Influence of long-term tillage and crop rotations on soil hydraulic properties in the US Pacific Northwest

G. Feng, B. Sharratt, and F. Young

Abstract: In the low precipitation zone (<0.3 m [11.8 in] annual precipitation) of the Inland Pacific Northwest, no-tillage continuous spring cereal and no-tillage spring cereal-chemical fallow rotations are being examined as alternatives to the traditional winter wheat–summer fallow rotation for soil conservation. There is limited information, however, regarding the long-term effects of no-tillage cropping systems on soil hydraulic properties in this semiarid region. The objective of this study was therefore to characterize infiltration, water retention, saturated hydraulic conductivity and bulk density of a silt loam that had been subject to various tillage and crop rotations in east-central Washington. Treatments examined included no-tillage spring barley–spring wheat (NTSB–SW), no-tillage spring wheat–chemical fallow (NTSW–ChF), and traditional winter wheat–summer fallow (WW–SF). Soil properties were measured in spring and late summer 2006 due to the vulnerability of the soil to rapidly dry and erode during these seasons. Saturated hydraulic conductivity was determined by the falling-head method, infiltration was measured using a double-ring infiltrometer, and water retention characteristics was assessed by examining the temporal variation of in situ soil water content. NTSB–SW resulted in higher infiltration and saturated hydraulic conductivity, lower bulk density, and larger and/or more continuous pores in the upper soil profile (<0.1 m [<3.9 in] depth) than WW–SF and NTSW–ChF. Infiltration and saturated hydraulic conductivity were lower for chemical fallow than for traditional fallow in spring whereas hydraulic conductivity was lower for summer fallow than chemical fallow in late summer. Soil hydrologic properties appeared more favorable for no-tillage continuous spring cereal rotations. These results are useful for soil and water management and conservation planning in the low precipitation zone of the Inland Pacific Northwest.

Key words: bulk density—chemical fallow—hydraulic conductivity—infiltration—no-tillage—soil water retention—summer fallow—wheat

Water is the principal environmental factor limiting crop production in the Inland Pacific Northwest of the United States. Winter wheat–summer fallow (one crop in two years) is the traditional rotation employed on more than 2 million ha (4.94 million ac) in the low precipitation zone (annual precipitation <0.3 m [<11.8 in]) of the region (Schillinger and Young 2004). This crop rotation includes a 13-month fallow period between the time of wheat harvest in summer and planting the subsequent crop the following summer. The primary purpose of fallow is to allow time for the soil profile to recharge with sufficient water for the establishment of the subsequent winter wheat crop. During the summer fallow period, traditional tillage involves eight or more passes with various tillage implements to control weeds and establish a moisture barrier to minimize evaporative water loss (Schillinger and Young 2004). Traditional tillage, however, degrades and denudes the soil that can result in erosion by wind and water. This tillage system has also contributed to degraded air quality (Saxton et al. 2000), pest problems, and reduced crop yields (Bewick 2007). There has been growing interest among farmers, governmental agencies, and conservation groups in seeking alternatives to the wheat-fallow system. Options for improving soil and environmental quality include intensifying the crop rotation or reduce or eliminate tillage. Few long-term cropping systems studies have been conducted in the region; those for which information is available have focused on crop performance and not soil attributes. For example, comparisons were made of the economic and agronomic feasibility of reduced tillage and annual cropping systems (Forte-Gardner et al. 2004; Thorne et al. 2003; Young and Thorne 2004) but not of the soil physical and hydraulic properties that largely affect soil resource conservation.

Tillage plays a key role in changing the hydro-physical properties. Blanco-Canqui et al. (2004) indicated that water infiltration and runoff are closely related to the physical condition of the upper layer of the soil profile. Shaver et al. (2002) reported that physical properties such as bulk density and porosity near the soil surface are most important for dictating the infiltration characteristics of the soil at the soil-water interface. Francis et al. (1987), however, found that infiltration was more closely related to pore continuity than to porosity. Liebig et al. (2004) and Wuest et al. (2006) concluded that soil properties as affected by tillage and cropping systems were largely limited to the surface 0.075 m (2.95 in) of the soil profile. Mielke and Wilhelm (1998) also found that changes in soil physical properties in response to tillage practices were most prevalent in the 0 to 0.076 m (0 to 2.99 in) surface layer.

Many studies have investigated the effect of long-term tillage on soil hydro-physical properties. These studies generally indicate that no-tillage and reduced tillage systems have positive impacts on conserving soil and water resources by reducing soil erosion (Blanco-Canqui et al. 2004; Diaz-Zorita et al. 2004; Hobbs 2007; Jiang et al. 2007; Wuest et al. 2005), improving soil quality (Blanco-Canqui et al. 2004; Schillinger et al. 2007; Wuest et al. 2005), increasing water infiltration (Allamaras et al. 1973; Blanco-Canqui et al. 2004; Dam et al. 2005; Dao 1993; Diaz-Zorita et al. 2004; Freese 1993; Hobbs 2007; Kay 1990; Lal 1982; Mengel et al. 1982; Shaver et al. 2002; Schillinger et al. 2006; Standford et al. 1973; Wuest et al. 2004), increasing saturated hydraulic conductivity

Guanglong Feng is a soil scientist at Washington State University, Pullman, Washington. **Brenton Sharratt** is a soil scientist and **Frank Young** is an agronomist for the USDA Agricultural Research Service, Pullman, Washington.

(Azooz et al. 1996; Diaz-Zorita et al. 2004; Gantzer and Blake 1978; Hill and Cruse 1985; Hill 1990; Zhai et al. 1990), retaining more water in the soil profile (Diaz-Zorita et al. 2004; Hill and Cruse 1985; Hill et al. 1985; Hill 1990; Lindstrom et al. 1984; Zhai et al. 1990), increasing soil water content (Allamaras et al. 1973; Diaz-Zorita et al. 2004; Lal 1982; Mengel et al. 1982; Standford et al. 1973), enhancing soil aggregation and stability (Dam et al. 2005; Diaz-Zorita et al. 2004; Hobbs 2007; Wuest et al. 2004), and increasing water use efficiency (Diaz-Zorita et al. 2004). In addition, no-tillage and reduced tillage systems generally result in higher bulk densities and smaller soil porosities (Dam et al. 2005; Hill 1990; Kravchenko et al. 2006; Mielke et al. 1986). We recognize, however, that opposite conclusions from those previously presented can be found in the literature. For example, some studies reported that no-tillage resulted in lower bulk densities (Blevins et al. 1994; Dao 1993; Fausey et al. 1994) and greater soil porosities (Ferreras et al. 2000). In addition, Kennedy and Schillinger (2006) reported no differences in over-winter soil water storage or water infiltration rate between no-tillage and traditional (intensive) tillage in the Palouse region of eastern Washington, United States. The latter finding is possibly due to the high quantity of wheat root channels produced in both tillage systems.

