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Soil and water conservation in the Pacific Northwest through no-tillage and intensified crop rotations

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Abstract: The winter wheat (*Triticum aestivum* L.)/summer fallow rotation typically practiced in the intermediate precipitation zone (300 to 450 mm [12 to 18 in]) of the inland Pacific Northwest has proven to be economically stable for producers in this region. However, multiple tillage operations are used to control weeds and retain seed-zone soil moisture, which disturbs the soil and makes it prone to substantial erosion. Alternatives to this conventional disturbance tillage (DT) system include either no-tillage (NT) or minimum tillage (MT) in combination with increasing cropping intensity. The objective of this study was to compare runoff, soil erosion, crop residue, and yield productivity resulting from NT, and DT, or MT. Small collectors and flumes were used to quantify runoff and soil erosion from small drainages and slopes in three different experiments near Pendleton, Oregon. The first experiment included two neighboring drainages: one farmed using DT with a two-year crop rotation over eight years (2001 to 2008) and the other NT with a four-year crop rotation (2001 to 2008). The second experiment comprised a hillslope planted to different crops using NT over eight years (1998 to 2005) and MT over three years (2006 to 2008). The third experiment was situated in a shallow draw in which NT and MT with a four-year (2004 to 2008) crop rotation was compared. Runoff measured in flumes was substantially influenced by tillage method in the order of DT > NT in a ratio of 10:1 at the first site. At the second site, NT produced no runoff compared to 1.6 mm y^{-1} (0.06 in yr^{-1}) from MT. Soil erosion was found to be DT > NT in a ratio of 5:1 at the first site and 2:1 for the second site. For small collectors the differences were significant: runoff was DT > NT in a ratio of 47:1 for the first site, and MT > NT in a ratio of 2:1 for the third site. Winter wheat yields did not differ significantly among NT, DT, and MT. Broader acceptance of NT cropping systems in the intermediate precipitation zone of this region would substantially decrease soil losses from farm fields and improve downstream water quality.

Key words: cropping systems—erosion—no-tillage—Pacific Northwest—runoff—small watersheds

Alternate winter wheat (*Triticum aestivum* L.)/summer fallow is a common cropping system in the intermediate precipitation zone (300 to 450 mm [12 to 18 in]) of the inland Pacific Northwest (Smiley et al. 2005). This crop rotation has proven to be economically stable for producers in this region, with more than 900,000 ha (2,223,948 acres) planted to winter wheat (WW) following fallow each year (NASS 2005a, 2005b; Smiley et al. 2005). A combination of deep soils and cold, wet winters provide adequate soil water for winter wheat through hot dry summers (Schillinger and Papendick 2008). This system was widely practiced well into the 1990s with crop yields from 1.79 to 5.20 Mg ha^{-1} (27 to 77 bu ac^{-1}) (Janosky et al. 2002). Much of its success stems from the use of disturbance tillage (DT) (also called conventional or intensive tillage) to control weeds and root diseases, and prepare a seed bed with adequate soil moisture for germination and establishment in the fall. Because of multiple tillage operations, generally ≤15% residue cover (≤0.56 Mg ha^{-1} [500 lb ac^{-1}]) is present from November through March.

Abundant runoff and soil erosion have long been associated with unique regional weather patterns and dryland wheat production on loessial soils developed on steep slopes (McCool et al. 2006; McGregor 1982). In this cropping system, susceptibility to soil loss is so great that unprotected soil moves downslope in the absence of rainfall when the top 3 to 4 cm (1.2 to 1.6 in) of soil thaws and becomes a viscous, flowing slurry (Zuzel and Pikul 1987). Annual soil losses due to overland flow ranged from 3 to 50 Mg ha^{-1} y^{-1} (1.35 to 22.30 tn ac^{-1} yr^{-1}) (Nagle and Ritchie 2004; Zuzel et al. 1982), with a mean soil loss estimated at 24.5 Mg ha^{-1} y^{-1} (10.93 tn ac^{-1} yr^{-1}) between 1939 and 1972 in the wetter parts of the region (USDA 1978). These loss rates generally exceed the established USDA soil loss tolerance limits of 2.2 to 11.2 Mg ha^{-1} y^{-1} (0.98 to 5 tn ac^{-1} yr^{-1}) for sustained economic productivity in most areas of the region (Renard et al. 1997).

Efforts to reduce soil erosion on steep slopes rely upon conservation practices that leave crop residues on the surface and promote infiltration of winter rain and snow melt when crop cover is minimal (McCool et al. 1995). In northeastern Oregon, Zuzel and Pikul (1993) reported that percentage of straw cover and soil loss were inversely correlated (r = –0.99). Surficial crop residue of 1 to 2 Mg ha^{-1} (0.45 to 0.89 tn ac^{-1}) can reduce runoff and soil erosion 40% to 80% compared to bare soil (Zuzel and Pikul 1987). Conservation tillage includes minimum tillage (MT) and no-tillage (NT) and leaves 30% or more residue cover (≥1.12 Mg ha^{-1} [≥0.50 tn ac^{-1}]). Unlike conventional DT, MT disturbs the soil surface without burying crop residue. A single secondary tillage operation can be used to retain seed-zone soil moisture, but additional operations might be replaced with herbicide to control weeds yet maintain residue cover. NT leaves the soil relatively undisturbed from harvest to planting and promotes soil macroaggregate formation (Cambardella and Elliott 1993). Though conservation efforts can reduce soil erosion and maintain or increase soil carbon (C), they can also result in reduced grain yields due to increased pressure from weeds, disease, and insect pests (Ball et al. 2008).

