Soil Water Dynamics in Continuous Winter Wheat in the Semiarid Pacific Northwest, USA

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In semiarid climates, efficient precipitation capture and storage are necessary for successful small grain production. This is especially true in Mediterranean climates dependent on winter precipitation occurring before the most active growth and grain development stages of winter wheat (WW, *Triticum aestivum* L.). The effects of residue cover and tillage on soil water under annual WW were investigated at Pendleton, OR, on a Walla Walla silt loam soil, (coarse-silty, mixed, superactive, mesic Typic Haploxerolls). These effects were investigated using three treatments in annually cropped WW, (i.e., no fallow year), consisting of no-till (NT), crop residue incorporated with tillage (TI), and crop residue removed before tillage and then returned to the soil surface after tillage (RR). Field data showed that ground cover from crop residue resulted in more soil water from December 24 through May 20 in the driest crop year, 2005, of the 3-yr experiment, but no differences in the two relatively wet crop years 2004 and 2006. The mean soil water in a 105-cm profile when treatment differences occurred were as follows; NT = 187 mm, RR = 168 mm, and TI = 155 mm. The differences were relatively small, however, with NT 31.7 mm more than TI and 19.2 mm more than RR, and RR 12.5 mm more than TI. During normal years these differences could be expected to diminish. This research indicates that tillage practices in the Pacific Northwest have small effect where the land surface is essentially level, but ground cover can play an important role during exceptionally dry years on precipitation capture and storage.

Abbreviations: NT, no-till; PNW, Pacific Northwest; RR, crop residue removed before tillage and then returned to the soil surface after tillage; SF, summer fallow; SOC, soil organic carbon; TI, crop residue incorporated with tillage; WW, winter wheat.

The rainfed small grain-producing region of the inland Pacific Northwest (PNW) extends across central and eastern Washington, north central and northeastern Oregon, and northern Idaho. With a semiarid, cool Mediterranean climate (wet winters, dry summers), this region is ideally suited for WW production. Three quarters of the annual precipitation occurs between September and April, tapering off after the primary growing season begins. Thus, efficient precipitation capture and effective soil water storage are critical for plant development and grain fill in the fall (Rasmussen et al., 1994). Over summer storage of water not used by the previous crop, or captured in the previous 8 to 9 mo of fallow, is also important for seed germination. Topography influences these conditions further, with annual precipitation increasing from 150 mm in the rain shadow of the Cascade Mountains and lower elevations near the Columbia River to 610 mm in the foothills of the Clearwater Mountain Range in the border region of Washington and Idaho. Due to this gradient, farming practices and crop

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yields within this region fall within three precipitation zones; low < 300 mm yr^{-1}, intermediate 300 to 450 mm yr^{-1}, and high > 450 mm yr^{-1} (Schillinger and Papendick, 2008).

In the high precipitation zone, abundant water allows for successful annual or continuous cropping whereas biennial or alternate year crops with an intervening fallow year are typical in the low precipitation zone. Conditions are often suitable for annual crop production in the intermediate zone, but with highly variable seasonal and annual precipitation the risk of crop failure leads most producers to use a 3-yr WW-spring cereal-fallow system in the intermediate-precipitation zone and the 2-yr WW-fallow in the low-precipitation zone. Complicating crop production in the intermediate zone is a wide range of soil depth and microclimate patterns of precipitation rainfall, temperature, wind, and evaporation. Under these conditions, maximizing crop-water-use efficiency through precipitation capture and storage is critical to risk reduction.

The relationship between tillage practice, precipitation capture, and soil water storage in WW production systems has been extensively explored. In eastern Colorado, (Peterson et al., 1993; Peterson and Westfall, 2004), working in three sites where the soil was loam, clay loam, loamy sand, sandy loam, or sandy clay loam, reported an increase in precipitation use efficiency of 30% through cropping intensification and increased soil organic carbon (SOC) from the previous crop's residue, regardless of tillage practice. In a silt loam soil in Kansas, Norwood (1994) recorded more water stored and stored deeper in the soil profile under NT than under conventional tillage, with greater gains in an intensified rotation over WW–summer fallow (SF). In Oklahoma, Patrignani et al. (2012) conducted an experiment that extended across a variety of soils that included clay loam, sandy clay loam, and silty clay loam. Their results indicated no differences in precipitation storage efficiency or available plant water between conventional tillage and NT in continuous WW. They did find more soil water near the soil surface in NT during the critical preharvest ripening period than in the conservation tillage. These higher, late season soil water levels were attributed to abundant residue cover in the NT. Similarly, Heer and Krenzer (1989) reported more soil water throughout the fine sandy loam profile in the NT at jointing-phenology stage in Lahoma, OK, but in a wetter location (Stillwater) there was no tillage effect on soil water. In silt loams near El Reno, OK, there was more soil water in NT during every season except during soil profile recharge in late fall and early spring (Dao, 1993). These studies were conducted at various locations throughout the Great Plains where 75% of mean annual precipitation, ranging from 400 to 900 mm, falls from April through September coincidental with the region's highest temperatures. Although autumn rains can apparently recharge soil profiles regardless of tillage practice (Dao, 1993; Patrignani et al., 2012), open pan evaporation in this region can exceed precipitation from two to five fold, frustrating efforts to store sufficient soil water even in these fallow systems (Farahani et al., 1998; Peterson and Westfall, 2004).