Chemical fallow (ChF) implies the use of herbicides instead of tillage to control weeds during the fallow phase of a crop-fallow rotation. Weed control during the fallow phase of the rotation is critical to conserving soil moisture for subsequent crops. In the low precipitation zone of the Inland Pacific Northwest, ChF has the potential to reduce multiple tillage and rod-weeding operations during summer fallow. Wicks and Smika (1973) found that ChF reduced weed growth and increased soil water storage and grain yield in the Northern Great Plains region of the United States where precipitation predominately occurs during late spring and summer. Fenster and Peterson (1979) suggested that herbicides substituted for tillage operations should enhance crop residue cover on the soil surface and therefore decrease evaporation and reduce soil temperatures. Retention of residue on the soil surface will likely decrease the diurnal fluctuation in soil temperature, which influences water movement and storage within the soil profile. Residues also protect the soil surface from the forces of wind and raindrop impact and thus may result in less runoff and soil erosion.

Conservation tillage has the potential to reduce soil erosion and input costs (Forte-Gardner et al. 2004; Hobbs 2007; Thorne et al. 2003; Wuest et al. 2006). There is some concern, however, that conservation tillage or increased cropping intensity may not always improve soil properties for plant growth and water retention (Dam et al. 2005; Guy and Lauver 2007). Research is needed, therefore, to understand the long-term impact of tillage and crop rotation on soil physical and hydraulic properties considered to be indicators of soil quality and water conservation. Changes in soil properties in response to tillage or cropping are usually more evident and consistent 10 years or more after initiating a change in tillage and cropping systems (Hobbs 2007; Kay and VandenBygaart 2002; Wuest et al. 2006). The objective of this paper was to determine the long-term effect of tillage and crop rotations on changes in soil hydraulic properties in the Inland Pacific Northwest, where crop-fallow is the predominate rotation in dryland agriculture.

Materials and Methods

This study was conducted on a farm located near Ralston in east-central Washington, United States (46°55'N, 118°24'W), where the annual precipitation is about 0.25 m (9.84 in) (figure 1). The field site is at an elevation of 527 m (1,729 ft) (figure 2) and nearly level. The soil at the field site is a Ritzville silt loam (coarse-silty, mixed, mesic, Calcidic Haploxeroll according to the USDA classification system) comprised of 30% sand, 62% silt, and 8% clay. Organic matter in the top 0.3 m (11.8 in) of the soil profile averaged 2%.

Establishment and Maintenance of Long-Term Treatments. Detailed information about the establishment and maintenance of cropping systems over the previous 11 years prior to our measurements at the field site have been previously published (Thorne et al. 2003, 2007; Young and Thorne 2004). Long-term cropping system plots (each plot was 9 × 69 m [30 × 226 ft]) were established in 1995 on a relatively level field (about 1% slope) that was in the summer fallow phase of a winter wheat–summer fallow rotation. Soil properties were assumed uniform across the field site at the initiation of the study because of the flat topography, homogeneous cropping history, limited or no macrofauna activity, and small variation in organic matter content (1.9% to 2.0%) across the landscape. The experimental design was a randomized complete block with each treatment replicated four times. Treatments consisted of four crop rotations: (1) traditional winter wheat–reduced-tillage 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–ChF). Wheat harvest occurred in July followed by ~20 months of chemical fallow prior to sowing the next spring wheat crop, (3) no-tillage spring barley–spring wheat (NTSB–SW). Barley harvest occurred in July followed by ~8 months of chemical fallow prior to sowing the next spring wheat crop, and (4) no-tillage continuous spring wheat. Wheat harvest occurred in July followed by ~8 months of chemical fallow prior to sowing the next spring wheat crop. Each phase of all crop rotations was present in all years.

Soil properties of the no-tillage continuous spring wheat rotation were not investigated in this study as we assumed hydraulic characteristics would be similar to the NTSB–SW treatment. In addition, we did not measure soil properties during the WW phase of the WW–SF rotation, SW phase of the NTSW–ChF rotation, and SW phase of the NTSB–SW rotation. Our intention was to measure soil properties during the phase of the rotation most susceptible to soil erosion (crop rotations in the low precipitation zone of the Inland Pacific Northwest are most susceptible to erosion immediately after sowing spring and winter crops). The soil in the NTSB–SW rotation is most vulnerable to erosion during the SB phase of the rotation because spring barley produces less biomass to protect the soil surface against the forces of wind and water than spring wheat (Thorne et al. 2007).

A weather station was located adjacent to the long-term experimental plots for obtaining air temperature, relative humidity, solar radiation, wind speed, and precipitation.

Field Operations 2005 to 2006. Field operations over the course of 11 years prior to this study are reported by Thorne et al. (2003) and Young and Thorne (2004). Detailed field operations from the time of harvest of wheat and barley in 2005 to the completion of this study in 2006 are listed

Figure 1
Location of the experimental field site in Adams County and contour of annual precipitation across Washington state.