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Increased frequency and variety of crops grown in a rotation is another means to enhance soil quality and long-term crop productivity (Rasmussen et al. 1998a). An increase in crop frequency leads to a corresponding reduction of fallow, which has been shown to either stabilize or improve soil organic matter levels and reduce the frequency of winters during which the soil lies unprotected (Rasmussen et al. 1998b; Sherrod et al. 2003). Improved levels of soil organic matter have been shown to promote soil aggregation and infiltration (Wuest et al. 2005), resulting in improved soil and water conservation (Williams et al. 2009). In the Pacific Northwest, control of winter annual broadleaf weeds and annual grasses, especially downy brome (*Bromus tectorum*) and rattail fescue (*Vulpia myuros* L.C.C. Gmel.), is aided with the inclusion of either broadleaf crops or spring small grains (Ball et al. 2008). This control is critical for the adoption of NT, where increased weed pressure leads to lost productivity in wheat-fallow rotations (Ball et al. 2008; Smith et al. 1996). However, the variability of annual precipitation and its timing would appear to substantially increase the risk of crop failure in the intermediate precipitation zone and prohibit adoption in the drier parts of the region because of inadequate soil water.

Much of the farming that takes place in the inland Pacific Northwest region is on loess hills with about 65 m (213 ft) of topographic relief (Birkeland 1974). The use of NT and MT has been advocated for controlling erosion on these landscapes, but the previous studies were limited to small plots and did not quantify their potential to protect the soil resource at the field scale. The objective of this study was to compare the hydrologic response, soil erodibility, crop residue, and yield productivity of DT and MT versus NT in different landscape components.

Materials and Methods

Study Area Description. The study area is located within the Wildhorse Watershed in Oregon (figure 1a), which is representative of the moderately dissected, loess-covered basalt plains of the Columbia Plateau. Long-term (1930 to 2008) annual precipitation is 417 mm (16 in) with 70% falling during winter and spring (November to April). Minimum and maximum air temperatures are −34°C and 46°C (−29°F and 115°F) with mean annual temperature of 11°C (52°F) and 135 to 170 frost-free days (June to September). Snow cover is transient with accumulated snow subject to rapid melting by frequent warm fronts. The growing season for winter wheat is approximately 10 months (October to July), and spring crops are seeded from early March through early April. The soils are well drained silt loams (table 1). Loessal soils are derived from Pleistocene aeolian deposits (Johnson and Makinson 1988). These silt loams are found extensively across the intermediate precipitation zone of the inland dryland small grain production areas of Oregon and Washington. At each location, a meteorological station recorded instantaneous precipitation as well as hourly air and soil temperature.

Field Experiments and Cultural Practices. Different field experiments comparing NT, DT, and MT practices were established near Adams, Oregon, on each of three landforms: draw, hillslope, and drainage (figure 1b, 1c, and 1d). These landforms, listed in order of increasing size, are defined in accordance with accepted US hydrological nomenclature (REIC 1995; Sullivan 2004). Each experiment encompassed different geomorphic and hydrologic conditions that determine runoff, infiltration, and soil erosion (tables 2 and 3; figure 2). Experimental sites had been managed for 80 years or more using DT in which residue cover seldom exceeded 15%.

Draw Experiment. A four-year (2005 to 2008) draw experiment was positioned on either side of a shallow draw (table 2) forming a second order tributary of Wildhorse Creek (figure 1b). This study was a split plot experiment with whole plots arranged in randomized complete block design (Littell et al. 2006). Whole plot treatments were NT and MT, and the split plots were crop rotations, each starting with one of four phases: fallow, winter wheat following fallow, peas, or winter wheat following peas (table 4). Split plots were 45.7 m (150 ft) by 3.7 m (12 ft). Each set of 8 treatments was replicated 4 times bringing the total number of split-plot experimental units to 32. All farming operations were conducted with small plot equipment. Extensive management details for this field study can be found in Williams and Long (2011) and Williams and Wuest (2012).

Hillslope Experiment. The hillslope experiment was established on a steep, north facing hillslope (table 2) adjacent to Wildhorse Creek (figure 1c). Crops were grown for seven years (1998 to 2005) under NT and for three years (2006 to 2008) under MT. Farming operations in both NT and MT were conducted up and down the slope using production-scale equipment. Control ditches prevented overland flow from the field above and directed flow from on the hillslope to weirs at the bottom of the field (table 3). Similar to a paired-watershed approach (Clausen and Spooner 1993), the slope was divided on its central break with each side serving as a watershed (figure 1). Efforts to establish different crops on the split hillslope proved less than satisfactory because of the area required for maneuvering large equipment. Therefore, we farmed the entire site as a single unit, changing from NT to winter wheat–fallow using MT in 2005 (table 5). Percentage ground cover consisting of current year's growth and previous year residue was measured from late November through late February when the risk of soil erosion was the greatest using a digital adaptation of the cross-hair frame method developed by Floyd and Anderson (1982).

