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Best Management Practices for Summer Fallow in the World's Driest Rainfed Wheat Region

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The Horse Heaven Hills (HHH) located in south-central Washington contains the world's driest rainfed wheat (*Triticum aestivum* L.) production region, where farms receive as little as 150 mm average annual precipitation. Late summer establishment of winter wheat into carryover seed-zone water after a year of fallow is essential to achieve the highest grain yield potential. Tillage of fallow land during the spring is considered necessary to retain adequate seed-zone water during the dry summer months, but blowing dust from excessively tilled fallow is a major safety, environmental, and soil-quality concern. We compared three fallow management systems for soil water dynamics, wheat stand establishment, grain yield, and economic returns on two farms over 5 yr in western and eastern portions of the HHH where long-term annual precipitation averages 153 and 211 mm, respectively. Treatments were: (i) traditional tillage (TTF), undercutter conservation tillage (UTF), and no-till (NTF). Late-summer planting of winter wheat in TTF and UTF was possible in only 1 of 5 yr at the western site due to lack of adequate seed-zone water, whereas late-summer planting was possible every year at the eastern site. There were no significant differences in net economic returns among fallow management treatments at the western site; however, net returns per hectare averaged a positive US$101 for TTF and UFT vs. a negative US$92 for NTF at the eastern site. Although seed-zone water in late summer was consistently lowest with NTF at both sites, we recommend NTF in the western HHH because achieving adequate seed-zone water for early wheat establishment is generally not possible with any fallow management practice and NTF is economically viable and excellent for wind erosion control. On the other hand, in the eastern HHH, where adequate seed-zone water for early planting can be achieved with tillage most years, farmers should practice UTF. This study documented that NTF in the western HHH and UTF in the eastern HHH are best management practices for farmers and the environment in a region where wind erosion from excessively tilled soils is a severe problem.

Abbreviations: HHH, Horse Heaven Hills; HRW, hard red winter wheat; NTF, no-till fallow; TTF, traditional tillage fallow; UTF, undercutter conservation tillage fallow.

Wheat has been produced on 120,000 rainfed ha in the Horse Heaven Hills (HHH) region in south-central Washington since the land was broken out of native bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve] intermixed with big sagebrush (*Artemisia tridentata* Nutt.) by pioneer farmers in the early 1880s. The western portion of the HHH receives as little as 150 mm average annual precipitation. An annual average of 210 mm of precipitation falls in the eastern portion. Two-thirds of the precipitation occurs from October to March, and summers are warm and dry. Farmers practice a 2-yr tillage-based winter wheat–summer fallow rotation, where one crop is grown every other year on a particular field. Given the low precipitation, wheat grain and straw production are generally modest to low (Papendick, 2004).

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Soils in the HHH are highly vulnerable to wind erosion due to the dry environment, high winds, limited straw cover, and intensive tillage during fallow. These soils contain high quantities of particulate matter ≤10-μm diameter (PM10) that, when exposed, are readily transmitted hundreds of kilometers in the airstream by suspension (Sharratt et al., 2007). Major dust storms may occur several times a year (Sharratt and Edgar, 2011). In addition to displacing soil, dust storms close roads and highways due to limited to zero visibility and impair human health (World Health Organization, 2005). Exceedances of the U.S. Federal Air Quality Standard for PM10 (150 μg m^{-3} in 24 h) occurred 20 times between 2000 and 2010 in the city of Kennewick, WA, which is located immediately downwind of the HHH (Sharratt and Edgar, 2011). The highest daily PM10 concentration measured in Kennewick during this time period was 1438 μg m^{-3}, nearly 10 times the concentration allowed by law. All of these PM10 exceedances were attributed to windblown dust. Dust emissions on pulverized and exposed soils in the HHH measured by B.S. Sharratt (unpublished data, 2014) were the equivalent of 38 Mg ha^{-1} in just a 10-min period with a sustained 15 m s^{-1} wind generated in a wind tunnel.

No-till fallow (NTF) for control of erosion is successfully used in many regions of the world but is not yet widely practiced in the low-precipitation winter wheat–summer fallow zone in the Pacific Northwest because of seed-zone drying during the summer. Instead, farmers till the soil during the spring of the fallow year to break soil capillary continuity to best retain seed-zone water (Hammel et al., 1981; Wuest, 2010) and plant winter wheat in late August to early September for the highest potential grain yield. Farmers and scientists have long had interest in the feasibility of continuous annual (i.e., no fallow year) no-till cropping of spring wheat and other potential crops in this dry region. A long-term experiment conducted in the western HHH to test this concept showed that, although production of continuous annual no-till spring wheat provided clear environmental advantages, it was not economically competitive with the tillage-based winter wheat–summer fallow system (Schillinger and Young, 2004).

Undercutter tillage fallow (UTF), where narrow-pitched, 80-cm-wide V-shaped sweep blades are used to slice beneath the soil surface to sever capillary pores with minimum soil lifting, has shown excellent agronomic potential (Papendick, 2004) and has been proven to significantly reduce blowing dust emissions compared with traditional tillage fallow (TTF) (Sharratt and Feng, 2009a, 2009b). The objective of this study was to compare the effects of three fallow management systems on soil water dynamics, wheat stand establishment, grain yield, and economic returns.

