is PM10 concentration above background concentration (mg m^{-3}), and u is wind speed at height z (m s^{-1}). Wind speed was measured at a frequency of 1 Hz using pitot tubes mounted at heights corresponding to aerosol monitor inlets. The use of pitot tubes necessitated measuring air temperature, relative humidity, and atmospheric pressure at a height of 2 m near the tunnel entrance to compute wind speed. Eq. (1) was evaluated by plotting PM10 flux (the product of C and u) as a function of height. Horizontal PM10 flux was determined by integrating this function from the soil surface to the height at which PM10 concentrations reached background concentration. Sampling height was plotted as a function of PM10 concentration and fit with an exponential equation to determine the height at which profile concentrations attained background concentration.

2.3. Statistics

Horizontal sediment and PM10 flux from tillage treatments were analyzed for differences using Analysis of Variance. In the event that significant F-values ($P \leqslant 0.1$) were found, differences among treatment means were separated using Least Significant Difference (LSD).

3. Results and discussion

Our intention was to assess horizontal sediment and PM10 flux immediately after tillage operations in August 2004 and May 2005 and rodweeding and sowing operations in 2005 using the portable wind tunnel. Unfortunately, intermittent precipitation events and high winds delayed ascertaining horizontal sediment and PM10 flux from tillage treatments for 24 days after tillage in May 2005 (tillage occurred on 2 May). Precipitation occurred on 12 days (totaling 24 mm) while sustained winds (hourly mean wind velocities) in excess of 6.5 m s^{-1}, sufficient to cause erosion (Sharratt et al., 2007), occurred on three additional days prior to assessing sediment and PM10 flux on 26 May 2005. Intermittent precipitation events and high winds also precluded ascertaining sediment and PM10 flux from tillage treatments after the June 2005 rodweeding operation. Precipitation (totaling 15 mm) occurred on six days while sustained winds in excess 6.5 m s^{-1} occurred on 10 additional days between the 13 June and 11 July rodweeding operations. Herbicide application prevented measuring sediment flux and PM10 concentrations from no tillage treatments after the 11 July 2005 rodweeding operation.

3.1. Sediment flux

An increase in dustiness of the tillage treatments with time is apparent in the trend of horizontal sediment flux across measurement dates (Table 1). Averaged across the conventional, reduced, and delayed-minimum tillage treatments, sediment flux (in the absence of abrader) increased by 105% between August 2004 and May 2005, 385% between May and July 2005, 25% between July and August 2005, and 55% between the August and September 2005. The 105% increase in horizontal sediment flux between the August 2004 and May 2005 measurement dates was smaller than we expected because sediment flux was believed to dramatically increase as a result of disturbing the soil surface by invasive tillage using narrow sweeps and chisels (conventional tillage) or wide sweeps (reduced and delayed-minimum tillage) in November 2004 and/or May 2005. However, a total of 24 mm of rain following tillage on 2 May 2005 resulted in the formation of a soil crust that suppressed sediment flux from tillage treatments on 26 May 2005. Similarly, the 385% increase in horizontal sediment flux between the May and July 2005 measurement dates was larger than we expected because sediment flux was believed to be little affected by rodweeding. The only disturbance to the soil occurring between these dates resulted from rodweeding on 13 June and 11 July. In fact, rodweeding in August 2005 resulted in only a 25% increase in sediment flux over the previous measurement date averaged across the conventional, reduced, and delayed-minimum tillage treatments. The large increase in sediment flux between the May and July 2005 measurement dates possibly resulted from breakage of the soil crust that formed after tillage in May 2005 (as a result of 24 mm of precipitation) and/or after rodweeding conventional and reduced tillage plots in June 2005 (as a result of 15 mm of precipitation).