Drainage Experiment. The drainage experiment included two adjacent, upland drainages (table 2) that contribute to Wildhorse Creek (figures 1d and 1e). This study was designed as a field-scale, side-by-side, nonreplicated comparison of two crop production systems with the drainages as the experimental units. The drainages were instrumented to record rainfall, runoff, and soil erosion (table 3) between 2001 and 2008. One drainage was cropped using DT practices (moldboard or chisel plow) in a winter wheat–fallow rotation, initially from 2001 through 2004 as a single management unit, and as a split management unit with half the drainage in crop and half the drainage in fallow from 2005 through 2008 (table 6). Decisions for DT crop production and fallow management were left to the cooperating farmer and varied somewhat throughout the course of the study (table 6). The second drainage was subdivided into four areas and cropped in a four-year NT rotation: winter wheat–chemical fallow–winter wheat–chickpea (*Cicer arietinum*)/or dry spring peas (*Pisum sativum* L.) (table 6). Fallow management for the NT drainage consisted of applications of herbicides to control various weeds (table 7). Crop residue production was determined from hand-harvested 1 m^2 (11 ft^2) plots randomly located on transects along the drainage bottom, toe, back, and top slopes in a stratified random sampling on the north and south aspects of each drainage. Percentage

Figure 1

(a) Research site locations in Umatilla County conducted for comparisons of no-tillage and disturbance tillage dryland crop production and (b) small plots on low relief draw. (c) High relief steep hillslope; the 2002 crop year is shown with winter wheat growing on the left and recently spring planted chickpeas planted in the right. (d) Small drainage with steep back slopes and very low relief drainage floor. (e) Fall 2005 crop year aerial photo showing winter wheat residue to the left in the disturbance tillage drainage and winter wheat residue in the bottom half and winter wheat stubble residue in the top half in the no-tillage drainage to the left.

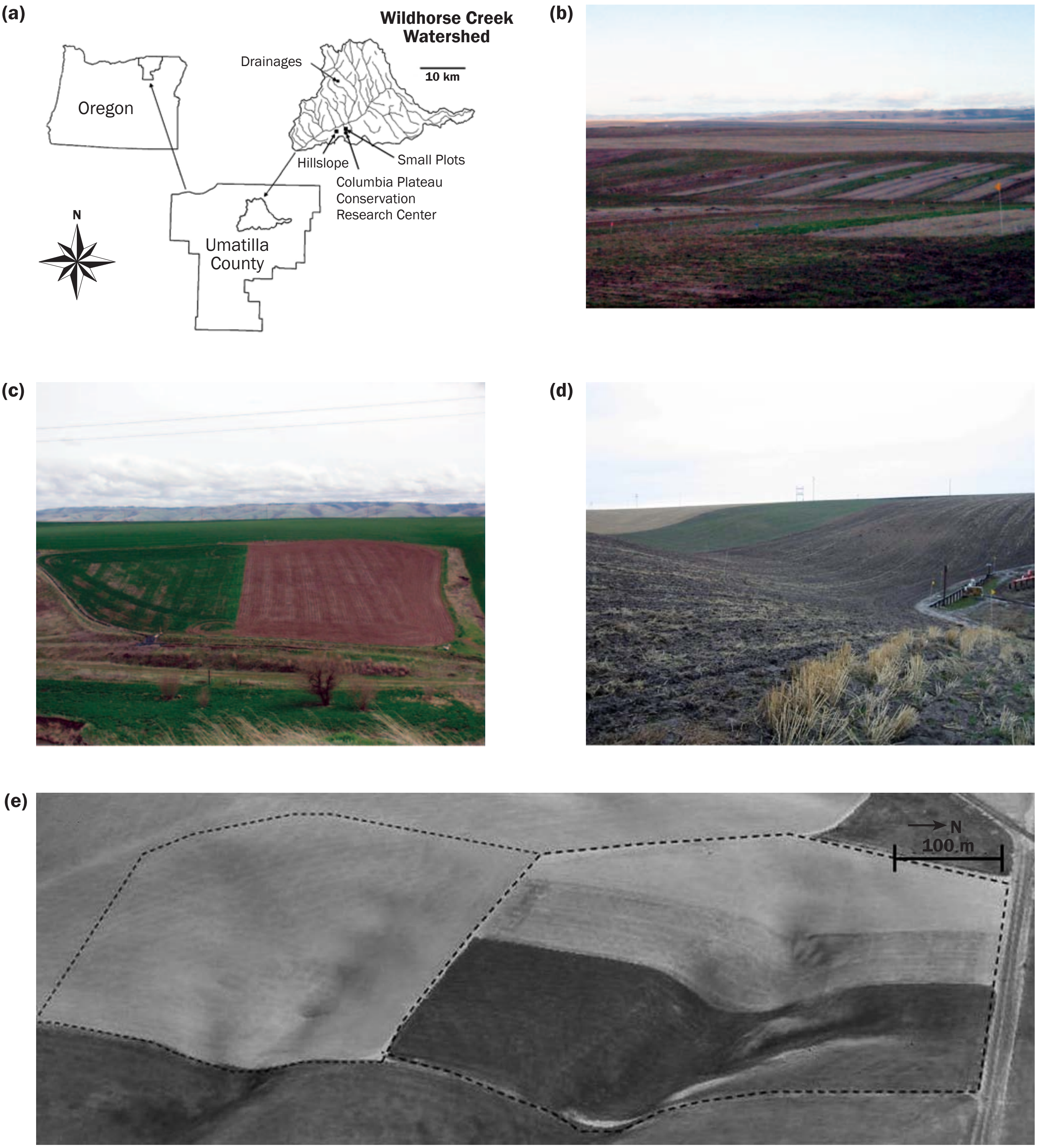

Table 1
Descriptions of three research sites located in Wildhorse Watershed used to evaluate runoff, soil erosion, and crop production under no-tillage and disturbance tillage.

