Cropping Systems Research in the World's Driest Rainfed Wheat Region

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ABSTRACT

Winter wheat (*Triticum aestivum* L.)–summer fallow (WW-SF) is the predominant cropping system in the 120 000-ha Horse Heaven Hills (HHH) region in south-central Washington, USA. Blowing dust from residue- and roughness-deficient SF results in soil loss and causes health problems. Annual no-till cropping to replace SF would provide year-round protection against wind erosion. A 6-yr field study was conducted from 1996 to 2002 to evaluate the agronomic and economic feasibility of continuous annual no-till hard red spring wheat (HRSW) as an alternative to traditional WW-SF. Long-term average annual precipitation at the experiment site is 152 mm, which we believe is the lowest for any nonirrigated wheat region of the world. Annual precipitation during the study ranged from 111 to 240 mm and averaged 153 mm, with two wet years followed by a 4-yr drought. Russian thistle (*Salsola iberica* Sennen and Pau) heavily infested HRSW plots and depleted soil water during the two wet years. Seed-zone water content in SF was sufficient to plant WW in late August in only 2 of 6 yr. Mean (6-yr) grain yield was 1190 kg ha^{-1} for WW-SF (one crop every 2 yr) and 530 kg ha^{-1} for annual no-till HRSW. The number of kernels per spike had a significant contribution to yield during years of acute water stress. Net economic returns for annual HRSW lagged WW-SF by an average \$95 ha^{-1} yr^{-1}. Although continuous annual no-till cropping has clear environmental advantages, it is not economically competitive with WW-SF with current technology in the HHH.

Drought, tillage, low production of crop residue, nonaggregated soils with low organic matter content, and high winds often combine to leave soil vulnerable to wind erosion in the HHH region of south-central Washington. Winter wheat–summer fallow, where only one crop is produced every 2 yr, is the dominant dryland crop rotation. Farmers in the HHH are considered some of the best practitioners of conservation tillage in the inland Pacific Northwest, but wind erosion from SF or newly planted WW fields is a major soil loss and air quality concern. The WW-SF rotation is practiced on 1.56 million ha in the low (<300 mm annual) precipitation region of eastern Washington and north-central Oregon, by far the largest dryland cropping precipitation zone in the western USA. Many farmers and others feel that successful new cropping technologies developed for the HHH may be applicable also to the higher-precipitation portions of the WW-SF region.

While annual spring crops are not typically grown in the HHH, they have the potential to markedly control wind erosion. One computer model estimated that annual no-till spring cropping would reduce predicted dust emissions by 94% during severe wind events compared with conventional WW-SF (Lee, 1998).

The main purpose of SF is to store a portion of overwinter precipitation to enable successful establishment of WW planted deep into moist soil in late August. Precipitation storage efficiency (PSE, the percentage of precipitation stored in the soil) during the year-long SF period is 30% or lower (Leggett et al., 1974). About half the time, the seed zone (15 to 20 cm deep) is too dry for HHH farmers to plant WW in late August; thus, they plant shallow (2–3 cm deep) into dry soil or delay planting until the onset of fall rains in late October or November. Planting in late October reduced straw and grain yields in a 240-mm annual precipitation zone by 60 and 30%, respectively, compared with planting deep in late August into moist soil with 15 cm of soil covering the seed (Donaldson et al., 2001). These reductions seriously impact erosion potential and farm economics in the region. Papendick et al. (1973) explained the processes of water loss and seed-zone water retention from SF under Pacific Northwest conditions.

Due to inefficient PSE, frequent difficulty with WW stand establishment from deep planting depths, and wind erosion hazard, farmers in the HHH are interested in alternatives to WW-SF. The purpose of our study was to compare WW–SF with continuous annual no-till HRSW for grain yield, grain yield components, straw production, weed control PSE during the noncrop period, and farm economics.