Although an apparent increase in horizontal sediment flux with time was also observed for the conventional, reduced, and delayed-minimum tillage treatments under conditions of copious saltation (Table 1, with abrader), the largest increase in sediment flux occurred between the August 2004 and May 2005 measurement dates. Averaged across these tillage treatments, horizontal sediment flux after tillage in May 2005 was 670% higher than after tillage in August 2004. The increase in horizontal sediment flux after subsequent rodweeding or sowing operations in 2005 was about 50%. The large increase in sediment flux between the August 2004 and May 2005 measurement dates was contrary to our expectation that sediment flux would be suppressed, even under conditions of copious saltation, by the presence of a soil crust in May 2005. A soil crust with a thickness of about 10 mm was pres-

Table 1
Horizontal sediment flux from tillage treatments measured with a wind tunnel during the summer fallow period of a winter wheat–summer fallow rotation near Lind, WA.

Date of measurement[a]	Sediment flux (g m^{-1} min^{-1})[b]							
	Without abrader				With abrader			
	Conv[c]	Red	Min	No	Conv	Red	Min	No
16 August 2004	20a[d]	10ab	9b	8b	24a	7b	5b	9b
26 May 2005	23a	26a	22a	4b	127a	55b	50bc	17c
12 July 2005	150a	103ab	88b	ND	145a	93b	84b	ND
10 August 2005	210a	130b	93bc	38c	275a	101b	83bc	14c
8 September 2005	312a	149b	181b	25c	188a	169a	147a	23b

ND indicates no data.
[a] Measurements taken after primary tillage (16 August 2004 and 26 May 2005), rodweeding (12 July and 10 August 2005), and sowing (8 September 2005) operations.
[b] Sediment flux measured over two consecutive 10 min sampling periods; the first period without abrader and the second period with abrader added to the air stream.
[c] Conv is conventional, Red is reduced, Min is delayed-minimum, and No is no tillage.
[d] No abrader or abrader means followed by the same letter on same date are not significantly different at $P = 0.10$.

ent in the conventional, reduced, and delayed-minimum tillage treatments at the time of measurement on 26 May 2005. The largest increase in sediment flux was expected to occur between the May and July 2005 measurement dates due to the absence of a soil crust on the latter measurement date.

Horizontal sediment flux after tillage in August 2004 was higher for conventional tillage than for delayed-minimum and no tillage (Table 1). No differences in sediment flux were observed among reduced, delayed-minimum, and no tillage despite reduced tillage being undercut by 0.8-m wide sweeps whereas delayed-minimum and no tillage remained undisturbed in August 2004. The undercutter implement does not invert the soil and thus promotes retention of crop residue on the soil surface (Sharratt and Feng, 2009). After tillage in May 2005, horizontal sediment flux was lower from no tillage than other tillage treatments while sediment flux was the same among conventional, reduced, and delayed-minimum tillage treatments. The similarity in sediment flux among these three tillage treatments was due to a 10-mm thick crust that had formed on the soil surface of these treatments in response to 24 mm of rain that occurred between the time of tillage (2 May 2005) and our measurements (26 May 2005). Under conditions of copious saltation, however, sediment flux in May 2005 was higher for conventional tillage than for reduced and delayed-minimum tillage. The higher sediment flux observed for conventional tillage suggests that the crusted soil of conventional tillage was either less protected from saltating particles or less resistant to breakage or degradation by saltating particles. Less protection was afforded the crusted soil in conventional tillage because crop residue cover was 5% for conventional tillage, 10% for reduced and delayed-minimum tillage, and 45% for no tillage. In addition, total above-ground biomass was about 50 g m^{-2} for conventional tillage, 150 g m^{-2} for reduced and delayed-minimum tillage, and 350 g m^{-2} for no tillage in May 2005. Horizontal sediment flux after rodweeding in August 2005 and sowing in September 2005 tended to be higher for conventional tillage and lower for no tillage under condition of limited and copious saltation. In addition, no differences in sediment flux were evident between reduced and delayed-minimum tillage despite reduced tillage being subject to two additional tillage operations (undercut in August 2004 and rodweeded in June 2005) than delayed-minimum tillage. The lack of difference in sediment flux between reduced and delayed-minimum tillage after sowing in September 2005 is likely due to similarities in surface characteristics of tillage treatments. Crop residue cover and above-ground biomass, for example, were respectively about 10% and 50 g m^{-2} for both tillage treatments.