Site	Location	Total area (ha)	Maximum slope (%)	Elevation (m)	Elevation change (m)	Slope length (m)*	R_r†
Drainage							
No-tillage	49°49′00.03″ N	10.68	30	535	17.5	30	0.05
Disturbance tillage	118°38′35.84″ W	5.76	20	540	20.8	63	0.08
Hillslope	45°43′26.12″ N 118°39′32.50″ W	1.53	23	350	26.0	100	
Draw	45°43′31.12″ N 118°37′49.94″ W	2.14	4	446	5.0		

*Slope length measured at maximum percentage slope.

†R_r = R/L, where R is the elevation difference between mouth and headwater divide and L is the maximum length of the basin measured in the same units as R along a line parallel to the main channel.

Table 2
Runoff and soil erosion sample collection matrix.

Sample area	Drainage	Hillslope	Draw
Weirs	10.68 ha	1.43 ha	—
Steel-frame runoff collectors	1 m^2	—	1 m^2

Table 3
Soil as mapped at each of the three research sites (Floyd and Anderson 1982).

Site	Soil series	US classification	Landscape position
Drainage	Walla Walla silt loam, 1% to 7% slopes	Coarse-silty, mixed, mesic Typic Haploxerolls	Summits and shoulders
	Walla Walla silt loam, 12% to 25% slopes*	Coarse-silty, mixed, mesic Typic Haploxerolls	Back and toe slopes, and drainage floor
Hillslope	Walla Walla silt loam, 25% to 40% slope	Coarse-silty, mixed, mesic Typic Haploxerolls	
Draw	Walla Walla silt loam, 7% to 12% slopes	Coarse-silty, mixed, mesic Typic Haploxerolls	Upper half of plots on northeast face of draw
	Pilot Rock silt loam, 7% to 12% slopes	Coase-silty, mixed, mesic Haplic Durixerolls	Lower half of plots on northeast face of draw and entire plots on southwest face of draw

*Based on survey-grade global positioning system terrain mapping. Slopes of 30% exist over a substantial portion of the north face backslope of the north drainage.

ground cover was measured as described for the draw experiment. A detailed management description for the NT rotation can be found in Williams and Long (2011).

Runoff and Soil Erosion Measurements. Runoff and soil erosion were measured using metal-frame collectors consisting of a 9.5 mm (0.374 in) thick by 254 mm (10 in) wide steel plate bent into a rectangle about 800 mm (31 in) wide and 1,200 mm (47 in) long, with the bottom side formed into a slight V-shaped funnel. The total surface area circumscribed by the frame was 1 m^2 (11 ft^2). The frame was placed with the funnel pointing down-slope, and the entire frame was driven 10 cm (4 in) into the ground. The soil immediately inside the frame was tamped to seal the soil surface to the frame and prevent leakage. A hose attached to a tube at the bottom of the funnel led to a 20 L (5 gal) container on the slope below the frame. The containers were checked periodically, and runoff was collected after multiple events to avoid overflow. Total annual runoff and eroded material from these small plots were determined by weighing, drying, and reweighing material collected in the containers.

Frames were used in the draw and drainage experiments only. One frame was installed in the center of each plot (figure 1b) of the draw experiment where runoff and erosion measurements were obtained from 2006 to 2008. In the drainage experiment, six frames, three on each facing back slope, were installed where the back slopes were steepest. In the NT drainage, each of the three treatments not in fallow had two frames assigned to it. Within the DT drainage, the frames were distributed approximately equal distance across the back slopes. For each experiment, measurements were obtained during the typical erosion season (November through March) for this region (Williams et al. 2009). Containers were checked periodically, and runoff was collected after multiple events to avoid overflow with the intention of quantifying annual runoff and eroded soil. H-flumes and Parshall flumes were used to measure runoff and flow rate in surface water from the hillslope and drainage experiments. Initially, H-flumes were installed at the hillslope experiment, and Parshall

Figure 2

Cross sections representing relative topographic relief at three research sites and positions where hydrologic and soil erosion samples were collected. Six runoff collectors were installed in each drainage.

