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Tillage and no-tillage conservation effectiveness in the intermediate precipitation zone of the inland Pacific Northwest, United States

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Abstract: A common cropping system in the intermediate precipitation zone (300 to 450 mm [12 to 18 in]) of the inland Pacific Northwest is the two-year, winter wheat-fallow rotation typically practiced using multiple secondary tillage operations to control weeds and retain seed-zone soil moisture. This crop rotation has proven to be a stable system for producers in this region. However, even conservation tillage (CT) practices such as mulch tillage leave this system prone to substantial erosion where the soil surface is disturbed. Alternatives to this system include no-tillage (NT) practices, increasing the cropping intensity, or a combination of both. Our objective was to evaluate and compare soil and water conservation attributes between NT and a variation on CT, hereafter referred to as tillage practice (TP) under a four-year dryland crop rotation. We established a four-year rotation consisting of winter wheat (*Triticum aestivum* L.), spring peas (*Pisum sativum* L.), winter wheat, and fallow. No-tillage consisted of seeding and fertilizing in one pass, two applications of herbicide, and harvest. Conservation tillage consisted of seed bed preparation using a chisel plow, fertilization injection with a disk applicator for spring peas or at time of seeding with a shank drill for wheat, two to three passes with secondary tillage (sweep-rod and rodweeder), applications of herbicide as needed, and harvest. The experimental design was a complete randomized block with four blocks, two tillage treatment main plots per block and four subplots in each main plot for each phase of the four-year rotation. We measured groundcover, infiltration using ring infiltrometers, and runoff and soil erosion from natural weather events. Weather during the four years was relatively mild. Groundcover (81% and 59%) and infiltration rates (41 mm h^{-1} [1.63 in hr^{-1}] and 14 mm h^{-1} [0.57 in hr^{-1}]) were significantly greater in the NT treatment than in the TP treatment. Runoff (0.4 mm [0.02 in] and 0.5 mm [0.0.02 in]) and soil erosion (10 kg ha^{-1} [0.004 tn ac^{-1}] and 21 kg ha^{-1} [0.009 tn ac^{-1}]] were both significantly less in the NT than the TP. The changes in infiltration, runoff, and soil erosion rates occurred more quickly and to a greater degree than we anticipated. Earlier studies in the inland Pacific Northwest have been ambiguous in their conclusions about the effectiveness of NT to significantly reduce runoff and soil erosion compared to TP. This research found that NT provided a significant improvement in soil and water conservation over TP at this location under mild weather conditions.

Key words: conservation tillage—infiltration—no-tillage—soil erosion—runoff—winter wheat

Soil losses in the inland Pacific Northwest (PNW) of the United States are estimated to have averaged 2.3 Mg ha y^{-1} (1.03 tn ac yr^{-1}) from 1939 through 1978 (USDA 1978). These erosion rates have resulted from traditional farming practices used for dryland crop production in combination with severe weather events (frozen soil with rain during warm maritime fronts) to produce extremely high erosion rates between December and March. Zuzel et al. (1982) reported as high as 31.0 Mg ha^{-1} (13.8 tn ac^{-1}) soil loss from 18.3 m (60 ft) long experimental plots during a five-week period. Increased cropping intensity and conservation tillage (CT) practices are recommended to reduce soil erosion by wind and water in wheat-based systems in the inland Pacific Northwest (PNW) of the United States (Rasmussen et al. 1998; Schillinger and Young 2004). Conservation tillage for summer fallow generally consists of primary tillage with a disk or chisel plow, and secondary tillage with a cultivator or sweep-rod to control weeds and create an evaporation barrier by disrupting capillary paths to the soil surface (Huggins and Reganold 2008). Although more than half the soil surface is covered with crop residue, crusting of low organic matter surface soil controls the hydrologic responses of ponding and time to runoff (Hammel et al. 1981), leaving the field susceptible to rill formation and soil erosion (Williams et al. 2000). Beyond conservation practices that use tillage and disturb the soil surface, the next option for reducing or preventing soil erosion is the adoption of no-tillage (NT) practices (Huggins and Reganold 2008).

Considerable effort has gone into development of effective systems that use NT in the inland PNW. These efforts have focused on economic and agronomic considerations such as plant variety selection, field equipment modification, optimum planting dates and fertilizing methods, effective weed control methods, and development of multiple crop rotations with reduced fallow (Solutions To Environmental and Economic Problems [STEEP] research reports, http://pnwsteep.wsu.edu/index.htm).