MATERIALS AND METHODS

Overview

A 5-yr summer fallow management field experiment was conducted from 2006 to 2011 at each of two locations in the HHH, denoted as the western and eastern sites. A 2-yr winter wheat–summer fallow rotation, where only one crop is grown every other year on a given field, is the standard farming practice throughout the region.

Long-term average annual precipitation is 153 and 211 mm at the western and eastern sites, respectively. Pan evaporation (March–November) averages 1010 mm. Precipitation during the study period for the two sites was recorded at two meteorological stations of the Washington State University Agricultural Weather Network (http:/weather.wsu.edu/awn.php). Station McKinley Spring is located 1.0 km north of the western site (45°59′ N, 119°51′ W, 240 m asl) and Station Carlson is located 0.7 km northeast of the eastern site (46°8′ N, 119°28′ W, 440 m asl). Annual crop-year (1 September–31 August) precipitation during the study period ranged from 134 to 207 mm and averaged 164 mm at the western site (Table 1). At the eastern site, crop-year precipitation during the study ranged from 168 to 252 mm and averaged 217 mm (Table 1). The distance between the two sites is 30 km.

The 2-yr winter wheat–summer fallow rotation has been practiced almost exclusively at the two study sites, and indeed throughout the HHH region, for >125 yr. Due to relatively low grain yield potential, farmers are generally conservative in their use of fertilizer and other inputs. Average individual farm size in the HHH is 2500 ha, with some farms in the drier western HHH as large as 7000 ha.

Soils

Soil at the western site is a Warden silt loam (a coarse-silty mixed, superactive, mesic Xeric Haplocambid). Textural classification of the A horizon (i.e., 0–15 cm) is 500, 320, and 180 g kg^{-1} sand, silt, and clay, respectively (Singh et al., 2011). The pH is 7.0, and the organic matter content is 6.3 g kg^{-1}. These Warden soils have a mantel of loess over lacustrine sediments that were deposited by soil sediments suspended in water during the massive, cataclysmic outburst floods that occurred during the last ice age about 15,000 yr ago following the sudden rupture of the ice dam that contained Glacial Lake Missoula (Rasmussen, 1971; Sweeney et al., 2005). Soil at the eastern site is a Ritzville silt loam (a coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll). The A horizon consists of 560, 310, and 130 g kg^{-1} sand, silt, and clay, respectively (Singh et al., 2011). The pH is 6.0, and the organic matter content is 9.0 g kg^{-1}. Ritzville soils were formed in loess. Both sites are characterized by a slope of <2% and soil depth of >180 cm. There is a thin, weak layer of $CaCO_3$ (i.e., caliche) accumulation located about 50 cm below the soil surface, but otherwise no rocks or impermeable layers are present within the 180-cm profile at either site.

Establishment of Tillage Treatments

Traditional tillage fallow, UTF, and NTF treatments were established from 2006 through 2010 at both the western and eastern sites. Different parcels of land were used each year, but the location of experiment plots were kept within a 3-km radius during the 5 yr at both sites to reduce within-site soil variability. The experimental design was a randomized complete block

Table 1. Crop-year (1 September–31 August) precipitation at two experimental sites from 2005 to 2011 in the Horse Heaven Hills, Washington. The 2006 data are shown because this was the fallow year (i.e., 1 Sept. 2005–31 Aug. 2006) before planting wheat in the first year of the experiment. The 5-yr average crop-year precipitation was 164 mm at the western site and 217 mm at the eastern site.

Month	Western site						Eastern site					
	2006	2007	2008	2009	2010	2011	2006	2007	2008	2009	2010	2011
	mm											
Sept.	18	17	4	5	1	34	20	13	11	3	3	27
Oct.	4	21	7	5	22	20	12	13	16	5	26	22
Nov.	8	28	12	17	5	14	17	46	20	24	10	32
Dec.	66	19	45	17	10	47	61	45	31	23	10	50
Jan.	41	4	26	29	38	22	47	21	38	26	47	13
Feb.	9	18	10	24	15	6	11	19	17	27	18	8
Mar.	13	5	10	11	6	27	17	26	12	25	7	35
Apr.	20	9	1	8	10	8	42	11	5	7	19	14
May	28	4	6	15	51	21	33	10	10	23	50	46
June	31	20	11	6	24	7	29	29	20	5	43	7
July	1	0	0	0	3	1	0	1	0	1	5	0
Aug.	1	7	2	1	4	0	0	3	5	0	3	0
Total	240	153	134	137	189	207	289	237	186	168	240	252

with four replications. Individual plot size was 61 by 18 m to accommodate the use of commercial-size farm equipment. The cooperating farmers were paid an annual fee to conduct all field operations, except grain harvest, with their equipment in accordance to the study's protocols. Wheat residue was always left standing and undisturbed from harvest in July through the winter. For all treatments, glyphosate [*N*-(phosphonomethyl) glycine] herbicide was applied in March or early April at rates that averaged 0.33 acid equivalent (a.e.) ha^{-1} at the western site and 0.51 a.e. ha^{-1} at the eastern site.

In the TTF treatment, the soil was tilled with a tandem disk to a depth of 13 cm in April. A 5-yr average of 16 kg ha^{-1} aqua NH_3–N (NH_4OH in H_2O) at the western site and 54 kg ha^{-1} of aqua NH_3–N at the eastern site was injected into the soil with shanks spaced 30 cm apart in May or June.

