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Soil properties governing soil erosion affected by cropping systems in the U.S. Pacific Northwest

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ABSTRACT

In the low-precipitation zone (<300 mm annual precipitation) of the inland US Pacific Northwest, no-tillage spring cereal rotations are being examined as alternatives to the traditional winter wheat–summer fallow rotation to control wind erosion. There is limited information, however, regarding the effects of no-tillage cropping systems on soil physical properties and surface characteristics that govern wind erosion in this semiarid region. The objective of this research was to characterize soil aggregates, wetness, strength, roughness, crusting, and crop residue cover and biomass of a silt loam that had been subject to various crop rotations for 11 years in east-central Washington. Crop rotations examined included no-tillage spring barley–spring wheat (NTSB/SW), no-tillage spring wheat–chemical fallow (NTSW/CF), and winter wheat–summer fallow (WW/SF). Soil physical properties were measured in spring 2006 after sowing wheat in the NTSB/SW rotation and in late summer 2006 after sowing winter wheat in the WW/SF and NTSW/CF rotations. In spring, the NTSB/SW and NTSW/CF rotations were characterized by a wetter soil as compared with the WW/SF rotation. In late summer, the NTSB/SW rotation was characterized by a soil surface with more standing stubble and greater crust cover and soil strength as compared with the WW/SF and NTSW/CF rotations. Our results suggest that spring-sown cereal and chemical fallow cropping systems result in wetter soils in spring and retain more surface residue in the late summer that will reduce the risk for wind erosion as compared with the traditional WW/SF rotation in the Pacific Northwest.

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1. Introduction

Winter wheat–summer fallow is the most common dryland crop rotation utilized in the inland U.S. Pacific Northwest where annual precipitation is less than 300 mm (Schillinger and Young, 2004). This rotation is characterized by a 13-month fallow period between the harvest and planting of wheat crops. Traditional summer fallow involves eight or more passes with various tillage implements to control weeds and conserve seed-zone soil water; this tillage-intensive system often creates a dry, loose bed of fine soil particles (Schillinger et al., 2007). Strong winds occur in spring and late summer/early autumn when soils are dry, fragile, and partially denuded (Papendick, 2004). Wind erosion causes soil degradation, poor visibility, and exposure to inhalable dust particulates that impair health in the region (Saxton et al., 2000). Alternative tillage and cropping systems are therefore sought for maintaining and improving soil and environmental quality.

Wind erosion of arable land is related to the physical properties and characteristics of the soil surface. Tillage and crop rotations play a key role in changing the physical properties of the soil surface. Changes in soil properties resulting from tillage and cropping systems are largely limited to the near-surface of the soil profile (Liebig et al., 2004; Mielke and Wilhelm, 1998; Wuest et al., 2006). Near-surface soil physical properties that affect soil erodibility include soil aggregation, surface shear strength and penetration resistance, bulk density, soil water content or potential, random roughness, and surface residue cover. Previous studies generally indicated that no-tillage and reduced tillage systems increase soil water content (Allmaras et al., 1973; Standford et al., 1973; Lal, 1982; Mengel et al., 1982; Diaz-Zorita et al., 2004), enhance soil aggregation and stability (Arshad et al., 1999; Mahboubi et al., 1993; Diaz-Zorita et al., 2004; Wuest et al., 2005; Dam et al., 2005; Hobbs, 2007), and increase penetration resistance (Mahboubi et al., 1993; Hill, 1990). Other researchers found soil strength was increased in transitioning from intensive tillage to no-till (Wilkins et al., 2002; Hammel, 1989; Voorhees and

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Lindstrom, 1983; Larney and Kladivko, 1989). No-tillage and reduced tillage systems generally result in greater bulk density and smaller soil porosity (Mahboubi et al., 1993; Hill, 1990; Dam et al., 2005; Kravchenko et al., 2006). We recognize, however, that opposite conclusions from those previously presented can be found in the literature. For example, studies have reported that no-tillage resulted in lower or no change in bulk density (Dao, 1993; Blevins et al., 1994; Fausey et al., 1994; Arshad et al., 1999; Mahboubi et al., 1993) and lower soil water content (Wilkins et al., 2002; Hammel et al., 1981).