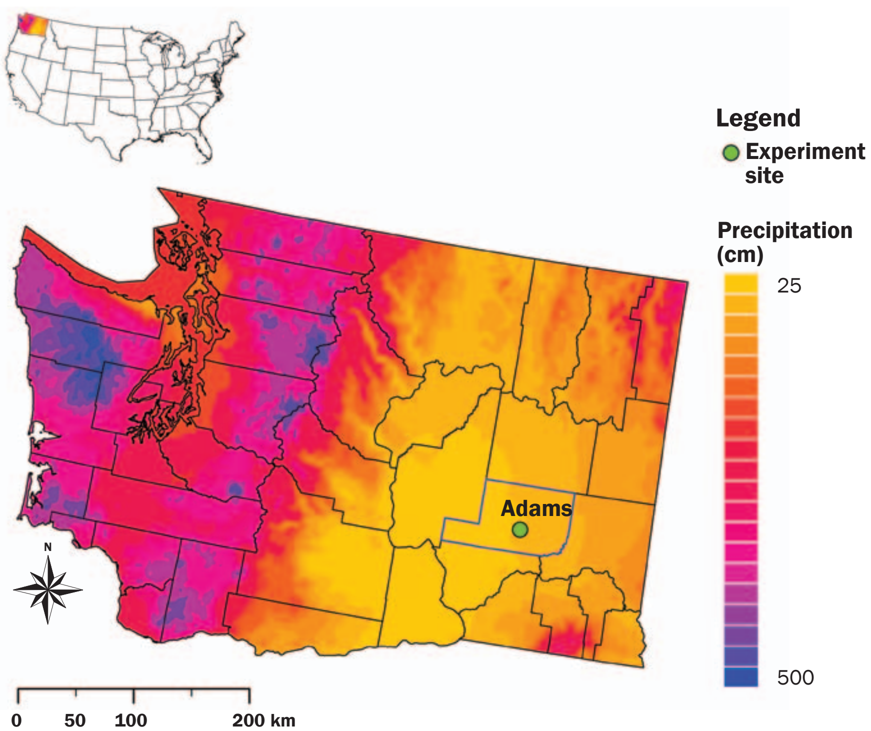
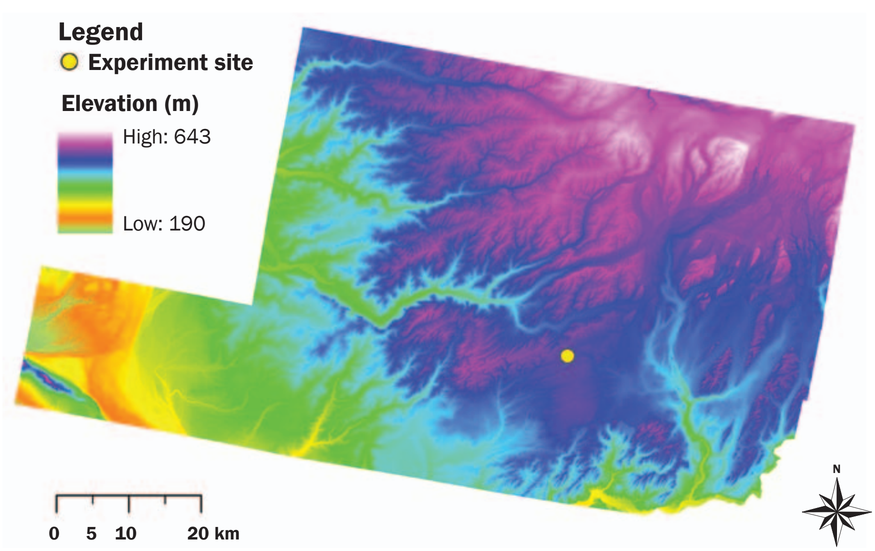


Figure 2
Location of experimental field site and contour of elevation across Adams County, Washington.



in table 1. 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 to a depth of 0.13 m (5.12 in) in October 2005, applying herbicide (Glyphosate) in November 2005 to control winter-annual weeds, disking and fertilizing in May 2006, weeding with a rod weeder (the rod weeder had a 0.019 m [0.75 in] square rod) in June 2006, and then packing prior to seeding in September 2006. Field measurements were expedited in this study by simulating seeding on a portion of the summer fallow plot on September 7, 2006 (remainder of plot was sown to winter wheat on September 15). Seeding was simulated by one pass of a deep-furrow drill with openers set at a depth of 0.10 m (3.94 in) and on a spacing of 0.40 m (15.75 in).

The chemical fallow phase of the NTSW–ChF 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 simulating seeding of a portion of the plots on August 29, 2006. Seeding was simulated by one pass of a hoe drill equipped with 0.06 m single-point hoe openers set at a depth of 0.03 m (1.18 in) and at a spacing of 0.18 m (7.09 in). Sowing wheat in August had not been previously done in the NTSW–ChF rotation since the experiment was established in 1995, but this simulation 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 barley phase of the NTSB–SW rotation began after barley harvest in July 2005. The spring barley 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 (1.18 in) using the hoe drill on March 22, 2006.

Measurement of Soil Properties. Soil properties were measured twice during the course of this study, in spring and late summer of 2006. These seasons were chosen because tillage effects on intrinsic soil properties are time-dependent (Strudley et al. 2008) and soils are most vulnerable to erosion at these times of the year. Soil erosion typically occurs in spring and late summer in the low precipitation zone of the Pacific Northwest because denuded or partially denuded soils are exposed to high winds (Saxton et al. 2000). The soil surface of the spring barley phase of the NTSB–SW rotation was partially exposed after sowing wheat with the hoe drill in spring (March 22, 2006) to the time of emergence (April 15, 2006). The soil surface of the ChF phase of the NTSW–ChF rotation was partially exposed after simulating sowing with the hoe drill in late summer

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 to 2006 near Ralston, Washington.

Date	WW–SF	NTSW–CF	NTSB–SW
July 21, 2005	Harvest winter wheat	Harvest spring wheat	Harvest spring barley
Oct. 20, 2005		Herbicide applied to stubble	Herbicide applied to stubble
Oct. 27, 2005	Disk stubble plots		
Nov. 9, 2005	Summer fallow sprayed with herbicide		
Feb. 13, 2006		Chemical fallow sprayed with herbicide	
March 21, 2006			Herbicide applied to stubble
March 22, 2006			Seeded spring wheat using hoe drill
April 11, 2006	Measure soil properties	Measure soil properties	Measure soil properties
May 23, 2006	Summer fallow disked and fertilized		
June 21, 2006	Rod weed summer fallow		
June 22, 2006			Pesticide applied to spring wheat
July 27, 2006			Harvest spring wheat
Aug. 25, 2006			Sprayed stubble with herbicide
Aug. 29, 2006		Seeded winter wheat using hoe drill	
Sept. 5, 2006	Packed summer fallow plots		
Sept. 7, 2006	Seeded winter wheat using deep furrow drill		
Sept. 12, 2006	Measure soil properties	Measure soil properties	Measure soil properties

(August 29, 2006) and remained exposed for the duration of the study. The soil surface of the summer fallow phase of the SW–SF rotation was partially exposed from the time of autumn tillage (October 27, 2005) to the completion of this study in September 2006. Soil properties were measured on April 11, 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–ChF treatments. Soil properties were also measured on September 12, 2006, which was 5 days after simulating sowing in summer fallow of the WW–SF treatment and 14 days after simulating sowing in chemical fallow of the NTSW–ChF treatment.

Soil properties were assessed between crop rows and wheel tracks. Saturated hydraulic conductivity was determined by the falling head method (Klute and Dirksen 1986). Five soil core samples were extracted from the 0 to 0.05 m (1.97 in) depth in each plot using stainless steel tubing (0.07 m [2.76 in] diameter and 0.05 m [1.97 in] 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, and cheese cloth was wrapped around the lower edge to stabilize the bottom of the soil column. Soil core samples were allowed to soak for 24 h inside a 0.01 m (0.39 in) deep tray filled with water. A standpipe, constructed by mounting a graduated cylinder to a lid that is attached to one end of 0.07 m (2.76 in) diameter tubing, was then secured to the top of sample. This assembly was then placed on a wire mesh screen located on the bottom of a 0.2 m (7.87 in) deep pan. Water was slowly added to the pan to achieve a rise in the water level of about 0.05 mm s^{-1} (0.002 in sec^{-1}) until the sample was immersed. The standpipe was then filled with water, and after lowering the water level inside the pan (0.005 m [0.197 in] above the lower edge of the bottom of the soil core sample), the rate of fall of the water column inside the standpipe was measured three separate times. After the measurement of saturated hydraulic conductivity, the soil cores were then oven-dried at 105°C (221°F) for 48 h to determine bulk density.

