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Seven rainfed wheat rotation systems in a drought-prone Mediterranean climate

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ABSTRACT

Increasing cropping intensity and use of no-till fallow (NTF) has been successful in many rainfed Mediterranean agricultural regions around the world, including of the Inland US Pacific Northwest (PNW) where annual precipitation exceeds 290 mm. However, in the low-precipitation (<290 mm annual) region east-central Washington and north-central Oregon, these practices have not been widely adopted and a 2-year winter wheat (*Triticum aestivum* L.)-tilled summer fallow rotation is practiced by the vast majority of farmers. The objective here was to evaluate the productivity of seven wheat rotation systems that reduce or eliminate tillage and increase cropping intensity in a 6-year study at Lind, WA. The study included: (i) soft white, hard red, and hard white market classes of wheat; (ii) both NTF and undercutter conservation-tillage summer fallow (UTF), and; (iii) continuous annual no-till cropping of wheat. Crop-year (September 1–August 31) precipitation over the six years averaged just 217 mm. Across years, market class, and rotation system, spring wheat (SW) grain yield was only 33% of winter wheat (WW) after UTF. Thus, although only one crop was produced every other year with WW-UTF, this system had water use efficiency (WUE) of 5.5 grain/mm precipitation versus as low as 3.0 kg grain/mm precipitation for SW with no preceding fallow year. Possible mechanisms for differences in grain yield and WUE among rotations were: (i) Russian thistle (*Salsola tragus* L.) weed infestation was at least eleven times greater in the various SW systems and much greater still with WW after SW with no fallow year compared to in WW after NTF and UTF, and; (ii) precipitation storage efficiency (PSE) in the 180 cm soil profile during fallow for NTF-WW-SW was only 30% compared to 39 and 42% for the UTF-WW-SW and UTF-WW treatments, respectively. Critically, the seed zone of NTF was too dry for early planting of WW in most years whereas adequate seed-zone water was present every year in the UTF systems. Primarily due to late planting necessitated from lack of seed-zone water, grain yield of WW after NTF was reduced 35% compared to WW after UTF. Optimum grain yields and soil conservation are both required for sustainable agriculture, and WW with the UTF method was the clear winner of systems evaluated in this study.

1. Introduction

A major problem with tillage-based fallow in all semiarid regions of the world is soil erosion. In the drylands of the PNW, wind erosion is of particular concern because soils are generally weakly structured and subject to pulverization with tillage. Soils also contain high quantities PM-10-sized particulates that are easily suspended and carried long distances in the wind stream (Sharratt and Vaddella, 2012).

Wheat has always been the dominant crop throughout the Inland PNW as it can be grown over a range of climatic and soil conditions (McGregor, 1982). Pioneer farmers and scientists soon learned that growing wheat after a year of fallow (i.e., only one crop every other year) increased and stabilized grain yields as well as helped control weeds and diseases compared to “recrop” wheat that was planted without a preceding year of fallow (McCall and Holtz, 1921).

In the US Great Plains, where summer rain is frequent, there is general agreement that an equal or slightly greater quantity of water is stored in the soil during the 14 month fallow period with no-till fallow (NTF) compared to tillage-based fallow (Nielsen and Vigil, 2010). The opposite is the case during 13 month fallow period in the PNW where summers are dry (Hammel et al., 1981; Wuest and Schillinger, 2011; Schillinger and Young, 2014).

Abbreviations: HRSW, hard red spring wheat; HWSW, hard white spring wheat; NTF, no-till summer fallow; PNW, Pacific Northwest of the United States; SW, generic term for spring wheat; SWSW, soft white spring wheat; WW, soft white winter wheat; UTF, undercutter conservation tillage summer fallow.

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Winter wheat in the low-precipitation region of east-central Washington needs to be planted into carryover moisture in fallow in late summer to achieve optimum grain yield potential. Farmers till the soil in the spring of the fallow year to disrupt capillary pores and channels to retard evaporation of stored soil water to enable planting winter wheat into a moist seed zone in late August to early September (Wuest, 2010). With NTF, the seed zone generally dries to a deeper depth that mostly prevents timely planting of WW into stored fallow moisture (Hammel et al., 1981), in which case planting must be delayed until the arrival of fall rains in mid-October or later. Late planting of WW (i.e., mid-October or later) has, on average, reduced grain yield by 35% or more compared to early-planted WW in east-central Washington (Higginbotham et al., 2013).

Conservation tillage methods have been developed that better retain surface residue, soil clods, and surface roughness during fallow to reduce wind erosion compared to traditional tillage practices (Papendick, 2004), and these conservation methods are successfully practiced by many regional farmers (Young and Schillinger, 2012). Compared to traditional high-soil-disturbance primary spring tillage methods, the UTF method has proven equally effective in conserving seed-zone water, total-profile water, and achieving WW grain yield with the advantage of a significant increase in surface clods and residue retention (Schillinger, 2001) that reduce blowing dust emissions by 50% or more (Sharratt and Feng, 2009). 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 liquid fertilizer, all in one pass. The UTF method causes less soil disturbance and retains more surface residue than other tillage-based fallow methods so far tested and is considered a best management practice for conservation-tillage farming (Papendick, 2004). However, major blowing dust storms still occur (Sharratt and Lauer, 2006) and are most common in the <250 mm annual precipitation areas where grain and residue production is modest to low.