The impact of crop rotations on soil properties remain poorly described (Baumhardt and Jones, 2002). Schillinger et al. (2007) also indicated that the effects of summer fallow on soil physical properties have not been widely documented in the drier areas of the western US. Therefore, an understanding of the changes in soil surface physical properties as affected by long-term tillage and cropping systems is needed to minimize the impact of field management on wind erosion and foster the use of sustainable agricultural practices (Franzluebbers, 2002; Benjamin et al., 2007). Although numerous studies have been conducted to investigate soil physical properties in more humid areas outside of the inland Pacific Northwest, the effects of crop rotations and no-tillage or reduced tillage are often site specific (Kennedy and Schillinger, 2006; Fuentes et al., 2004; Pedrotti et al., 2005; Blanco-Canqui et al., 2004; Arshad et al., 2002). Conclusions drawn from these studies are sometimes contradictory and confusing due to differences in antecedent conditions, inherent soil properties, crop rotation, prevailing climate, and duration of the study period (Ferreras et al., 2000; Lal and Van Doren, 1990).

A cropping systems experiment was initiated in east-central Washington in 1995 for identifying alternative cropping systems to replace the traditional winter wheat–summer fallow system. The aim of the experiment was to examine the economic and agronomic feasibility of no-tillage spring cropping systems as compared with winter wheat–summer fallow (Forte-Gardner et al., 2004; Young and Thorne, 2004) and to examine cursory soil surface characteristics and estimate wind erosion susceptibility for the dryland cropping systems (Thorne et al., 2003). These analyzes were conducted within three years of establishing the experiment. Thorne et al. (2003) assessed soil surface cover and soil roughness of the cropping systems, but failed to examine the suite of soil physical properties or surface characteristics of these cropping systems which govern soil erosion. The objective of our research was to determine the effect of long-term crop rotations on changes in a suite of soil physical properties that govern wind erosion in the low precipitation zone (<300 mm annual precipitation) of the inland Pacific Northwest

2. Materials and methods

Soil physical properties were measured in the spring and late summer of 2006 in an existing long-term dryland cropping systems experiment which was initiated in the summer of 1995 at a field site located near Ralston, Washington, USA (T 17N, R 35E; 46°55′N, 118°24′W). The soil is a Ritzville silt loam (coarse-silty, mixed, mesic, Calcidic Haploxeroll according to the USDA classification system) with a texture of 30% sand, 62% silt, and 8% clay. Organic matter in the top 30 cm averaged 2%. Annual precipitation is about 250 mm.

2.1. Establishment and maintenance of long-term treatments

Young and Thorne (2004) and Thorne et al. (2003, 2007) have previously described the establishment and maintenance of cropping systems at the field site. Long-term crop rotations were established on a relatively level field (about 1% slope) that was in the summer fallow phase of a winter wheat–summer fallow rotation. The experimental design was a randomized complete block with each rotation (plots were 9×69 m) replicated four times. Rotations examined in this study include: (1) winter wheat/summer fallow (WW/SF). Wheat harvest occurred in July followed by ~13 months of reduced-tillage summer fallow prior to sowing the next winter wheat crop, (2) no-tillage spring wheat/chemical fallow (NTSW/CF). Wheat harvest occurred in July followed by ~20 months of chemical fallow prior to sowing the next spring wheat crop, and (3) no-tillage spring barley/spring wheat (NTSB/SW). Barley harvest occurred in July followed by ~8 months of chemical fallow prior to sowing spring wheat.

2.2. Field operations 2005–2006

Our intention was to measure soil properties when the soil surface was susceptible to wind erosion. Soils are most prone to erode during the fallow phase of rotations and in spring and late summer/early autumn. Indeed, high winds often coincide with the sowing of spring and winter crops which expose the soil surface to the forces of the wind. Therefore, soil properties of the WW/SF and NTSW/CF rotations were measured during the fallow phase of the rotation and after sowing wheat. Soil properties of the NTSB/SW rotation were measured only during the spring wheat phase of the rotation since there is a tendency for lower straw production, and thus protection from erosion by surface residue, in spring barley than spring wheat in the region (Schillinger, 2005).

Table 1 shows detail field operations during our 2005–2006 experiment. The summer fallow phase of the WW/SF rotation began after wheat harvest in July 2005. The fallow phase of this rotation consisted of disking plots to a depth of 0.1 m in October 2005, applying herbicide (Glyphosate) to plots in November 2005 to control winter-annual weeds, disking and fertilizing plots in May 2006, weeding plots with a rodweeder in June 2006, and then packing the soil prior to seeding in September 2006. Seeding was accomplished using a deep-furrow drill with openers set at a depth of 0.1 m and on a spacing of 0.4 m.