Infiltration was measured at five locations in each plot using a double ring infiltrometer, which consisted of a 0.3 m (11.8 in) diameter pipe centered over a 0.125 m (4.92 in) diameter pipe. Both the inner and outer plastic pipes were inserted 0.05 m (1.97 in) into the soil. Soil water content was measured prior to infiltration using time domain reflectometry (TDR) with 0.1 m (3.94 in) waveguides. The waveguides were installed vertically into the soil profile around the perimeter of the larger pipe. Water was then added to both the inner and outer pipe using a deflector to minimize splashing and disturbing the soil surface. Cumulative infiltration from the inner pipe was monitored for 45 minutes and then over an additional 15 minutes. Periodic assessments of infiltration during the course of this study indicated that steady state was achieved within 45 minutes for all treatments. In-situ soil water retention was then assessed near the center of the infiltrometer by measuring the temporal change in water content in the upper 0.1 m (3.94) of the soil profile.

Table 2

Cumulative and steady-state infiltration, saturated hydraulic conductivity and bulk density of no-tillage spring barley–spring wheat (NTSB–SW), winter wheat–summer fallow (WW–SF), and no-tillage spring wheat–chemical fallow (NTSW–CF) rotations measured in the spring and late summer 2006 near Ralston, Washington.

Season	Rotation	Infiltration: Cumulative (mm h^{-1})	Infiltration: Steady state (mm h^{-1})	Hydraulic conductivity (10^{-5} m s^{-1})	Bulk density (Mg m^{-3})
Spring					
	NTSB–SW	67.0 ± 4.5aβ	40.9 ± 3.4aβ	15.4 ± 3.5aβ	0.87 ± 0.02bα
	WW–SF	58.4 ± 4.3aα	34.4 ± 3.2aα	18.8 ± 4.5aα	0.98 ± 0.03aβ
	NTSW–CF	35.1 ± 3.6bβ	22.2 ± 2.3bβ	3.8 ± 3.7bβ	1.03 ± 0.02aα
Late summer					
	NTSB–SW	100.0 ± 3.8aα	64.6 ± 2.9aα	37.1 ± 3.5aα	0.85 ± 0.01cα
	WW–SF	58.2 ± 4.7bα	36.7 ± 3.5bα	3.4 ± 3.4cβ	1.04 ± 0.01aα
	NTSW–CF	60.6 ± 4.3bα	43.0 ± 2.1bα	16.2 ± 3.4bα	0.95 ± 0.01bβ

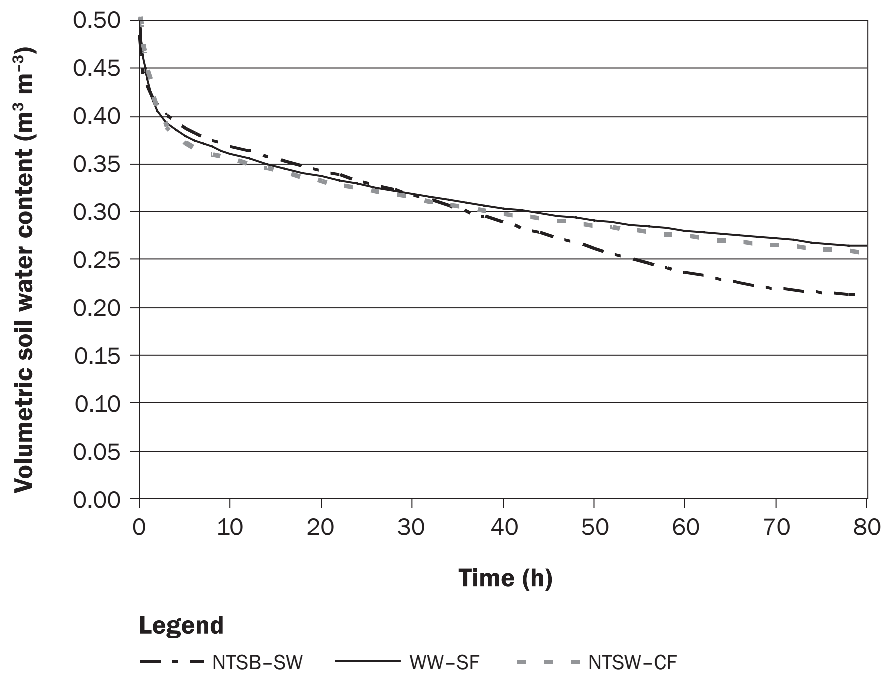
Note: Treatment means within the same season followed by same English letter or means for same treatment across seasons followed by same Greek letter are not significantly different at $p < 0.05$.

Water content was measured at 0, 0.5, 1, 6, 24, 48, and 80 h after the water completely infiltrated the soil surface (water not visible on the soil surface). Evaporation from these infiltration sites was prevented by covering the soil surface with a 0.8 m^2 (8.6 m^2) piece of plastic immediately after the infiltrometer was removed from the soil surface.

Statistical Analysis. Analyses of variance were done using the mixed 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. Normality of the distributions was examined by the Shapiro-Wilk test. Tukey-Kramer adjustments were used for multiple comparisons.

Figure 3

Volumetric soil water content as a function of time after infiltration of surface water in no-tillage spring barley–spring wheat (NTSB–SW), no-tillage spring wheat–chemical fallow (NTSW–CF), and winter wheat–summer fallow (WW–SF) rotations. Water content was measured in the upper 100 mm of the profile in spring 2006 near Ralston, Washington.



Results and Discussion

Changes in soil hydraulic properties occurred from spring to late summer. These changes are apparent for infiltration and saturated hydraulic conductivity in table 2 and evident for water retention by comparing trends in figures 3 and 4. Fuentes et al. (2004) suggested that seasonal variations in hydraulic properties can occur in response to root development, earthworm activity, compaction, and other natural processes such as freezing and thawing, or shrinking and swelling. Earthworm activity and freezing and thawing, however, did not influence hydraulic properties in this study because agricultural soils in the more arid regions of the Pacific Northwest have little or no macrofauna activity (Wuest et al. 2005) and subfreezing temperatures rarely occurred between measurement dates (daily minimum air temperature was below 0°C [0°F], but never below –3°C [–37°F], on 11 days). In addition, shrinking and swelling did not influence hydraulic properties as Ritzsville silt loam does not contain expanding clays (German-Heins and Flury 2000). Seasonal differences in infiltration and saturated hydraulic conductivity and water retention were likely due to soil disturbance or fracturing associated with seeding the NTSW–ChF treatment and root growth of wheat in the NTSB–SW treatment. Higher cumulative infiltration in late summer may also occur in response to drier soil in late summer than in spring. In the low-precipitation zone of the Pacific Northwest, soil drying occurs from spring until autumn in response to large precipitation deficits. The precipitation deficit between measurement dates in 2006 was 0.955 m (37.6 in) based upon 1.015 m

(3.33 ft) of potential evapotranspiration, estimated by the Kimberly-Penman equation (Wright 1982), and 0.06 m (2.36 in) of precipitation. Soil drying is more rapid, however, when capillary continuity of the soil can be maintained during the summer. For this reason, Schillinger and Bolton (1993) found that soils dry more quickly when subject to no-tillage as compared with conventional summer fallow in the low precipitation zone of the Pacific Northwest. The lack of capillary continuity in summer fallow may have conserved subsoil water and mitigated any change in cumulative infiltration (table 2) as opposed to the NTSW–ChF and NTSB–SW treatments.