With technological advances in no-till farming, current performance may exceed what was observed previously and may provide opportunity for more intensive crop rotations. A focused effort was needed to reevaluate wheat production systems with the goal to increase cropping intensity using no-till and/or the practice of NTF. Optimism for the experiment was spurred by the advent of modern no-till drills with precise seed and fertilizer placement capability and new wheat cultivars better suited to withstand abiotic stress. Specific objectives of the study were to compare seven wheat rotation systems that differed in tillage, rotation sequence, cropping intensity, and cultivar market class. Soft white WW and soft white SW (SWSW) were grown in 2 and 3-year rotations using UTF and NTF methods and SWSW, HRSW (hard red), and HWSW (hard white) market classes of SW were grown continuously on an annual basis using no-till.

2. Materials and methods

2.1. Overview

A 6-year dryland cropping systems experiment was conducted from 2003 to 2008 at the Washington State University Dryland Research Station near Lind, Washington. Long-term (95-year) average annual precipitation at the site is 242 mm. Average pan evaporation from April through September is 1412 mm. Crop-year (September 1–August 31) precipitation during the study period ranged from 174 to 304 mm and averaged 217 mm; 90% of the long-term average (Table 1). Precipitation was measured at an official U.S. National Weather Service recording site located <50 m from the study. The soil is 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 "caliche" accumulation at a depth about 50 cm, but otherwise no restrictive layers or rocks within the 180 cm profile. Soil textural size distribution is 10% clay, 51% silt, and 39% fine sand. Shano soils, and closely-related soil series, are common throughout much of the low-precipitation farming region of east-central Washington and north-central Oregon.

Table 1
Crop-year (September 1–August 31) precipitation at Lind, Washington from 2003 to 2008 as well as 95-year average.

Month	2003	2004	2005	2006	2007	2008	95-year avg.
	(mm)						
September	1	7	15	8	2	4	13
October	2	7	15	27	8	17	21
November	21	17	17	29	63	28	32
December	52	52	27	43	45	30	33
January	69	26	17	85	10	41	28
February	18	33	1	19	31	6	22
March	18	8	22	12	17	21	22
April	29	15	9	20	13	5	19
May	5	15	24	37	8	3	20
June	0	7	10	25	14	12	21
July	0	0	9	0	4	0	8
August	1	18	6	0	13	7	8
Total	215	205	174	304	229	174	242

The experiment was discussed, designed, and approved as the "most promising" approach to test potential wheat monoculture rotations by a 16 member committee of regional farmers along with university and federal scientists in February 2001. The driving theme for the experiment was to test methods to increase cropping intensity (i.e., reduce the frequency of fallow) using both conservation-till and no-till practices for both crop and fallow years. Three market classes of wheat were included in the experiment because each class differs in optimum grain protein content and market price. The crop rotations chosen and implemented over the 6-year period were:

1. A 2-year rotation of winter wheat-undercutter tillage fallow (WW-UTF)
2. A 3-year rotation of WW-SWSW-UTF
3. A 3-year rotation of WW-SWSW-no-till fallow (NTF)
4. A 3-year no-till rotation of WW-SWSW-SWSW
5. Continuous annual no-till hard white spring wheat (HWSW)
6. Continuous annual no-till soft white spring wheat (SWSW)
7. Continuous annual no-till hard red spring wheat (HRSW).

The cultivars used were 'Eltan' WW, '377S' HWSW, 'Alpowa' SWSW, and 'Scarlet' HRSW. Certified seed for all cultivars was used every year and seed was treated with a fungicide as well as an insecticide for wireworm (*Agriotes lineatus*) control.

Experimental design was a randomized complete block with four replications of all treatment combinations. Each phase of all rotations was present every year for a total of 56 individual plots. Size of individual plots of crop rotation treatments that were exclusively no-till were 3 × 70 m, whereas those involving the UTF method were 10 × 70 m to accommodate undercutter and rodweeder tillage implements.

Annual no-till SWSW was grown on the entire experiment area for the five consecutive years prior to initiation of the experiment, except for 12 plots left in either NTF or UTF during 2002; i.e., the year before the start of the experiment. Throughout the 6-year experiment, glyphosate herbicide was applied in March to standing undisturbed stubble from the previous crop at a rate of 0.43 kg acid equivalent (ae)/ha to control weeds. Primary spring tillage plus 56 kg/ha aqua NH_3–N + 11 kg/ha thiosol S fertilizer injection was conducted with the undercutter implement at a depth of 13 cm in the fallow portion of the WW-UTF and WW-SW-UTF treatments in mid-April with a Haybuster™ undercutter. Phosphorus fertilizer was not applied to UTF as it is not compatible with either aqua or anhydrous forms on N that are used by essentially all farmers in the region. A 3 bar tine harrow was attached behind the undercutter to break up large soil clods and fill air voids.