MATERIALS AND METHODS

A 6-yr field experiment was conducted from 1996–2002 in the HHH region of Benton County of south-central Washington to compare the traditional WW-SF rotation to continuous annual no-till HRSW. Annual long-term precipitation in the HHH ranges from 150 to 215 mm (Rasmussen, 1971). The experiment was designed in collaboration with an advisory committee of regional farmers. The farmers requested that the experiment site be located in the driest portion of the HHH cropping region located 20 km due south of Prosser, WA, that receives only 152 mm of average annual precipitation. Pan evaporation (Mar. to Nov.) averages 1010 mm. Land

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Abbreviations: HHH, Horse Heaven Hills; HRSW, hard red spring wheat; PSE, precipitation storage efficiency; SF, summer fallow; WW, winter wheat.

for the experiment was provided by farmer/cooperator Doug Rowell.

Precipitation was recorded from July 1996 to July 2002 at the Washington State University Public Agricultural Weather Station (PAWS) located at the experiment site. Historic (20-yr) WW grain yield (after fallow) on the farmer's field at the site ranged from 200 to 2000 kg ha^{-1} and averaged 1250 kg ha^{-1}.

The soil is a Warden very fine sandy loam (coarse-silty mixed, superactive, mesic Xeric Haplocambids) formed in a thin mantle of loess over lacustrine sediments (Rasmussen, 1971). There is a thin weak layer of calcium carbonate accumulation at ≈50 cm, but otherwise no impermeable layers or rocks exist within the 180-cm profile. Slope was less than 2%.

Treatments and Field Operations

There were two cropping system treatments: (i) WW–SF and (ii) continuous annual HRSW. Both crop and SF phases of the WW-SF rotation were present each year. Experimental design was a randomized complete block with six replications. There were 18 plots that covered a total land area of 2.92 ha. Individual plot size was 90 by 18 m.

In the WW-SF system, equipment and field management was provided by Doug Rowell. A complete list of field operations and inputs is shown in Table 1. After harvest (start of fallow), wheat stubble was left standing and undisturbed through the winter. Glyphosate herbicide [*N*-(phosphonomethyl) glycine] was applied at 0.28 kg a.e. (acid equivalent) ha^{-1} in February in 2 of 6 yr to control winter-annual grass weeds, mostly downy brome (*Bromus tectorum* L.). Primary tillage in March to a soil depth of 15 cm was conducted with either a tandem offset disk with 56-cm-diam. circular blades or an undercutter equipped with overlapping 46-cm-wide high-pitch V-shaped sweeps spaced 30 cm apart. An average of two secondary tillage operations was conducted during late spring and midsummer with a rodweeder (a 3-cm square rotating rod) at a depth of 10 cm to control Russian thistle and other broadleaf weeds. Ammonium thiosulfate was injected into fallow with shanks spaced 46 cm apart in late spring in 2 of 6 yr when it was felt application was economically justified based on stored soil water, i.e., yield potential. Soft white WW 'Eltan' or 'Malcolm' was planted at a rate of 30 kg ha^{-1} with a modified Flexi-Coil (Saskatoon, SK, Canada) deep-furrow drill with 53-cm-wide row spacing into moist soil in late August of 1996 and 1997. When seed-zone water was insufficient (<11 cm^3 cm^{-3}, August 1998, 1999, 2000, and 2001), planting was delayed until mid-November after fall rains had wet the soil surface, and a John Deere (Moline, IL) 9300 series hoe-opener drill with 25-cm-wide row spacing was used to plant WW at 71 kg ha^{-1}. Adequate WW stands that averaged 95 plants m^{-2} were achieved each year, and no winterkill of plants occurred using either of the two planting methods. In-crop broadleaf weeds were controlled in March with 2,4-D (2,4-dichlorophenoxyacetic acid) ester herbicide at 0.84 kg a.e. ha^{-1} or with 2,4-D amine herbicide at 0.69 kg a.e. ha^{-1} in April when WW was in the tillering phase of development (Table 1).

