Evaporation from High Residue No-Till versus Tilled Fallow in a Dry Summer Climate

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Farmers in the low-precipitation (<300 mm annual) region of the Inland Pacific Northwest of the USA practice summer fallow to produce winter wheat (*Triticum aestivum* L.) in a 2-yr rotation. No-till fallow (NTF) is ideal for wind erosion control but is not widely practiced because of seed-zone soil drying during the summer, whereas adequate seed-zone water for germination and emergence of deep-sown winter wheat can generally be retained with tilled fallow (TF). Successful establishment of winter wheat from late August– early September planting is critical for optimum grain yield potential. A 6-yr field study was conducted to determine if accumulations of surface residue under long-term NTF might eventually be enough to substitute for TF in conserving seed-zone water over summer. Averaged over the 6 yr, residue rates of 1500, 6000, and 10 500 kg ha^{-1} (1×, 4×, and 7× rates, respectively) on NTF produced incrementally greater seed-zone water but were not capable of conserving as much as TF. Total root zone (0–180 cm) over-summer water loss was greatest in the 1× NTF whereas there were no significant differences in the 4× and 7× NTF versus TF. Average precipitation storage efficiency ranged from 33% for 1× NTF to 40% for TF. We conclude that for the low-precipitation winter wheat-summer fallow region of the Inland Pacific Northwest: (i) Cumulative water loss during the summer from NTF generally exceeds that of TF; (ii) there is more extensive and deeper over-summer drying of the seed-zone layer with NTF than with TF; (iii) increased quantities of surface residue in NTF slow the rate of evaporative loss from late-summer rains, and (iv) large quantities of surface residue from April through August will marginally enhance total-profile and seed-zone water in NTF, but will not retain adequate seed-zone water for early establishment of winter wheat except sometimes during years of exceptionally high precipitation or when substantial rain occurs in mid-to-late August.

Abbreviations: NTF, no-till fallow; TF, tilled fallow.

No-till is an attractive method of farming because it can lower production costs, leave the soil in a less erodible condition, and improve soil quality compared with tillage-based systems (Blanco-Canqui and Lal, 2008). Wheat farmers in many regions of the world have developed no-till systems that are economically and environmentally superior to tillage-based systems. Attempts to develop NTF for the dry (<300 mm annual precipitation) winter wheat-summer fallow region of the Pacific Northwest USA, however, have produced limited success (Schillinger and Papendick, 2008). This region is unique to the world because winter wheat is planted as deep as 20 cm below the soil surface with deep-furrow drills to reach adequate seed-zone water for germination and emergence.

One recurring question about the adoption of NTF in regions with hot, dry summers involves possible changes in soil surface characteristics over time. If crop residues are allowed to accumulate on the surface for several years in a no-till system, will this create an effective barrier to evaporation? If long-term no-till changes surface characteristics enough to reduce evaporation and retain seed-zone water contents adequate for germination and emergence of deep-sown winter wheat, this knowledge would encourage continued development efforts. On the other hand, if NTF can never, or only rarely, retain adequate seed-zone water then efforts might

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be better redirected to other techniques for reducing soil erosion and improving sustainability.

Efforts to minimize fallow water loss have produced considerable information on infiltration and evaporation, and the effect of surface residue on these processes. Penman (1941) showed that movement of free water depends on capillary conductivity and the tension gradient, both of which are functions of water content. Field experiments by Idso et al. (1974) demonstrated that evaporation from soil occurs in three stages. The first stage is characterized by a high evaporative rate similar to a free water surface. This stage lasts as long as the water flow rate to the soil surface equals the loss rate by evaporation. Crop residues on the soil surface have the greatest influence during the first stage of drying by reflecting sunlight that would otherwise be absorbed as heat by the soil and increase evaporation. Residue also acts as a thermal insulator to limit the flow of heat from the atmosphere to the soil, and reduces turbulent air exchange by creating a dead air space above the soil surface that slows the transfer rate of water vapor from the soil to the atmosphere (Lemon, 1956; Papendick and Campbell, 1974).