The UTF treatments were rodweeded once or twice as needed during late spring and summer at a depth of 10 cm to control Russian thistle and other broadleaf weeds. Weeds in NTF were controlled with late-fall application of the soil-residual herbicide sulfentrazone and thereafter during the spring and summer as needed with glyphosate herbicide. Both UTF and NTF treatments were successfully kept nearly weed-free during fallow throughout the experiment.

2.2. Planting

With UTF, WW seed was planted 15–18 cm deep into carryover soil moisture at a rate of 45 kg/ha with a deep-furrow drill with 40 cm row spacing in late August–early September all years. Deep-furrow drills with row spacing of either 40 cm or 46 cm are standard throughout the region. This relatively wide row spacing is needed to move dry surface soil into furrow ridges to reduce the distance WW seedlings need to elongate for emergence. Such wide row spacing does not reduce grain yield potential compared to narrower spacing (Donaldson, 1996) because early-planted WW tillers well. Winter wheat emerged through an average of 11.5 cm of soil cover.

Due to lack of seed-zone moisture in NTF during most years, WW seed was "dusted in" to dry soil at a shallow 3 cm depth at a seeding rate of 55 kg/ha in mid-October prior to the arrival of fall rains. Thunderstorm rain of 13 mm and 12 mm on August 24–25, 2004 and August 19, 2007, respectively, wetted the surface of NTF to a depth of 10 cm and WW was planted into NTF at 45 kg/ha at a depth of 3 cm immediately after these rain events. A Cross-slot™ no-till disc drill on 20 cm row spacing was used during the first three years and Kile-opener™ no-till hoe drill with 10 cm paired rows on 30 cm row spacing was used in the final three years of the experiment for planting NTF. An average of 56 kg N, 9 kg P, and 11 kg S per hectare in Solution 32 was applied at time of planting below and to the side of seed (Cross-slot drill) or between and below the paired seed rows (Kile drill).

For recrop WW in the 3-year WW-SW-SW, the procedures for planting WW in mid-October were identical to those for planting WW into NTF as described above. The only exception was that fertilizer rate was reduced to an average of 45 kg N, 9 kg P, and 9 kg S per hectare. Required nitrogen for soft white WW was calculated as 4.0 kg N per 100 kg expected grain yield to achieve 10% grain protein (Koenig, 2005; Wysocki et al., 2005).

Spring wheat of all classes and in all treatment combinations was planted in early-to-mid March at a rate of 67 kg/ha with the Cross-slot and Kile-opener drills. Fertilizer rate was based on soil test residual soil fertility, available soil water, and perceived grain yield potential. Fertilizer applied at time of planting of SW averaged over the 6-years was 27 kg N, 6 kg P, and 6 kg S per hectare for SWSW and HWSW and 39 kg N, 6 kg P, and 6 kg S per hectare for HRSW. The optimum grain protein requirement for SWSW and HWSW was the same as for soft white WW (preceding paragraph), but nitrogen need for HRSW was calculated as 5.8 kg N per 100 kg expected grain yield to achieve 14% grain protein (Wysocki et al., 2005).

Wheat plant stand establishment was measured by counting individual plants in 1 m row segments in March for WW and in mid-to-late April for SW. Three row segments were assessed in each plot. Plants per unit area were then determined by accounting for row width differences in treatments planted with deep-furrow drill versus no-till drills.

2.3. In-crop and post-harvest weed control with herbicides

For WW in all treatment combinations, 2,4-D ester was applied in April at an average rate of 0.84 kg ae/ha. Farmers in the region use 2,4-D ester extensively for broadleaf weed control in WW due to its effectiveness and relatively low cost. In-crop broadleaf herbicide for all SW treatments was applied in May and herbicides used were: 2,4-D ester at a rate 0.46 kg ae/ha in 2003 and 2004; 2,4-D + 0.02 L active ingredient (ai)/ha thrifensulfuron + tribenuron in 2005, 2007; and dicamba at a rate of 0.8 kg ae/ha in 2008. In all four WW plots, sulfosulfuron grass-weed herbicides were used in November 2006 for in-crop control of downy brome (*Bromus tectorum* L.).

Post-harvest herbicide application for control of Russian thistle was never required after WW in the WW-UTF, WW-SW-UTF, and WW-SW-NTF, but was required in 2005, 2007, and 2008 following WW in the WW-SW-SW treatment. Post-harvest herbicide application for Russian thistle control was required every year following SW in all treatment combinations. Post-harvest herbicides and rates were either 0.90 kg ae/ha glyphosate or 0.42 kg ai/ha paraquat +0.21 kg ai/ha diuron.

2.4. Soil water

Soil water was measured to a depth of 180 cm three times each year: (i) in early August immediately after wheat grain harvest (44 plots); (ii) at the end of fallow in late August for UTF and NTF (12 plots); and in mid-March (all 56 plots). Volumetric soil water content in the 0–30 cm depth was determined from two 15 cm core samples with gravimetric procedures (Topp and Ferre, 2002) using known soil bulk density values. Soil volumetric water content in the 30–180 cm depth was measured in 15 cm increments by neutron thermalization (Hignett and Evett, 2002). Additionally, seed-zone volumetric water content was determined in late August in 2 cm increments to a depth of 26 cm with an incremental soil sampler in the UTF and NTF treatments.