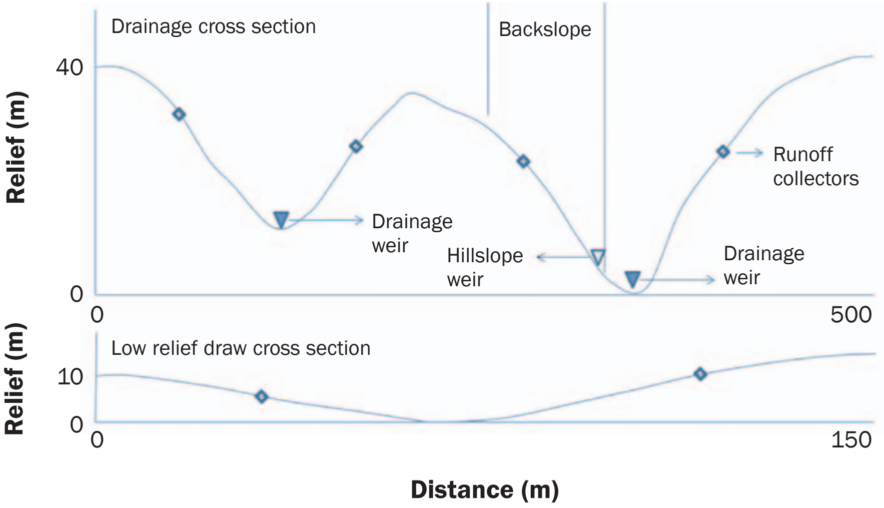

Table 4

Crop rotation in draw tillage and crop rotation study used to evaluate runoff, soil erosion, and crop production under no-tillage and disturbance tillage dryland crop production.

Crop year	No-tillage				Minimum tillage			
	NT1	NT2	NT3	NT4	MT1	MT2	MT3	MT4
2005	WW	WW	SP	F	F	SP	WW	WW
2006	SP	F	WW	WW	WW	WW	SP	F
2007	WW	WW	F	SP	SP	F	WW	WW
2007	F	SP	WW	WW	WW	WW	F	SP

Notes: NT = no-tillage. MT = minimum tillage. SP = spring peas. F = fallow. WW = winter wheat.

Table 5

Crop grown on hillslope site used to evaluate runoff, soil erosion, and crop production under no-tillage and disturbance tillage dryland crop production.

Crop year	A	B	Farming practice
1998	WW$_r$	WW$_r$	NT
1999	WW$_r$	WW$_r$	NT
2000	WW$_r$	WW$_r$	NT
2001	F	SW	NT
2002	WW	CP	NT
2003	SW	SW	NT
2004	WW$_r$	WW$_r$	NT
2005	F	F	MT
2006	WW	WW	MT
2007	F	F	MT
2008	WW	WW	MT

Notes: NT = no-tillage. MT = minimum tillage. CP = chickpea. F = fallow. SW = spring wheat. WW = winter wheat. WW$_r$ = recropped winter wheat.

flumes (23 cm [9 in]) were installed at the mouth of each drainage, but after large sediment loads in 2004 plugged the flumes in the drainage experiment, the flumes in both experiments were replaced with drop-box weirs from 2005 through 2008 (Bonta 1998). Flow stage was recorded using ultrasonic distance sensors, and flow rate was calculated using the appropriate standard rating curve for flume or weir (Bonta 1998; USDI-BoR 2001). Runoff samples were collected using flow-activated, commercial storm water samplers using a liquid level switch at a stage of 1 cm (0.4 in) or greater. Samples (0.5 L [0.1 gal]) were collected every 40 minutes for up to 8 hours of continuous runoff. Samples were analyzed for suspended sediment concentrations (Glysson and Gray 2002).

Statistical Analyses. Tillage treatments in the draw experiment were compared in terms of annual runoff, soil erosion, and infiltration rate using the ANOVA MIXED procedure of SAS (SAS Institute, Cary, North Carolina) with blocks and years as random effects. Least square means separation test at $p < 0.05$ was used. Data were evaluated using conditional Studentized residuals and log transformed where necessary to meet the assumption of normality. The whole plot treatments were NT and MT, and the split plots were crop rotations, each starting with one of the following: fallow, winter wheat following fallow, peas, and winter wheat following peas. In the drainage experiment, the experimental units are the drainages. All statistical tests were conducted at $p < 0.05$. Because of the lack of replication, results from the hillslope experiment were limited to descriptive statistics i.e., mean values for runoff, soil erosion, and crop yield. Drainages were compared in terms of runoff and soil erosion data and were analyzed using paired *t*-tests in Microsoft Office Excel 2003 and PROC GLM in SAS with allowance for pseudoreplication (Hurlbert 1984). Annual values were tested from 1 m^2 (11 ft^2) plots for 2003 and 2004 ($n = 2$) and individual event values from the drainages–runoff ($n = 17$) and soil erosion ($n = 15$). Difference in treatment means for winter wheat yields from 2002 through 2008 ($n = 7$) were analyzed using PROC GLM. Crop yield data from 2001 were not used in the analysis to eliminate confounding factors associated with a previous research project conducted at the site.

Table 6

Description of drainage experiment used to evaluate runoff, soil erosion, and crop production under no-tillage and disturbance tillage dryland crop production.

Crop year	No-tillage NT1	NT2	NT3	NT4	Disturbance tillage DT1	DT2
2001	CP	F	SW	WW	F	F
2002	WW	WW	F	CP	WW	WW
2003	F	CP	WW	WW	F	F
2004	WW	WW	CP	F	WW	WW
2005	DP	F	WW	WW	F	WW$_r$
2006	WW	WW	F	DP	WW	WW$_v$
2007	F	DP	WW	WW	F	WW
2008	WW	WW	DP	F	WW	F

Notes: NT = no-tillage. MT = minimum tillage. CP = chickpea. DP = dry spring peas. F = fallow. WW = winter wheat. WW$_r$ = recropped winter wheat. WW$_v$ = volunteer winter wheat.