Capturing or conserving sufficient soil water in the seed zone for early fall germination and stand establishment is a critical issue in the PNW where soil water recharge typically does not begin before mid-October. In the low precipitation zone, NT has proven a poor conservator of seed-zone soil water in SF (Schillinger and Papendick, 2008; Wuest and Corp, 2011) and crop residue production is insufficient to provide thermal insulation to reduce soil water loss through the hot, dry summers (Wuest and Schillinger, 2011). The same problem can extend into the intermediate precipitation zone, particularly in northeastern Oregon, where most producers adhere to a tillage-based 2-yr WW-SF rotation. As demonstrated in the Great Plains, improving crop water-use efficiency under these conditions can be improved somewhat by increasing crop intensity (Peterson and Westfall, 2004). Residue production with annual cropping reduces loss of SOC and soil erosion while increasing the economic and biological sustainability of wheat production in certain regions of the PNW (Duff et al., 1995; Huggins et al., 2011; Rasmussen et al., 1998). In the intermediate precipitation zone of northeastern Oregon, crop residue production in conventionally tilled continuous WW is ≈ 6.00 Mg ha^{-1} (based on a conversion rate of 1.7:1 kg residue/grain; Rasmussen et al., 1994), similar to the 5.60 Mg ha^{-1} for continuous WW in eastern Colorado under similar annual, but abundant spring and summer, precipitation (Peterson and Westfall, 2004). Throughout the PNW, WW crop residue production can range from 2.670 Mg ha^{-1} in the low precipitation zone to 11.32 Mg ha^{-1} in the high precipitation zone, as estimated for use in soil erosion models (McClellan et al., 2012). Increased crop residue, however, can be detrimental to grain yield and quality by affecting N availability and harboring pests according to Rasmussen et al. (1980); Rasmussen and Parton (1994) and Smiley et al. (1996) reported that some sort of tillage incorporation and soil disturbance will aid in crop yield quality and disease control. Our objective with this research was to determine if residue placement in a seedbed prepared using a chisel plow affected the capture and storage of precipitation, and how that type of seedbed preparation and residue management compared with capture of precipitation in a NT system. We used a continuous WW cropping system to intensify water use and to eliminate the effects of having a fallow year.

MATERIALS AND METHODS

This research was conducted at the United States Department of Agriculture–Agricultural Research Service Columbia Plateau Conservation Research Center, located 15 km northeast of Pendleton, OR (45°43′ N, 118°38′ W). Elevation at the site is 458 m. This site lies within the intermediate precipitation zone (300–450 mm yr^{-1}) of the inland PNW, at the boundary between annual and semi-annual wheat-fallow production. The 83-yr mean and 95% confidence interval for crop year precipitation is 418 ± 13 mm, with a minimum of 245 mm and maximum of 608 mm. Approximately 70% of precipitation occurs between November and April, resulting from maritime fronts that produce low intensity storms. Snow cover is transient and subject to rapid melting by frequent, warm maritime fronts. Minimum, maximum, and mean annual air temperatures are -34.5, 46.1, and 10.3°C, respectively. Annually, 135 to 170 d are frost-free between May and September. A meteorological station located at the site recorded precipitation, wind speed and direction, solar radiation, relative humidity, and air and soil temperature for each crop year of this study. The soil type is a Walla Walla silt loam soil, (coarse-silty, mixed, mesic, superactive Typic Haploxerolls–US; Kastanozems–FAO) containing 21% fine to very fine sand, 69% silt, and 10% clay (Johnson and Makinson, 1988).

Cropping Treatments

Annual WW was grown in 53 m × 3.7 m plots during crop years (September–August) 2004 through 2006. The treatments were (i) no-till (NT), (ii) crop residue incorporated with tillage (TI), and (iii) crop residue removed before tillage and then returned to the soil surface after tillage (RR), using hand rake and tarps. Plots were replicated four times in a randomized complete block design. In the TI and RR treatments, tillage was 25.4 cm deep with a twisted shank chisel plow followed with a disk and ending with a Brillion culti-packer (tine attachments not used; Landoll Corp., Marysville, KS). All tillage was conducted between late July harvest and mid-October seeding. The conditions established were therefore minimal soil disturbance in the NT treatment versus thorough soil disturbance in the TI and RR treatments. In the TI treatment all surface residue was incorporated into the soil, leaving the surface bare at planting time. The NT and RR treatments had continuous surface residue cover, except for the brief period when the RR treatment was being tilled and the surface residues were raked to the side of the plot. Plots were harvested with a plot combine and crop yields determined using a weigh wagon. Crop residue measurements were made only 1 yr, following planting, in November 2004. Photographs were taken on 1-m^2 plots and the images processed to determine the percentage of cover using a digitally modified grid sampling technique (Floyd and Anderson, 1982). Samples were collected from three sample points within two replications of each treatment, oven dried, and weighed, to determine crop residue biomass.

Crop rotations, fertilizer, and crop management were identical in all three treatments. Seeding and fertilizing were performed in mid-October in a one-pass system using a Conserva-Pak (Indian Head, SK, Canada) medium disturbance hoe-opener drill equipped on 305-mm spacing. Fertilizer was placed 25 mm below and 25 mm to the side of the seed (N at 100 kg ha^{-1} and P at 20 kg ha^{-1}). Wheat cultivars and fertilizer rates differed from year to year (Table 1). In 2004 and 2005, herbicide applications were applied as needed; Roundup Original Max (Monsanto, St. Louis, MO; glyphosate: *N*-[phosphonomethyl]glycine, 1.54–2.24 L ha^{-1}) or Landmaster (Monsanto, St. Louis, MO; 2,4-D: [2,4-dichlorophenoxy]acetic acid + glyphosate, 3.78 L ha^{-1}) applied before planting if needed and weed appropriate broadleaf herbicides in the spring—Banvel (Arysta Lifescience North America, LLS, Cary NC; dicamba: 3,6-Dichloro-2-methoxybenzoic acid, 0.14– 0.56 L ha^{-1}), Huskie (Bayer CropScience LP, Research Triangle Park, NC; bromoxynil: 3,5-dibromo-4-hydroxybenzonitrile, 0.84 L ha^{-1}). In 2006 and in conjunction with planting ORCF-102, applications of glyphosate in the fall and a spring application of Beyond (BASF Corp., Research Triangle Park, NC; imazamox: 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethl)-3-pyridinecarboxylic acid [0.21- 0.42 L ha^{-1}) for downy brome (*Bromus tectorum* L.) control was added to the broadleaf herbicide mix.