2.5. Weeds

Weed species were identified, counted, and collected just before grain harvest in all treatments every year with a 3 m^2 sampling frame randomly placed in each plot. Each weed species present was counted, hand clipped at ground level, and placed in a separate paper bag. Above-ground dry biomass of each weed species was determined by placing samples in a low-humidity greenhouse for 30 days, then weighing on a digital scale.

2.6. Grain yield

Grain yield was determined in mid-to-late July in each 70 m long plot with a Hege™ 140 plot combine equipped with 1.5 m wide cutting platform. Grain in each plot was collected in a paper bag then weighed on a digital scale. The plot combine was equipped with a specially-designed blower to spread straw and chaff behind the machine. Uniform distribution of straw and chaff across the combine cutting width has long been understood as perquisite for successful no-till and conservation-till farming (Johnson, 1983; Allmaras et al., 1985). After grain harvest with the plot combine, the remaining standing grain in the experiment was harvested with a commercial-size combine equipped with a straw and chaff spreader.

2.7. Water use efficiency

Water use efficiency was determined after harvest of all crops in all rotations. Water use efficiency for rainfed wheat production (Sadras and Angus, 2006) is commonly and simply defined as grain yield divided by precipitation received since the previous harvest. For WW grown after a year of fallow, precipitation during both the fallow and the crop cycle must be included in the WUE calculation whereas only one year of precipitation is used for determining WUE for crops grown on an annual bases or for all SW combinations in this study that were produced without a preceding year of fallow.

2.8. Statistical analysis

Statistical analyses were conducted for soil water content, weed number, weed dry matter accumulation, and wheat grain yield using a randomized complete block design analysis of variance (ANOVA) for each year and a split-plot in time ANOVA across all six years with treatment as the fixed effect factor and year as the random effect factor. Tukey's honest significance difference test was used to detect statistical differences in treatment means and control the experiment-wise error rate for multiple comparisons. All ANOVA tests were done at the 5% level of significance.

3. Results

3.1. Soil water in entire soil profile during fallow

Averaged over years, soil water content in the top 90 cm as well as the entire 180 cm profile at time of harvest (i.e., at the beginning of fallow) was significantly less in the 2-year WW-UTF compared to after SW in the 3-year WW-SW-NFT or WW-SW-UTF treatments (Table 2), as WW extracts more water than SW. There were no soil water differences in the 0–90 or the entire 180 cm profile at time of harvest in any of the spring wheat treatment combinations (data not shown).

There were no soil water differences in the three fallow treatments in mid-March (Table 2). As a general rule, the drier the soil, the greater percentage of overwinter precipitation will be stored (McCall and Wanser, 1924), and this was the trend in this study although the quantity of overwinter soil water gain was not significantly different (Table 2).

By late-August, water content in the top 90 cm as well as the entire 180 cm profile was equal in the three fallow treatments. However, precipitation storage efficiency (PSE), the percentage of precipitation occurring during the fallow season that is stored in the soil, was significantly ($P < 0.001$) lower with NTF compared to the two UTF systems in the top 90 cm as well is in the entire 180-cm profile ($P < 0.03$) (Table 2). Almost all soil water loss from March to August occurred from the surface 90 cm. There was a slight water gain in the 90–180 cm profile from March to August in the two UTF treatments and a slight water loss from NTF (Table 2).

3.2. Seed-zone water content in UTF and NTF in late August

Seed-zone water content in 2 cm increments to a depth of 26 cm averaged over the six years is shown in Fig. 1. On August 24–25, 2004 and August 19, 2007, thunderstorm rain events of 13 and 12 mm, respectively, wetted the surface of NTF to a depth of 10 cm because the surface-soil capillary channels and pores had not been severed by tillage. In contrast, these rains only wetted the surface of UTF to 3 cm and this water soon evaporated. Seed-zone water contents for individual years in this study have been shown and discussed by Wuest and Schillinger (2011).

The 6-year average seed-zone water contents in Fig. 1 show a typical profile for late August after 13 months of fallow, being extremely dry in the top 8–10 cm and gradually becoming wetter with each depth increment. The surface 10 cm of NTF averaged over years was slightly, but significantly, less dry than in the UTF treatments because of the August rains in 2004 and 2007 as described in the previous paragraph. Below 12 cm there is a transition where water content below the depth of primary spring tillage in the UTF systems trends greater than with NTF (Fig. 1). Such seed-zone water profiles in late August between tilled and no-till fallow have been reported from several sites over numerous decades in the low-precipitation Inland PNW (McCall and Wanser, 1924; Hammel et al., 1981; Wuest, 2010; Schillinger and Young, 2014). Due to less than average precipitation in five of six years, soil water content below 18 cm remained static or declined slightly with depth (Fig. 1), whereas in an "average" year (i.e., 242 mm annual precipitation) water content immediately below seed placement tends to increase with depth and is an important water source for emerging WW seedlings (Donaldson, 1996).