3.2. PM10 flux

Differences in horizontal sediment flux among tillage treatments after tillage, rodweeding, and sowing operations strongly suggested that horizontal PM10 flux also varied among tillage treatments since sediment and PM10 flux are related for soils of the Columbia Plateau (Saxton et al., 2000). Indeed, differences in horizontal PM10 flux were found among tillage treatments (Table 2) and originated from differences in PM10 concentration (see Eq. (1)). The time series in PM10 concentration observed at various heights in the wind tunnel during subsequent 10 min sampling periods appeared quite different among tillage treatments. This is exemplified for PM10 concentrations measured during periods of limited and copious saltation in the wind tunnel after rodweeding in August 2005 (Fig. 1). PM10 concentrations measured under limited saltation increased almost instantaneously and then rapidly decreased during the sampling period. The magnitude of rise in PM10 concentration at the beginning of the sampling period diminished with height. Relatively little change in PM10 concentration at any height was noticed in the no tillage treatment. PM10 concentrations measured under copious saltation remained nearly constant for the duration of the sam-

Table 2
Horizontal PM10 flux from tillage treatments measured with a wind tunnel after tillage, rodweeding, and sowing operations during the summer fallow period of a winter wheat–summer fallow rotation near Lind, WA.

Date of measurement[a]	PM10 flux (g m^{-1} min^{-1})[b]							
	Without abrader				With abrader			
	Conv[c]	Red	Min	No	Conv	Red	Min	No
16 August 2004	2.2a[d]	1.2b	0.8b	0.7b	2.2a	1.1b	1.0b	1.6ab
26 May 2005	0.2a	0.2a	0.2a	0.1b	0.7a	0.6ab	0.5ab	0.3b
12 July 2005	1.7a	0.7b	0.9ab	ND	1.4a	0.5b	0.8b	ND
10 August 2005	3.3a	2.0b	1.2bc	0.4c	1.9a	1.4ab	0.9ab	0.2b
8 September 2005	3.7a	2.0b	1.4bc	0.2c	1.9a	1.5a	1.3a	0.3b

ND indicates no data.
[a] Measurements taken after primary tillage (16 August 2004 and 26 May 2005), rodweeding (12 July and 10 August 2005), and sowing (8 September 2005) operations.
[b] PM10 flux measured over two consecutive 10 min sampling intervals, the first interval without abrader and the second interval with abrader added to the air stream.
[c] Conv is conventional, Red is reduced, Min is delayed-minimum, and No is no tillage.
[d] No abrader or abrader means followed by the same letter on same date are not significantly different at $P = 0.10$.

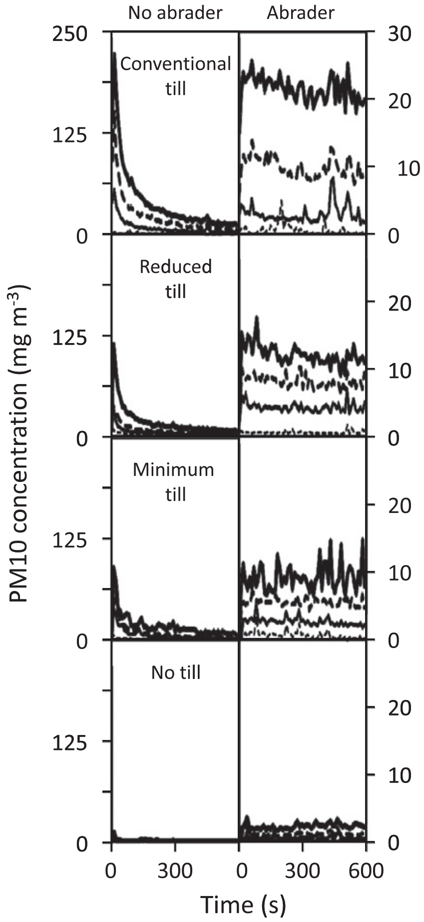

Fig. 1. Time series in PM10 concentration at 0.05, 0.1, 0.2, and 0.3 m above the soil surface (upper trend line is 0.05 m height and lower trend line is 0.3 m height) in conventional, reduced, delayed-minimum, and no tillage. PM10 trend lines represent one replication of tillage treatments taken in August 2005 over subsequent 10 min periods without and with abrader introduced in a wind tunnel.

pling period. PM10 concentrations were higher, particularly nearer the soil surface, for conventional tillage and lower for no tillage.