For UTF, an undercutter sweep implement equipped with overlapping 80-cm-wide V blades on two ranks was used to slice beneath the soil at a depth of 13 cm and simultaneously deliver aqua NH_3–N fertilizer with minimum soil lifting or disturbance of surface residue. Application rates of aqua NH_3–N for UTF were identical to those for TTF as described above. The soil was subsequently rod-weeded an average of two times at both locations for both TTF and UTF at a depth of 10 cm in June and again in July or August to control Russian thistle (*Salsola kali* L.) and other broadleaf weeds.

The stubble remained standing and the soil undisturbed throughout the 13-mo fallow period in the NTF treatment. Weeds in NTF were controlled with two to four herbicide applications from March to August. Herbicides used were glyphosate or tank mixtures of glyphosate + dicamba (3,6-dichloro-2-methoxybenzoic acid) or paraquat (1,1′-dimethyl-4,4′-bipyridinium) + diuron [*N*′-(3,4-dichlorophenyl)-*N*,*N*-dimethylurea]. A 5-yr average of 21 kg ha^{-1} of anhydrous NH_3–N at the western site and 46 kg ha^{-1} N as Solution 32 (NH_4NO_3 + urea) at the eastern site was applied at the time of planting with the drill in the NTF treatment. Thus, the fertilizer application rate among the three treatments was approximately the same.

Planting

The hard red winter wheat (HRW) cultivars Finley and Bauermeister were selected for use by both cooperating farmers. The same cultivar was used for planting of all three fallow management treatments within a given site and year. The seeding rate for early planting in the TTF and UTF treatments at the western site (only possible in 2006; conducted on 6 September) was 22 kg ha^{-1}. Early planting of HRW (dates ranged 26 August–7 September) was possible all 5 yr for TTF and UTF at the eastern site, and the average seeding rate was 32 kg ha^{-1}. A crusting rain occurred soon after early planting but before HRW seedling emergence in late August 2009, resulting in spotty stand establishment, and the TTF and UTF were replanted at 67 kg ha^{-1} after the onset of fall rains on 16 November. Early planting at both sites was conducted with an International Harvester 150 deep-furrow drill with 46-cm row spacing. This drill is used by every dryland wheat farmer in the HHH region for early planting into tilled summer fallow because it is capable of placing the wheat seed >20 cm below the soil surface to reach seed-zone water.

For NTF, seed at the western site was "dusted in" at a shallow (2-cm) depth in the first half of October before the onset of fall rains at an average seeding rate of 46 kg ha^{-1}. A Flexi-Coil 6000 no-till double-disk drill on 19-cm row spacing was used in the first 2 yr, and a John Deere 1835 no-till hoe-opener drill on 25-cm row spacing was used in the third to fifth years. As noted above, early planting of the TTF and UTF treatments was only possible during the first year of the experiment. Thereafter, in the remaining 4 yr, planting for TTF and UTF took place on the same date as for NTF. The International Harvester 150 deep-furrow drill with 46-cm row spacing was used for late planting of TTF and UTF because the deep, loose tillage mulch in these treatments rendered them unsuitable for planting with a no-till drill (i.e., no-till drills are not designed for this planting environment).

At the eastern site, planting of NTF was conducted at a depth of 2 cm in the first half of November, generally after the onset of fall rains, at an average seeding rate of 67 kg ha^{-1}. A Great Plains 3010 no-till disk drill on 25-cm row spacing was used in all 5 yr.

Field Measurements

In late March and again in late August during fallow from 2006 to 2010, soil volumetric water content in the 30- to 180-cm depth was measured in 15-cm increments by neutron thermalization (Hignett and Evett, 2002). Volumetric soil water content in the 0- to 30-cm depth was determined from two 15-cm core samples using gravimetric procedures (Topp and Ferré, 2002) and known soil bulk density values. Because the treatments at both sites were always established on a different parcel of land each year, the late-March soil water baseline measurements were collected at six representative locations within each 1.76-ha site before initiation of the experiment and the values then averaged. The late-August total-profile soil water measurements were obtained in each of the 12 plots. 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 for all plots at both sites.

Wheat plant stand establishment was assessed by counting individual plants in 1-m row segments in March. Three row segments were measured in each plot and the values then averaged. Grain yield was determined in mid-July each year from 2007 to 2011 by harvesting a swath through each 61-m-long plot with a Hege 140 plot combine with a 1.5-m-wide cutting platform. Harvested grain from each swath was collected in a sack and then weighed on a digital scale.

Economic Assessment

Enterprise budgets (University of Idaho, 2013, Crop enterprise budget worksheet [CEBW] and machinery cost worksheet [MACHCOST]) were constructed to assess the profitability and cost of the three fallow systems at both sites. Costs are based on the actual sequence of operations and machinery utilized by the cooperating farmers annually for each system on the two sites. Fertilizer and herbicide types and rates along with seeding rates were those used during each of the 5 yr for each site and system. The cooperating farmers carefully gauged both their machinery operations and input applications to the different conditions, and some costs differed between the two sites. For example, property taxes at the western site were US\$2.79 ha^{-1} yr^{-1} compared with US\$6.82 ha^{-1} yr^{-1} at the higher yielding eastern site. Of course, both cooperating farmers received the same price for HRW and paid the same market prices for all inputs including diesel fuel, fertilizer, herbicides, seed, and labor.