Soil Water Measurements

Volumetric soil water was measured using time domain reflectometry probes with a 5.0- to 5.5-cm radius sampling zone and two 300-cm wave guides (CS-616, Campbell Scientific, Logan, UT), with the data stored on data loggers (CS-10x, Campbell Scientific). Soil temperature values were recorded using probes and logged on data loggers (CS-107 and CS-21x, Campbell Scientific). Probes at 30 cm below the soil surface were installed in September of 2003 by digging an access trench and inserting the probes horizontally into the soil profile with the aid of a tine guide. Probes at 10 and 20 cm were installed each year shortly after planting and before substantial fall precipitation. Measurement zones, hereafter referred to as 10-, 20-, and 30-cm depths, were from 5 to 15 cm, 15 to 25 cm, and 25 to 35 cm. The 60- and 90-cm probes were installed vertically at the bottom of 10-cm bore holes. Since the wave guides are 30 cm long, they were centered at 60 and 90 cm, but actually span the depths of 45 to 75 cm and 75 to 105 cm. Values were recorded by the data loggers at 1-h intervals. Periodicity values (τ) were temperature corrected using manufacturer calibration equations developed for the probes (CS-616);

$$\tau_{corrected}(T_{soil}) = \tau_{uncorrected} + (20 - T_{soil}) \times (0.526 - 0.052\tau_{uncorrected} + 0.00136\tau_{uncorrected}^{2}) \quad [1]$$

where τ = periodicity and T = soil temperature. These values were then converted to volumetric soil water using the Campbell Scientific standard quadratic formula;

$$\theta = -0.0663 - 0.0063\tau_{corrected}(T_{soil}) + 0.0007\tau_{corrected}(T_{soil})^{2} \quad [2]$$

Probe accuracy was checked against soil samples collected and processed for volumetric soil water over the range of depths represented by the probes on 23 Nov. 2004 and 15 Apr. 2005. The mean error and standard error of the mean calculated from all depths from both dates was 0.02 ± 0.003 cm^3 cm^{-3} (2%).

Table 1. Winter wheat varieties and rates of seeding and fertilizer applications crop years 2004, 2005, and 2006 at Columbia Plateau Conservation Research Center, Adams, OR.

Crop year	Wheat variety	Seeding date	Seeding rate	46–0–0 fertilizer	16–20 fertilizer
			kg ha^{-1}		
2004	Stephens	27 Oct. 2003	118.9	196.2	130.0
2005	Stephens	21 Oct .2004	122.2	210.7	112.1
2006	ORCF-102	21 Oct. 2005	118.9	211.8	112.1

Table 2. Monthly precipitation for crop years 2004, 2005, and 2006 at Columbia Plateau Conservation Research Center, Adams, OR with 83-yr monthly mean annual precipitation and 95% confidence intervals (CI) (1930–2013).

	Precipitation, mm			
Month	2003–2004	2004–2005	2005–2006	83–yr Mean ± CI
Sep	18	14	7	18 ± 3
Oct	19	21	45	34 ± 4
Nov	43	50	32	52 ± 6
Dec	84	24	68	52 ± 6
Jan	68	137	89	49 ± 5
Feb	56	15	24	38 ± 4
Mar	23	39	63	44 ± 4
Apr	51	35	69	40 ± 5
May	72	76	41	39 ± 5
Jun	47	18	54	32 ± 5
Jul	4	5	3	8 ± 2
Aug	24	1	0	12 ± 3
Annual	508	309	495	419 ± 18

Volumetric water content values were converted to depth of water values to test for soil water and precipitation capture and storage efficiency differences among treatments as follows;

1. $SW_{profile}$ = soil water in 0- to 90-cm soil profile, change in profile soil water [$\Delta SW_{profile}$(mm)]

2. $SW_{profile} = (\theta_{10}100) + (\theta_{20}100) + (\theta_{30}100) + (\theta_{60}300) + (\theta_{90}300)$, where θ_i represents the incremental depth of measurement of volumetric soil water below the soil surface, multiplied by 100 for 0 to 10, 10 to 20, and 20 to 30 cm and by 300 for 30- to 60- and 60- to 90-cm depths and summed for depth of soil water in millimeters,

3. SW_d = soil water (mm) at d incremental depth of measurement below the soil surface,

4. Precipitation storage efficiency (PSE) = change in soil water [ΔSW(mm)]/precipitation (mm).

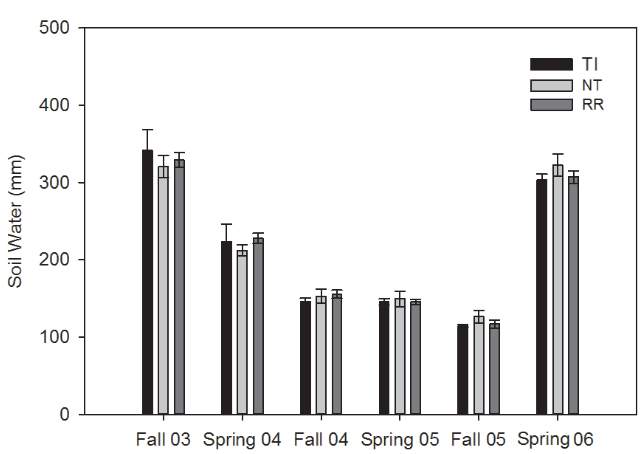

Fig. 1. Soil water measurements in the 105-cm profile made after fall planting and in the spring and summer when precipitation typically begins to decrease. Treatments were not significantly different. TI = crop residue incorporated into soil profile, NT = no-till, RR = crop residue removed before tillage and replaced after tillage. Each error bar is constructed using 1 standard error from the mean.

Data were consolidated into daily time steps. We assumed there was no runoff because the land is essentially level, and that drainage loss was not a factor in this semiarid region (Chen et al., 1998).