The chemical fallow phase of the NTSW/CF rotation began after wheat harvest in July 2005. The fallow phase of this rotation consisted of spraying plots with herbicide in October 2005 and February 2006 to control winter and spring weeds and then seeding the plots on 29 August 2006 using a hoe drill equipped with 0.06 m single-point hoe openers set at a depth of 0.03 m and at a spacing of 0.18 m. Sowing wheat in August had not been previously done in the NTSW/CF rotation since the experiment was established in 1995, but was desirable for the purpose of this study to examine the potential of sowing winter wheat in chemical fallow in years when soil moisture is adequate in late summer or early autumn to promote germination and emergence.

The spring wheat phase of the NTSB/SW rotation began after barley harvest in July 2005. The spring wheat phase of this rotation consisted of spraying plots with herbicide in October 2005 and March 2006 to control weeds and then sowing wheat at a depth of 0.03 m using the hoe drill in late March 2006.

2.3. Measurement of soil properties

Soil properties were measured twice during the course of this study – after sowing but before emergence of spring and winter wheat in 2006. Measurements were taken in spring and late summer because soils are most exposed after sowing and high winds are prevalent at these times of the year in the Pacific Northwest (Saxton et al., 2000). The soil surface of the spring wheat phase of the NTSB/SW rotation was partially exposed between the time wheat was sown in late March to the time of emergence in mid-April 2006. The soil surface of the chemical fallow phase of the

Table 1
Field operations for winter wheat–summer fallow (WW/SF), no-tillage spring wheat–chemical fallow (NTSW/CF), and no-tillage spring barley–spring wheat (NTSB/SW) rotations during 2005–2006 near Ralston, Washington.

Date	WW/SF	Date	NTSW/CF	Date	NTSB/SW
21 July 2005	Harvest winter wheat	21 July 2005	Harvest spring wheat	21 July 2005	Harvest spring barley
27 October 2005	Disk stubble plots	21 October 2005	Post-harvest herbicide applied to stubble	20 October 2005	Post-harvest herbicide applied to barley stubble
09 November 2005	Sprayed summer fallow plots with herbicide	13 February 2006	Chemical fallow plots sprayed with herbicide	21 March 2006	Sprayed plots with herbicide for weed control
				22 March 2006	Seeded plots with spring wheat using hoe drill
11 April 2006			Measure soil physical properties		
23 May 2006	Summer fallow plots disked and fertilized				
21 June 2006	Rodweed summer fallow plots	29 August 2006	Seeded using hoe drill	22 June 2006	Sprayed spring wheat to control grain aphid
05 September 2006	Packed summer fallow plots to establish soil moisture line			27 July 2006	Harvest spring wheat
07 September 2006	Seeded using deep furrow drill			25 August 2006	Sprayed stubble with herbicide
12 September 2006			Measure soil physical properties		

NTSW/CF rotation was partially exposed after sowing winter wheat in late August to the completion of this study in September 2006. The soil surface of the summer fallow phase of the WW/SF rotation was partially exposed from the time of autumn tillage (October 2005) to the completion of this study in September 2006.