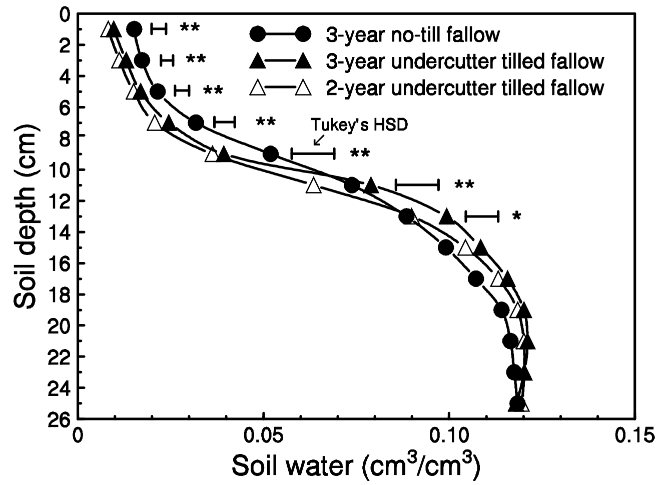

Fig. 1. Seed-zone water content in 2 cm increments to a depth of 26 cm at the end of the fallow cycle in late August in three fallow-based wheat- production systems. Data are the average over the 6-year experiment. HSD = Tukey's honest significance difference. * and ** significantly different at the 0.05 and 0.01 probability levels, respectively.

3.3. Wheat seedling establishment

A minimum of water potential of $-500\,kP_a$ ($10.5\,cm^3/cm^3$) is required to reasonably expect adequate stands in a Shano soil when winter wheat seedlings must emerge through thick soil cover (Lindstrom et al., 1976). Averaged over years, this minimum water potential requirement was achieved at a depth of 16 cm in the UTF treatments and at 18 cm depth in NTF (Fig. 1).

Satisfactory stands of WW (average 64 plants/m^2) were achieved in all six years from deep-furrow planting at a depth of 15–18 cm in late August into both UTF systems despite the fact that fallow-year precipitation was appreciably less than the long-term average in five of the six years. This illustrates the resiliency of the tilled fallow method and the reason why it has long been the standard practice of farmers in this region. Deep planting into NTF was not feasible in any year because: (i) minimum water content for WW seedling emergence was located deeper in the soil profile than with UTF; and (ii) dry, crumbly soil aggregates in NTF drop immediately behind the seed opener covering the seed with "BB" sized soil particles that are not as effective for retaining seed-zone moisture compared to the more finely divided soil aggregates that generally cover the seed with UTF.

Winter wheat was planted in NTF at a shallow 3 cm depth in late August of 2004 and 2007, one day after the August rain events

Table 2
Soil water content at the beginning (after wheat harvest), early spring, and end of fallow (before planting winter wheat) and associated gain or loss of water and precipitation storage efficiency (PSE) in undercutter-tillage fallow (UTF) and no-till fallow (NTF) systems averaged over six years. The upper portion of table shows water in the top 90 cm of soil and the bottom portion shows water in the entire 180 cm soil profile. ns = no significant differences.

	Timing in fallow period					
	Beginning (late August) Soil water content (mm)	Spring (mid March)	Over-winter gain	End (late August)	March– August water loss	PSE† (%)
	A. Top 90 cm of soil profile					
Treatment						
No-till fallow (NTF-WW-SW)	64 a	144	80	108	36	19 b
Tilled fallow (UTF-WW-SW)	60 a	148	88	114	34	24 a
Tilled fallow (UTF-WW)	50 b	139	89	109	30	26 a
P-value	0.002	ns	ns	ns	ns	0.001
	B. Complete 180 cm soil profile					
Treatment						
No-till fallow (NTF-WW-SW)	163 a	272	109	232	40 a	30 b
Tilled fallow (UTF-WW-SW)	155 ab	274	118	243	30 b	39 a
Tilled fallow (UTF-WW)	140 b	259	119	234	25 b	42 a
P-value	0.02	ns	ns	ns	0.04	0.03

† PSE = precipitation storage efficiency. The percentage of precipitation occurring from September 1–August 31 that was stored in the soil during fallow.

that occurred in these years as described in the previous section. Excellent WW stands in NTF (average 97 plants/m^2) were achieved in both of these years. However, since there was a dry layer below the depth of water infiltration from the August rain events, movement of soil water from lower depths did not occur. When the WW seedlings in NTF reached the 2–3 leaf stage in mid-September, they turned white and appeared dead as all available water from the August rain had evaporated or been used for plant transpiration needs. However, when fall rains began in mid-to late-October the plants again commenced growth.

Excellent stands (average 103 plants/m^2) of late-planted WW in NTF (i.e., all years except 2004 and 2007) were consistently achieved as seed placed 3 cm below the soil surface readily emerged after the onset of fall rains. Similarly, full stands (average 104 plants/m^2) of recrop WW in the WW-SW-SW rotation were always obtained, although plants tended to grow more slowly in late fall and early spring compared to WW after NTF, presumably due to differences in soil water content.