Bulk Density and Saturated Hydraulic Conductivity. Bulk density (BD) is considered to be a measure of soil quality because of its impact on other soil properties such as porosity, soil water content, and hydraulic conductivity. Tillage and cropping systems can influence BD, but any change in BD as a result of changing management practices is likely to be detected nearer the soil surface (Dam et al. 2005; Wuest et al. 2006). Numerous studies have investigated the effect of tillage practices on BD. Blevins et al. (1994) found no differences in BD between no-tillage and conventional tillage, while Fausey et al. (1994) found BD was 7% lower for no-tillage versus conventional tillage in continuous corn, corn-soybean, and corn-oat-meadow rotations. Fausey et al. (1994) concluded after 28 years that BD was lowest in no-tillage due to the retention of more crop residue on the soil surface than in conventional tillage. Wilkins et al. (2002) and Wuest et al. (2006) reported a temporal decline in soil strength or BD with adoption of no tillage. However, opposing trends can be found in the literature. Dam et al. (2005) and Kushwaha et al. (2001), for example, found that near-surface bulk density was 10% higher in no-tillage than in conventional tillage. Others have also found that no-tillage results in a higher BD near the soil surface than intensive tillage (Douglas et al. 1986; Hussein et al. 1998; Kay and VandenBygaart 2002; Schjonning and Rasmussen 2000; VandenBygaart et al. 1999).

In this study, BD of the NTSB–SW rotation was significantly (10%) lower than the WW–SF and NTSW–ChF rotations in spring and late summer. The lower BD of the NTSB–SW rotation in spring may in part be attributed to disturbance or fracturing of the inter-row area during the seeding operation prior to the measurement of BD (table 1). In addition, higher organic matter in NTSB–SW than in WW–SF and NTSW–ChF (Pan et al. 2001) likely contributed to the lower BD of NTSB–SW. Other scientists have also found that soil organic matter is typically higher under no-tillage cropping systems than conventional tillage cropping systems (Bowman et al. 1999; Campbell et al. 1996, 1997; Halvorson et al. 2002; Kay and VandenBygaart 2002; Liebig et al. 2004; Wuest et al. 2005). Dam et al. (2005) indicated that summer fallow with intensive tillage, a common practice in the low precipitation zone of the Pacific Northwest, results in lower soil organic matter than continuous cropping. A decline in soil organic matter, associated with intensive tillage, can cause structural degradation and retard infiltration and hydraulic conductivity (Tisdall and Oades 1982). The similarity in BD for WW–SF and NTSW–ChF in spring may be attributed to over winter consolidation of the soil in these treatments.

Saturated hydraulic conductivity (Ks) of NTSB–SW was higher than NTSW–ChF in spring and NTSW–ChF and WW–SF in late summer (table 2). The WW–SF rotation had the lowest Ks of all rotations in late summer and collaborates previous reports that Ks is usually lower for conventional tillage than no-tillage systems (Azooz 1996; Gantzer 1978). The low Ks of the WW–SF treatment may be due to the high BD of the WW–SF treatment. In fact, the relationship between Ks and BD for WW–SF rotation in late summer suggested a decrease in Ks with an increase in BD. A decrease in Ks with an increase in BD was also found for the NTSB–SW and NTSW–ChF rotations (figure 5). The WW–SF treatment was packed prior to simulating seeding (table 1); packing is typically done to establish a moisture line for germination of seed. Packing summer fallow seven days prior to measuring soil properties likely resulted in a high BD and low Ks.

Infiltration and Water Retention. Tillage had a significant influence on cumulative and steady-state infiltration. Cumulative and steady-state infiltration in both spring and late summer were greater for NTSB–SW than NTSW–ChF. Seeding spring wheat in the NTSB–SW treatment on March 22, 2006, may have contributed to the higher infiltration rate (table 2). The NTSB–SW rotation may also have resulted in a higher infiltration rate as a result of changes in intrinsic soil characteristics with long-term no-tillage

Figure 4

Soil water content as a function of time after infiltration of surface water in three crop rotations as illustrated in figure 1, except water content in the upper 100 mm of the profile was measured in late summer 2006.

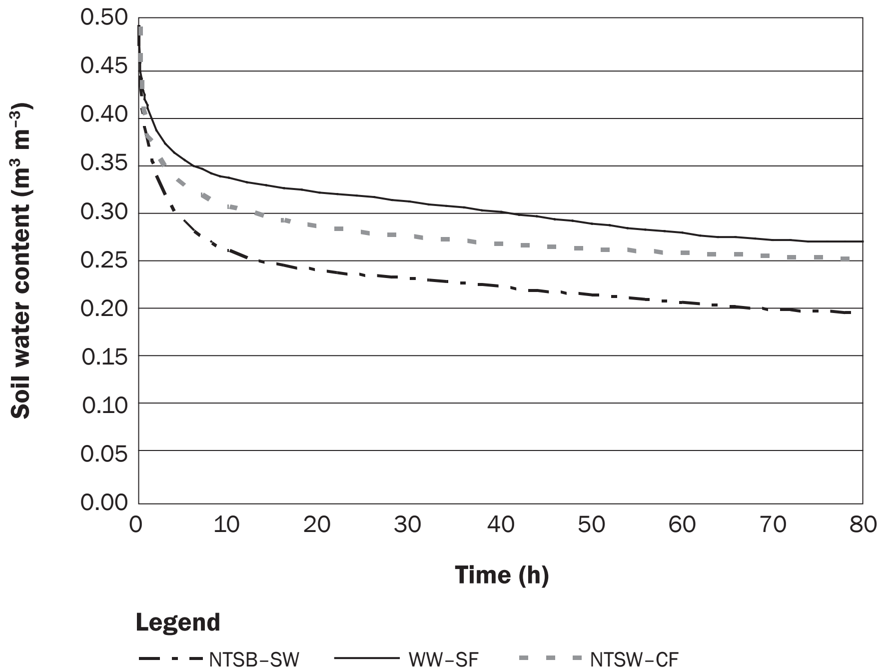


Figure 5
Saturated hydraulic conductivity as a function of bulk density for no-tillage spring barley–spring wheat (NTSB–SW), no-tillage spring wheat–chemical fallow (NTSW–CF), and winter wheat–summer fallow (WW–SF) rotations. The linear function represents all data collected in late summer 2006 near Ralston, Washington.