The second stage of evaporation begins when soil water cannot be transmitted to the surface fast enough to meet evaporative demand, so the soil surface begins to dry. During the second stage of drying the effect of surface residue is greatly reduced, since the evaporation rate now depends on water conductivity and diffusivity below the surface. The third stage is characterized by a low and relatively constant evaporation rate, because liquid water evaporates before getting to the surface and moves as vapor through the dry surface layer. For this reason, research on the effects of crop residue on soil water loss often demonstrates significant short-term changes, but small to no long-term effect. Greb et al. (1970) found that increasing amounts of wheat residue improved over-winter soil water storage, but had much less effect on conserving summer rainfall. Field and laboratory experiments by Army et al. (1961) showed that residue decreased evaporation from NTF when the soil surface remained wet, but only if rains were frequent could surface residue be expected to improve water storage by increasing depth of infiltration. In a laboratory study, Bond and Willis (1970) demonstrated how rates of surface residue from 0 to 17 920 kg ha^{-1} reduced first stage evaporation from a wet soil, but a substantial reduction in total water loss after 20 d only occurred with extremely high wheat residue rates. Other laboratory research has shown that diffusive resistance of a layer of wheat residue depends mostly on its thickness (Flury et al., 2009).

The effects of fallow methods on soil water retention have been widely studied in the U.S. Great Plains. Because of the complexity of evaporation and infiltration processes involved in water storage plus year-to-year and site-to-site variability, conclusions have been somewhat contradictory. Studies in the Great Plains indicate that NTF either stores more water than TF (Good and Smika, 1978; Wicks and Smika, 1973; Fenster and Peterson, 1979; Nielsen and Vigil, 2010; Smika, 1990), or that there is little to no difference between the two methods (Wiese and Army, 1960; Black and Power, 1965, Tanaka, 1985). In the Great Plains, much of the precipitation occurs during the period of high potential evaporation, where it is necessary to consider evaporation and infiltration as simultaneous processes when evaluating the effect of tillage on water storage.

In the Pacific Northwest, which has high winter precipitation and low summer rainfall, infiltration is generally of little concern during the period of high evaporation (Papendick et al., 1973; Wuest, 2010). Under these conditions, the transfer of heat from the surface down to water below the surface is a primary driving force for evaporation, in addition to the hydraulic conductivity of liquid water upward toward the surface (Massee and Cary, 1978). Studies in the low-precipitation region of the Pacific Northwest show that over-summer seed-zone water loss from NTF is greater than from TF (Oveson and Appleby, 1971; Hammel et al., 1981; Schillinger and Bolton, 1993), and that this limits or prevents the establishment of winter wheat sown in late August to early September. In this region, winter wheat successfully established from deep planting depths into carryover water in fallow during late summer consistently produces 30% or more grain and straw yield compared with late-planted wheat that is dependent on fall rains for emergence (Donaldson et al., 2001).

In semiarid areas where evaporation and water conservation are important issues, large quantities of crop residue are often not available. This may limit the effectiveness of surface residues unless they can accumulate over a number of years. Our experiment was designed to investigate the potential of surface residue to reduce evaporation and serve as a substitute for tillage in winter wheat-summer fallow cropping systems in a low-precipitation climate with dry summers. We hypothesized that evaporation suppression would be related to the quantity of surface residue, and that large amounts of residue would be needed to approach the effectiveness of a tilled fallow.

MATERIALS AND METHODS

Layout of Experiment

A 6-yr dryland cropping systems experiment was conducted from 2003 to 2008 at the Washington State University Dryland Research Station near Lind, WA. Long-term (88-yr) average annual precipitation at the site is 241 mm. Average pan evaporation from April through September is 1323 mm. About two-thirds of the precipitation occurs from October to March, with about one-third as snow. Snow drifting occurs during some years but was not a major factor in the experiment as wheat stubble in all treatments was left standing and undisturbed through the winter to trap snow. One-fourth of the annual precipitation occurs during April to June, with July to September the driest months.

The soil is a Shano silt loam (coarse-silty, mixed, superactive, mesic, Xeric Haplocambids) with uniform texture throughout the profile. Slope is <2%. There is a thin, weak layer of calcium carbonate accumulation at about the 50-cm depth, but otherwise no restrictive layers or rocks within the 180-cm profile. Soil textural size distribution of the soils in this study is 10% clay, 51% silt, and 39% fine sand. Shano soils are widely found throughout the low-precipitation farming region of east-central Washington.

Crop rotations implemented over the 6-yr period were continuous annual no-till soft white, hard white, and hard red spring wheat, and several 2- and 3-yr rotations both with and without fallow. Experimental design was a randomized complete block with four replications of all treatment combinations. Each segment of all rotations occurred every year. Size of individual plots of crop rotation treatments that were exclusively no-till were 3 × 70 m, whereas those involving tillage-based fallow were 10 × 70 m to accommodate tillage implements. This paper is focused on soil water dynamics during the fallow segment of two of the seven crop rotation treatments: (i) the 2-yr winter wheat—TF rotation and, (ii) the 3-yr winter wheat-spring wheat—NTF rotation.