Hypotheses Tests

Hypothesis 1; There were no differences among treatments in $SW_{profile}$ when measured after fall planting but before substantial precipitation, and beginning of summer following winter and spring precipitation. Data used in the first analysis were collected on 30 Dec. 2003, 16 Nov. 2004, and 19 Dec. 2005, when accumulated crop year precipitation was 129, 61, and 87 mm. The post-winter data were collected on 26 Apr. 2004, 17 Aug. 2005, and 17 Apr. 2006, with accumulated crop year precipitation of 331.0, 308.3, and 386.2 mm.

Hypothesis 2; There were no differences in $SW_{profile}$, SW_d, or PSE throughout the time period between fall and spring. If differences among treatments were found, they were further analyzed in time increments bounded by time periods of gain or loss of soil water.

Statistical Analysis

Data were examined to determine if transformation was needed (Gbur et al., 2012). Missing data of less than 13 h time steps was in-filled by extrapolation from last known data points, when data was missing for 13 h or more the daily value was entered as missing data. Daily data were not analyzed if two of the four replications were missing. Single day $SW_{profile}$ data from after planting and at the end of data collection in the spring (2004, 2006) or summer (2005) were analyzed using a mixed model ANOVA (Littell et al., 2006; SAS, 2012). Values for $SW_{profile}$, SW_d, DSW, and PSE were analyzed using time series analysis in sets of graphically determined time periods when there was a gain or loss in soil water, and for the entire data set from each year (Gbur et al., 2012; Littell et al., 2006; SAS, 2012). Time series analysis was conducted on a 1-d time step for $SW_{profile}$, and SW_d. Where treatment differences were found, least squares means separation tests were conducted with Tukey-Kramer adjustment for multiple comparisons. Treatments differences were considered significant at $P \leq 0.05$.

RESULTS

Soil Water in the 105-cm Soil Profile

Annual variability in soil water recharge depends on the timing and quantity of precipitation. Precipitation was 121 and 118% of normal in 2004 and 2006, and 75% of normal in crop year 2005 (Table 2). Despite the dry conditions in 2005, exceptionally high precipitation in January (280%) contributed to abundant soil water content until March 30, with 175 mm accumulated crop year precipitation. Maximum soil water in the soil profile was recorded on January 20 in crop year 2004 and April 9 in 2006, with accumulated precipitation values of 155 and 371 mm.

There were no differences in $SW_{profile}$ among treatments at the beginning of the high-precipitation season (30 Dec. 2003, 16 Nov. 2004, or 19 Dec. 2005), or after the rainy season (26 Apr. 2004, 17 Aug. 2005, and 17 Apr. 2006) (Fig. 1). Time series analysis of $SW_{profile}$ showed no difference among treatments in any given year ($P = 0.62$), although there was evidence ($P < 0.01$) of a crop year by treatment interaction in 2005. In 2005, within days after the soil profile began to recharge, significant differences among the treatments indicated NT > RR > TI, a relationship that continued from December 24 through May 20 (Fig. 2).

There were significant differences during individual periods of gain or loss of soil water in crop year 2005 (Table 3). The NT and RR treatments gained more soil water, respectively 31 ± 7 and 13 ± 8 mm, than the TI treatment beginning in late November and through the winter until 13 June 2005. During the five time periods where significant differences developed in DSW values, NT gained more soil water than TI during four of those intervals, and RR did so twice (Table 3). The TI treatment gained more soil water between January17 and February 1 when all three treatments were gaining soil water, (TI 1.6 mm, RR 1.2 mm, NT 0.9 mm), but this was not enough to substantially or significantly close the gap between TI and the other treatments. This one occurrence of greater gain by TI followed immediately after a single day of frozen soil at a depth of 25.4 mm and a 4-mm precipitation event. The two instances where DSW differences were significant after February were brief periods of soil water gain in an overall losing trend. The NT treatment gain was significantly greater than TI, but RR was not significantly different than either of the other treatments in these events.

Despite differences in $SW_{profile}$ throughout 2005, a statistically significant difference in PSE occurred only once among treatments; from May 20 through June 7 corresponding with significant differences in DSW. The NT treatment lost 2.6 mm, RR lost 1.7 mm, and TI lost 1.2 mm during this period, the loss was ameliorated in the TI treatment by more efficient capture of the 2.0-mm precipitation falling on May 31 and June 21 (Table 3). After May 8 the differences in the three treatments dropped off to near equal levels (Fig. 2).

Table 3. Time series analysis of precipitation storage efficiency and change in soil water during recharge or depletion time periods in soil profile after fall planting through the 2005 growing season.

Start	End	Soil profile status	Δ SW†	PSE‡
11/16/04	12/12/04	recharge	$NT^a > RR^b > TI^c$	$NT^a = RR^a = TI^a$
12/24/04	01/04/05	recharge	$NT^a > RR^b > TI^c$	$NT^a = RR^a = TI^a$
01/17/05	02/01/05	recharge	$NT^a < RR^b < TI^c$	$NT^a = RR^a = TI^a$
02/12/05	03/05/05	recharge	$NT^a > TI^b \gg RR^{ab}$	$NT^a = RR^a = TI^a$
03/21/05	03/31/05	recharge	$NT^a > TI^b \gg RR^{ab}$	$NT^a = RR^a = TI^a$
05/20/05	06/07/05	depletion	$NT^a > RR^b > TI^c$	$NT^a = RR^a < TI^b$

† Treatment differences at $P \leq 0.05$ indicated by different letter within columns under change in soil water (ΔSW) and precipitation storage efficiency (PSE). Treatments are NT = no-till, RR = crop residue removed before tillage and replaced after tillage, and TI = crop residue incorporated into soil profile. Vector of change indicated in by '<' or '>' in ΔSW.

‡ PSE = precipitation/change in soil water.