Rain-fed crop research conducted in this region is usually specific to one of three precipitation zones generally described as low (<300 mm [12 in]), intermediate (300 to 450 mm [12 to 18 in]), or high (450 to 600 mm [18 to 24 in]). Huggins et al. (2001) compared the performances of a wide variety of broadleaf and graminoid winter and spring crops under NT and traditional tillage (TT) in the wettest area of the region. They found no difference in yield between NT and TT treatments. Schillinger and Young (2004) compared continuous annual spring wheat production using NT to winter wheat-summer fallow (tilled) in the driest portion of the low-precipitation region. They reported

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that NT spring wheat was not competitive with CT winter wheat due to low water use efficiency and low and highly variable grain yield compared with the more stable winter wheat/summer fallow system. Recently, Machado et al. (2007) established a variety of rotations to directly compare NT to CT in the low and intermediate precipitation zones.

The reduction or elimination of tilled fallow can raise soil organic carbon levels (Rasmussen et al. 1998; Kennedy and Schillinger 2006; Schillinger et al. 2007). Bezdicek et al. (2002) reported that particulate organic matter and light fraction organic matter can increase substantially in as few as three years in NT systems in the PNW higher intermediate and high precipitation zones. In general, surficial accumulations of soil organic matter contribute to well formed macroaggregates (Cambardella and Elliott 1993) and are associated with the development of superior soil hydrologic conditions (Williams 2004, 2008; Wuest et al. 2005). This relationship is well established (Bissett and O'Leary 1996; Six et al. 2000; Wuest et al. 2005; Kennedy and Schillinger 2006) and improvements in soil and water conservation when using NT have been observed in many areas of the world (McGregor and Greer 1982; Angle et al. 1984; Dickey et al. 1984; Edwards et al. 1993; Shipitalo and Edwards 1998; Castro et al. 1999).

Research to determine the effect of NT on infiltration, runoff, and soil erosion has been conducted since the late 1970s in the PNW. The earliest research was conducted on large hillslope plots (lengths ≥ 22 m [73 ft], slopes 15% to 30%) from 1979 through 1984, at two sites in the high precipitation zone. At one site, Dowding et al. (1984) demonstrated that NT and minimum tillage substantially reduced winter runoff and erosion in winter wheat planted after spring peas. At the second site, NT and minimum tillage conserved substantially more soil and water than TT, results that were attributed to cover and roughness (McCool et al. 2000). Tillage disturbance and cover had the greatest effect when soil was not frozen. On small scales using 1 m^2 (10.8 ft^2) plots, Alvi and Chen (2003) measured less runoff from a NT treatment than from a TT treatment in the high precipitation zone. Wuest et al. (2006) measured infiltration rates across a geo-climo sequence in perennial grass, NT, and TT fields. Compared to TT fields, infiltration rates were 30% higher with NT or perennial grass management. Kennedy and Schillinger (2006) found no significant differences between infiltration rates in standing stubble of NT or TT at the higher end of the intermediate precipitation zone. They attributed these results to capillary pore continuity from wheat roots and having left standing stubble protecting the soil surface for at least 12 months. Williams et al. (2009) reported substantially less runoff and soil loss from the first four years of a side-by-side comparison of a two-year winter wheat-summer fallow (tilled) with a four-year rotation (winter wheat, broadleaf, winter wheat, NT summer fallow) in two small drainages. Brooks et al. (2007) compared three tillage methods for two years in small, upland drainages in the high precipitation zone, where they recorded Hortonian overland flow, saturation excess flow resulting from argillic soil horizons, and topographic convergent zones that occurred regardless of tillage treatment. They did not identify differences in soil erosion among the treatments but did point out the importance of abundant surface residue in NT. Both studies were able to capture drainage or field-scale processes, but conclusions from both were confounded by inconsistent treatment application, pseudoreplication, or extreme variability in the landscape among the various treatments.

The importance of soil conservation and the difficulty in developing and promoting improved systems acceptable to farmers creates a need for accurate data on the performance of soil management options. Our objective was to evaluate and compare, at a small plot scale, soil and water conservation attributes between NT and CT under a four-year dryland crop rotation.

Materials and Methods

Research Site. This research was conducted at the USDA Agricultural Research Service (ARS) Columbia Plateau Conservation Research Center (CPCRC) and Oregon State University Columbia Basin Agricultural Research Center (CBARC), located 15 km (9 mi) northeast of Pendleton, Oregon (45°43'N, 118°38'W). The elevation at the site is 458 m (1,500 ft). The research site lies within the intermediate precipitation zone, a transition zone where annual cropping is potentially feasible, but where many producers continue to practice winter wheat-fallow.