Results and Discussion

Crop Residue. As expected, ground cover was significantly greater in the NT treatment than either the MT or DT treatment in each of the three experiments (table 8). In the drainage experiment, this difference increased in 2003 when the residue in the DT drainage was burned. There were no differences in winter wheat residue production by treatment in the hillslope and drainage experiments (table 8). In the drainage experiment, there was no difference in crop residue production by slope position, although there was significantly more residue produced on the south side (north aspect = 6.65 ± 0.13 Mg ha^{-1} [5,933 ± 114 lb ac^{-1}]) of the drainage than the north side (south aspect = 6.18 ± 0.11 Mg ha^{-1} [5,517 ± 102 lb ac^{-1}]). Residue production was not measured in the draw experiment. Overall, ground cover and residue level decreased in order of NT > MT > DT with increasing residue incorporation and soil disturbance. Despite this difference, winter wheat yields did not differ significantly between the NT and MT treatments in the draw experiment nor between the NT and DT treatments in the drainage experiment (data not shown).

Ground cover by crop residues physically protects the soil surface from raindrop impact and, by contributing to soil organic C, increases biological activity, aggregate stability, porosity, and water infiltration (Doran 1980a, 1980b; Wuest et al. 2005, 2006). Residue cover also reduces rill erosion by reducing shear stress of concentrated flow erosion (Knapen et al. 2008; McCool et al. 1995; Van Liew and Saxton 1983; Zuzel and Pikul 1993). When tested under laboratory conditions, reduction in shear stress by crop residues accounted for only 10% of the difference in soil erodibility between conventional and conservation tillage versus modification of soil properties (bulk density, soil water content, root growth, and decomposition) by crop residues, which accounted for 90% of the reduction (Knapen et al. 2008).

On the other hand, heavy crop residue accumulation in a NT system can increase disease and weed infestations (Ball et al. 2008; Rasmussen et al. 1997), interfere with operation of seed drills (Siemens and Wilkins 2006), and hinder crop establishment and yield (Rasmussen et al. 1997). Reducing the length and orientation of crop residue by harrowing or mowing, or reducing its mass by burning, can improve seed drill performance. However, burning is only marginally successful at eliminating weed seed, the C that was bound to end up in the near surface soil is exhausted to the atmosphere, and unburned material often provides substantially less than 30% cover (McCool et al. 2008). Disease and weed pressures can be relieved by increasing the diversity of the cropping system (Ball et al. 2000).

Runoff and Soil Erosion. Annual runoff and soil erosion were significantly greater from the DT treatments measured in small collectors within the drainage and draw experiments (table 9). In the drainage experiment, eight years of accumulated runoff and soil erosion were 10 times and 54 times greater in the DT treatment than the NT treatment. In the hillslope experiment, no runoff or soil erosion occurred from 1998 to 2005 using NT, but runoff and soil erosion were recorded during 2006 to 2008 when changed to MT in 2006. No runoff or soil erosion from the hillslope was recorded in 2005 and 2007 while the hillslope was in fallow with standing stubble.

Based on weather data recorded at each site, zero to seven freeze-thaw events occurred from 1997 through 2008, averaging slightly fewer at two per year with the weather generally warmer and drier than the previous 77 years. Precipitation was significantly less than expected in 6 of the 11 years of this study (1998, 2001 to 2003, 2005, and 2008) and mean annual mean air temperatures were greater than expected in 9 of 11 years (1998 to 2000 and 2002 to 2007). Consequently, the frequency of freeze-thaw events coincident with precipitation was fewer and resulted in fewer runoff and soil erosion events. This statistic fails to convey a sense of the variability in regional weather conditions and the connection to soil erosion events. For example, in eastern Oregon, Zuzel (1994) only recorded runoff and soil erosion during 6 of 12 years, totaling 100 runoff events with 31 producing soil erosion >0.25 Mg ha^{-1} (>0.11 tn ac^{-1}) from winter wheat planted after summer fallow. Three events were responsible for 60% to 70% of the total soil erosion.

Conversely, from 1998 through 2008, only 2 of the 22 runoff events in the hillslope experiment were associated with frozen soils. Twenty runoff and soil erosion events were recorded from the drainages from 2001 through 2008 of which 2 events were associated with frozen soils (only 1 event in common with the frozen soil events recorded at the hillslope experiment), and 8 events were associated with partially frozen soil. Overall, the total number of events was substantially fewer in number and of less magnitude than the 100 runoff events in winter wheat after summer fallow recorded by Zuzel et al. (1993) from 1977 to 1989. Zuzel et al. (1993) set a threshold of 0.25 Mg ha^{-1} (0.11 tn ac^{-1}) below which storms were not included in the analysis. None of the runoff and soil erosion events we recorded at the hillslope and drainage experiments approached this threshold. About 40% of the 22 events accounted for 90% of the soil loss in the hillslope and drainage experiments, unlike the 10% figure reported during the research in the 1970s and 1980s.

Soil erosion research in rainfed croplands of the Pacific Northwest has been conducted at either the plot scale from 1 m^2 (11 ft^2) to 136 m^2 (1,460 ft^2) (Khalid and Chen 2003; Zuzel et al. 1993) or watershed scale (fourth and fifth order hydrologic units) (Brooks et al. 2010; Nagle and Ritchie 2004). The for-

Table 7

Fallow management in drainage experiment used to evaluate runoff, soil erosion, and crop production under no-tillage and disturbance tillage dryland crop production.