Costs were divided into variable and fixed categories. The former vary by the number of hectares cultivated. These include fertilizer, herbicides, seed, fuel, machine rental, machinery repairs and maintenance, and labor. Fixed costs include depreciation, interest, property taxes, housing, and insurance on machinery. Land is also traditionally included as a fixed cost. Land cost equals the cash or share rent for land and property taxes.

Total economic costs include a market return for the farmer's land, machinery, and labor. Although the farmer may not pay him/herself or family members a wage, an "opportunity wage" for this labor is charged equal to what it could earn elsewhere. Correspondingly, the opportunity cost for owned land is the rent foregone by not renting it to another farmer. Total economic budgeting permits comparing production systems on an "apples to apples" basis even though different farmers may acquire their labor, machinery, and land by different methods.

Annual grain yields by fallow management system and site were those measured in the experiment. All cost and revenue figures are presented on a rotational hectare basis. For this study, this means one half hectare of winter wheat and one half hectare of fallow. This ensures comparability on a standard U.S. dollars per hectare basis for differing crop rotations in the literature.

The study used a 2009 to 2013 average regional farm gate price of US\$476 Mg^{-1} (US\$7.09 bu^{-1}) for HRW (Union Elevator, 2013). A recent multiyear average crop price is superior to using actual prices for each experimental year to avoid confounding such as might happen if one fallow system happened to produce a high yield concurrent with a wheat price spike. Gross returns also include government direct and counter cyclical payments according to Congressional formulae and a farmer's historic grain yield. The 5-yr experiment grain yield for HRW following TTF was used for each site's historic yield.

Unlike the price of wheat and other crops that vary up and down annually in response to world demand and supply conditions, farmers' average prices for fertilizer, herbicides, seed, fuel, and labor tend to move only upward with time. For example, the USDA's index of prices paid for crop production inputs rose from 188 to 225 between 2009 and 2013 with no annual downward movement (National Agricultural Statistics Service, 2014). To recognize this trend and to provide a forward-looking perspective for farmers and scientists, 2012 and 2013 input prices were utilized. Both cooperating farmers reported that they broke even with respect to crop insurance premiums and indemnities, so no charge was deducted for crop insurance.

Statistical Procedures

Analysis of variance was conducted for: (i) water lost from the 180-cm soil profile between late March and late August; (ii) volumetric water content at 15-cm increments throughout the 180-cm soil profile in late August; (iii) volumetric seed-zone water content in 2-cm increments to a depth of 26 cm in late August; (iv) plant stand establishment; (v) HRW grain yield; (vi) variable costs; (vii) fixed costs; (viii) total costs; (iv) gross returns; and (x) net returns. Tukey's honest significance test (Speed, 2002) was used to detect statistical differences in treatment means for all data. All analysis of variance tests were done at the 0.05 level of significance.

For comparing 5-yr means of soil water content, plant stand establishment, and grain yield among fallow systems within a site, replications were used as the statistical variate, as is traditional in biological sciences. For comparing mean economic returns and costs among fallow systems within a site, years rather than replications were used as the statistical variate. The reason is that farmers, and their bankers, desire to know which system is superior in terms of annual economic stability (Lien et al., 2007). Annual stability is critical because farmers typically make large payments for land and machinery on an annual basis. For this reason, economists typically measure risk and often test superiority of means on a temporal basis (Pendell et al., 2007; Richardson et al., 2000; Schillinger and Young, 2004). Economic superiority based on variance across replications (a proxy for a farmer's fields) is less critical because all the grain from different fields within a year is often dumped into a common bin and sold as a unit.

RESULTS AND DISCUSSION

Water in the Entire Soil Profile

Water content in the 180-cm soil profile was always greater at the western site than at the eastern site on all sampling dates despite the fact that annual precipitation was less at the western site every year and by a study-period average of 24% (Table 1). Water content in the soil profile in late March averaged 288 mm at the western site and 224 mm at the eastern site (Table 2). We feel that these water differences are due to different soil hydraulic characteristics related to the clay content of the Warden and Ritzville soils. Detailed soil properties from both of these experiment sites were reported by Singh et al. (2011). Appraisal of some of these soil properties in the A horizon in the NTF treatment for the western site compared with those for the eastern site showed that: (i) clay content was 180 vs. 130 g kg^{-1}, (ii) pore size distribution index (Assouline, 2005) was 2.75 vs. 2.98; (iii) bulk density was 1.38 vs. 1.30 g cm^{-3}, and (iv) saturated hydraulic conductivity was 57 vs. 77 cm d^{-1}. In addition, simulation using the Simultaneous Heat and Water (SHAW) model (Flerchinger, 2000) supports this explanation for soil water differences between the two soils (Singh et al., 2011).

Although most wheat cultivars will quickly germinate at soil water potential values above −1100 kPa and with slower but adequate germination to −1600 kPa (Wuest and Lutcher, 2013), a minimum water potential of −500 kPa is required to realistically expect adequate plant stands when wheat seedlings must emerge through 125 mm or more soil cover (Lindstrom et al., 1976). Fitted water potential curves indicated that −500 kPa equates to approximately 11.1 m m^{-3} soil water content for the Warden soil at the western site and 10.4 m m^{-3} soil water content for the Ritzville soil at the eastern site (M. Flury, unpublished data, 2014).