Soil properties were measured on 11 April 2006, which was 20 days after sowing wheat in the NTSB/SW rotation and two or more months after applying herbicide to the fallow plots of the WW/SF and NTSW/CF rotations. Soil properties were also measured on 12 September 2006, which was 5 days after sowing the WW/SF rotation and 14 days after sowing the NTSW/CF treatment. Soil properties were assessed between crop rows and wheel tracks at 3 locations within each plot. Penetration resistance was measured using a handheld, recording penetrometer with a 30° cone. The penetrometer was inserted into the soil at a rate of 20 mm s^{-1} and resistance (resolution of 0.1 kPa) was recorded when the base of the cone was at the same elevation as the soil surface. Shear strength of the soil surface was measured using a torsional vane shear device. The device recorded the maximum force (resolution of about 0.2 kPa) to produce slippage as a torsional force was applied to the head of the vane. The head of the vane was 48 mm in diameter and comprised of 16 blades, half of which were 7.5 mm wide and half 17 mm wide. Each blade was 5 mm high. The vane shear device was pressed into the soil surface to the depth of the vane. Soil bulk density was determined by extracting soil core samples from the 0–0.05 m depth using stainless steel tubing (0.07 m diameter and 0.05 m long). The tubing was inserted into the soil until the upper edge of the tube was level with the soil surface; the tubing was then extracted by hand from the soil. The soil was trimmed level with the upper and lower edges of the tube. The core samples were then placed in an oven and allowed to dry at 105 °C prior to measuring the soil dry weight (for bulk density). Soil water content was assessed gravimetrically and soil matric potential was measured by a thermocouple psychrometer (Tru Psi Model SC10X, Decagon Devices, Inc., Pullman, WA) on soil samples collected in the upper 5 mm of the soil profile. Dry aggregate size distribution was determined by sieving 1 kg samples collected in the upper 30 mm of the soil profile using a flat-bottom shovel. Straw lying on the surface of the sample was removed prior to sieving. A rotary sieve (Chepil, 1962; Lyles et al., 1970) was used to measure the size fraction of aggregates 0.42, 0.84, 2.0, 6.4, and 19.0 mm in diameter. Soil aggregate geometric mean diameter, or size at which 50% of the soil mass passed through a sieve, was determined based upon a log-normal and Weibull distribution (Zobeck et al., 2003). Surface random roughness, crop residue cover, soil crust cover, and soil aggregate (>6 mm in diameter) cover were determined using a microrelief pin meter. The meter consisted of a rigid frame with 40 pin guides, with the foot of each guide being 6 mm in diameter and spaced 25 mm apart. Pins moved vertically through the pin guides. Once the pins came to rest on the surface, residue cover was determined by counting the number of pins that touched a piece of plant residue (Shelton and Dickey, 1992). Pins resting on a piece of residue were then adjusted so that each pin rested on the soil surface. The height of the top of each pin (to within 1 mm) was then determined from a scale mounted on the frame. Random roughness was calculated as the standard deviation of height readings, after the readings were corrected for slope, using the procedure of Currence and Lovely (1970). Crop residue biomass was assessed by separately collecting prostrate and standing residue on the soil surface from an area of 0.25 m^2. Standing residue included any residue element anchored to the soil surface and only that portion protruding above the surface. The residue was dried at 40 °C and weighed.

2.4. Statistical analysis

A one-way analysis of variance (ANOVA) was performed using the Mixed Model Procedure of the Statistical Analysis System (SAS institute version 9.1.3) to test differences among treatments for a randomized complete block design at a 95% level of confidence. The blocking factors were replications. A compound symmetric covariance structure was imposed on the covariance matrix (based on AICC criteria). Multiple samples taken within the blocking elements were treated as repeated measures. Tukey's procedure was used for multiple pairwise comparisons. Data obtained in the spring and late summer were analyzed separately. Normality of the distributions was examined by the Shapiro–Wilk test. In order to satisfy the normality assumption necessary for an ANOVA, a log transformation was performed on dry aggregate geometric mean diameter, all aggregate size classes, standing residue, stem density, bulk density, penetration resistance, total biomass, and standing residue density. Means were back transformed for presentation in tables.

3. Results and discussions

3.1. Soil aggregates

Aggregate geometric mean diameter (GMD) is a convenient way to generalize dry aggregate size distribution as a single number

Table 2
Percentage of non-erodible aggregates (>0.85 mm) and aggregate geometric mean diameter in spring and late summer for different crop rotations in the inland Pacific Northwest.

Rotation	Non-erodible aggregates (%)	Aggregate mean diameter (mm)	
		Log-normal	Weibull
Spring			
NTSB/SW	66.6b	6.75b	6.8b
WW/SF	72.5ab	31.18a	38.09a
NTSW/CF	73.6a	17.99ab	19.55ab
P-value	0.0001	0.0033	0.0041
Late summer			
NTSB/SW	40.8a	0.44b	0.48b
WW/SF	38.8a	0.23b	0.30b
NTSW/CF	50.0a	2.27a	2.12a
P-value	0.527	0.0001	0.0001

Mean values in spring or late summer followed by the same letter are not significantly different.