Excellent SW stands (average 112 plants/m^2) were always obtained in all SW treatment combinations as surface soils were relatively wet in March and seed was placed at a shallow 3 cm depth. There were never any differences in plant stand establishment among the various SW treatment combinations.

3.4. Weeds

The most problematic weeds in the study were Russian thistle and downy brome. Other, relatively minor, weeds were prickly lettuce (*Lactuca serriola* L.), horseweed (*Conyza canadensis* L.), tumble mustard (*Sisymbrium altissimum* L.), tansy mustard (*Descurainia pinnata* Walt.), netseed lambsquarters (*Chenopodium berlandieri* Moq.) and western yarrow (*Achillea lanulosa* Nutt.).

3.4.1. Russian thistle

There were no differences in Russian thistle density or dry biomass production in WW in the WW-UTF, WW-SW-UTF, and WW-SW-NTF rotations (Table 3). However, there was a minimum 18-fold increase in Russian thistle density in WW in the WW-SW-SW rotation (9.1 plants/m^2) compared to WW after any of the three fallow treatments (Table 3). Russian thistle in WW in the WW-SW-SW rotation was most problematic during the five years of drought. In 2006, when precipitation was 26% greater than the long-term average at Lind (Table 1), there was essentially no infestation (data not shown). Recrop WW is completely reliant on the onset of fall rains in mid-October to late-November for germination and emergence. WW seedlings were in the 0–2.5-leaf stage going into winter and growth was slow thereafter. Average Russian thistle biomass production of WW in the WW-SW-SW rotation was significantly greater than in any other treatment combination (Table 3). Although WW after NTF was also "dusted in" on the same date as recrop WW in four of six years, it had a reserve of stored soil water that apparently enabled plants to go into winter dormancy with bigger size compared to recrop WW and these plants grew more rapidly in the spring, allowing much more effective competition against Russian thistle. At time of grain harvest, average Russian thistle population in SW ranged from 1.8 to 7.6 plants/m^2, being lowest in the WW-SW-NTF and with no difference among the other SW treatments (Table 3).

3.4.2. Downy brome

Downy brome is a winter annual grass weed with a growth cycle that mimics WW; thus it is of particular problem for WW. Early-planted and well-established WW stands are much more competitive against downy brome than late-planted WW (Blackshaw, 1994).

Although a fall in-crop application sulfosulfuron grass weed herbicide was applied to WW (all four WW treatment combinations) in one year only, downy brome pressure was, overall, fairly modest. However, in 2006, the one year with above-average precipitation, downy brome population in WW was particularly heavy in the WW-SW-SW treatment, and to a somewhat lesser extent in WW-SW-NTF, possibly due to smaller and less competitive wheat plants (Stahlman and Miller, 1990) compared to WW in the two UTF-based treatments. The 6-year average downy brome population and dry biomass data also show this trend (Table 3).

Glyphosate herbicide was applied in late winter to effectively control downy brome prior to planting of all SW treatments, and there was essentially no downy brome present in any of the three continuous annual SW treatments (Table 3). Spring wheat following WW in the WW-SW-SW rotation tended to have more downy brome than any other SW treatment (Table 3); this likely a reflec-

Table 3
Average population and dry biomass of Russian thistle and downy brome as well as total weeds measured in wheat immediately prior to wheat harvest during six years as affected by seven crop rotations.

	Russian thistle	Downy brome	Total weeds[a]
Rotation	Population (plants/m^2)		
1. Two-year rotation			
Winter wheat (after UTF)	0.5	1.7	2.3
2. Three-year rotation I			
Winter wheat (after UTF)	0.2	1.8	2.2
Soft white spring wheat	5.8	0.4	6.2
3. Three-year rotation II			
Soft white spring wheat	1.8	0.6	2.5
4. Three-year rotation III			
Winter wheat	9.1	4.9	14.6
Soft white spring wheat	6.5	2.2	8.0
5. Annual hard white spring wheat	5.7	0.2	6.4
6. Annual soft white spring wheat	7.2	0.1	7.3
7. Annual hard red spring wheat	7.6	0.1	8.3
Tukey's HSD (0.05)	3.7	3.0	4.4
	Dry biomass (kg/ha)		
1. Two-year rotation			
Winter wheat (after UTF)	18	37	56
2. Three-year rotation I			
Winter wheat (after UTF)	13	44	57
Soft white spring wheat	105	4	113
3. Three-year rotation II			
Winter wheat (after NTF)	10	65	77
Soft white spring wheat	106	7	80
4. Three-year rotation III			
Winter wheat	204	162	364
Soft white spring wheat	76	29	100
Soft white spring wheat	104	6	111
5. Annual hard white spring wheat	90	4	94
6. Annual soft white spring wheat	108	3	122
7. Annual hard red spring wheat	101	1	111
Tukey's HSD (0.05)	63	102	113

[a] Total weeds also includes prickly lettuce, horseweed, tumble mustard, tansy mustard, Netseed lambsquarters, and Western yarrow.

tion of the relatively high incidence (and seed production) of downy brome during the WW portion of this rotation.