Before the start of the study, soft white spring wheat was grown on the entire experiment area during the 2002 crop year. Throughout the 6-yr period for both TF and NTF systems, glyphosate herbicide [*N*-(phosphonomethyl) glycine] was applied in March to standing undisturbed stubble from the previous crop at a rate of 0.43 kg acid equivalent ha^{-1} to control weeds. Primary spring tillage was conducted at a depth of 13 cm in the fallow portion of the winter wheat-TF treatment in mid April with a Haybuster undercutter. The undercutter implement is equipped with narrow-pitched and overlapping 80-cm-wide V blades to slice beneath the soil with minimum surface lifting or disturbance and simultaneously deliver aqua ammonia-N, all in one pass. A 3-bar tine harrow was attached behind the undercutter to break up large soil clods and fill air voids. Following primary spring tillage, the TF was rodweeded once or twice during the late spring and summer at a depth of 10 cm to control Russian thistle (*Salsola iberica*) and other broadleaf weeds as needed. Compared with traditional high-soil-disturbance primary spring tillage methods, the undercutter method has been proven equally effective in conserving seed-zone and total-profile water (Schillinger, 2001), with the advantage of a significant reduction in wind erosion hazard (Sharratt and Feng, 2009). Weeds in the NTF were controlled with herbicides as needed. Both TF and NTF treatments were kept practically weed-free throughout the experiment.

In early March, standing residue from the previous year's winter wheat crop in a nearby field was hand clipped in 15 cm lengths and allowed to air dry in a greenhouse for 45 d. In mid April, before the period of high potential evaporation, wheat residue representing 4500 and 9000 kg ha^{-1} was placed horizontally on 1.73 × 1.73 m subplots bordered with 1-cm^2 mesh, 30-cm tall metal screen in the center of each of the four replicate NTF plots. The purpose of the mesh-screen border was to keep the residue contained within the desired area. The average existing standing stubble in the NTF plots was 1500 kg ha^{-1} (based on weight after harvest), the result of spring wheat with grain yields averaging 900 kg ha^{-1}. Therefore the 4500 and 9000 kg ha^{-1} wheat residue additions produced residue loads of 6000 and 10 500 kg ha^{-1}. Wheat produces ≅ 1.7 kg of residue for every 1.0 kg of grain, so these residue loads were representative of grain yields of 3530 and 6200 kg ha^{-1}, respectively. For simplicity, the 1500 (baseline), and added 4500 and 9000 kg ha^{-1} residue rates are referred to as 1×, 4×, and 7× residue treatments. The 7× residue rate represented about double the highest single-growing-season residue yield that could realistically be achieved at this location under the most favorable winter wheat production conditions.

Soil Water Measurements

Soil water was measured to a depth of 180 cm three times during each of the six fallow cycles: (i) early August immediately after wheat grain harvest and the beginning of fallow, (ii) early April before primary tillage for TF, and (iii) at the end of the 13-mo fallow cycle in late August. Soil volumetric water content in the 30- to 180-cm depth was measured in 15-cm increments in one access tube in the center of each subplot by neutron thermalization (Hignett and Evett, 2002). Volumetric soil water content in the 0- to 30-cm depth was determined from two 15-cm long volumetric core samples in each subplot using gravimetric procedures (Topp and Ferre, 2002). Precipitation storage efficiency was calculated as the soil water gain divided by the precipitation received. In addition to the root-zone samples, volumetric seed-zone soil water content in all TF and NTF subplots was measured in one location in 2-cm increments to a depth of 26 cm (22 cm in 2003) with an incremental soil sampler in late August. From the surface to slightly less than 26 cm deep is referred to as the seed zone, since this represents the depths where deep-furrow drills place seed.

Data Analysis

To measure differences in seed-zone soil water content between TF and NTF that were not confounded with differences in bulk density, depth in the seed-zone soil profile is expressed in terms of mass of dry soil per unit area instead of linear depth (e.g., cm) from the soil surface (McGarry and Malafant 1987; Ellert and Bettany 1995; VandenBygaart and Angers 2006; Wuest 2009). Mass-depth uses the cumulative dry soil mass of each soil increment in a soil core to determine depth in the soil profile. The cross-sectional area of the soil core is used to convert the sample mass to kg m^{-2}. The usual linear depth measurement uses the soil surface as a starting point to measure depth. Measuring depth as kg dry soil m^{-2} can be used to compare soil constituents like water without confounding treatment effects with soil bulk density.