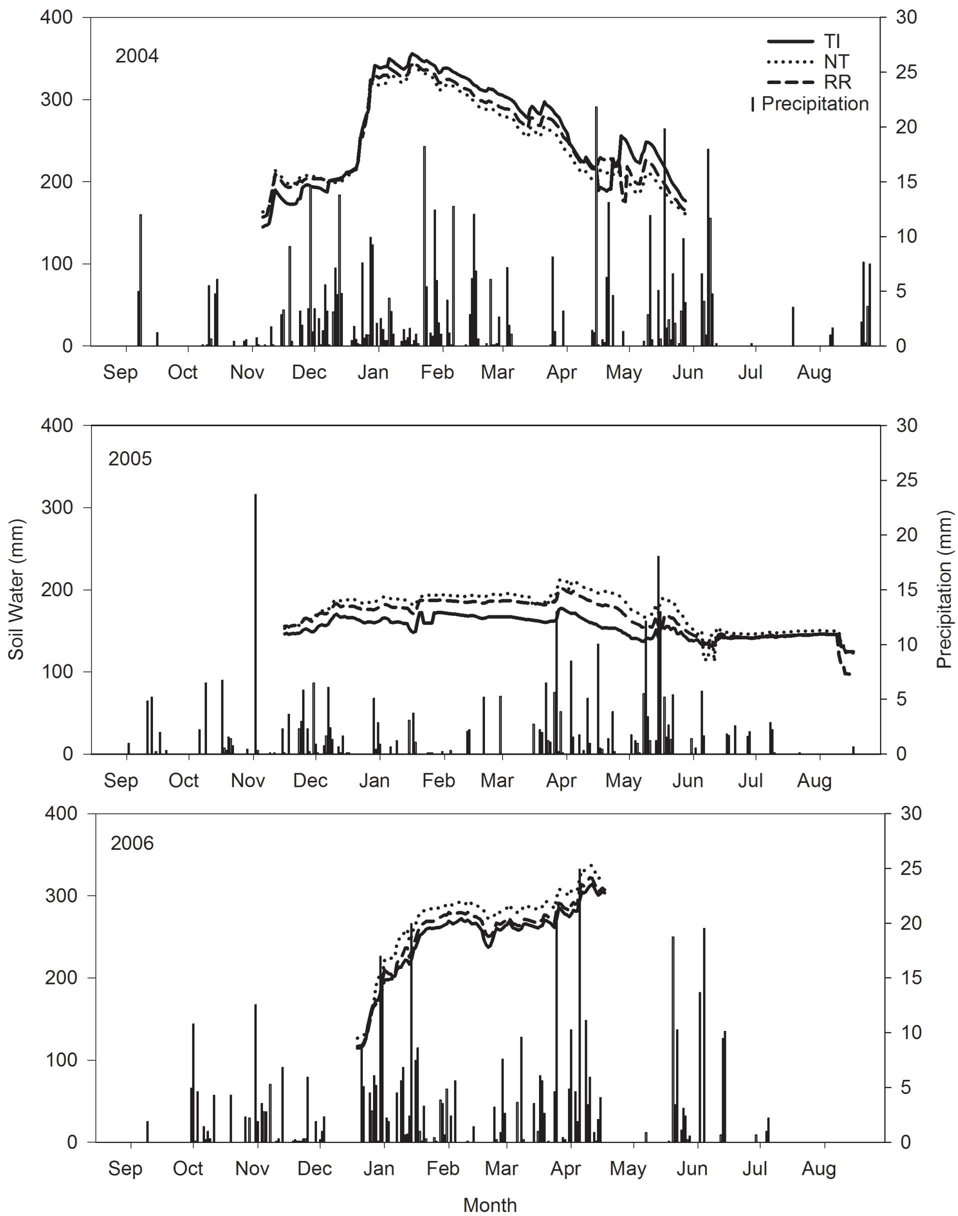

Fig. 2. Soil water in 105-cm profile and daily precipitation in crop years 2004, 2005, and 2006 beginning September 1 and ending August 30. TI = crop residue incorporated into soil profile, NT = no-till, RR = crop residue removed before tillage and replaced after tillage.

Table 4. Time series analysis of precipitation storage efficiency (PSE) and change in soil water (ΔSW) during recharge or depletion time periods at incremental depths after fall planting through the 2005 growing season.

Depth	Start	End	Soil profile status	Δ soil water†	PSE‡
cm					
10	11/16/04	12/12/04	recharge	$NT^a > RR^b > TI^c$	$NT^a = RR^a < TI^b$
10	01/03/05	01/17/05	depletion	$NT^a = RR^a = TI^a$	$NT^a = RR^a < TI^b$
10	01/17/05	02/12/05	recharge	$NT^a = RR^a < TI^b$	$NT^a = RR^a = TI^a$
10	05/21/05	08/10/05	depletion	$NT^a > RR^b = TI^b$	$NT^a = RR^a = TI^a$
20	11/16/04	12/12/04	recharge	$NT^a = RR^a = TI^a$	$NT^a > TI^b = RR^{ab}$
20	02/22/05	03/03/05	recharge	$NT^a = RR^a = TI^a$	$NT^a > RR^b > TI^c$
30	12/12/04	12/25/04	depletion	$NT^a = RR^a > TI^b$	$NT^a = RR^a > TI^b$
30	03/26/05	04/06/05	depletion	$NT^a = RR^a > TI^b$	$NT^a = RR^a > TI^b$
30	04/06/05	05/11/05	depletion	$NT^a = RR^a > TI^b$	$NT^a = RR^a = TI^a$
30	05/14/05	06/10/05	depletion	$NT^a < TI^b = RR^{ab}$	$NT^a < TI^b = RR^{ab}$
60	12/06/04	12/14/04	recharge	$NT^a = RR^a = TI^a$	$NT^a = RR^a < TI^b$
60	12/14/04	12/25/04	depletion	$NT^a = RR^a = TI^a$	$NT^a < RR^b < TI^c$
60	01/06/05	04/22/05	recharge	$NT^a > RR^b > TI^c$	$NT^a = RR^a = TI^a$
60	04/25/05	05/12/05	depletion	$NT^a > RR^b = TI^b$	$NT^a = RR^a = TI^a$
60	06/12/05	06/21/05	depletion	$NT^a = RR^a = TI^a$	$NT^a = RR^a > TI^b$
60	07/09/05	07/12/05	depletion	$NT^a = RR^a = TI^a$	$NT^a = RR^a < TI^b$
60	08/10/05	08/17/05	depletion	$NT^a < TI^b = RR^{ab}$	$NT^a = RR^a = TI^a$
90	11/16/04	01/20/05	recharge	$NT^a = RR^a = TI^a$	$NT^a > RR^b > TI^c$

† Treatment differences at $P \leq 0.05$ indicated by different letter within columns under ΔSW and PSE. Treatments are NT = no-till, RR = crop residue removed before tillage and replaced after tillage, and TI = crop residue incorporated into soil profile. Vector of change indicated in by '<' or '>' in ΔSW.