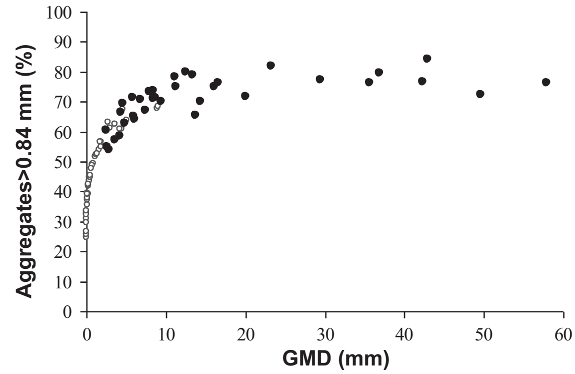

Fig. 1. Relationship between percentage of non-erodible aggregates and aggregate geometric mean diameter (GMD) as determined after sowing in the spring (solid symbols) and late summer (open symbols).

(Pikul et al., 2005). The type of distribution used to characterize dry aggregate sizes appeared to have little influence on the aggregate GMD as the GMD of the spring wheat phase of NTSB/SW, summer fallow phase of WW/SF, and chemical fallow phase of NTSW/CF (hereafter referred to as the NTSB/SW, WW/SF, and NTSW/CF rotations) in spring or late summer was similar for the log-normal and Weibull distributions (Table 2).

Non-erodible aggregate percentage, defined as the percent soil mass with aggregates >0.84 mm diameter, is related to soil erodibility caused by wind (Chepil, 1942; Pikul et al., 2005). Treatments with a larger percentage of non-erodible aggregates appeared to have a larger aggregate GMD (Table 2). Indeed, the percentage of non-erodible aggregates was closely related to GMD (Fig. 1). Aggregate GMD and percentage of non-erodible aggregates of treatments appeared to decrease from spring to late summer (Table 2). The decrease in size of aggregates of the NTSB/SW rotation was not associated with tillage (Table 1), but was likely due to precipitation (19 events totaling 61 mm of precipitation) occurring between sampling dates. While degradation of aggregates of the WW/SF and NTSW/CF rotations may have been caused by tillage and/or seeding operations, precipitation likely contributed to the break-down of soil aggregates between sampling dates. In fact, precipitation may have contributed substantially to the degradation of aggregates of the NTSW/CF rotation because ancillary measurements in the NTSW/CF rotation not sown to winter wheat (portion of plot remained in chemical fallow) indicated an aggregate GMD of 3.4 mm and percentage of non-erodible aggregates of 60.9% at the time of sampling in late summer.

Aggregate GMD was smaller for the NTSB/SW rotation than for the WW/SF rotation in spring while the GMD was smaller for the NTSB/SW and WW/SF rotations than for the NTSW/CF rotation in late summer (Table 2). Similar trends can be found for the percentage of non-erodible aggregates. The smaller aggregate GMD of the NTSB/SW rotation in spring was likely due to soil disturbance caused by sowing with the hoe drill prior to sampling in spring. Similarly, soil disturbance caused by disking, rodweeding, and packing the WW/SF rotation resulted in a smaller aggregate GMD as compared with the NTSW/CF rotation in late summer. These findings support earlier work by Tisdall and Oades (1982) who found that chemical fallow promoted formation of larger aggregates as well as Wuest et al. (2005), Liebig et al. (2004), and Saver et al. (2002) who found that tillage tends to break-down soil aggregates. Campbell et al. (1993) reported that soils comprised of less than 40% non-erodible aggregates are at serious risk of being eroded by wind. Based upon this criterion, the WW/SF rotation was very susceptible to wind erosion after sowing winter wheat in late summer (Table 2). No rotations examined in this study posed a serious risk for wind erosion in spring due to the high percentage (>60%) of non-erodible aggregates.

3.2. Surface residue, crust and clod cover and residue biomass

Crop residue on the soil surface aids in protecting the soil against the forces of wind. Crop residue biomass on or above the soil surface was significantly lower for the NTSB/SW rotation than the NTSW/CF and WW/SF rotations in spring (Table 3). The low surface residue biomass of the NTSB/SW rotation was due in part to shorter and fewer stems. In late summer, surface residue biomass was lower for the WW/SF and NTSW/CF rotations than for the NTSB/SW rotation. A total biomass of <1000 kg ha^{-1} remained after sowing the WW/SF and NTSW/CF rotations whereas a biomass of >2500 kg ha^{-1} remained after harvest of spring wheat in the NTSB/SW rotation. Although Papendick and Moldenhauer

Table 3
Surface residue cover, crust cover, aggregate cover, stem height and density, and residue biomass after sowing in spring and late summer of 2006 as influenced by crop rotations that were established in 1995.