Seed-zone water content data was analyzed for heterogeneity of variance. Since years were found to be heterogeneous, but treatments were not, the data was analyzed using a reduced heterogeneous variance structure in a mixed model (Littell et al., 2006). Water content at an equivalent mass-depth of 200 kg m^{-2} was therefore analyzed in a mixed model of treatment, year and their interaction, with year as a repeated measure. For the measurements of rooting zone water, the quantity of water in the 180-cm soil profile was analyzed using a mixed model with treatment as the fixed effect, and year the random effect.

RESULTS

Daily precipitation for the six fallow periods is shown in Fig. 1. In most years, there was little rainfall between June and October. Rainfall events during periods of low relative humidity and high daytime temperatures often result in little to no increase in stored water. The precipitation data can be used to explain some of the yearly variation in seed-zone water content (Fig. 2). In mid-to-late August of 2004 and 2007, thunderstorm rainfall events of 13 and 12 mm, respectively, wetted the surface of NTF to a depth of 8 cm or more. In 2004 the precipitation was very close to the sampling date, and in 2007 there was more time for drying between the precipitation event and sampling. Seed-zone

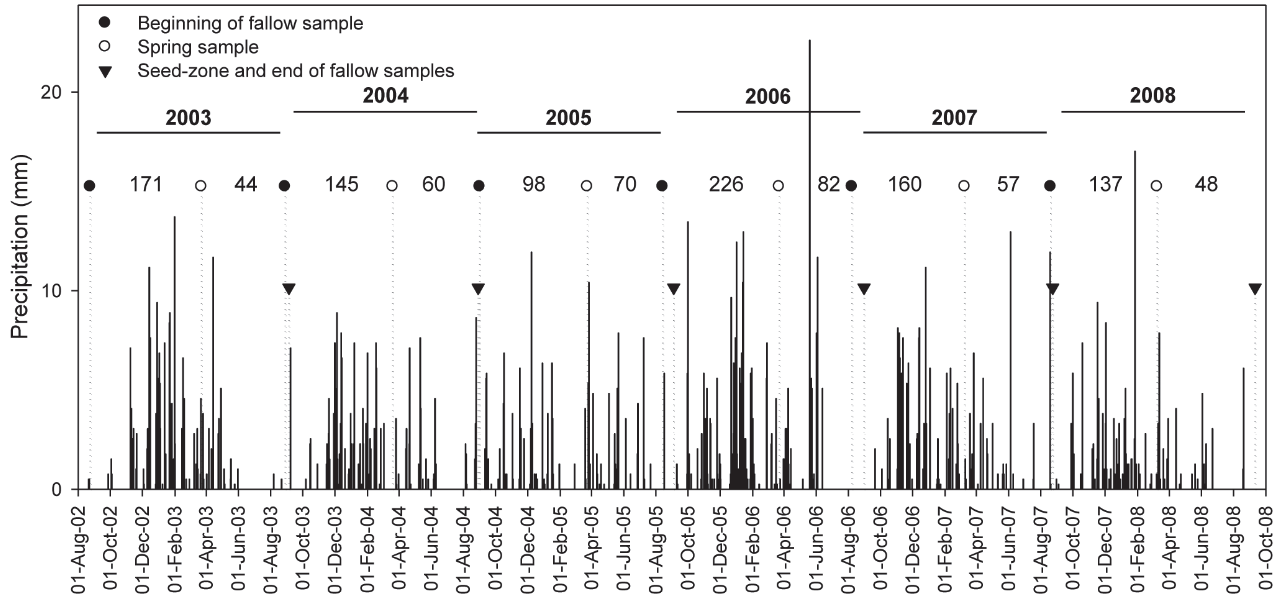

Fig. 1. Daily precipitation during the 2003 to 2008 fallow periods at Lind, WA. Also shown is the timing of 180-cm deep volumetric water profile measurements obtained each year at the beginning of the fallow period, in the spring of the fallow period, and at the end of the fallow period. Total precipitation (mm) between those points is noted. The date when incremental seed-zone water samples were obtained is indicated by a triangle. Horizontal bars indicate individual fallow periods and are labeled with the year the fallow period ends.