PM10 concentration profiles over the duration of the sampling period differed among the tillage treatments; this is exemplified for PM10 profiles measured after rodweeding in August 2005 (Fig. 2). Under conditions of limited saltation, PM10 concentration did not vary with height for no tillage and suggests vigorous mixing within the near surface boundary layer or very little PM10 that is freely available at the surface for suspension in the atmosphere. On the contrary, an apparent change in PM10 concentration with height was observed for the other tillage treatments. A more dramatic decrease in PM10 concentration with height was observed for conventional tillage than reduced and delayed-minimum tillage. Under conditions of copious saltation, PM10 concentration declined with height for all tillage treatments, including no tillage.

Differences in horizontal PM10 flux among tillage treatments (Table 2) paralleled differences in horizontal sediment flux among tillage treatments (Table 1). For instance, under conditions of limited saltation, horizontal PM10 flux after tillage in May 2005 was lower from no tillage than other tillage treatments while PM10 flux was the same for all other tillage treatments. In addition, horizontal PM10 flux was lowest from no tillage and highest from conventional tillage after rodweeding in August 2005. Subtle dissimilarities are noted, however, between treatment differences in horizontal sediment flux and horizontal PM10 flux. For example, although no difference was observed in horizontal sediment flux after tillage in August 2004 between conventional and reduced tillage, horizontal PM10 flux was higher for conventional tillage than reduced tillage. Likewise, although differences in horizontal sediment flux after rodweeding in July 2005 were observed between conventional and delayed-minimum tillage, differences in horizontal PM10 flux were only observed between conventional and reduced tillage. Under conditions of copious saltation, we also found similarities and dissimilarities between treatment differences in horizontal sediment flux and horizontal PM10 flux. For example, differences in horizontal PM10 flux among tillage treatments paralleled differences in horizontal sediment flux among tillage treatments after rodweeding in July 2005 and sowing in September 2005. Noteworthy, however, are differences in sediment and PM10 flux among treatments found after tillage in August 2004, tillage in May 2005, and rodweeding in August 2005. Although horizontal sediment flux was lower for no tillage than for conventional or reduced tillage, horizontal PM10 flux was the same for no tillage and conventional or reduced tillage. We expected that PM10 flux would be suppressed for no tillage more so than for other tillage treatments because of the greater protection afforded the soil surface by crop residue in the no tillage treatment.

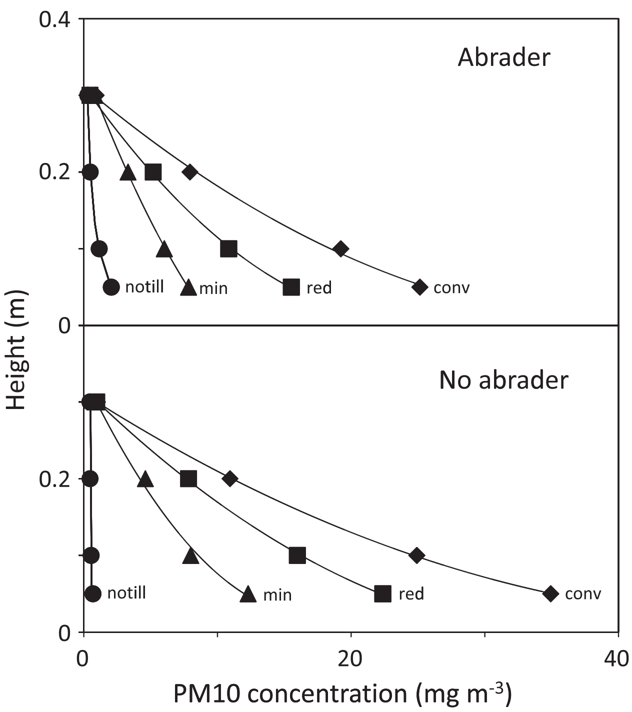

Fig. 2. PM10 concentration as a function of height above the soil surface of conventional (conv), reduced (red), delayed-minimum (min), and no tillage (notill) over subsequent 10 min periods without and with abrader introduced into the wind tunnel in August 2005. Each data point is an average of four replications.