Soil water content of the three treatments measured at the end of August in the 0- to 90-cm depth as well as the complete 0- to 180-cm profile at both sites averaged across the 5 yr is shown in Table 2 and Fig. 1. At the western site, March to August water loss was 35, 35, and 43 mm from the upper 90 cm of soil in the TTF, UTF, and NTF treatments, respectively; these differences were highly statistically significant. The same water loss trend among treatments occurred in the upper 90 cm at the eastern site, with NTF losing significantly ($p < 0.001$) more than the other treatments (Table 2). At both sites, the majority of water loss from March to August occurred from the upper 90 cm rather than from below this depth (Fig. 1). Essentially no water loss occurred from below 90 cm with NTF at either site, whereas for TTF and UTF, some loss occurred at the western site and, conversely, some water was gained below 90 cm at the eastern site (Table 2; Fig. 1). In the entire 180-cm profile, there were no differences in water content among treatments at the western site but a highly significant lower water content for NTF at the eastern site (Table 2). Averaged across the 5 yr, NTF had significantly less water in late August than both TTF and UTF to a depth of 45 cm at the western site and significantly less water than either TTF or UTF at every sampling increment to a depth of 105 cm at the eastern site (Fig. 1). These data provide the first documentation of such deep over-summer soil drying from NTF compared with tillage-based summer fallow in the Pacific Northwest.

Seed-Zone Water in Late August

Volumetric water content in the seed zone was markedly lowest for NTF in all 5 yr and when averaged across years at both sites (Fig. 2). Highly significant ($p < 0.001$) reductions in seed-zone water with NTF compared with TTF or UTF occurred in every 2-cm measurement increment from 10 to 26 cm at both

Table 2. Soil water content during fallow in late March and again in late August (before planting) and associated soil water loss during this 5-mo period with traditional tillage, undercutter tillage, and no-till fallow systems averaged across 5 yr at two on-farm locations in the Horse Heaven Hills.

Fallow system	Soil water content†		
	Spring (late March)	Planting (late August)	March–August water loss
	mm		
	Western site		
Top 90-cm depth			
Fallow system			
Traditional	149	114	35 b‡
Undercutter	149	114	35 b
No-till	149	106	43 a
p value			<0.01
Entire 180-cm profile			
Fallow system			
Traditional	288	247	41
Undercutter	288	250	38
No-till	288	244	43
p value			NS
	Eastern site		
Top 90-cm depth			
Fallow system			
Traditional	146	105	41 b
Undercutter	146	110	36 b
No-till	146	97	49 a
p value			<0.001
Entire 180-cm profile			
Fallow system			
Traditional	224	192	32 b
Undercutter	224	192	32 b
No-till	224	174	50 a
p value			<0.001

† Average soil water content (m^3 m^{-3}) for all sampling increments × depth of soil profile (m) × 1000 = soil water content (mm).

‡ Within a column, water loss means at each site followed by a different letter are significantly different at $p < 0.05$; NS, no significant difference.