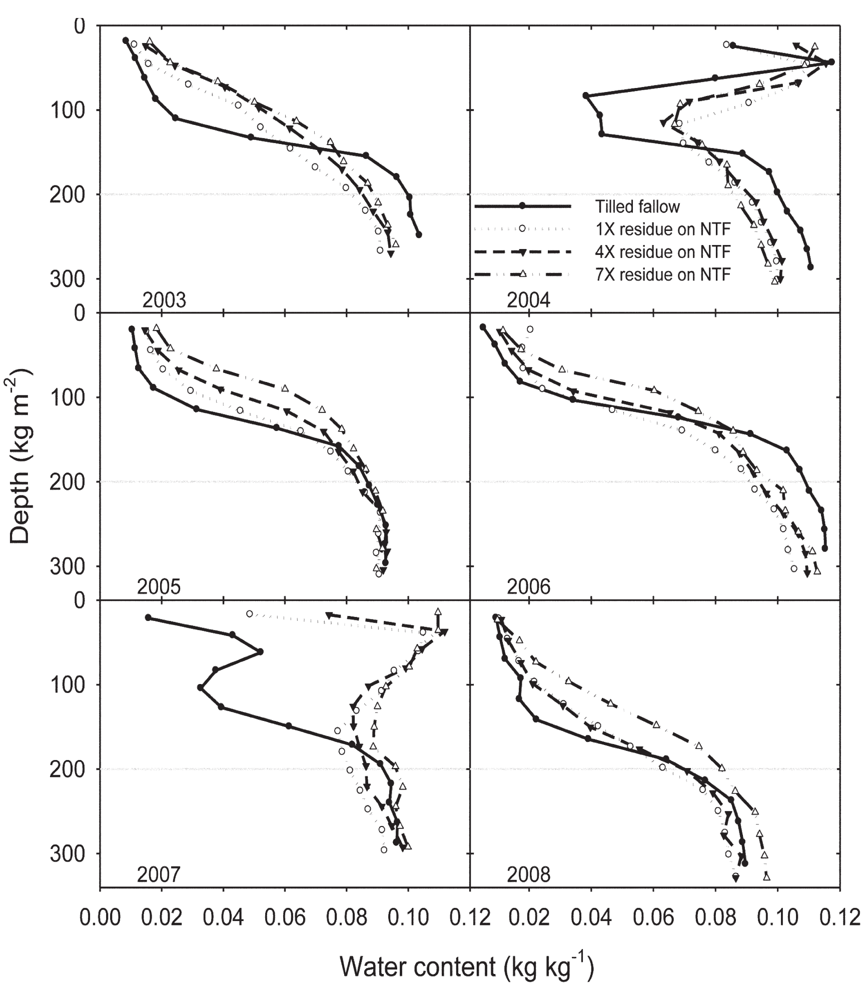

Fig. 2. Seed-zone water content profiles measured in late August from 2003 to 2008. Samples were taken in 2-cm increments from 0- to 26-cm depth (22 cm in 2003) and are plotted on a dry soil mass per area basis. The horizontal guideline marks 200 kg m−2 used for equivalent-mass treatment comparisons. NTF = no-till fallow.

water was adequate to establish early-planted winter wheat on NTF in 2004 and 2007. In contrast, these August rains penetrated only a short distance into TF (Fig. 2) and did not contribute to additional seed-zone water.

The effect of winter and spring precipitation on seed-zone water at the end of fallow can be seen when comparing 2005 and 2006 (Fig. 1 and 2). Low precipitation totals in 2005 resulted in water contents of about 0.09 kg kg^{-1} in the lower seed zone, whereas higher precipitation in the winter and spring of 2006 resulted in lower seed-zone water contents from 0.10 to almost 0.12 kg kg^{-1}.

Water content profiles (Fig. 2) at planting depths (below about 150 kg m^{-2}, approximately 16 to 20 cm from the surface) in 2003, 2004, and 2006 demonstrate a clear difference between TF and NTF, with lesser differences between residue addition levels. In 2005, conditions were so dry that all treatments resulted in the same water content of about 0.09 kg kg^{-1} at the lowest measured depths. This same low water content occurred in the second driest year, 2008, except for the 7× residue treatment. It appears that the 7× treatment allowed more water to migrate downward into the seed zone and below where it was better conserved and less likely to be lost by evaporation (Hillel, 1971). The relatively low seed-zone water retention in TF in 2007 (Fig. 2) can be at least partially attributed to unusually large surface clods up to 15 cm in diameter created by primary spring tillage, with many individual clods extending from the surface down to the depth of tillage. Such exceptionally large clods are formed during primary spring tillage with low-surface-disturbance implements like the undercutter following winters of especially hard soil freezing and their size needs to be reduced with a tine harrow, rotary hoe, or similar secondary implement attached behind the undercutter. In 2007, our use of a tine harrow behind the undercutter was not sufficient to break up the unusually large clods. Fields adjacent to the experiment that were tilled with a rotary hoe behind the undercutter did a better job in breaking up large clods and had greater seed-zone water than the TF in our experiment in 2007.