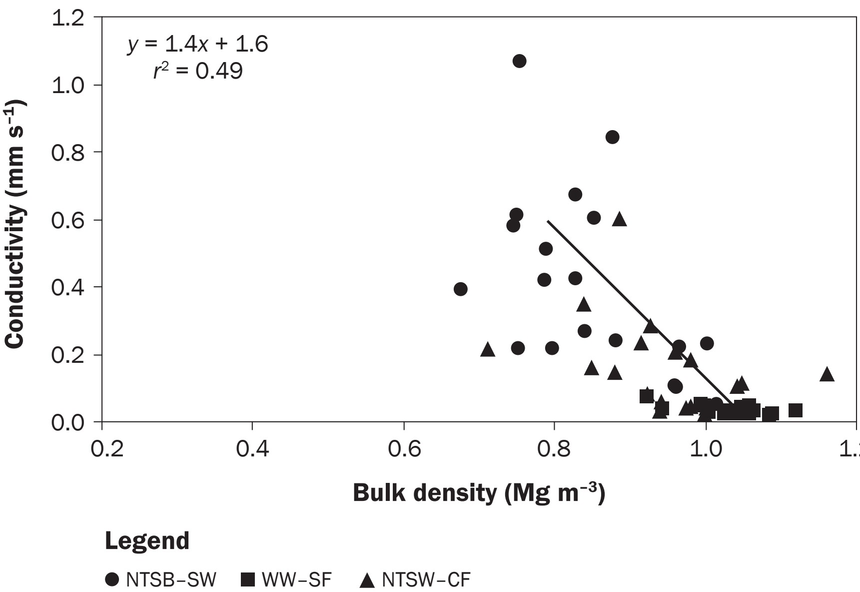


Table 3
Soil water content measured 0 and 80 h after infiltration of surface water and associated water loss in spring and late summer 2006 for no-tillage spring barley–spring wheat (NTSB–SW), winter wheat–summer fallow (WW–SF), and no-tillage spring wheat–chemical fallow (NTSW–CF) rotations near Ralston, Washington.

		Soil water content (m^3 m^{-3})		
Season	Rotation	0 h	80 h	Water loss (mm)*
Spring				
	NTSB–SW	0.49	0.21	28
	WW–SF	0.50	0.26	24
	NTSW–CF	0.50	0.26	24
Late summer				
	NTSB–SW	0.50	0.20	30
	WW–SF	0.49	0.27	22
	NTSW–CF	0.48	0.25	23

* Water loss was determined as the difference in soil water content 0 and 80 h after infiltration of surface water over a depth of 0 to 100 mm.

annual cropping. This is in agreement with numerous studies conducted at other locations (Ambassa-Kiki and Nill 1999; Fabrizzi et al. 2005; Freese et al. 1993; Hobbs 2007; Liebig et al. 2004; Sharratt 2006; Wuest et al. 2005). Infiltration and bulk density appeared to be influenced by seeding the NTSW–ChF rotation on August 29, 2006, as infiltration increased and bulk density decreased from spring to late summer (table 2).

Infiltration in the WW–SF treatment was retarded in late summer as compared with the NTSB–SW treatment. Arshad et al. (2004) found average infiltration was 30% lower under conventional tillage as compared with no-tillage in western Canada. No-tillage practices have been reported to maintain and sometimes enhance soil aggregation (Liebig et al. 2004; Shaver et al. 2002; Wuest et al. 2005), increase soil porosity (Dam et al. 2005), and produce more root channels (Kennedy and Schillinger 2006). Tillage-based cropping systems, like the WW–SF treatment in this study, may cause more surface sealing or a shear plane at the depth of tillage (tillage pan) and therefore impede water infiltration. Tillage also mechanically breaks pore continuity and hinders biopore formation which reduces infiltration (Diaz-Zorita et al. 2004).

Soil water retention characteristics were influenced by tillage treatments as illustrated by the temporal variation in soil water content following the infiltration of surface water (figures 3 and 4). Soil water content within about 36 h after infiltration of surface water in spring was identical for all three treatments. Thereafter, soil water content was lower for NTSB–SW than for WW–SF and NTSW–ChF (figure 3). The NTSB–SW treatment lost 0.004 m (0.16 in) of additional water in the upper 0.1 m (3.94 in) of the soil profile compared to WW–SF and NTSW–ChF during the course of our observation that concluded 80 h after ponded infiltration (table 3). Similar trends were found in the late summer (figure 4) with NTSB–SW losing an additional 0.007 to 0.008 m (0.28 to 0.32 in) water over an 80 h observation period as compared with WW–SF and NTSW–ChF (table 3). Differences in water retention characteristics between WW–SF and NTSW–ChF were observed in the late summer, but not in spring. The similarity in water retention characteristics between WW–SF and NTSW–ChF in spring may be due to over winter consolidation of soil as well as lack of soil disturbance prior to assessing water retention in spring in these treatments. The temporal variation in soil water content in late summer (figure 4) indicates that drainage from the upper soil profile was not as rapid after the infiltration of surface water for WW–SF as compared with NTSW–ChF and NTSB–SW. This is substantiated by the differences in slope estimates of the log-transformed water content-time relationship. Slope estimates were –0.072 cm^3 cm^{-3} h^{-1} (–0.004 in^3 in^{-3} hr^{-1}) for WW–SF, –0.095 cm^3 cm^{-3} h^{-1} (–0.006 in^3 in^{-3} hr^{-1}) for NTSW–ChF, and –0.115 cm^3 cm^{-3} h^{-1} (–0.007 in^3 in^{-3} hr^{-1}) for NTSB–SW. Differences in slope estimates or drainage among treatments in late summer are due to differences in pore size and/or continuity. More rapid drainage in NTSB–SW indicates larger and/or more continuous soil pores as compared with WW–SF. Indeed, larger and/or more continuous pores in NTSB–

SW may be a result of root channels from wheat that was harvest seven weeks prior to measurement of soil properties. Retention of less water against the force of gravity in NTSB–SW does not collaborate previous findings that conservation tillage promotes water retention (Hill et al. 1985; Lindstrom et al. 1984) due to improved soil structure and pore arrangement. Water loss from gravitational and soil matric forces over 80 h was 0.03 m (1.18) for NTSB–SW and about 0.022 (0.87 in) m for WW–SF and NTSW–ChF (table 3).