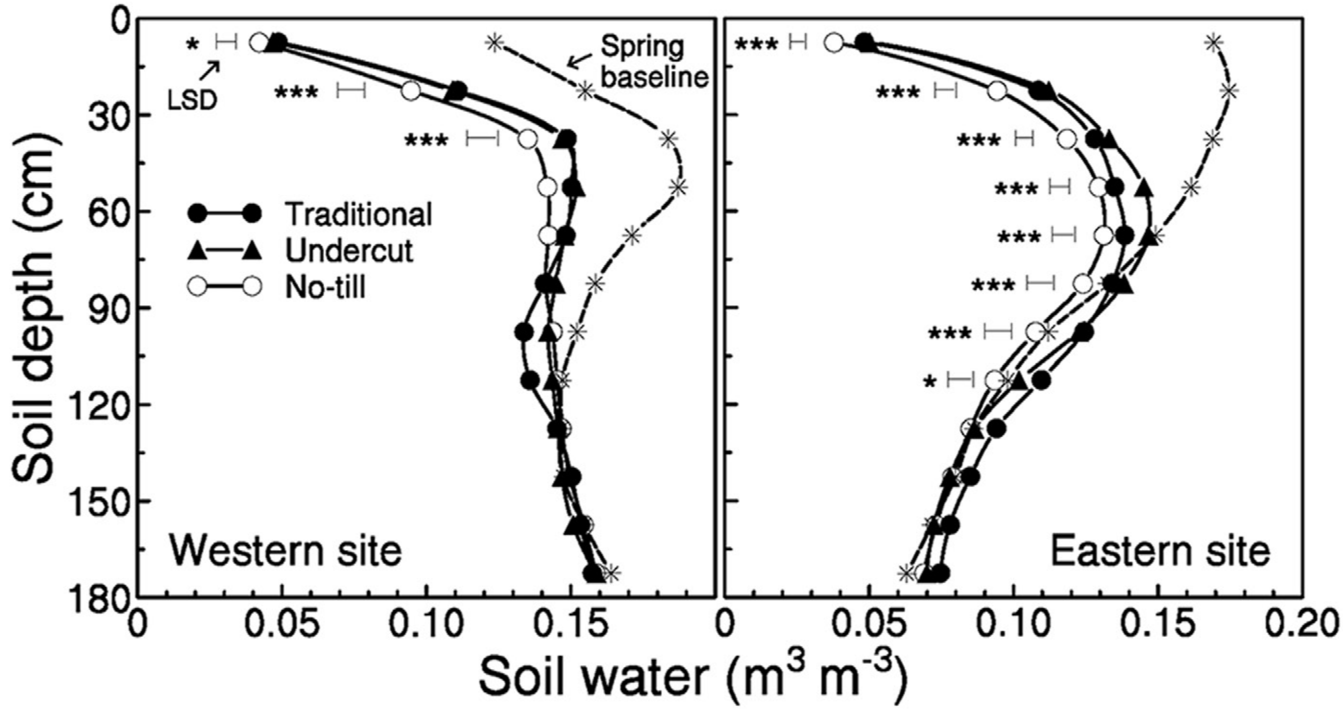

Fig. 1. Soil volumetric water content measured in 15-cm increments to a depth of 180 cm in late August for three fallow management systems at the two experiment sites in the Horse Heaven Hills, Washington. Data points are the mean values for the 5-yr experiment. The early spring baseline soil water content (dotted line with asterisks) was not included in the statistical analysis. Width of horizontal bars shows least significant difference (LSD) for each depth increment. *Significantly different at the 0.05 probability level. ***Significantly different at the 0.001 probability level.

sites. This drying of the seed zone under NTF during the warm, dry summer months is consistent with the findings of numerous other studies on this topic from the Pacific Northwest (Hammel et al., 1981; Wuest, 2010; Wuest and Schillinger, 2011).

There were no seed-zone volumetric water differences between TTF and UTF at any sampling increment at the western site (Fig. 2), but at the eastern site, UTF had significantly less water than TTF at the five increments between the 10- and

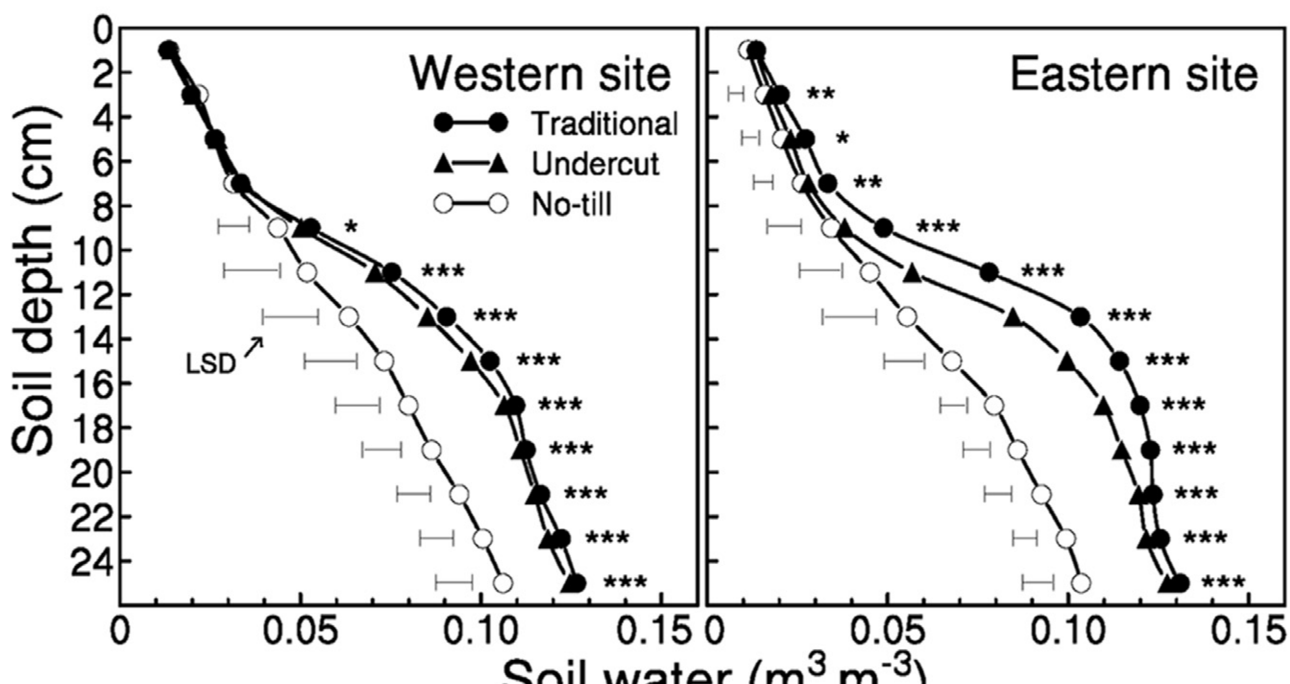

Fig. 2. Seed-zone volumetric water content in 2-cm increments for three fallow management systems measured in late August at the two experiment sites in the Horse Heaven Hills, Washington. Data points are mean values for the 5-yr experiment. Width of horizontal bars shows least significant difference (LSD) for each depth increment. *Significantly different at the 0.05 probability level. **Significantly different at the 0.01 probability level. ***Significantly different at the 0.001 probability level.

18-cm depth. These 5-yr mean differences between TTF and UTF at these sampling depths at the eastern site were due to large differences measured during the first 2 yr of the study (data not shown) when the farmer cooperator was still getting used to, and adjusting, his new undercutter implement to achieve consistent depth control. Consequently, the UTF tillage mulch at the eastern site was somewhat less than the desired 13-cm thickness during the first 2 yr of the study, but uniform depth in this treatment was achieved in the final 3 yr, during which time no seed-zone water differences between TTF and UTF occurred. This is consistent with findings of long-term research (Papendick, 2004) as well as testimonials from 47 farmers throughout the low-precipitation region (Young and Schillinger, 2012) who compared TTF and UTF and observed no differences in seed-zone water or winter wheat grain yield between the two.