Crop year	DT Date	Management	NT Date	Management
2001	Mar. 15, 2001	Moldboard	Apr. 10, 2001	Glyphosate
	Mar. 25 2001	Cultivate	May 10, 2001	Glyphosate
	May 10, 2001	Fertilize	July 13, 2001	Glyphosate
	June 15, 2001	Rodweed		
	Sept. 10, 2001	Cultivate		
2002	Crop		Nov. 26, 2001	Glyphosate
			Apr. 24, 2002	Glyphosate
2003	Oct. 10, 2002	Burn residue	Aug. 14, 2002	Harrow stubble
	Nov. 15, 2002	Moldboard	Jan. 28, 2003	Glyphosate
	Mar. 15, 2003	Cultivate	July 22, 2003	Glyphosate
	May 10. 2003	Fertilize		Banvel
	June 15, 2003	Rodweed		
	Sept. 15, 2003	Rodweed		
2004	Crop		Feb. 19, 2004	Glyphosate
			Apr. 29, 2004	Glyphosate
				Banvel
			July 15, 2004	Glyphosate
				Banvel
2005	Sept. 5, 2004	Chisel chop with fertilizer application	Mar. 3, 2005	Glyphosate
			Mar. 18, 2005	Sulfentrazone
	Oct. 5, 2004	Cultiweed	June 4, 2005	Glyphosate
				Banvel
			July 13, 2005	Glyphosate
				Banvel
2006	Apr. 15, 2005	Cultivate	Mar. 1, 2006	Sulfentrazone
	May 15, 2005	Cultivate and fertilize	Mar. 29, 2006	Glyphosate
	June 15, 2005	Cultiweed	May 23, 2006	Glyphosate
	July 10, 2005	Rodweed		Banvel
	Sept. 15, 2005	Rodweed		
2007	Oct. 26, 2006	Cultivate	Aug. 9, 2006	Glyphosate
		Seed		Dicamba
			Oct. 30, 2006	Glyphosate
			May 25, 2007	Glyphosate
				Dicamba
			July 3, 2007	Glyphosate
				Banvel
				Dicamba
2008	Mar. 30, 2007	Moldboard	Oct. 30, 2007	Glyphosate
	July 13, 2007	Rodweed		
	Sept. 28, 2007	Rodweed, cultivate, fertilize		

Notes: DT = disturbance tillage. NT = no-tillage.

mer captures splash erosion and the initial process of rill development, but not catena dynamics of source, transport, and deposition areas and sediment delivery to channels. The latter integrates all management practices and cannot discern their effect on soil erodibility and soil movement.

Based on observations from the small collectors placed internally within the DT drainage, a substantial amount of soil crept downhill on steep back-slopes of the site (table 9). We also observed the development of rills in association with large runoff and soil erosion events in 2003 and 2004. In contrast, no rill development, runoff, or soil erosion was observed in the NT drainage. Clearly, when the runoff is concentrated into rills, sediment will be readily delivered to toe-slopes. Otherwise, if runoff is not concentrated in flow paths, soil will be slowly redistributed from backslopes to toe slopes before moving into and through the drainage bottoms. Indeed, the measured runoff and eroded soil at the drainage outlets and at the bottom of the hillslope study was substantially less than measured on the slopes within the drainages. Therefore, sufficient crop residue covering the soil resists rill development.

Small amounts of runoff and soil erosion were generated in the draw experiment, which apparently resulted from the use of small plots located on the toe-slope. Without rills and concentrated flow to carry soil across it, the toe-slope becomes a deposition zone. Though there were statistical differences in the amount of runoff and erosion between the MT and NT treatments, the absolute difference is small (0.01 Mg ha^{-1} [10 lb ac^{-1}]). In contrast, the difference found between DT and NT on the backslopes in the drainage experiment was substantial at 45% (10.8 Mg ha^{-1} [4.8 t ac^{-1}]).

Results from the drainage experiment are confounded by changes made in the management of the DT drainage after crop year 2004. We intended to leave the DT drainage in the same management rotation as the rest of the field extending beyond the two drainages. After recording substantial runoff and soil erosion from the DT drainage in 2003 and 2004, we decided to split the management of the drainage into equal parts fallow and crop so that both years of the rotation would be represented in the drainage. This change is essentially representative of an increase in the management complexity of a given field, not unlike strip farming where horizontal strips of alternating crop-fallow are established on long slopes to decrease slope length or wind fetch and thus the potential for soil erosion. It is worth noting that adaptive management is a major tool used by successful producers. The cooperating farmer made two cropping practice decisions from 2005 through 2008: (1) switching to minimum tillage and (2) harvesting the crop from a dense stand of volunteer wheat. Consequently, runoff and erosion from the DT drainage was substantially reduced after 2005 by increases in crop cover and rotation intensity resulting in no difference in treatments (table 9).

Table 8

Mean annual ground cover measured during winter crop growth.