Summary and Conclusions

Soil hydraulic properties were measured 11 years after establishing a no-tillage spring barley–spring wheat (NTSB–SW), no-tillage spring wheat–chemical fallow (NTSW–ChF), and winter wheat–summer fallow (WW–SF) rotations in eastern Washington. The NTSB–SW rotation resulted in larger and/or more continuous pores, higher infiltration rate, higher saturated hydraulic conductivity, higher drainage rate, and lower bulk density in the upper soil profile than WW–SF in late summer and NTSW–ChF in spring and late summer. Previous studies conducted at the same long-term site also indicated that no-tillage spring cropping significantly reduced wind erosion as compared with WW–SF rotation (Thorne et al. 2003). Thus, benefits in terms of enhancing hydraulic properties and minimizing erosion of the soil were gained after 11 years of no-tillage continuous spring cropping in the low precipitation zone of the Pacific Northwest. The results of this study may offer a semiarid agricultural land management strategy for soil and water conservation and land degradation mitigation.

References

Allmaras, R.R., A.L. Black, and R.W. Rickman. 1973. Tillage soil environment, and root growth. *In* Conservation Tillage: The Proceedings of a National Conference, 62-86. Ankeny, IA: Soil Conservation Society of America.

Ambassa-Kiki, R., and D. Nill. 1999. Effects of different land management techniques on selected topsoil properties of a forest Ferralsol. Soil & Tillage Research 52(3-4):259-264.

Arshad, M.A., A.J. Franzluebbers, and R.H. Azooz. 2004. Surface-soil structural properties under grass and cereal production on a Mollic Cyroboralf in Canada. Soil & Tillage Research 77(1):15-23.

Azooz, R.H., M.A. Arshad, and A.J. Franzluebbers. 1996. Pore size distribution and hydraulic conductivity affected by tillage in northwestern Canada. Soil Science Society of America Journal 60(4):1197-1201.

Bewick, L.S. 2007. No-till facultative wheat production in the dryland winter wheat-fallow region of the Pacific Northwest. MS thesis, Washington State University, Pullman, WA.

Blevins, R.L., W.W. Frye, and I. Ismail. 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Science Society of America Journal 58(1):193-198.

Bowman, R.A., and A.D. Halvorson. 1998. Soil chemical changes after nine years of differential N fertilization in a no-till dryland wheat–corn–fallow rotation. Soil Science 163(3):241-247.

Campbell, C.A., B.G. McConkey, V.O. Biederbeck, R.P. Zenter, S. Tessier, and D.L. Hahn. 1997. Tillage and fallow frequency effects on selected soil quality attributes in a coarse-textured Brown Chernozem. Canadian Journal of Soil Science 77(4):497-505.

Campbell, C.A., B.G. McConkey, R.P. Zenter, F. Selles, and D. Curtin. 1996. Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Canadian Journal of Soil Science 76(3):395-401.

Dam, R.F., B.B. Mehdi, M.S.E. Burgess, C.A. Madramootoo, G.R. Mehuys, and I.R. Callum. 2005. Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. Soil & Tillage Research 84(1):41–53.

Dao, T.H. 1993. Tillage and winter wheat residue management effects of water infiltration and storage. Soil Science Society of America Journal 57(6):1586-1595.

Diaz-Zorita, M., J.H. Grove, L. Murdock, J. Herbeck, and E. Perfect. 2004. Soil structural disturbance effects on crop yields and soil properties in a no-till production system. Agronomy Journal 96(6):1651-1659.

Douglas, J.T., M.G. Jarvis, K.R. Howse, and K.R. Goss. 1986. Structure of a silty soil in relation to management. Journal of Soil Science 37(1):137-151.

Fabrizzi, K.P., F.O. Garcia, J.L. Costa, and L.I. Picone. 2005. Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. Soil & Tillage Research 81(1):57-69.

Fausey, N.R., R. Lal, and A.A. Mahboubi. 1994. Long-term tillage and rotations effects on properties of a central Ohio soil. Soil Science Society of America Journal 58(2):517-522.

Fenster, C.R., and G.A. Peterson. 1979. Effects of No-tillage Fallow as Compared to Conventional Tillage in a Wheat-Fallow System. Research Bulletin 289. Lincoln, NE: University of Nebraska.

Ferreras, L.A., J.L. Costa, F.O. Garcia, and C. Pecorari. 2000. Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic Paleudoll of the southern "Pampa" of Argentina. Soil & Tillage Research 54(1-2):31-39.

Forte-Gardner, O., F.L. Young, D.A. Dillman, and M.S. Carroll. 2004. Increasing the effectiveness of technology transfer for conservation cropping systems through research and field design. Renewable Agriculture and Food Systems 19(4):199-209.

Francis, G.S., K.C. Cameron, and R.S. Swift. 1987. Soil physical conditions after six years of direct drilling or conventional cultivation on a silt loam soil in New Zealand. Australian Journal of Soil Research 25(4):517-529.

Freese, R.C., D.K. Cassel, and H.P. Denton. 1993. Infiltration in a Piedmont soil under three tillage systems. Journal of Soil and Water Conservation 48(3):214-218.

Fuentes, J.P., M. Flury, and D.F. Bezdicck. 2004. Hydraulic properties in a silt loam soil under natural prairie, conventional till, and no-till. Soil Science Society of America Journal 68(5):1679-1688.

Gantzer, C.J., and G.R. Blake. 1978. Physical characteristics of Le Sueur clay loam soil following no-till and conventional tillage. Agronomy Journal 70(5):853-857.

German-Heins, J., and M. Flury. 2000. Sorption of Brilliant Blue FCF in soils as affected by pH and ionic strength. Geoderma 97(1-2):87-101.

Guy, S.O., and M.A. Lauver. 2007. No-till and conventional-till effects on spring wheat in the Palouse. Crop Management (May 2007):1-3.

Halvorson, A.D., B.J. Wienhold, and A.L. Black. 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Science Society of America Journal 66(3):906-912.

Hill, R.L. 1990. Long-term conventional and no-tillage effects on selected soil physical properties. Soil Science Society of America Journal 54(1):161-166.

Hill, R.L., R. Horton, and R.M. Cruse. 1985. Tillage effects on soil water retention and pore size distribution of two Mollisols. Soil Science Society of America Journal 49(5):1264-1270.

Hill, R.L., and R.M. Cruse. 1985. Tillage effects on bulk density and soil strength of two Mollisols. Soil Science Society of America Journal 49(5):1270-1273.

Hobbs, P.R. 2007. Conservation agriculture: What is it and why is it important for future sustainable food production? Journal of Agricultural Sciences 145(1):127-137.

Hussein, I., K.R. Olsen, and J.C. Siemens. 1998. Long-tern tillage effects on selected soil physical properties. Soil Science 163(12):970-981.