3.5. Grain yield

The ANOVA for grain yield showed highly significant differences ($P < 0{,}001$) among treatments. Differences among years was also highly significant ($P < 0.001$), explained by the wide range of precipitation (174–304 mm) that occurred during the six years (Table 1). The variability in precipitation among years can also explain the highly significant ($P < 0.001$) treatment × year interaction since recrop SW and recrop WW were proportionately more responsive to precipitation fluctuations compared to early-planted WW (Table 4). With five of six years having less than average precipitation, the above-average precipitation in the 2006 crop year resulted in the following grain yield increases over the average for the five drought years: 209% averaged over all recrop SW treatments, 175% for recrop WW, 59% for WW after NFT, and 25% for WW in the two early-planted WW after UTF treatments.

By far the greatest WW grain yield was achieved in the WW-UTF and WW-SW-UTF rotations which averaged 2390 and 2327 kg/ha, respectively over the six years. Average WW grain yield in the WW-SW-NTF rotation was significantly reduced at 1548 kg/ha, or about 35% less than the average yield of the two UTF systems (Table 4). Higginbotham et al. (2013) grew 21 WW cultivars in a 3-year experiment conducted both at Lind and nearby Ritzville, WA and reported an average 39% reduction in grain yield for late-planted WW in NTF compared to early-planted WW in UTF.

Winter wheat in WW-SW-NTF that was planted early following the thunderstorm rain events in mid-August of 2004 and 2007 (i.e., 2005 and 2008 crop years) tended to fare better than that "dusted in" in mid-October in the other four years. The greatest WW grain yield in WW-SW-NTF occurred in 2006 when ample rain in mid-October 2005 allowed for earlier plant stand establishment than normal combined with this being the one crop year of the study with above-average precipitation.

Grain yield of recrop WW in the WW-SW-SW rotation averaged just 863 kg/ha (Table 4). Small plant size going into winter dormancy, slow plant growth in the spring, water stress, and heavy Russian thistle and downy brome pressure all likely contributed to low grain yield. These same problems with the performance of recrop WW in the region were reported by Schillinger et al. (2007).

Average SW grain yield in all rotation combinations ranged from 641 to 898 kg/ha (Table 4). There were no significant differences among SW grain yields within any year or when averaged over the six years (Table 4). Spring wheat in all rotations responded favorably in the relatively wet 2006 crop year, which included greater than average precipitation during the critical months of May and June (Tables 1 and 4).

3.6. Water use efficiency

Winter wheat produced in the WW-UTF and WW-SW-UTF rotations had 6-year average WUE of 5.5 and 5.3 (kg grain/mm precipitation), respectively; these being significantly greater than for both WW and SW in any other rotation sequence (Table 4). Winter wheat in the WW-SW-NTF rotation had a WUE of only 3.6.

The lowest WUE of 3.0 was in first year SW in the WW-SW-SW rotation (Table 4); this likely a reflection of high weed pressure in the preceding WW crop that carried over to the next year's SW (Table 3). There were no other significant differences in WUE among

Table 4
Grain yield of winter wheat and spring wheat in seven rotation systems during six years and averaged over years as well as average water use efficiency (WUE) for each rotation system. Crop-year (September 1–August 31) precipitation for each year as well as the 6-year average are shown at the bottom of the table.

	Year							
	2003	2004	2005	2006	2007	2008	6-year avg.	Avg. WUE
Rotation	Grain yield (kg/ha)							(kg/mm)
1. Two-year rotation								
Winter wheat (after UTF)	1973	2760	2297	2784	2882	1644	2390	5.5
2. Three-year rotation I								
Winter wheat (after UTF)	2008	2738	2016	2884	2367	1950	2327	5.3
Soft white spring wheat	723	841	454	2096	675	520	885	4.1
3. Three-year rotation II								
Winter wheat (after NTF)	1619	1043	1608	2242	990	1791	1548	3.6
Soft white spring wheat	748	783	639	2026	625	567	898	4.2
4. Three-year rotation III								
Winter wheat	1096	757	517	1835	697	274	863	4.0
Soft white spring wheat	689	595	221	1647	494	199	641	3.0
Soft white spring wheat	666	585	426	1729	797	449	775	3.6
5. Annual hard white spring wheat	984	834	286	1783	599	297	797	3.7
6. Annual soft white spring wheat	568	516	366	1751	784	398	730	3.4
7. Annual hard red spring wheat	787	706	313	1787	717	368	780	3.6
Tukey's HSD (0.05)	622	534	368	729	436	450	263	1.0
	Crop-year precipitation (mm)							
	215	205	174	304	229	174	217	

the other SW combinations although this value did trend somewhat higher for SW in WW-SW-UTF and WW-SW-NTF (Table 4).