Rotation	Surface cover (%)			Stem height (cm)	Stem density (# m^{-2})	Residue biomass (kg ha^{-1})		
	Aggregate	Crust	Residue			Prostrate	Standing	Total
Spring								
NTSB/SW	26.9a	0b	15.3b	4.54b	45c	269.6b	39.6c	309.2b
WW/SF	18.1a	64.4a	17.5b	29.10a	196b	570.8b	1103.1a	1673.9a
NTSW/CF	0b	43.6a	56.4a	29.76a	315a	982.4a	785.5b	1767.9a
P-value	0.0001	0.0001	0.008	0.0001	0.0001	0.0001	0.0001	0.0001
Late summer								
NTSB/SW	12.0a	65.5a	22.5a	29.25a	435a	850.3a	1662.4a	2512.7a
WW/SF	11.7a	0.0b	26.9a	4.71b	67b	530.1a	61.6b	591.7b
NTSW/CF	8.5a	17.1a	44.4a	6.33b	68b	840.3a	53.2b	893.5b
P-value	0.1954	0.0001	0.0774	0.0001	0.0001	0.1000	0.0001	0.0001

Mean values in spring or late summer followed by the same letter are not significantly different.

Table 4
Water content and matric potential (0–50 mm depth), surface shear stress, penetration resistance, bulk density (0–50 mm depth), and surface random roughness of different crop rotations measured after sowing in the spring and late summer 2006 near Ralston, Washington.

Rotation	Water content ($g\,g^{-1}$)	Matric potential (MPa)	Bulk density ($Mg\,m^{-3}$)	Shear stress (kPa/100)	Penetration resistance (kPa/10)	Random roughness (mm)
Spring						
NTSB/SW	0.026a	−79.1b	1.075a	0.003b	0.35c	8.0b
WW/SF	0.017b	−137.2c	1.047a	0.023a	1.68a	11.1a
NTSW/CF	0.055a	−17.7a	1.058a	0.021a	1.13b	7.1b
P-value	0.0001	0.0001	0.764	0.0001	0.0001	0.0001
Late summer						
NTSB/SW	0.016ab	−210.3b	0.931b	0.016a	0.41a	8.4a
WW/SF	0.014b	−284.5b	1.147a	0.007b	0.26b	7.8a
NTSW/CF	0.017a	−197.8a	1.146a	0.006b	0.24b	9.3a
P-value	0.0456	0.0001	0.0001	0.0001	0.0001	0.0579

Mean values in spring or late summer followed by the same letter are not significantly different.

(1995) reported that the sowing operation could reduce surface residue biomass by as much as 20%, sowing chemical fallow with a hoe drill in late summer appeared to reduce surface biomass by 40%. Indeed, ancillary measurements in the NTSW/CF rotation not sown to winter wheat indicated a surface residue biomass of 1502 kg ha^{-1}. Standing residue is more protective of the soil surface than prostrate residue as standing residue alters the wind speed profile (Siddoway et al., 1965; Armbrust and Bilbro, 1997). Standing residue offered greater protection of the soil surface in the spring for the NTSW/CF rotation than for the NTSB/SW and WW/SF rotations. Indeed, stem density in spring was greater for the NTSW/CF rotation (Table 3). The lower stem density of the NTSB/SW and WW/SF rotations was likely due to sowing spring wheat in the NTSB/SW rotation and disking the WW/SF rotation prior to measuring soil properties in the spring. However, differences in stem density between the WW/SF and NTSW/CF rotations are not representative of differences in standing biomass in spring. Weeds contributed to the greater standing biomass of the WW/SF rotation. In late summer, the NTSB/SW rotation had the highest stem density whereas the WW/SF rotation had the lowest stem density as compared to other rotations. The high stem density in the NTSB/SW rotation was due to the recent harvest of spring wheat while the low stem density in the WW/SF rotation was due to multiple tillage operations prior to measuring soil properties.