Jiang, P., S.H. Anderson, N.R. Kitchen, E.J. Sadler, and K.A. Sudduth. 2007. Landscape and conservation management effects on hydraulic properties of a claypan soil toposequence. Soil Science Society of America Journal 71(3):803-811.

Kay, B.D. 1990. Rates of change of soil structure under different cropping systems. Advances in Soil Science 12(1):1-52.

Kay, B.D., and A.J. VandenBygaart. 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Tillage Research 66(2):107-118.

Kennedy, A.C., and W.F. Schillinger. 2006. Soil quality and water intake in traditional-till vs. no-till paired farms in Washington's Palouse region. Soil Science Society of America Journal 70(3):940-949.

Klute, A., and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. *In* Methods of Soil Analysis: Part I. Physical and Mineralogical Methods, ed. A. Klute, 687-734. Agronomy Monograph 9. Madison, WI: American Society of Agronomy.

Kushwaha, C.P., K.P. Singh, and S.K. Tripathi. 2001. Soil organic matter and water-stable aggregates under different tillage and residue conditions in a tropical dryland agroecosystem. Applied Soil Ecology 16(3):229-241.

Kravchenko, A.N., G.P. Robertson, X. Hao, and D.G. Bullovk. 2006. Management practices effects on surface total carbon: Differences in spatial variability patterns. Agronomy Journal 98(6):1559-1568.

Lal, R. 1982. No-Till Farming: Soil and Water Conservation and Management in the Humid and Subhumid Tropics. IITA Monograph 2. Ibadan, Nigeria: International Institute of Tropical Agriculture.

Liebig, M.A., D.L. Tanaka, and B.J. Wienhold. 2004. Tillage and cropping effects on soil quality indicators in the northern Great Plains. Soil Tillage Research 78(2):131-141.

Lindstrom, M.J., W.B. Voorhees, and C.A. Onstad. 1984. Tillage system and residue cover effects on infiltration in northwestern Corn Belt soil. Journal of Soil and Water Conservation 39(1):64-68.

Mengel, D.B., D.W. Wilson, and D.M. Huber. 1982. Placement of nitrogen fertilizer for no-till and conventional tillage corn. Agronomy Journal 74(3):515-518.

Mielke, L.N., J.W. Doran, and K.A. Richards. 1986. Physical environment near the surface of plowed and no-tilled soils. Soil & Tillage Research 7(4):355-366.

Mielke, L.N., and W.W. Wilhelm. 1998. Comparisons of soil physical characteristics in long-term tillage winter wheat-fallow tillage experiments. Soil Tillage Ressearch 49(1-2):29-35.

Pan, W.L., F.L. Young, and K.K. Kidwell. 2001. Carbon and nitrogen cycling in direct-seeded spring cereal alternatives to summer fallow. *In* Proceedings of the Western Nutrient Management Conference, Salt Lake City, Utah.

Saxton, K., D. Chandler, L. Stetler, B. Lamb, C. Claiborn, and B.H. Lee. 2000. Wind erosion and fugitive dust fluxes on agricultural lands in the Pacific Northwest. Transactions of the American Society of Agricultural Engineers 43(3):623-630.

Schillinger, W.F., and F.E. Bolton. 1993. Fallow water storage in tilled vs untilled soils in the Pacific Northwest. Journal of Production Agriculture 6(2):267-269.

Schillinger, W.F., and D.L. Young. 2004. Cropping systems research in the world's dries rainfed wheat region. Agronomy Journal 96(4):1182-1187.

Schillinger, W.F., A.C. Kennedy, and D.L. Young. 2007. Eight years of annual no-till cropping in Washington's winter wheat-summer fallow region. Agriculture, Ecosystems and Environment 120:345-358.

Schjonning, P., and K.J. Rasmussen. 2000. Soil strength and soil pore characteristics for direct drilled and ploughed soils. Soil Tillage Research 57(1-2):69-82.

Sharratt, B., M. Zhang, and S. Sparrow. 2006. Twenty years of tillage research in subarctic Alaska II. Impact on soil hydraulic properties. Soil & Tillage Research 91(1-2):75-81.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface soil physical properties after twelve years of dryland no-till management. Soil Science Society of America Journal 66(4):296-1303.

Standford, G., O.C. Bennett, and J.F. Power. 1973. Conservation tillage practices and nutrient availability. *In* Conservation Tillage: The Proceedings of a National Conference, 54-62. Ankeny, IA: Soil Conservation Society of America.

Strudley, M.W., T.R. Green, and J.C. Ascough III. 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. Soil & Tillage Research 99(1):4-48.

Thorne, M.E., F.L. Young, and J.P. Yenish. 2007. Cropping systems alter weed seed banks in Pacific Northwest semi-arid wheat region. Crop Protection 26(8):1121-1134.

Thorne, M.E., F.L. Young, W.L. Pan, R. Bafus, and J.R. Alldredge. 2003. No-till spring cereal cropping systems reduced wind erosion susceptibility in the wheat/fallow region of the Pacific Northwest. Journal of Soil and Water Conservation 58(5):250-257.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33(1):141-163.

VandenBygaart, A.J., R. Protz, and A.D. Tomlin. 1999. Changes in pore structure in a no-till chronosequence of silt loam soils, southern Ontario. Canadian Journal of Soil Science 79(2):149-160.

Wicks, G.A., and D.E. Smika. 1973. Chemical fallow in a winter wheat-fallow rotation. Weed Science 21(2):97-102.

Wilkins, D.E., M.C. Siemens, and S.L. Albrecht. 2002. Changes in soil physical characteristics during transition from intensive tillage to direct seeding. Transactions of the American Society of Agricultural Engineers 45(4):877-880.

Wright, J.L. 1982. New evapotranspiration crop coefficients. Journal of Irrigation Drainage Engineering 108(1):57-74.

Wuest, S.B., T.C. Caesar-TonThat, S.F. Wright, and J.D. Williams. 2005. Organic matter addition, N, and residue burning effects on infiltration, biological, and physical properties of an intensively tilled silt-loam soil. Soil & Tillage Research 84(2):154-167.

Wuest, S.B., J.D. Williams, and H.T. Gollany. 2006. Tillage and perennial grass effects on ponded infiltration for seven semi-arid loess soils. Journal of Soil and Water Conservation 61(4):218-223.

Young, F.L., and M.E. Thorne. 2004. Weed-species dynamics and management in no-till and reduced-till fallow cropping systems for the semi-arid agricultural region of the Pacific Northwest, USA. Crop Protection 23(11):1097-1110.

Zhai, R., R.G. Kachanoski, and R.P. Voroney. 1990. Tillage effects on the spatial and temporal variations of soil water. Soil Science Society of America Journal 54(1):186-192.