Figure 3 shows the 6-yr average seed-zone water content. To analyze for treatment differences independent of soil bulk density differences, water contents for each soil core were interpolated to a depth of 200 kg m^{-2} dry soil mass. The treatments were significantly different in water content (g g^{-1}) at that depth ($P <$ 0.0016). Although adjacent means were not significantly different, the trend is a uniformly spaced progression from 1× residue, to 4×, 7×, and finally the TF treatment.

Figure 4 shows root zone water profiles for each of the 6 yr, and Table 1 shows millimeters of water in the 0- to 90-cm profile and in the entire 0- to 180-cm profile of NTF (1× residue) and TF averaged over the 6-yr period. At the beginning of fallow (i.e., just after wheat harvest) the TF had significantly less water than the NTF in the 0- to 90-cm profile because of greater water use by the previous crop. Grain yields in the 2-yr winter wheat-TF rotation averaged 2390 kg ha^{-1} compared with wheat yields of 1540 for winter wheat and 900 kg ha^{-1} for spring wheat in the 3-yr winter wheat-spring wheat-NTF rotation. This means nearly identical quantities of grain were produced in the 2-yr rotation (winter wheat-TF) as in the 3-yr rotation (winter wheat-spring wheat-NTF). Reduced productivity per crop and over the 6-yr period indicates a lower capacity for soil water exploitation in the late-emerging winter wheat crop after NTF, and again in spring wheat the following year. Over-winter water gain during fallow was the same in TF and NTF, so NTF still had significantly more water than TF in the 0- to 90-cm profile in early spring (Table 1). Water loss in the surface 0 to 90 cm from April to August was significantly greater in 1× NTF than in TF, resulting in nearly identical 6-yr averages for stored soil water at the end of fallow. In the 180-cm profile 1× NTF lost an average of 11 mm more water than TF between early April and late August and had a precipitation storage efficiency of 33% compared with 40% for TF (Table 1). The 4× and 7× NTF treatments had precipitation storage efficiencies of 34 and 36%, respectively, (data not shown).

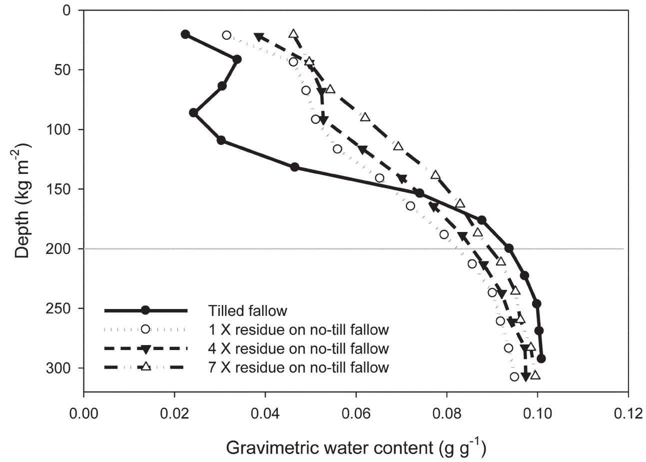

Fig. 3. Average seed-zone water content over the 6-yr period (each point is the mean of 6 yr and four replications). Treatments are significantly different at 200 kg m^{-2} ($p > F = 0.0016$). All non-adjacent means at 200 kg m^{-2} are significantly different at $p > |t| = 0.04$. The year by treatment interaction was not significant.