Table 3. Grain yield of hard red winter wheat for three fallow management systems for 5 yr as well as the 5-yr average at two locations in the Horse Heaven Hills, Washington.

Fallow system	Grain yield					
	2007	2008	2009	2010	2011	5-yr avg.
	kg ha^{-1}					
	Western site					
Traditional	1726 ab†	1050	1179 a	1531 a	1814 c	1460 b
Undercut	1878 a	1072	1138 a	1537 a	2446 b	1614 a
No-till	1687 b	1058	798 b	1200 b	2798 a	1508 b
p value	<0.05	NS	<0.01	<0.05	<0.001	<0.001
	Eastern site					
Traditional	3222 a	1712 a	1860 a	1344	2643 a	2156 a
Undercut	3241 a	1840 a	1835 a	1336	2523 ab	2155 a
No-till	2137 b	454 b	1512 b	1152	2228 b	1497 b
p value	<0.001	<0.001	<0.01	NS	<0.05	<0.001

† Within a column, winter wheat grain yield means at each site followed by a different letter are significantly different; NS, no significant difference at $p < 0.05$.

Planting and Stand Establishment

Early planting of HRW into the TTF and UTF treatments at the western site was only possible during the first year of the study after 240 mm of precipitation occurred during the 2006 (1 September–31 August) fallow year (Table 1), this being 158% greater than the long-term average precipitation for this site. In the other 4 yr of the study, seed-zone water conditions were too dry for early planting (Fig. 2). Early planting of NTF was not possible in any year.

At the eastern site, seed-zone water was adequate for early planting of TTF and UTF all 5 yr. Seed-zone water content in TTF and UTF, however, was extremely marginal in late August 2008 when Finley HRW was planted with 200 mm of soil covering the seed. Stand establish in TTF and UTF was adequate all years except in 2009, when a crusting rain occurred after planting but before seedling emergence, resulting in spotty stands that necessitated replanting as mentioned above. The seed zone of NTF was too dry for early planting in all years of the study (Fig. 2).

During the 5-yr period, HRW plant stand establishment averaged 44, 41, and 66 seedlings m^{-2} at the western site and 35, 32, and 56 seedlings m^{-2} at the eastern site for TTF, UTF, and NTF, respectively. This statistically significant higher number of seedlings in NTF was expected. Although the time of planting (i.e., late) and seed rate were the same at the western site in 4 or 5 yr, the drill used for planting NTF was more precise in the depth of seed placement and had much narrower row spacing than the drill with 46-cm row spacing used for TTF and UTF. At the eastern site, in addition to shallower seed placement, NTF also had a higher seed rate. A relatively low number of wheat plants per unit area is common with deep planting depths. Farmers in the region are generally satisfied with 30 plants m^{-2} and most will not replant if they have at least 15 plants m^{-2}.

Wheat Grain Yield

Grain yield of HRW under the fallow systems for the 5 yr as well as the 5-yr yield average are shown for both sites in Table 3. At the western site, there were no differences in grain yield between TTF and UTF, except in 2011 when UTF produced 34% more grain than TTF. We have no explanation for this yield difference in 2011 because both of these treatments had equal amounts of stored soil water before planting and seed was "dusted in" on the same day. This boost in grain yield in 2011 resulted in UTF producing significantly greater grain yield than TTF when averaged across the 5 yr (Table 3). Grain yield for NTF was equal (2008), almost equal (2007), less than (2009 and 2010), and greater than (2011) that of the TTF and UTF treatments (Table 3). Grain yield of NTF far exceeded UTF, and especially TTF, in 2011. We, again, have no clear explanation for

Table 4. Mean variable, fixed, and total costs and gross and net returns over 5 yr for three fallow management systems at two sites in the Horse Heaven Hills, Washington.

Fallow system	Costs			Returns		CV for net returns
	Variable costs	Fixed costs	Total costs	Gross returns	Net returns	
	$US ha^{-1}					%
	Western site					
Traditional	143	184	327	404	77	55
Undercut	144	199	343	444	101	75
No-till	147	194	341	416	75	152
p value	NS	NS	NS	NS	NS	
	Eastern site					
Traditional	223 b†	274 a	497	598 a	101 a	130
Undercut	218 b	275 a	493	594 a	101 a	126
No-till	301 a	216 b	517	425 b	−92 b	88
p value	<0.001	<0.01	NS	<0.01	<0.001	

† Within a column, means at each location followed by a different letter are significantly different; NS, no significant difference at $p < 0.05$.

this phenomenon because there were no differences among treatments for total soil water in the 180-cm soil profile in fallow in late August 2010 and treatments were all planted on the same date. We speculate that residue cover may have been a factor since grain yield was NTF > UTF > TTF ($p < 0.001$) in 2011. These treatment differences were also visibly obvious in all four replicates at the time of harvest. Averaged across the 5 yr, UTF produced the highest grain yield followed by NTF and TTF (Table 3). Although these 5-yr grain yield treatment differences were highly significant ($p < 0.001$), the spread from highest to lowest average yield was only 154 kg ha^{-1}.