‡ PSE = precipitation/change in soil water.

Soil Water at Incremental Depths

The treatment differences in crop year 2005 were evident in the incremental depth measurements (Table 4). Although there were differences in DSW and PSE in 2004 and 2006, they did not result in differences among treatment's SW_d or $SW_{profile}$ values.

In 2005, SW_d was significantly greater in the NT than RR or TI treatments at 10 and 20 cm through much of the crop year and for shorter time periods at 30 cm (Fig. 3, Table 4). At 10 and 20 cm, the difference was established before data collection began (although these differences were not reflected in the $SW_{profile}$). The difference persisted at the 10-cm depth until August 13 and at the 20-cm depth until June 14. At the 30-cm depth, SW_d in the NT treatment was greater than TI between December 13 and May 2. Treatment RR periodically had significantly more SW_d than TI or significantly less than NT throughout the year.

Significant differences in DSW did not occur consistently among treatments or immediately in conjunction with precipitation events (Table 4). The November 17th DSW response to 2.4 mm of precipitation falling the previous 48 h provides an example of the complex responses that we recorded. From this one small precipitation event, falling at a rate of 0.5 mm h^{-1}, the NT treatment gained 0.13 mm compared with 0.12 mm in TI and 0.04 mm in RR. The following day (the 18th), another 3.6 mm of precipitation fell, but SW_d actually decreased in all three treatments from the 18th through 19th. The longer time period bracketing these events, November 17 through December 12, was a period of recharge during which 37.7 mm of precipitation fell and the DSW for NT of 0.6 mm was significantly more than the 0.4 mm recorded in TI and RR treatments. This was typical for all time periods of gain or loss at all depths, with the differences among treatments developing and disappearing relatively slowly.

Precipitation storage efficiency was significantly different among treatments one time for $SW_{profile}$ (Table 3), and only once at 10 cm for DSW_d leading up to, during, and immediately after significant differences in 2005 SW values (Table 4). The date when this occurred did not match nor preceed immediately either of the dates when treatment DSW_d were significantly different at deeper depths, indicating no immediate connection between precipitation and what occurred down through the soil profile. There were more PSE differences among treatments at the subsurface depths than occurred in the 10-cm depth near the surface; two times at 20 cm, three times at 30 cm (all corresponding to significant differences in DSW), and five times at 60 cm (one of which corresponded to DSW).

Grain and Residue Yield

Three year mean grain yields were not significantly ($P = 0.98$) different among treatments (Table 5), although RR produced significantly greater yield than NT in 2005. There was substantially more crop residue in the NT and RR treatments, respectively 8.43 ± 2.91 Mg ha^{-1} (94% cover) and 8.37 ± 3.93 Mg ha^{-1} (83% cover), than the TI treatment with 0.88 ± 0.44 Mg ha^{-1} (23% cover).

DISCUSSION

The lack of differences among treatments in soil water content in the fall and spring/summer in the total soil profile and in 2 out of 3 yr at the 10- and 20-cm depths is contrary to what other researchers have reported outside of the PNW (Dao, 1993; Heer and Krenzer, 1989; Norwood, 1994; Patrignani et al., 2012). In crop year 2005, we found more soil water in the 10- to 20-cm depth in the NT and RR treatments than in the TI treatment. In four out of four times in the NT treatment and two out of four times in the RR treatment the DSW were significantly greater that TI (Table 3). Precipitation in crop year 2005 was more commensurate with the drier precipitation zone of the inland PNW where a 2-yr WW-SF rotation is more commonly practiced (Table 2). It would appear the soil surface conditions in the NT and RR treatments had qualities that captured more precipitation than TI (Fig. 2). Precipitation late in crop year 2004 and in the first 2 mo of crop year 2005 were near to or below normal, which does not explain the early differences in soil water in the 10- and 20-cm depths. Annual cropping was initiated in this plot area in 1999, although the plots were not instrumented until crop year 2004. Thus, the responses we measured were largely the result of crop residue present on the soil surface, not vestigial carry over from previous experiments. Changing tillage systems alone is unlikely to affect changes in precipitation capture and storage to the degree that maintaining adequate residue on the soil surface will (Peterson and Westfall, 2004; Williams et al., 2000). During the wet years, 2004 and 2006, all three treatments were above 0.20 cm^3 cm^{-3} from late November through April. In the dry year, 2005, the NT and RR profiles were at or above field capacity from December 5 through the May 1, whereas the TI soil profile never recharged to field capacity. Because precipitation in this region is almost always of low intensity, there is much time for evaporative drying at the soil surface even in the middle of winter when vapor pressure is relatively high and mean daily wind speed is 2.5 m s^{-1}. Through the course of this experiment precipitation fell 1769 h, with a mean rate of 0.71 mm h^{-1} (95% confidence interval of 0.04 mm h^{-1}), a median rate of 0.41 mm h^{-1}, and a maximum rate of 12.12 mm h^{-1}. During crop years 2004 through 2005, the mean length of continuous precipitation was 3 h (± 14 min), and the mode 1 h. Under these circumstances, recharge of the soil profile occurs over periods of days, not hours. Precipitation on the soil surface or captured by the crop residue will be subject to evaporation. However, with sufficient precipitation to exceed the water storage capacity in crop residue, water making it to the soil surface can be protected from evaporation in the boundary layer, (the still air zone created by the crop residue cover), to infiltrate into the soil profile. In the surface 10 cm, there were 20 periods of gain or loss between November and late March 2005, when $SW_{profile}$ recharge ended and summer draw-down began. This means that even while soil water was recharging in the winter, the soil surface went through wetting and drying periods. Without residue cover to insulate water on or near the surface from evaporative forces, significant amounts of water evaporates that otherwise could be stored in the soil profile.