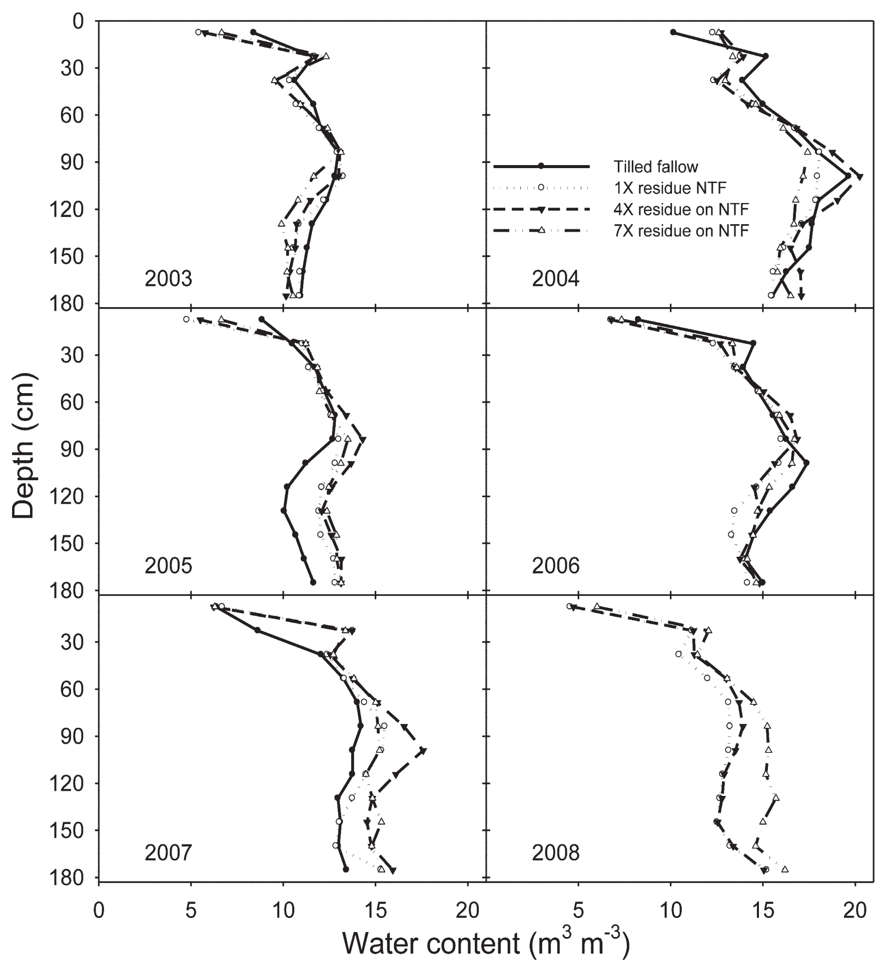

Fig. 4. Volumetric water content at the end of the fallow period to a depth of 180 cm from 2003 to 2008. Each data point is the mean of four replications. NTF = no-till fallow.

Table 1. Soil water content at the beginning (after harvest), early spring, and end of fallow (before planting) and associated gain or loss of water and precipitation storage efficiency (PSE = gain in soil water/precipitation) in tilled versus no-till summer fallow (at 1× residue rate) averaged over 6 yr. The top portion of the table shows water in the surface 90 cm of soil and the bottom portion of the table shows water content in the entire 180-cm profile. NS = no significant differences.

Treatment	Timing in fallow period: Beginning (early Aug.)	Spring (mid Mar.)	Over-winter gain	End (late Aug.)	April- Aug. water loss	
			——— Soil water content (mm) ———			PSE (%)
			Top 90 cm of soil profile			
No-till fallow	57	145	88	104	41	20
Tilled fallow	49	138	89	104	33	25
P > F	0.04	0.01	ns	ns	0.02	ns
			Entire 180 cm soil profile			
No-till fallow	145	258	113	218	40	33
Tilled fallow	132	248	116	219	29	40
P > F	ns	ns	ns	ns	ns	ns

DISCUSSION

A potential limitation in interpretation of data from this study involves the fact that the rotations leading up to the fallow seasons of the TF and NTF were different and that the residue additions were applied in the spring and therefore not in place during the winter part of the fallow period. Wheat residue was added in the spring rather than immediately after harvest because we were primarily interested in residue effects on evaporation during the late spring and summer rather than soil water gain during the wet winter months. As it turns out, the NTF started the fallow period with an average of 13 mm more soil water in the root zone than TF (Table 1) due to more efficient extraction of water (and much higher grain yield) in the 2-yr winter wheat-TF rotation compared with the 3-yr winter wheat-spring wheat-NTF rotation. This means that NTF had the advantage of more water at the start of the summer fallow period and in early April, but even with added residue NTF had less seed-zone water in late August (6-yr average) compared with TF. Therefore, the experiment was a robust test of the capacity for NTF to preserve as much seed-zone water as TF. It is possible, however, that if the 4× and 7× residue rates had been in place over the winter precipitation period, greater water storage could have occurred in those treatments. The NTF treatments averaged 1500, and TF 4060 kg ha^{-1} residue over winter and had equal winter precipitation storage. This is evidence that residue load did not have a big influence on over-winter storage, but we cannot say for certain what the effect of even higher residue loads would have been.