In the continuous annual no-till HRSW system, an average of 0.30 kg a.e. ha^{-1} glyphosate herbicide was applied in January or February to control winter annual grass weeds in 5 of 6 yr. In late February or early March, HRSW 'Kulm' or 'Scarlet' was planted at 76 kg ha^{-1} with two separate custom-built drills equipped with cross-slot (Baker Manufacturing, Christchurch, New Zealand) notched-coulter openers on 25-cm-wide (1997, 1998, and 1999) and 20-cm-wide (2000, 2001, and 2002) row spacing for simultaneous and precision placement of seed and fertilizer in the same row. Fertilizer was placed 2 cm below and 3 cm to the side of the seed. Ammonium nitrate + urea provided the liquid base to supply a 6-yr average of 19 kg N ha^{-1} yr^{-1}, 7 kg P ha^{-1} yr^{-1} (aqueous solution of $NH_4H_2PO_4$), and 5 kg S ha^{-1} yr^{-1} [aqueous solution of $(NH_4)_2S_2O_3$]. Nitrogen fertilizer rate was based on 5.8 kg of available N for each expected 100-kg grain yield to achieve 14% grain protein content of HRSW as described by Mahler and Guy (1998). The wheat cultivars used in the study were considered the best available based on multiple site and year yield data from the Washington State University cereal cultivar testing program. Excellent HRSW stands that averaged 130 plants m^{-2} were consistently achieved. In-crop broadleaf weeds were con-

Table 1. Field operations and inputs for winter wheat–summer fallow (WW-SF) compared with continuous annual no-till hard red spring wheat (HRSW) during six crop years (1997–2002).

	WW-SF system		
Month	WW	SF	Annual hard red spring wheat
Aug.	WW planted 20 cm deep at 30 kg ha^{-1} in 53-cm-wide rows in 1996 and 1997.† Stands failed in 1997.‡		Postharvest herbicide: 0.42 kg a.i. ha^{-1} paraquat + 0.21 kg a.i. ha^{-1} diuron in 1997, 1998, and 2000.
Nov.	WW planted 3 cm deep at 71 kg ha^{-1} in 25-cm-wide rows after the onset of fall rains in 1997, 1998, 1999, 2000, and 2001.		
Feb.		Herbicide: 0.30 kg a.e. ha^{-1} glyphosate in 1997 and 2000 only.	Herbicide: 0.30 kg a.e. ha^{-1} glyphosate in 5 of 6 yr.
Mar.	In-crop broadleaf herbicide: 0.84 kg a.e. ha^{-1} 2,4-D ester in 1997, 1998, and 1999; 0.69 kg a.e. ha^{-1} 2,4-D amine in 2000, 2001, and 2002.	Primary tillage: tandem offset disk with 56-cm-diam. blades to a depth of 15 cm in 1997, 1999, and 2002; undercutter with 46-cm-wide V-shaped sweeps spaced 30 cm apart in 1998, 2000, 2001.	HRSW planted 3 cm deep at 76 kg ha^{-1} and fertilized at 19 kg N ha^{-1}, 7 kg P ha^{-1}, and 5 kg S ha^{-1} in 25-cm-wide rows (1997, 1998, 1999) and 20-cm-wide rows (2000, 2001, and 2002) in one pass with Cross-slot no-till drill.
Apr.		Fertilizer injection: Aqua NH_3 at 28 kg ha^{-1} plus S at 9 kg ha^{-1} in 1996 and 1997 only.	In-crop broadleaf herbicide: 0.69 kg a.e. ha^{-1} 2,4-D amine in 1997, 2000, 2001, and 2002; 0.14 kg a.e. ha^{-1} dicamba in 1998 and 2000.
May		First rodweeding, 10-cm depth.	
June			
July	Grain harvest.	Second rodweeding, 10 cm depth.	Grain harvest.

† Although placed 20 cm below the preplant soil surface, only 15 cm of soil covered the seed as some soil was stacked in furrow ridges by the deep-furrow drill.