Meteorological Records and Soils. Seventy years of meteorological data recorded at the CPCRC/CBARC from 1930 through 2000 show minimum, maximum, and mean annual air temperatures of −34°C (−29°F), 46°C (115°F), and 11°C (52°F), respectively. Annually, 135 to 170 days are frost-free between May and September. Mean annual precipitation is 422 mm (16.6 in), with a minimum of 243 mm (9.6 in) and maximum of 583 mm (23.0 in). Approximately 70% of precipitation occurs between November and April, resulting from maritime fronts that produce low intensity storms with a median duration of 3 h with 50% of storms lasting 1 to 7 h. A summary of records in 1983 (Brown et al. 1983) reported a maximum 1 h storm intensity of 13 mm h^{-1} (0.51 in hr^{-1}), and median storm size of 1.5 mm (0.06 in) at 0.5 mm h^{-1} (0.02 in hr^{-1}). Snow cover is transient and subject to rapid melting by frequent, warm maritime fronts. A meteorological station located at CPCRC/CBARC recorded precipitation, wind speed and direction, solar radiation, relative humidity, and air and soil temperature each crop year of this study.

The soil type is a Walla Walla silt loam, hardpan substratum (coarse-silty, mixed, mesic, superactive Typic Haploxerolls–US; Kastanozems–FAO) (Johnson and Makinson 1988). This phase of Walla Walla silt loam occurs across 7% (47,500 ha) of Umatilla County, and is deep and well drained. The hardpan classification is the result of a discontinuous silica layer developed between 1.0 to 1.5 m (3.3 to 4.9 ft) below the soil surface, less than 10 mm (0.4 in) thick and occupying less than 15% of the area. This feature does not adversely affect soil surface hydrologic properties; Wuest (2005) conducted four-hour ponded infiltration tests within 500 m (1,640 ft) of the plots reported on here. The infiltration rates did not change after four hours, indicating that deep, less pervious layers were not influential. Our experimental plots were positioned on 5% slopes with west and east aspects.

Cropping System and Tillage Operations. Crops were grown in a four-year winter wheat/spring pea/winter wheat/fallow rotation using NT and a variation of CT hereafter referred to as tillage practice (TP) from crop year 2005 through 2008 (table 1). The research site was in commercial wheat production until 2002, sunflowers were grown and harvested in 2003, and winter wheat planted uniformly across the site fall 2002 and harvested summer 2003. The site was fal-

Table 1

Management operations, equipment, and settings used in no-tillage and tillage practice treatments, given for each phase of the four-year rotation.

Treatment	Crop	Year	Phase	Date	Operation (depth, row spacing)
NT	All		WW(f)	September	Seed (shank drill, 51 mm,305 mm)
			SP	April	Seed (shank drill, 51 mm, 305 mm)
				April	Incorporate herbicide with tine harrow (20 mm)
				April	Roll with packers
			WW(p)	September	Seed (shank drill, 51 mm, 305 mm)
			F		None
TP			WW(f)	September	Seed (shank drill, 51 mm, 254 mm)
			SP	March	Chisel Plow (305 mm, 305 mm)
				March	Fertilize (liquid, disc applicator, 76 mm)
				April	Seed (double disk, 51 mm, 178 mm)
				April	Incorporate herbicide with tine harrow
				April	Roll with packers
			WW(p)	August	Chisel plow (305 mm, 305 mm)
				August	Disc (51 mm deep)
				September	Seed (shank drill, 51 mm, 254 mm)
				September	Roll with packers (2006 only)
		2005 to 2007	F	April to May	Chisel plow (305 mm, 305 mm)
				May	Sweep-rod: Sweep (102 mm, 305 mm), Rodweed (76 mm)
				June	Rodweed (76 mm)
		2008	F	May 8	Undercut (101 mm)
				June 19	Rodweed (76 mm)

Notes: NT = no-tillage. TP = tillage practice. WW(f) = winter wheat after fallow. WW(p) = winter wheat after spring peas. SP = spring peas. F = summer fallow.

lowed until spring 2004, when preliminary tillage began for the tillage treatment plots. The first winter wheat crops were planted in the fall of 2004. Target seeding rates were the same in NT and TP. We seeded winter wheat at 221 seeds per m^2 (21 seeds per ft^2) and spring peas at 105 seeds per m^2 (10 seeds per ft^2). Soil fertility samples were collected each year before seeding, and fertilizer rates adjusted to targeted yields. Starter fertilizer was placed with seed and additional fertilizer placed 25 mm (1 in) below and 25 mm to the side of the seed. Plots in the NT treatment were sprayed with herbicides to control weeds as needed. Farming operations in the NT treatment were limited to one pass to sow seed and place fertilizer. In the TP treatment, primary tillage was done 305 mm (12 in) deep with a chisel plow and secondary tillage consisted of cultivation with a sweep-rod (305 mm V-sweeps with attached rodweeder), fertilizer injection, and two-to-three passes through the field with a rodweeder. We harvested all crops using a plot combine with a straw chopper and 2 m (6.5 ft) wide straw spreader.