A homogeneity of variance test on the seed-zone water content at equivalent mass-depth of 200 kg m^{-2} demonstrated significant heterogeneity between years, but not between treatments. The authors had speculated that variation in seed-zone water content might be greater in the NTF treatments compared with TF because of the well-established regional experience that, in the absence of significant rain, winter wheat emergence from deep planting in NTF is generally much less uniform than in TF. Since the homogeneity test indicated no difference in variance in seed-zone water between NTF and TF, the observed emergence variation is likely caused by other factors, such as (i) the hard, dry surface soil conditions of NTF that impede penetration by drill openers, (ii) less available water at and below the planting depth, and (iii) greater water potential differences if seed is not placed at a precise depth.

Seed-zone water content curves produced in this study (Fig. 2) were typical of Pacific Northwest soils under fallow. Taking 2003 as an example, a TF profile is usually drier at the surface and for several centimeters below the surface, and then exhibits a very sharp water content gradient change at the depth of tillage, during which it crosses over the profiles of NTF soil and then bends downward to a water content that becomes almost uniform with depth. In contrast, NTF soil generally has a more uniformly sloped water content profile, with greater water content at the surface and lesser at depth compared to TF (Hammel et al., 1981; Wuest, 2010).

Tillage produces the steep gradient of water with depth by reducing liquid water flow at the depth of tillage, above which vapor flow dominants. Surface residue works from the top, slowing vapor flow from the surface or heat input into the surface. Increased water content near the surface would be expected to maintain greater hydraulic conductivity, so the reduction in evaporation and improved infiltration after rainfall is apparently outweighed by the increase in evaporation during dry periods. When looking at the 2005 data in Fig. 2, another perspective that appears plausible is that the layer of residue simply moved the effective surface upward. For 2005 it appears that the three residue treatments have nearly identical shape and differ only in their vertical position.

The 13 mm of rain that occurred over a 3-d period from 23 to 25 Aug. 2004 penetrated to a depth of about 125 kg m^{-2} in NTF (Fig. 2). In 2007, 12 mm of rain on 19 August wet the soil to ≅ 150 kg m^{-2}, and therefore infiltrated more effectively than the August 2004 rains. In both 2004 and 2007, winter wheat was planted on 29 August into NTF at a depth of <5 cm (<60 kg m^{-2}) and adequate plant stands were achieved. At the time of seed-zone sampling, the 4× and 7× NTF residue treatments had greater surface water retention from the August rains than the 1× or TF treatments (Fig. 2). This is a visual case of the theory that surface residue exerts the greatest influence during the first stage of drying (Idso et al., 1974; Flury et al., 2009) by reducing the transfer rate of water vapor from the soil to the atmosphere.

Although significant August rains occurred 2 out of 6 yr in this study, long-term National Weather Service records for the WSU Dryland Research Station show that the likelihood of receiving a rain event of 12 mm or more from 10 to 31 Aug. is only 10%. In locations where substantial summer rain occurs, such as in the US Great Plains, NTF is likely to be successful most years. Similarly, NTF has proven to be highly successful in regions of the Inland Pacific Northwest that receive >380-mm annual precipitation.

We do not have an explanation for the greater recharge to a depth of 180 cm in the 7× residue treatment in 2008 (Fig. 4). This phenomenon occurred in the 7× seed-zone data as well (Fig. 2), and was consistent in all four replicates, indicating it was not a measurement outlier.

CONCLUSIONS

Even very large increases in surface residue in NTF over that normally available in the low precipitation, winter wheat-summer fallow production region of the Inland Pacific Northwest failed to result in seed-zone water contents comparable to TF. In three of the 6 yr, seed-zone water was far superior in a minimum tillage fallow. The 7× residue level on the surface of NTF improved seed-zone water substantially when averaged over 6 yr, but the 4× level produced only a slight average improvement. These results point to the need to further improve the sustainability of TF practices in regions with hot, dry summers where farmers rely on early establishment of winter wheat into carryover soil water in fallow for economic crop production. Promising results from research on delaying tillage in the spring and using non-inversion, low disturbance tillage provide hope for reducing soil erosion in areas where NTF has not yet proven attractive.

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