4. Discussion

4.1. Soil water

Drying of the seed zone (i.e., surface 0–26 cm) with NTF during the dry summer months has been reported in several Inland PNW studies (Hammel et al., 1981; Schillinger and Young, 2014). Until recently, this drying phenomenon was thought to occur primarily in the seed zone and not in the lower soil profile. However, a recent long-term study at two locations in the Horse Heaven Hills area of SE Washington, the world's driest rainfed wheat region, showed significantly greater soil drying to a depth of 105 cm in NTF versus UTF (Schillinger and Young, 2014). The soil water loss data from March to August and corresponding PSE values show a similar trend in this study (Table 2). Both the Horse Heaven Hills and Lind sites have a relatively high abundance (>33%) of sand.

At other PNW sites that receive more annual precipitation and where soils have a finer texture with less sand (Ritzville, WA, Moro, OR, and Pendleton, OR), soil profile water at the end of NTF has been either equal to (Schillinger et al., unpublished; Machado et al., 2015) or even slightly greater (Williams et al., 2015) than that of tilled fallow. Additionally, Schillinger and Young (2014) reported that WW-NTF was a best management practice in the driest (i.e., 150–200 mm annual precipitation) portion of the Horse Heaven Hills as it was equally profitable as WW-tilled fallow because storing adequate seed-zone water for early WW establishment was generally not possible even with tilled fallow.

In this study, late-August planting of WW into NTF was possible in two years when 12 and 13 mm of rain occurred in thunder storms in mid-to-late August. Based on long-term (95-year) weather records, the likelihood of receiving 12 mm or more rain within a 3 day period in the second half of August at Lind is 9%. A late-August rain event of 12 mm will wet the surface of NTF to a depth of about 10 cm. To be truly effective, the wetting front needs to extend to a depth of ≥14 cm until it reaches the stored moisture line below, otherwise this moisture will soon evaporate stranding new established WW seedlings in dry soil. At least 20 mm of late-summer rain is generally required to "wet through" the dry surface of NTF to stored water below. The historic likelihood of receiving 20 mm or more rain within any 3 day period from August 15–September 15 at Lind is 7%.

4.2. Russian thistle

Russian thistle has long been the most problematic broadleaf weed infesting wheat in the Inland PNW drylands (Young, 1988). Russian thistle is a spring annual, therefore it is most troublesome in SW. Well-established WW will generally compete fairly effectively against this weed.

It is not clear why Russian thistle population in SW was less than in WW-SW-NTF than in WW-SW-UTF other than tillage with UTF possibly enabled greater populations due to Russian thistle seed burial during tillage. Although the in-crop application of broadleaf weed herbicide in May was generally effective, repeated flushes of Russian thistle germinate and emerge with as little as 2 mm of rain (Young, 1988). Russian thistle has a C4 photosynthetic pathway with fast growth, aggressive soil water use, and prolific seed production. In fact, the most rapid growth of Russian thistle occurs after wheat harvest where, if not controlled post-harvest with either herbicides or undercut tillage, will produce prolific quantities of seed and extract soil water to much lower water potentials than capable by wheat (Schillinger and Young, 2000).

4.3. Grain yield of spring wheat

Recrop SW generally must produce at least 65% of the grain yield of WW after fallow to be economically viable because of higher input costs associated with increased cropping intensity (Juergens et al., 2004; Schillinger et al., 2007). Although an economic analysis was not conducted for this study, the various SW treatment combinations averaged only 27–38% of WW-UTF yields and were clearly not economically competitive (D.L. Young, personal communication, 2015).

Spring wheat can be profitably produced in a 3-year WW-SW-fallow rotation in the 350–450 mm annual precipitation region of the PNW where it is the standard rotation practiced by most farmers. Recrop SW can also be profitable in some wetter years in areas of the PNW that receive as little as 290 mm average precipitation, but averaged over both wet and dry years it is not as profitable or stable as early-planted WW after fallow (Juergens et al., 2004; Schillinger et al., 2007; Young et al., 2015).

5. Summary and conclusion

The objective of this study was to provide science-based information to wheat farmers and government farm-support agencies on the feasibility of increasing cropping intensity using no-till planting and/or the practice of NTF in a region of east-central Washington where tillage-based WW-fallow is the norm and blowing dust emissions from excessively-tilled fallow fields is a major environmental concern. Spring wheat grain yield in the various rotations sequences ranged from 27 to 38% of that of WW-UTF averaged over the six years. Winter wheat grain yield in the WW-SW-NTF and WW-SW-SW rotations averaged 65 and 36%, respectively, of that of WW-UTF. There was no difference in average WW grain yield in the WW-UTF and WW-SW-UTF treatments.

No-till fallow is successfully practiced by several farmers in areas of the PNW with annual average precipitation as low as 290 mm. In addition, many wheat farmers in the <200 mm annual precipitation zone of the region have successfully adopted NTF because adequate seed-zone water cannot generally be stored through the summer regardless of tillage practice. These NTF practices undeniably provide excellent control against wind erosion and benefit soil quality. Indeed, farm profit and soil conservation must both be achieved for a system to be sustainable. For the 200–290 mm annual precipitation zone of the Inland PNW, which covers approximately 1.3 million cropland hectares, the minimum soil disturbance undercutter method of WW-fallow farming offers unsurpassed year-to-year stability and economic viability and is a best management practice for farmers and the environment in this zone.

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