Cover afforded by residue, crust, and non-erodible elements (e.g. aggregate, rock) minimizes the soil surface area exposed to the wind. Residue cover between spring and late summer had diminished by >10% for the NTSW/CF rotation and increased by >5% for the NTSB/SW and WW/SF rotations (Table 3). A reduction in residue cover (NTSW/CF rotation) could be due to residue degradation and seeding operation while an increase in residue cover may be due to harvest of spring wheat (NTSB/SW rotation) or unearthing buried residue from rodweeding or sowing operations (WW/SF rotation). Previous studies suggest that residue cover can increase as a result of rodweeding (Schillinger and Papendick, 1997; Thorne et al., 2003). Crust cover was lowest for the NTSB/SW rotation in spring and for the WW/SF rotation in late summer. In spring, the absence of a soil crust in the NTSB/SW rotation may be due to the hoe drill either destroying or burying any crust previously formed by consolidation or raindrop impact. In late summer, the absence of a soil crust in the WW/SF rotation was likely due to soil disturbance caused by multiple field operations (tillage, packing, sowing) between measurement dates. Despite sowing the NTSW/CF rotation in late summer, the soil surface was partially covered by a crust (17% cover). The hoe drill was ineffective at completely destroying or burying the crust that was apparent in spring. In fact, ancillary measurements in the NTSW/CF rotation not sown to winter wheat indicated that a crust completely covered the soil surface in late summer. Coverage of non-erodible elements in our study was afforded by large aggregates (>6 mm in diameter) as our study site was devoid of rocks. Differences in coverage of large aggregates among rotations occurred only in spring when coverage was smaller for the NTSW/CF rotation than for the other rotations (Table 3). In spring, large aggregates were absent in the NTSW/CF rotation and may result from lack of soil disturbance since initiating the chemical fallow phase of the rotation and degradation of aggregates from overwinter processes and raindrop impact.

3.3. Surface soil moisture, bulk density, shear stress, penetration resistance, and random roughness

Surface soil water content and matric potential were lower in spring for the WW/SF rotation as compared with the NTSW/CF and NTSB/SW rotations (Table 4). While the data suggest that no tillage conserved soil water in spring, soil water content is well below the permanent wilting point of −1.5 MPa for all rotations. Feng and Sharratt (2005) found that soil water content was the most influential of 28 soil properties which affect wind erosion in the Columbia Plateau. Indeed, small changes in soil water content can greatly affect soil erosion. Based upon this sensitivity, the WW/SF rotation appears much more susceptible to wind erosion than the NTSB/SW and NTSW/CF rotations. Differences in soil water content and matric potential were more subtle among rotations in late summer. The soil was wetter for the NTSW/CF rotation as compared to the other treatments.

No difference in bulk density among rotations was observed in spring (Table 4). However, bulk density for the NTSB/SW rotation was significantly lower (19%) than for the WW/SF and NTSW/CF rotations in late summer. While we are uncertain as to the cause for the lower bulk density for the NTSB/SW rotation in late summer, a contributing factor may be the higher organic matter in the NTSB/SW rotation than in the WW/SF and NTSW/CF rotations (Pan et al., 2001). Other scientists have also found that soil organic matter is typically higher under no-tillage cropping systems than conventional-tillage cropping systems (Wuest et al., 2005; Liebig et al., 2004; Halvorson et al., 2002; Kay and VandenBygaart, 2002; Bowman and Halvorson, 1998; Campbell et al., 1996).

Surface torsional shear strength was lower in spring for the NTSB/SW rotation than the WW/SF and NTSW/CF rotations. In late summer, shear strength was lower for the WW/SF and NTSW/CF rotations than the NTSB/SW rotation. In general, lower shear stress corresponded to lower penetration resistance at the soil surface in spring and late summer (Table 4). Low shear stress and penetration resistance typically resulted after sowing spring or winter wheat. In fact, ancillary measurements in the NTSW/CF rotation not sown to winter wheat indicated a 4-fold higher shear stress (2.4 kPa) and 14-fold higher penetration resistance (34.7 kPa) than the NTSW/CF rotation sown to winter wheat in late summer. Although shear stress and penetration resistance are not considered in simulating

Table 5
Changes in surface random roughness (RR), flat soil residue cover (SRC) and soil loss ratio (SLR) of the three cropping systems.

Data source	Sample date	Treatment	RR (cm)	SRC (%)	SLR (index)[a]
Thorne et al. (2003)	May 1997	NTSB/SW	1.66	23.4	0.135
	May 1996	WW/SF	1.42	12.9	0.253
	Mar 1997	NTSW/CF	1.11	73.5	0.015
Feng et al.	April 2006	NTSB/SW	0.8	15.3	0.307
	April 2006	WW/SF	1.11	17.5	0.234
	April 2006	NTSW/CF	0.71	56.4	0.041
Thorne et al. (2003)	August 1998	NTSB/SW	1.02	93.8	0.005
	October 1995	WW/SF	1.28	16.4	0.231
	June 1998	NTSW/CF	1.02	84.5	0.009
Feng et al.	September 2006	NTSB/SW	0.84	22.5	0.210
	September 2006	WW/SF	0.78	26.9	0.174
	September 2006	NTSW/CF	0.93	44.4	0.067

[a] An indicator of wind erosion susceptibility; 0 = no erosion, 1 = maximum erosion potential.

wind erosion, these properties offer insight into shear or mechanical stresses that must be overcome at the soil surface to detach particles.