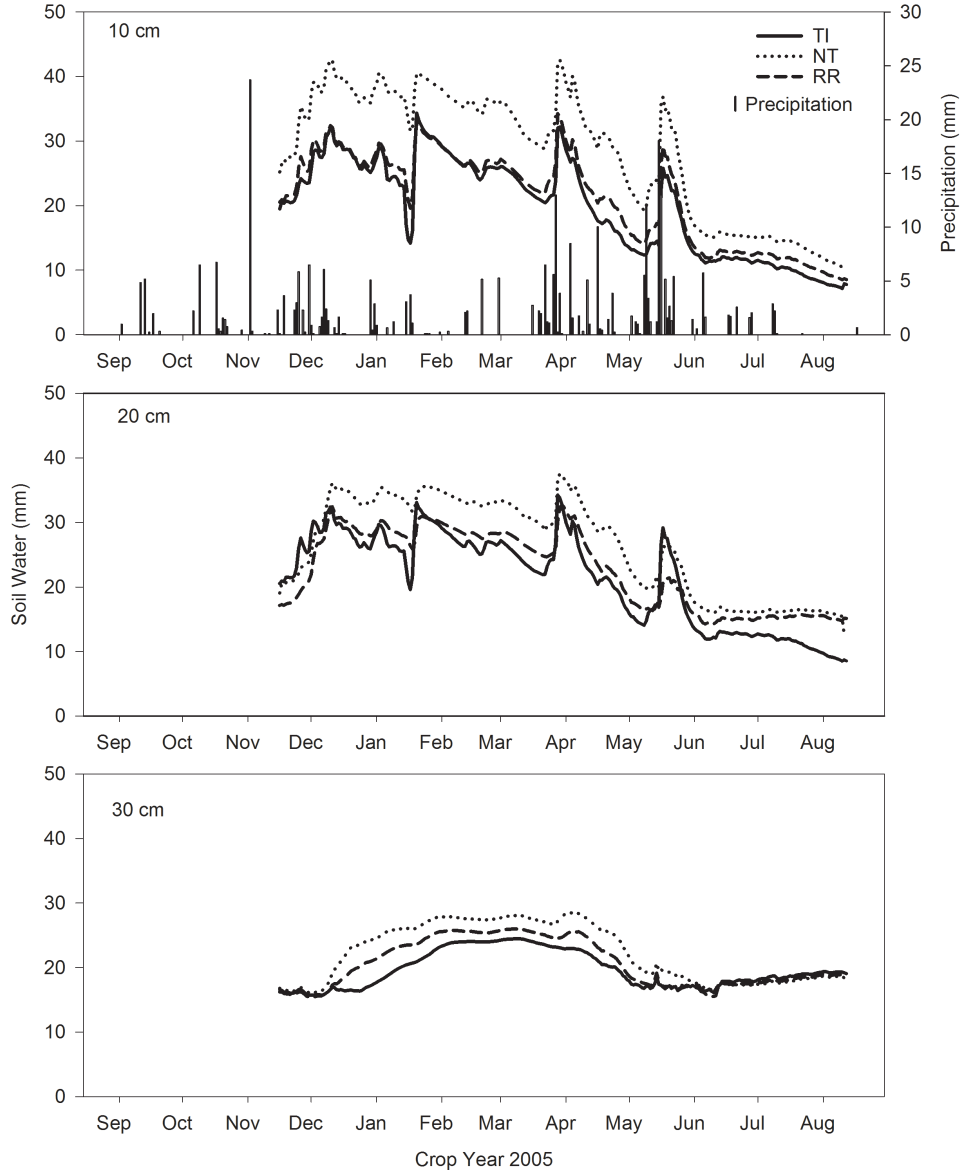

Fig. 3. Soil water at 10-, 20-, and 30-cm depths in the soil profile and daily precipitation in crop year 2005. TI = crop residue incorporated into soil profile, NT = no-till, RR = crop residue removed before tillage and replaced after tillage.

Insights gained from this study support observations from both research and production in the semiarid PNW. No-till does not appear to have markedly superior water storage efficiency in an average year, nor does it produce clearly superior wheat yields. Yield differences between NT and RR, and NT and TI, were »0.1 Mt ha^{-1}, with the difference between RR and TI only

Table 5. Annual winter wheat crop yield mean and standard error values at Columbia Plateau Conservation Research Center, Adams, OR during crop years 2004, 2005, and 2006.

Crop year	NT†	RR	TI
		Mg ha^{-1}	
2004	4.97 ± 0.13[a]‡	4.74 ± 0.06[a]	4.80 ± 0.06[a]
2005	2.67 ± 0.10[a]	3.14 ± 0.20[b]	2.73 ± 0.15[ab]
2006	3.63 ± 0.10[a]	3.66 ± 0.17[a]	3.54 ± 0.29[a]
Mean	3.76 ± 0.67[a]	3.85 ± 0.47[a]	3.69 ± 0.60[a]

† Treatments are NT = no-till, RR = crop residue removed before tillage and replaced after tillage, and TI = crop residue incorporated into soil profile.
‡ Row values with different letters are significantly different at $P \leq 0.05$.

slightly greater (»0.2 Mt ha^{-1}). The RR treatment had significantly higher yields in 2005 (Table 5), however this difference was not reflected in differences between the soil water content of these two treatments. Under certain weather conditions and during select parts of any particular growing season NT can capture and retain greater soil water, and under certain conditions this can lead to increased crop productivity. It is rare for a bare tilled surface to capture more soil water than a residue covered surface, and this would be especially true where SF is practiced. It should also be noted that this experiment was conducted on level land, and the superiority of NT cropping systems in reducing surface runoff is well established.