‡ Stands of early planted winter wheat failed in 1997 due to soil crusting caused by rain showers before seedling emergence. Early planting of WW was not attempted in 1998, 1999, 2000, and 2001 due to dry soil conditions.

trolled with either 0.14 kg a.e. ha^{-1} dimethylamine salt of dicamba (3,6-dichloro-2-methoxybenzoic acid) herbicide when wheat was at the two- to five-leaf stage of growth or 2,4-D amine at 0.69 kg a.e. ha^{-1} when wheat was in the tillering phase of growth. Postharvest herbicide of 0.4 kg a.i. (active ingredient) paraquat (1,1′-dimethyl-4,4′-bipyridinium ion) ha^{-1} plus 0.2 kg a.i. diuron [*N*′-(3,4-dichlorophenyl)-*N,N*-dimethylurea] ha^{-1} was applied in July in 3 of 6 yr to control Russian thistle growth, seed production, and water use. Thus, two or three herbicide applications (preplant, in-crop, and postharvest) were required each year to control grass and broadleaf weeds in the continuous annual no-till HRSW system (Table 1). Two or three annual herbicide applications such as those used in the study are common for spring wheat production in the inland Pacific Northwest.

Measurements

Soil water was measured to a depth of 180 cm in all plots immediately after grain harvest each year in early July (beginning in 1997) and again in late February or early March before primary tillage (for fallow) or planting (for annual HRSW). 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 (Top and Ferre, 2002). In addition, volumetric seed-zone soil water content in SF plots was measured in 2-cm increments to a depth of 22 cm with an incremental soil sampler in late August of 1999, 2000, and 2001.

Grain yield was determined by harvesting the grain from plants in a swath through each 90-m-long plot with: (i) a commercial combine with 9.1-m-wide cutting platform and auguring grain into a truck mounted on weigh pads (1997–2000) or (ii) a plot combine with 1.5-m-wide cutting platform, collecting grain in a cloth sack, and weighing grain on a digital scale accurate to 0.1 g (2001–2002). Spike density and total aboveground dry biomass production were measured by hand-cutting plants from 1-m-long row segments in three locations in each plot just before harvest in July. Unit area for the clipped row of each treatment was then calculated based on drill row spacing. Whole-plant samples were placed in a low-humidity greenhouse for 7 d and then weighed. Kernels per spike was calculated based on spikes per square meter and thousand-kernel weight after passing spikes though a hand-fed thresher. Straw production was determined by subtracting the weight of the grain from the whole-plant weight.

Russian thistle population and dry biomass were determined in HRSW plots (Russian thistle was not present in WW plots) immediately before grain harvest in 1997 and 1998 by first counting and then clipping and gathering the aboveground portion of all Russian thistle plants within a 1-m-diam. hoop randomly positioned in each plot of all replications. Russian thistle plants were placed in paper bags and allowed to air-dry in a low-humidity greenhouse before weighing on a digital scale accurate to 0.1 g.

Economic Assessment

Standard enterprise budgets were constructed to assess the profitability of the two cropping systems. Costs are based on the actual sequence of operations conducted on the research plots and assume the farmer/cooperator's farm-scale machinery (Table 1). Fertilizer, herbicide, seed and other input rates are averages used during the experiment. Total costs include a market return for the farmer's land, machinery, and labor. Under such total-cost budgeting, a *fair or normal profit* would be zero. This means that crop receipts exactly cover a market wage for the farmer's labor, a market rent for land and machinery, and all other production expenses. Grain yields are those measured from the experiment. All cost and revenue figures are presented on a rotational-hectare basis; for example, for WW-SF, one-half hectare of WW and one-half hectare of fallow. This ensures comparability on a standard dollar per hectare basis for differing crop rotations.

Six-year average crop prices of \$126 Mg^{-1} for WW and \$162 Mg^{-1} for HRSW were used. For HRSW, the analysis uses the 6-yr average price premium of \$1.50 Mg^{-1} for every 0.25% from 14 to 15.5% protein and a penalty of \$3.30 Mg^{-1} for each 0.25% protein shortfall below 14%. Protein premiums and penalties varied each year as did price margins for HRSW compared with soft white wheat.