The ratio of horizontal PM10 to sediment flux was determined for all tillage treatments to identify treatments in which the eroded sediment was enriched with finer soil material (i.e. PM10). The ratio of PM10 to sediment flux varied from about 0.01–0.17 across all treatments under conditions of limited saltation and from about 0.01–0.23 across all treatments under conditions of copious saltation (Table 3). Eroded sediment therefore appeared to be further enriched in PM10 as a result of stimulating saltation during high winds. Although differences in the ratio of PM10 to sediment flux existed among treatments after tillage in May, rodweeding in August, and sowing in September 2005, these differences were not consistent across measurement dates under conditions of limited saltation. In fact, the ratio was higher for the no tillage treatment than for the conventional and reduced tillage treatments after tillage in May 2005 but lower for no tillage than conventional and reduced tillage after rodweeding in August 2005. These results may have been affected by the presence or absence of a soil crust; a soil crust was apparent after tillage in May 2005 but not present after

Table 3
Ratio of horizontal PM10 to sediment flux measured after tillage, rodweeding, and sowing operations during the summer fallow period of a winter wheat–summer fallow rotation near Lind, WA.

Date of measurement[a]	Ratio[b]							
	Without abrader				With abrader			
	Conv[c]	Red	Min	No	Conv	Red	Min	No
16 August 2004	0.167a[d]	0.109a	0.118a	0.099a	0.113a	0.186a	0.184a	0.226a
26 May 2005	0.012b	0.009b	0.009b	0.083a	0.006b	0.011ab	0.010ab	0.023a
12 July 2005	0.011a	0.007b	0.010ab	ND	0.011a	0.006b	0.010a	ND
10 August 2005	0.016ab	0.019a	0.013bc	0.010c	0.007b	0.016b	0.018b	0.163a
8 September 2005	0.011ab	0.014a	0.008b	0.008b	0.011b	0.009b	0.009b	0.117a

ND indicates no data.
[a] Measurements taken after primary tillage (16 August 2004 and 26 May 2005), rodweeding (12 July and 10 August 2005), and sowing (8 September 2005) operations.
[b] Ratio over two consecutive 10 min sampling intervals, the first interval without abrader and the second interval with abrader added to the air stream.
[c] Conv is conventional, Red is reduced, Min is delayed-minimum, and No is no tillage.
[d] Abrader or no abrader means followed by the same letter on same date are not significantly different at $P = 0.10$.

rodweeding in August 2005. In the presence of a soil crust, and without a source of freely-available PM10 at the soil surface, fine soil particulates on the surface of wheat stubble may have been a source of enriching the eroded sediment with PM10 in no tillage. Differences in the ratio of PM10 to sediment flux among treatments under conditions of copious saltation, however, were consistent after tillage in May, rodweeding in July, and sowing in September 2005. The ratio was higher for no tillage than conventional tillage.

4. Conclusions

Horizontal sediment and PM10 flux as influenced by high winds were examined for various tillage practices that vary in intensity during the summer fallow phase of a winter wheat–summer fallow rotation. Sediment and PM10 flux appeared to diminish with a reduction in tillage intensity. The most intensive tillage, or conventional tillage which consists of sweep tillage after harvest and again the following spring followed by rodweeding and then sowing, generally resulted in higher sediment and PM10 flux compared to reduced or delayed-minimum tillage (undercut after harvest and/or the next spring followed by rodweeding and then sowing). No tillage typically resulted in the lowest flux of sediment and PM10. No tillage, however, is not yet an economically viable management option for the wheat–fallow region of the Columbia Plateau (Schillinger and Young, 2004). An alternate to conventional tillage to reduce sediment and PM10 flux during high wind events on the Columbia Plateau is reduced or delayed-minimum tillage whereby the soil is undercut after harvest and/or the following spring.