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REFERENCES

Chen, C., W.A. Payne, and J.D. Williams. 1998. Comparison of two field methods for measuring unsaturated soil hydraulic conductivity in eastern Oregon, American Society of Agronomy 90th Annual Meeting, Baltimore, MD, ASA, Madison, WI. p. 283.

Dao, T.H. 1993. Tillage and winter wheat residue management effects on water infiltration and storage. Soil Sci. Soc. Am. J. 57:1586–1595 doi:10.2136/sssaj1993.03615995005700060032x

Duff, B., P.E. Rasmussen, and R.W. Smiley. 1995. Wheat/fallow systems in semi-arid regions of the Pacific NW America. In: V. Barnett et al., editors, Agricultural sustainability: Economic, environmental and statistical considerations. Wiley, London. p. 85–111.

Floyd, D.A., and J.E. Anderson. 1982. A new point interception frame for estimating cover of vegetation. Plant Ecol. 50:185–186. doi:10.1007/BF00364113

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil water storage in dryland cropping systems: The significance of cropping intensification. Soil Sci. Soc. Am. J. 62:984–991. doi:10.2136/sssaj1998.03615995006200040020x

Gbur, E.E., W.W. Stroup, K.S. McCarter, S. Durham, L.J. Young, M. Christman, M. West, and M. Kramer. 2012. More complex examples. In: Analysis of generalized linear mixed models in the agricultural and natural resources sciences. ASA, CSSA, and SSSA, Madison, WI. p. 199–236.

Heer, W.F., J. Krenzer, and G. Eugene. 1989. Soil water availability for spring growth of winter wheat (*Triticum aestivum* L.) as influenced by early growth and tillage. Soil Tillage Res. 14:185–196. DOI:10.1016/0167–1987(89)90031–7.

Huggins, D.R., R.S. Karow, H.P. Collins, and J.K. Ransom. 2011. Introduction: Evaluating long-term impacts of harvesting crop residues on soil quality. Agron. J. 103:230–233. doi:10.2134/agronj2010.0382s

Johnson, D.R., and A.J. Makinson. 1988. Soil Survey of Umatilla County area, Oregon. USDA–Soil Conservation Service, U.S. Gov. Print. Office, Washington, DC.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models, 2nd ed., design 4.1.e. SAS Publishing, SAS Inst., Cary, NC. p. 97.

McClellan, R.C., D.K. McCool, and R.W. Rickman. 2012. Grain yield and biomass relationship for crops in the Inland Pacific Northwest United States. J. Soil Water Conserv. 67:42–50. doi:10.2489/jswc.67.1.42

Norwood, C. 1994. Profile water distribution and grain yield as affected by cropping system and tillage. Agron. J. 86:558–563. doi:10.2134/agronj1994.00021962008600030019x

Patrignani, A., C.B. Godsey, T.E. Ochsner, and J.T. Edwards. 2012. Soil water dynamics of conventional and no-till wheat in the Southern Great Plains. Soil Sci. Soc. Am. J. 76:1768–1775. doi:10.2136/sssaj2012.0082

Peterson, G.A., and D.G. Westfall. 2004. Managing precipitation use in sustainable dryland agroecosystems. Ann. Appl. Biol. 144:127–138. doi:10.1111/j.1744-7348.2004.tb00326.x

Peterson, G.A., D.G. Westfall, and C.V. Cole. 1993. Agroecosystem approach to soil and crop management research. Soil Sci. Soc. Am. J. 57:1354–1360. doi:10.2136/sssaj1993.03615995005700050032x

Rasmussen, P.E., S.L. Albrecht, and R.W. Smiley. 1998. Soil C and N changes under tillage and cropping systems in semi-arid Pacific Northwest agriculture. Soil Tillage Res. 47:197–205. doi:10.1016/S0167-1987(98)00106-8

Rasmussen, P.E., R.R. Allmaras, C.R. Rohde, and N.C. Roager. 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. Soil Sci. Soc. Am. J. 44:596–600. doi:10.2136/sssaj1980.03615995004400030033x

Rasmussen, P.E., H.P. Collins, and R.W. Smiley. 1994. Long-term management effects on soil productivity and crop yield in semi-arid regions of eastern Oregon. Station Bull. 675, Agric. Exp. Stn. Oregon State Univ., Corvallis, OR.

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. Soil Sci. Soc. Am. J. 58:523–530. doi:10.2136/sssaj1994.03615995005800020039x

SAS. 2012. SAS/STAT 9.3 user's guide. SAS Inst., Cary, NC.

Schillinger, W.F., and R.I. Papendick. 2008. Then and now: 125 years of dryland wheat farming in the Inland Pacific Northwest. Agron. J. 100:S-166–S-182. doi:10.2134/agronj2007.0027c.

Smiley, R.W., H.P. Collins, and P.E. Rasmussen. 1996. Diseases of wheat in long-term agronomic experiments at Pendleton, Oregon. Plant Dis. 80:813–820. doi:10.1094/PD-80-0813

Williams, J.D., D.E. Wilkins, C.L. Douglas, Jr., and R.W. Rickman. 2000. Mow-plow crop residue management influence on soil erosion in north-central Oregon. Soil Tillage Res. 55:71–78. doi:10.1016/S0167-1987(00)00100-8

Wuest, S.B., and M.K. Corp. 2011. One-pass tillage for summer fallow under arid summer conditions. Crop Manage. doi:10.1094/CM-2011-1223-03-RS.

Wuest, S.B., and W.F. Schillinger. 2011. Evaporation from high residue no-till versus tilled fallow in a dry summer climate. Soil Sci. Soc. Am. J. 75:1513–1519. doi:10.2136/sssaj2010.0368