Monitoring and Sampling Procedures. We measured percent cover, consisting of the current year's growth and previous year's residue, in late February 2007 using a digital adaptation of the cross-hair frame method developed by Floyd and Anderson (1982). Soil erosion occurs in the region predominately between December and March (Zuzel et al. 1982); soil surface cover measured near the end of this period quantifies conditions under which erosion occurred.

Single-ring infiltration measurements (Bertrand 1965) were made by driving 200 mm (7.9 in) diameter sharpened metal cylinders 250 mm (9.8 in) deep into the soil. Part of a crop row was always included inside the sample area. The inside circumference was tamped with a 4 mm (0.2 in) thick rod to seal any gaps between the cylinder and the soil. Water was maintained at a constant depth of 20 to 30 mm (0.8 to 1.2 in) with float valves for two hours (Wuest 2005). Two hours were sufficient to achieve near steady-state infiltration, which was usually approached within 30 to 60 min. Readings from calibrated reservoirs supplied periodic estimates of water infiltration rate. Infiltration measurements were performed in early April 2009. The crop portion of the experiment concluded with harvest 2008; after harvest the entire site was seeded to winter wheat in October using the same NT drill that had been used in the experiment. By measuring infiltration the following spring (2009), we were able to capture accumulated tillage effects at the end of the experiment and also the full effect of soil consolidation, slaking, and crusting that occurs from December through March when soil erosion is most likely to occur (Zuzel et al. 1982).

In crop years 2006 to 2008, 32 metal runoff collectors were installed that consisted of 9.5 mm (0.37 in) thick by 254 mm (10 in) wide steel plate bent into a rectangle about 800 mm (31.5 in) wide and 1,200 mm (47.2 in) long, with the bottom side formed into a slight V-shaped funnel. Frames were centered in each plot to include three crop rows. The total surface area within the frame was 1 m^2 (10.8 ft^2). Soil erosion in this region is predominately through rill erosion, which is better quantified by plots 10 m (33 ft) or longer (Williams et al. 1998). The 1 m^2 size of plot was chosen because of constraints imposed by availability of research site locations, with the intention of discerning relative treatment differences before overland

Table 2

Precipitation, temperature, runoff, and soil erosion from November through March during 2006, 2007, and 2008. Long-term precipitation and temperature values corresponding to these periods of measurement provided for reference.

Date	Precipitation (mm)	Temperature (°C)	Runoff (mm)* NT†	Runoff (mm)* TP	Erosion (kg ha^{-1}) NT	Erosion (kg ha^{-1}) TP
1931 to 2005	200.9 ± 12.1	3.2 ± 0.7*				
2006	206.4	2.9	0.6 ± 0.3	0.5 ± 0.3	0.3 ± 0.2	0.2 ± 0.2
2007	246.0	4.0	0.1 ± 0.0	0.4 ± 0.2	0.2 ± 0.1	37.7 ± 36.2
2008	191.8	2.6	0.5 ± 0.2	0.7 ± 0.1	29.7 ± 23.3	24.2 ± 12.3
Total			1.2	1.6	30.2	62.2

Notes: NT = no-tillage. TP = tillage practice.

* Mean daily temperature recorded from November through March.

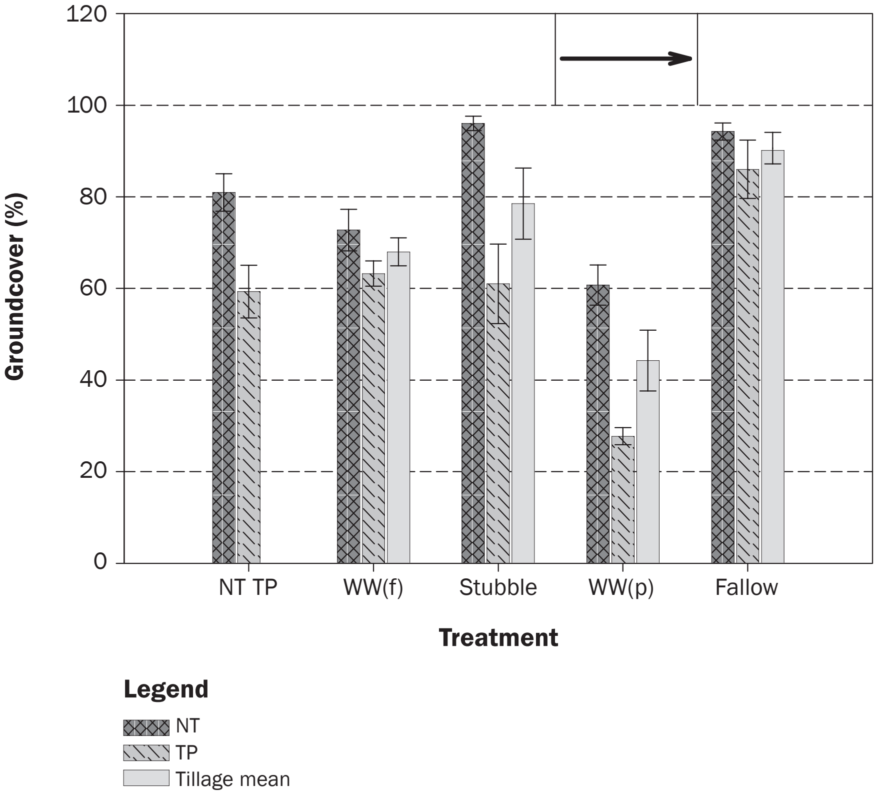
† Mean and standard error.