References

Gillette, D.A., Blifford Jr., I.H., Fenster, C.R., 1972. Measurements of aerosol size distributions and vertical fluxes of aerosols on land subject to wind erosion. J. Appl. Meteorol. 11, 977–987.

Graman, K., 2009. Winds bring dust, blackouts. The Spokesman Review, October 5, 2009, Page A6. Spokane, WA.

Hudson, T., Cary, A., 1999. Dust storm causes deadly pileup on I-84. Tri-City Herald Newspaper, September 26, 1999, A1. Kennewick, WA.

Merrill, S.D., Black, A.L., Fryrear, D.W., Saleh, A., Zobeck, T.M., Halvorson, A.D., Tanaka, D.L., 1999. Soil wind erosion hazard of spring wheat–fallow as affected by long-term climate and tillage. Soil Sci. Soc. Am. J. 63, 1768–1777.

Pietersma, D., Stetler, L.D., Saxton, K.E., 1996. Design and aerodynamics of a portable wind tunnel for soil erosion and fugitive dust research. Trans. ASAE 39, 2075–2083.

Saxton, K.E., Chandler, D., Stetler, L., Claiborn, C., Lee, B., 2000. Wind erosion and fugitive dust fluxes on agricultural lands in the Pacific Northwest. Trans. ASAE 43, 623–630.

Schillinger, W.F., 2001. Minimum and delayed conservation tillage for wheat–fallow farming. Soil Sci. Soc. Am. J. 65, 1203–1209.

Schillinger, W.F., Papendick, R.I., 1997. Tillage mulch depth effects during fallow on wheat production and wind erosion control factors. Soil Sci. Soc. Am. J. 61, 871–876.

Schillinger, W.F., Young, D.L., 2004. Cropping systems research in the world's driest rainfed wheat region. Agron. J. 96, 1182–1187.

Schillinger, W.F., Papendick, R.I., Guy, S.O., Rasmussen, P.E., Kessel, C.V., 2006. Dryland cropping in the western United States. In: Peterson, G.A., Unger, P.W., Payne, W.A. (Eds.), Dryland Agriculture. Agronomy Monograph, vol. 23. American Society of Agronomy, Madison, WI, pp. 365–393.

Sharratt, B., Lauer, D., 2006. Particulate matter concentration and air quality affected by windblown dust in the Columbia Plateau. J. Environ. Qual. 35, 2011–2016.

Sharratt, B.S., 2007. Instrumentation to quantify soil and PM10 flux using a portable wind tunnel. In: Proceedings of International Symposium on Air Quality and Waste Management for Agriculture, American Society Agricultural Biological Engineers, Publication Number 701P0907cd, St. Joseph, MI.

Sharratt, B., Feng, G., Wendling, L., 2007. Loss of soil and PM10 from agricultural fields associated with high winds on the Columbia Plateau. Earth Surf. Process. Landf. 32, 621–630.

Sharratt, B., Feng, G., 2009. Windblown dust influenced by conventional and undercutter tillage within the Columbia Plateau, USA. Earth Surf. Process. Landf. 34, 1323–1332.

Stetler, L., Saxton, K.E., Horning, L. 1997. Isokenetic sampling of eroded soil from a wind tunnel. ASAE Paper 97-2031. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Wantz, J.W., Sinclair, R.E., 1981. Distribution of extreme winds in the Bonneville Power Adminstration Service Area. J. Appl. Meteorol. 20, 1400–1411.

Zhang, M.K., He, Z.L., Calvert, D.V., Stoffella, P.J., Yang, X.E., Li, Y.C., 2003. Phosphorus and heavy metal attachment and release in sandy soil aggregate fractions. Soil Sci. Soc. Am. J. 67, 1158–1167.

Zobeck, T.M., Fryrear, D.W., Pettit, R.D., 1989. Management effects on wind-eroded sediment and plant nutrients. J. Soil Water Conserv. 44, 160–163.