At the eastern site, there were no grain yield differences between TTF and UTF in any year, and the 5-yr average grain yield for these two treatments was essentially identical (Table 3). This further confirms the observations of 47 regional famers who reported no agronomic differences in the TTF and UTF methods for winter wheat–summer fallow farming (Young and Schillinger, 2012). Grain yield of NTF was significantly less than the other two treatments in all years except 2010, that being the crop year when soil crusting caused by rain showers necessitated replanting of TTF and UTF (i.e., all three treatments were therefore planted on the same day in mid-November). Averaged across the 5 yr, the late-planted NTF grain yield was only 69% of that for TTF and UTF, these differences being significant at $p < 0.001$ (Table 3).

Economics

Economic returns and costs are discussed separately for each site because the objective of this study was to compare fallow systems within markedly different agroclimatic environments and management approaches. At the western site, UTF earned net returns of US$101 ha^{-1} (Table 4). Traditional tillage fallow and NTF trailed at US$77 and US$75 ha^{-1}, respectively, but there were no statistically significant differences among the three fallow systems (Table 4). These are environmentally welcome results because: (i) the widespread practice of NTF in the region would essentially eliminate wind erosion and blowing dust; and (ii) the UTF method substantially reduces blowing dust emissions compared with TTF (Sharratt and Feng, 2009a, 2009b). Annual profit varied markedly at the western site, with coefficients of variation (CVs) ranging from 55% for TTF to 152% for NTF (Table 4). It is comforting from a farmer's and banker's perspective that annual profit variability as measured by CV with the environmentally friendly UTF is only 20 percentage points higher than that of TTF.

At the eastern site, TTF and UTF achieved identical net returns of US$101 ha^{-1} (Table 4). The equal profit corresponded to essentially equal grain yields of 2156 and 2155 kg ha^{-1} for these systems (Table 3). No-till fallow at the eastern site lagged sharply in net returns, as did grain yield (Tables 4 and 3). All three fallow systems displayed high annual profit variability, with CVs ranging from 88 to 130%.

To provide a deeper understanding of the profit results, we analyzed gross returns and cost components for the fallow systems and sites as displayed in Table 4. Gross returns are comprised of HRW sales and government payments. Variable and fixed costs were defined above, and total costs equal their sum. Gross returns exceeded the total costs for all fallow systems at the western site and for all but NTF at the eastern site. The latter earned a net return of negative US$92 ha^{-1} (Table 4). A low average grain yield of 1497 kg ha^{-1} under NTF at the eastern site vs. about 2155 kg ha^{-1} from the other two fallow systems was the principal contributor (Table 4). High variable costs, especially herbicides for weed control for NTF, also limited its profit.

The cooperating farmers at the two sites selected their types and rates of herbicides and fertilizers and the annual machine operations for the three fallow systems. Table 4 reveals that the cooperating farmer at the western site exercised more careful cost control. Lower costs were to be expected given the lower grain yield potential for this site, but our analysis suggests that cost control was disproportionately tighter even considering grain yield potential. Reduced fixed costs are a result of calibrating machinery to the available acreage and achieving good efficiency in field operations. Variable cost control reflected adjusting fertilizer and herbicide applications to realistic grain yield expectations at the western site. The prior experience with NTF by the two cooperating farmers was also probably a factor in choosing inputs. The western site cooperator had several years of prior experience with NTF and was, therefore, quite aware of the variable cost effectiveness of various herbicides for control of Russian thistle during warm, dry summer conditions. Conversely, the eastern site cooperator, like most other farmers in the eastern HHH, had little to no experience with NTF and chose more expensive herbicides and higher application rates in the hope of achieving the best weed control.

SUMMARY AND MANAGEMENT RECOMMENDATIONS

1. At both sites, seed zone (0–26-cm depth) water as well as water in the surface 90 cm of soil was consistently and significantly lower for NTF than the tilled fallow treatments.
2. Seed-zone water was not adequate for early (late-August) planting in any fallow management treatment in 4 of 5 yr at the drier western site. Early planting was possible every year with TTF and UTF at the eastern site.
3. The UTF treatment had the highest average grain yield at the western site and there were no average grain yield differences between TTF and NTF. At the eastern site, early-planted TTF and UTF had near-identical average grain yields, while the late-planted NTF yields were only 69% of the other treatments.
4. Despite modest grain yields at the drier western site, economic net returns were positive for all three fallow management systems due to careful cost management, and there were no significant differences in net returns among treatments. At the eastern site, net economic returns were identical for TTF and UTF but returns

lagged substantially for late-planted wheat on NTF due to low grain yields and high variable costs.

The purpose of this study was to provide the science-based information needed by the NRCS to allow them to formulate farm programs that provide realistic incentives to wheat farmers to change from TTF to UTF or NTF. A major conclusion is that late-planted winter wheat on NTF was equally profitable as the tilled-fallow treatments at the western site. Widespread adoption of NTF in the western region of the HHH would, without question, sharply reduce wind erosion, blowing dust, and air quality problems. We are encouraged that some of the leading farmers in the western HHH are adopting NTF across large areas of their farms.

For the eastern HHH, where precipitation is relatively more abundant and where early planting of winter wheat into adequate seed-zone water in tilled fallow is the norm rather than the exception, the UTF method will generate the same grain yields and economic net return and provide much better wind erosion control compared with TTF.

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