flow was concentrated and rill were initiated. Frames were pounded into the ground using slide hammers or post-driving equipment. The soil immediately inside the frame was lightly tamped with a 4 mm (0.02 in) thick rod to seal gaps between soil and frame walls. A hose attached to the funnel led to a 20 L (5 gal) runoff container. Containers were checked periodically and runoff was collected after multiple events to avoid overflow. Runoff and eroded sediment from each subplot were determined by weighing, drying, and reweighing material collected in the containers. Runoff and soil loss were reported as annual total values.

Experimental Design and Statistical Procedures. The experimental design was a split plot, with whole plots in randomized complete blocks, using the terminology of Littell et al (2006, page 97, design 4.1.e). The whole plot treatments were NT and TP, and the split plots were the four entry points of the crop rotation: fallow, winter wheat, peas, winter wheat. Since there were four blocks, the total number of plots was eight, and the total number of split-plot experimental units was 32. The experiment was run for four years, and the meter-square collectors were installed three of the four years. The data was analyzed using a mixed model, with blocks and years as random effects. Splitplots were 45.7 m (150 ft) long by 3.7 m (12 ft) wide. Annual runoff, soil erosion, and post treatment infiltration rate were analyzed using a mixed-model, repeated measures ANOVA MIXED procedure to model the response, and least square means separation test where significant main effects and interaction terms were found (SAS Institute 2008). All statistical tests were conducted at $p < 0.05$. Data were evaluated using conditional Studentized residuals (SAS Institute 2008) and log transformed where necessary to meet assumptions of normality. Both infiltration and erosion data required transformation.

Figure 1

Groundcover means and standard errors by treatments and for each phase of the four-year rotation measured in February spring following high winter erosion potential. Arrow indicates phase of rotation when treatments are most susceptible to runoff and interrill erosion.



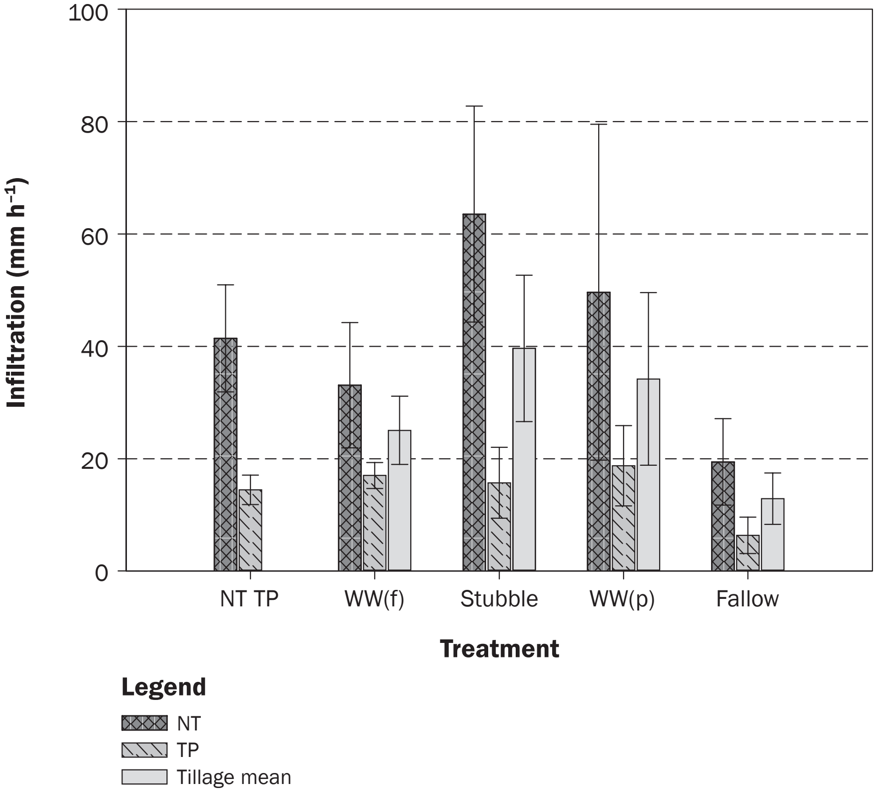
Notes: NT = no-tillage. TP = tillage practice. WW(f) = winter wheat following summer fallow. Stubble = wheat stubble between WW(f) and spring peas. WW(p) = winter wheat following spring peas. Fallow = summer fallow (July harvest–October seeding, 15 months).