Roughness elements influence the partitioning of shear stress at the soil surface and therefore soil erodibility. Partitioning of shear stress to roughness elements, which increases with surface roughness, reduces surface particle shear stress and thus sediment transport at the soil surface. Random roughness in spring was higher for the WW/SF rotation than for the NTSB/SW and NTSW/CF rotations (Table 4). The rougher surface of the WW/SF rotation is likely due to the disking operation the previous autumn and lack of any tillage operation since initiating the chemical fallow phase of the NTSW/CF rotation. In late summer, random roughness was not significantly different for all rotations examined in this study.

3.4. Potential impact on wind erosion

Thorne et al. (2003) estimated the soil loss ratio based upon random roughness and flat residue cover that were measured within three years after establishing crop rotations at our experimental site. Soil loss ratio was estimated using the Horning et al. (1998) equation:

$$SLR = e^{-0.05SRC} \times e^{-0.52RR}$$

where SLR is soil loss ratio, SRC is percent cover of residue laying flat on the soil surface, and RR is random roughness. The SLR ranges from 0 for a non-eroding soil surface to 1 for a dry, smooth, and bare soil surface (maximum erosion). We used the Horning et al. (1998) equation to estimate SLR of the WW/SF, NTSB/SW, and NTSW/CF rotations. The SLR and accompanying measured values of RR and SRC for the three crop rotations are listed in Table 5.

Thorne et al. (2003) indicated that the WW/SF rotation was most susceptible to soil loss due to low residue cover. However, soil loss after sowing spring wheat in the NTSB/SW rotation of our study appeared to be as high as summer fallow (Table 5). Chemical fallow appeared to be an effective strategy for reducing the susceptibility of soil to wind erosion in both spring and late summer.

After sowing but before the emergence of wheat in the spring, the potential for soil loss was greatest for the NTSB/SW rotation and smallest for the chemical fallow phase of the NTSW/CF rotation. The higher potential for soil loss from the NTSB/SW rotation was due to lower residue cover and smaller random roughness while the lower potential for soil loss from the NTSW/CF rotation was due to higher residue cover as compared with other rotations. After sowing but before emergence of wheat in late summer, the potential for soil loss was similar for the WW/SF and NTSB/SW rotations. The similarity in soil loss for these rotations seems counterintuitive because wheat was recently harvest from the NTSB/SW rotation and winter wheat was sown in the WW/SF rotation. The similarity in soil loss was due to the similarity in residue cover and random roughness for these rotations. We would expect, however, that the greater stem density and height for the NTSB/SW rotation would reduce the risk for wind erosion as compared with the WW/SF rotation. Soil loss from the NTSW/CF rotation was projected to be 50% of the WW/SF and NTSW/SB rotations. The lower projected soil loss from the NTSW/CF rotation was largely due to twice as much residue cover (Table 3) as the other rotations.

4. Conclusions

A long-term dryland cropping systems study was initiated at Ralston, WA in 1995 on a silt loam to identify alternate cropping systems to the traditional WW/SF system that is susceptible to wind erosion in the semiarid region. We examined the soil physical properties and surface characteristics that influence soil erodibility in spring and late summer 11 years after establishing NTSB/SW, NTSW/CF, and WW/SF rotations. The NTSB/SW rotation resulted in higher soil water content in spring and greater residue biomass, crust cover, and soil strength in late summer as compared with the WW/SF rotation. The NTSW/CF rotation resulted in higher soil water content and greater residue cover and stubble density in spring and higher soil water content, larger aggregates, and greater crust and residue cover in late summer than the WW/SF rotation. Residue cover for the NTSW/CF rotation was twice that of the other rotations and was projected to reduce wind erosion by at least half of the other rotations in spring and late summer. Thus, benefits of enhancing residue cover and soil wetness by using no tillage cropping systems will reduce wind erosion in the low precipitation zone of the inland Pacific Northwest.

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