Site	Farming practice	Ground cover (%)	Farming practice	Ground cover (%)
Drainage	NT	73 ± 4a*	DT	44 ± 16b
Hillslope	NT	81 ± 6a	MT	64 ± 3b
Draw	NT	81 ± 4a	MT	59 ± 6b

Notes: NT = no-tillage. DT = traditional/moldboard plow. MT = minimum tillage.

*Values in rows significantly different at $p \leq 0.05$ with different letters according to least-square means separation tests (SAS Institute, Cary, North Carolina).

Table 9

Mean runoff, soil erosion, and precipitation from comparisons of no-tillage and disturbance tillage dryland crop production in the intermediate rainfall zone of northeastern Oregon.

	Runoff (mm)		Soil erosion (Mg ha^{-1})		Annual precipitation (mm)
Site	NT	DT/MT	NT	DT/MT	
Drainage (internal)	36.9 ± 19.5a*	78.9 ± 10.1b	0.23 ± 0.16a	11.01 ± 1.61b	358 ± 28
Drainage (outlet)	0.1 ± 0.0a	0.7 ± 0.5a	0.01 ± 0.01a	0.05 ± 0.04a	
Hillslope	0.0 ± 0.0	1.6 ± 1.6	0.00 ± 0.00	0.17 ± 0.17	387 ± 25
Draw	0.4 ± 0.1a	0.6 ± 0.1b	0.01 ± 0.01a	0.02 ± 0.01b	385 ± 42

Notes: NT = no-tillage. DT/MT = traditional/moldboard plow in the drainage experiments and minimum tillage in the hillslope and draw experiments.

*Values in rows significantly different at $p \leq 0.05$ with different letters according to least-square means separation tests (SAS Institute, Cary, North Carolina).

Finally, a number of studies indicate that a regional shift to warmer winters and a corresponding shift in the timing of precipitation are occurring in the Pacific Northwest (Mote 2003; Pederson et al. 2011; Salathé et al. 2010; Stöckle et al. 2010). The results we report here reflect this change in the reduced number of freeze thaw events. If these conditions persist in combination with the application of NT and CT practices, the region should continue to experience low rates of runoff and soil erosion in the uplands of this region relative to the values reported in the 1980s and 1990s.

Summary and Conclusions

Three projects were undertaken between 1998 and 2008 to evaluate the soil and water conservation and crop production potential of NT crop production in the intermediate precipitation zone of the inland Pacific Northwest. The projects were conducted at three scales: drainage, hillslope, and draw. Crop yields were comparable among tillage treatments at the draw and drainage sites without any apparent loss of productivity in the NT system as demonstrated by the lack of treatment differences (table 10). Conversely, the lower runoff losses in the NT did not contribute to increased yields.

No-tillage consistently produced less runoff and eroded soil than DT in three experiments encompassing 1 m^2 (11 ft^2) collection plots to multihectare upland drainages. Across all scales of measurement, erosion rates increased as ground cover decreased in order of NT > MT > DT. Soil loss only exceeded the USDA soil loss tolerances of 2.2 to 11.2 Mg ha^{-1} y^{-1} (0.98 to 5 tn ac^{-1} yr^{-1}) (Renard et al. 1997) in the DT treatment on the backslopes of the drainage experiment. Adequate ground cover is critical at this landscape position, and the NT and MT treatments provided >60% ground cover. This was demonstrated at the hillslope site where the NT and MT treatments provided sufficient protection to prevent rill development and soil loss greater than allowed for sustained economic productivity on the 100 m (331 ft), 23% slope. Because the NT produced significantly less runoff or eroded soil in the drainage and draw experiments, it should outperform the MT during more erosive storms such as those recorded in earlier decades and observed outside the borders of this research. At all three sites, soil erosion was least in the treatment with the greatest crop residue cover (tables 8 and 9). This suggests that, in addition to maintaining economic sustainability as defined by soil loss tolerances established by the USDA, it might also contribute more to the sustainability of the physical and biological soil resource.

Finally, the drainages provided the opportunity to conduct a true field scale comparison of the productivity and conservation related attributes of the NT and DT management systems. Although within 10 km (6.2 mi) of each other, the three sites provide evidence that NT is a viable option for small grain production in the intermediate precipitation zone on the inland Pacific Northwest.

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Table 10

Comparisons of winter wheat yield between no-tillage (NT) and disturbance tillage (DT) in the drainage experiment, NT and minimum tillage (MT) in the hillslope experiment, and NT and MT in the draw experiment.

Year	Rainfall (mm)	Drainage		Hillslope		Draw	
		NT (Mg ha^{-1})	DT (Mg ha^{-1})	NT (Mg ha^{-1})	MT (Mg ha^{-1})	NT (Mg ha^{-1})	MT (Mg ha^{-1})
2001	396	2.28*	–	–	–	–	–
2002	263	3.87	4.34	2.04	–	–	–
2003	377	3.47	–	–	–	–	–
2004	492	5.82	5.22	–	–	–	–
2005	299	4.74	–	–	–	5.15	6.17
2006	474	4.46	4.69	–	3.30	5.51	5.13
2007	359	5.40	–	–	–	5.07	4.62
2008	320	4.91	4.07	–	3.86	4.44	4.93
Mean	387	4.37a	4.58a	2.04	3.58	5.05a	5.21a

*Values in rows significantly different at $p \leq 0.05$ with different letters according to least-square means separation tests (SAS Institute, Cary, North Carolina).

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