Results and Discussion

Meteorological and Soil Surface Conditions. From November through March, weather conditions were within the 95% confidence interval for the 76 y mean precipitation and air temperature in 2006 and 2008, with higher than normal precipitation and air temperatures in 2007 (table 2). Large soil erosion losses in this region typically result from rain on frozen soil, with or without snow cover, or

Figure 2

Infiltration mean rates and standard errors measured nine months after the 2008 (final) harvest. All plots were seeded to winter wheat using no-tillage when measurements were made. The subplot designations give the last rotation phase present in each plot at end of experiment.



Notes: NT = no-tillage. TP = tillage practice. WW(f) = winter wheat following summer fallow. Stubble = wheat stubble between WW(f) and spring peas. WW(p) = winter wheat following spring peas. Fallow = summer fallow (July harvest–October seeding, 15 months).

rain on snow-covered unfrozen soil (Zuzel et al. 1982). Although these events can occur up to five times each year (Zuzel et al. 1986), they occurred only three times from 2006 through 2008, thus resulting in relatively mild meteorological conditions for this research. With the infrequency of these events, we would expect to observe correspondingly low rates of runoff and soil erosion.

The NT treatment had significantly more groundcover than the TP treatment (figure 1), mostly due to the amount of residue remaining after winter wheat planted into fallow (WW[f]) and winter wheat planted after pea (WW[p]) phases of the rotation (table 3). A central purpose of conservation tillage is to leave adequate residue on the soil surface to protect it from raindrop impact. The USDA Natural Resources Conservation Service classifies cover greater than 30% an attribute of conservation tillage practices, which our TP treatment exceeded in all phases of the rotation except WW(p) (figure 1). The largest differences between tillage treatments were found in the wheat stubble before spring pea and WW(p) (figure 1) and in WW(p), due incorporation of residue into the soil surface in the TP treatment. The lack of significant difference in cover between tillage treatments in the WW(f) results from abundant residue production by winter wheat after fallow in the PNW, averaging as much as 7.5 Mg ha^{-1} (3.35 tn ac^{-1}) (Rasmussen and Parton 1994), and the relatively high degree of soil surface disturbance caused by the NT shank drill. We would expect no difference between the tillage treatments during the fallow phase of the rotation because the measurements were made after wheat harvest but before spring tillage in the TP treatment. Regardless of tillage treatment, groundcover was significantly different in the following order: fallow > stubble >WW(f) > WW(p) (figure 1). The low cover values for WW(p) are due to low pea residue production relative to wheat and quick decomposition of pea residue after harvest (Douglas and Rickman 1992). Wheat residue can persist on the soil surface substantially longer than pea residue. Even minimal disturbance and incorporation of residue subjects it to contact with soil and water, and therefore faster microbiological breakdown (Schlesinger and Andrews 2000). These results for groundcover are similar to those reported by Williams et al. (2009) for the same rotation in a companion study.

Soil Hydrology and Soil Erosion. Infiltration rates were significantly higher in NT than in TP (figure 2). There was a strong rotation effect, and no interaction between treatment and rotation (table 4). Infiltration is time/season-dependent and varies from year to year (Wienhold and Tanaka 2000; Wuest et al. 2006), and is influenced by the water content of the soil, residue and soil organic carbon accumulation at the soil surface (Burch et al. 1986; Radcliffe et al. 1988; Franzluebbers 2002; Shaver et al. 2002) and development and the presence and nature of surface pores (McGarry et al. 2000). Using the same soil as in this study, Wuest et al. (2006) found that soil texture, particulate organic matter, and the number of years that NT has been practiced influence infiltration rates. Because our study was relatively short-term (four years), we expected to find little or no increase in infiltration rates. On the contrary, NT infiltration rates were 2.9 times greater than in TP.

Based on the three winters of erosion data, significantly more runoff and interrill erosion occurred from the TP treatment (table 5 and figure 3). The largest differences between treatments occurred in the WW(p) treatment, which coincided with the combination of tillage disturbance and the least groundcover in the TP treatment.

The amounts runoff and soil erosion recorded were small compared to previous NT studies using the same plot size and natural meteorological events in the inland PNW (Alvi and Chen 2003; Williams et al. 2009). Sampling during the same winter months as in the research reported here, Williams et al. (2009) reported runoff values of 23 mm (0.9 in) (NT) and 79 mm (3.1 in) (TT), and soil erosion values of 0.21 Mg ha^{-1} (0.10 tn ac^{-1}) (NT) and 11.01 Mg ha^{-1} (4.91 tn ac^{-1}) (TT). The relatively low values reported in this study compared to those in Williams et al. (2009) resulted from a lower slope gradient and less disruption of the soil surface by our TP practice. Our research was conducted near the bottom of a shallow drainage with 5% slope compared to a 15% to 25% back slope in Williams et al. (2009). Small values were also reported by Alvi and Chen (2003), where plots were installed on shoulder slopes and winter runoff averaged 0.01 mm (0.0004 in) in NT and 0.07 mm (0.003 in) in TT. The TT that produced the greatest amount of erosion reported by Williams et al. (2009) consisted of burning the crop residue and moldboard plowing after harvest, and later spring cultivated, fertilized, and rod weeded twice before fall planting. This left a bare soil surface through two winters.

In both tillage treatments, runoff and soil erosion from plots in stubble following WW(f) were significantly less than any of the other three phases of the rotation (table 5) (figure 3). It seems that runoff and erosion from the fallow should be similar or identical to the stubble (figure 3). There was significantly more cover in the fallow than in the stubble, but it appears this was not enough to overcome other unmeasured differences between winter wheat stubble following WW(f) and that following WW(p).

Water lost as runoff from both treatments represented less than 0.5% of the precipitation from November through March during the experiment (table 2). Although significantly more soil was lost from the TP treatment (table 5), total soil loss in that treatment for the three-year period was 0.06 Mg ha^{-1} (0.03 tn ac^{-1}). These low values are representative of small scale runoff and interrill erosion processes. However, they provide indices of better soil and water conservation under NT relative to practices that result in residue incorporation and disturbance of the soil surface.

Summary and Conclusions

We evaluated the soil and water conservation effectiveness of a four-year rotation managed using NT and TP management. We found the NT system superior to the TP system with significantly more groundcover, higher infiltrations rates, and less runoff and soil erosion measured in the NT. We attribute these results to limited disturbance of crop residue and the soil surface under NT. Within the four-year rotation, the most critical period for runoff and soil loss occurred in winter wheat following spring peas, especially in the TP corresponding to the lowest measured groundcover.

Results from small plot research such as reported here do not capture the primary processes of soil loss in the PNW: overland flow concentration and rill development. They do, however, provide an insight to the initial stages of overland flow and soil loss and indicate performance in production fields. Our data suggest that we can expect improved soil conservation and reduced off-farm sedimentation with broader adoption of NT in preference to conservation tillage.

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Table 3

Analysis of variance (ANOVA) and mean separation tests where main effects are significant of groundcover measured in February 2007.

Groundcover (ANOVA)	$p > F$
Tillage treatment	<0.0001
Rotation	<0.0001
Treatment × rotation	0.0086
Means separation tests*	
NT – TP	<0.0001
Stubble – fallow	0.0197
Stubble – WW(f)	0.0334
Stubble – WW(p)	<0.0001
Fallow – WW(f)	<0.0001
Fallow – WW(p)	<0.0001
WW(f) – WW(p)	<0.0001
NT WW(f) – TP WW(f)	0.1617
NT Stubble – TP stubble	<0.0001
NT WW(p) – TP WW(p)	<0.0001
NT Fallow – TP fallow	0.2219

Notes: NT = no-tillage. TP = tillage practice. WW(f) = winter wheat after fallow. Stubble = standing stubble after harvest of WW(f). WW(p) = winter wheat after spring peas. Fallow = standing stubble after harvest of WW(p).

* Least squares mean separation tests.

Table 4

Analysis of variance and mean separation tests (ANOVA) where main effects are significant for infiltration measured in April 2009.

Infiltration (ANOVA)	p > F
Tillage treatment	0.0029
Rotation	0.0545
Treatment × rotation	0.6061
Means separation tests*	
NT – TP	0.0029

Notes: NT = no-tillage. TP = tillage practice.

* Least squares mean separation tests.

Table 5

Analysis of variance and mean separation tests (ANOVA) where main effects are significant for runoff and erosion.

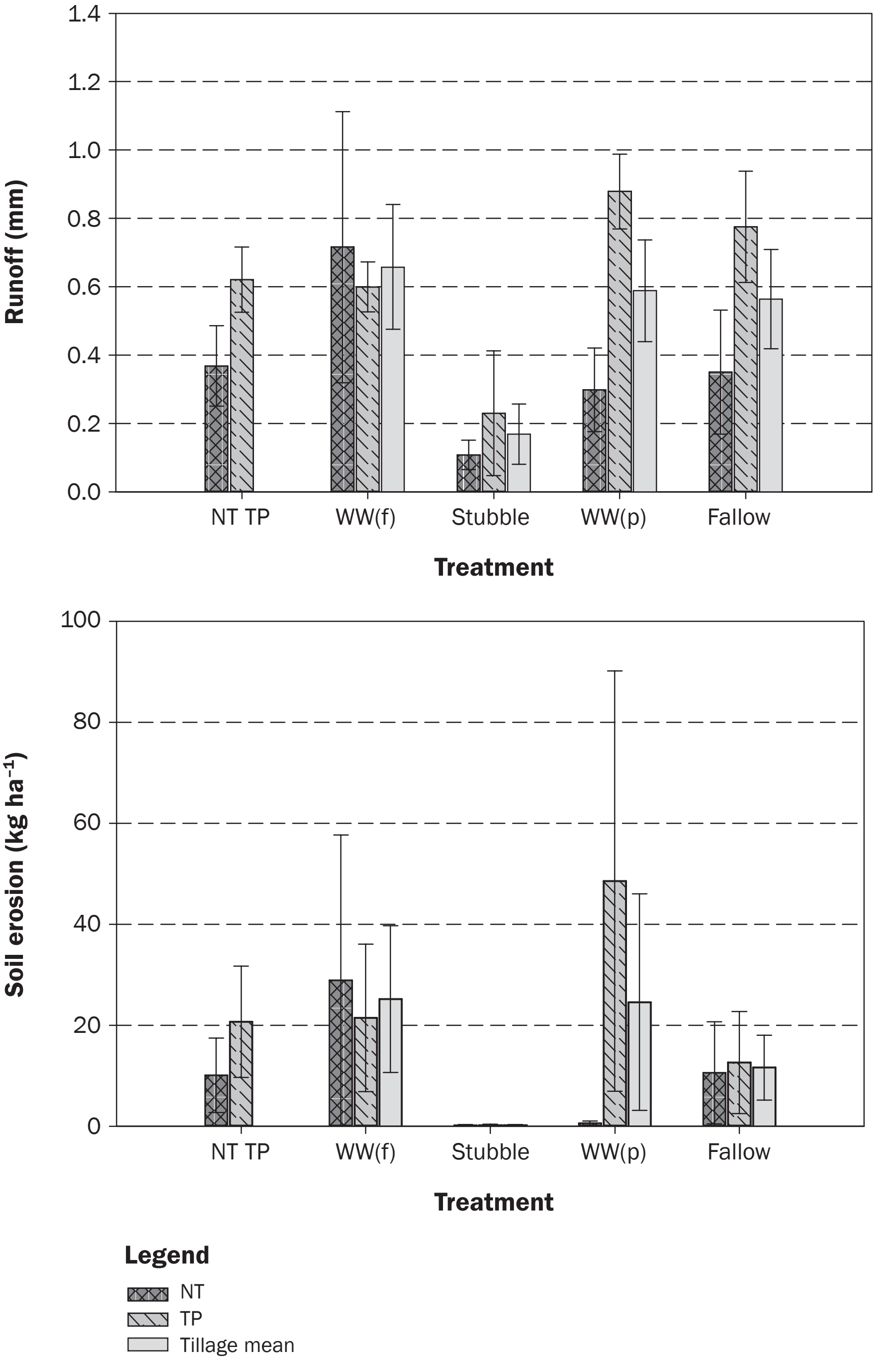
Runoff (ANOVA)	p > F
Tillage treatment	0.0441
Rotation	0.0276
Treatment × rotation	0.1995
Means separation tests*	
NT – TP	0.0441
Fallow – stubble	0.0264
Fallow – WW(f)	0.5920
Fallow – WW (p)	0.8888
Stubble – WW(f)	0.0064
Stubble – WW(p)	0.0186
WW(f) – WW(p)	0.6918
Erosion (ANOVA)	**p > F**
Tillage treatment	0.0301
Rotation	0.0166
Treatment × rotation	0.1572
Means separation tests*	
NT – TP	0.0301
Fallow – stubble	0.0027
Fallow – WW(f)	0.3882
Fallow – WW (p)	0.4968
Stubble – WW(f)	0.0284
Stubble – WW(p)	0.0179
WW(f) – WW(p)	0.8538

Notes: NT = no-tillage. TP = tillage practice. WW(f) = winter wheat after fallow. Stubble = standing stubble after harvest of WW(f). WW(p) = winter wheat after spring peas. Fallow = standing stubble after harvest of WW(p).

* Least squares mean separation tests.

Figure 3

Winter runoff and soil erosion means and standard errors by treatments and for each phase of the four-year rotation.



Notes: See table 5 for statistical relationships. NT = no-tillage. TP = tillage practice. WW(f) = winter wheat following summer fallow. Stubble = wheat stubble between WW(f) and spring peas. WW(p) = winter wheat following spring peas. Fallow = summer fallow (July harvest–October seeding, 15 months).

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