Government payments are not included in the formal net revenue results as the emphasis is on market profitability rather than on varying government payments. Including decoupled direct government payments from this time period would not influence the ranking of the two treatments as these payments were not tied to choice of cropping system.

Statistical Procedures

Analysis of variance was conducted for PSE, grain yield, grain yield components, straw production, and economic net returns. The procedure used to compare treatment means was Fisher's protected least significant difference. All statistical tests were done at the 5% level of significance. Significant year × treatment interactions were observed for grain yield components. Because of these interactions, the agronomic data were analyzed separately by year.

RESULTS AND DISCUSSION

Precipitation and Soil Water

Annual crop-year (1 Aug.–31 July) precipitation ranged from 111 to 240 mm and averaged 153 mm over 6 yr (Table 2). Precipitation was much greater than the long-term average in 1997 and 1998, but drought occurred during the final 4 yr of the experiment. Overwinter precipitation (that occurring from grain harvest until planting of HRSW and primary tillage of SF plots in late February/early March) was 69% of the crop-year total averaged over 6 yr.

Overwinter PSE averaged 71% for no-till HRSW stubble compared with 65% for WW stubble (Table 2), but there were no significant PSE differences in any year or when analyzed over years. The trend toward greater PSE in no-till HRSW plots was probably because these soils were drier than in WW plots due to extensive soil water use by an average 58 Russian thistle plants m^{-2} that produced an average 1270 kg ha^{-1} dry biomass (data not shown) present in HRSW during the two wet years (1997 and 1998), despite the timely application of in-crop broadleaf herbicide. Russian thistle is a C_4 plant with high water use and prolific seed production (Schillinger and Young, 2000) that has long plagued spring-planted crops in dry regions of the western USA (Dewey, 1893). Russian thistle is not as big a problem in WW since it has more vigorous early-spring growth and canopy closure to compete against Russian thistle compared with spring wheat. The HRSW plots had

Table 2. Precipitation (6 yr) and precipitation storage efficiency (5 yr) with continuous annual no-till hard red spring wheat (HRSW) vs. winter wheat–summer fallow (WW-SF). Precipitation storage efficiency (PSE) is the percentage of precipitation that was stored in the soil.

Crop year	Annual (crop-year) precipitation†	Overwinter precipitation	Overwinter PSE‡ HRSW stubble	Overwinter PSE‡ WW stubble	12-mo PSE tilled SF
	mm	mm	%	%	%
1997	240	188	§		
1998	200	114	72	70	30
1999	112	76	65	62	18
2000	121	81	83	75	29
2001	111	66	57	57	6
2002	136	102	78	62	22
Avg.	153	105	71¶	65	21

† Crop-year precipitation is from 1 August to 31 July.

‡ Overwinter is the time from grain harvest in the summer to planting (no-till HRSW) or primary tillage (SF) in late winter. Soil water measurements for all plots were always obtained within a 2-d interval.

§ The first soil water measurements were obtained in February 1997; thus, PSE values are not available for 1997.

¶ There were no significant differences in overwinter PSE between HRSW stubble and WW stubble in any year or when analyzed over all years.

27 mm less soil water than WW plots by harvest in July 1998, and soil water in the 180-cm profile remained significantly less in HRSW stubble compared with WW stubble throughout the four subsequent drought years (data not shown).

Summer fallow 12-mo PSE ranged from 6 to 30% and averaged 21% (Table 2). The worst SF year (and crop year) was 2001 when only 66 mm of overwinter precipitation occurred and the wetting front in early March extended only to a soil depth of 30 cm (data not shown), resulting in a net gain of only 7 mm of water (6% PSE) during the SF period (Table 2).

Early planting of WW into moist soil was conducted in August of 1996 and 1997. Stands failed in 1997 due to soil crusting caused by rain that occurred before germinating WW seedlings could emerge through 15 cm of soil cover. Early planting of WW was not attempted during the ensuing drought years (1998 to 2002) as seed-zone water content in SF was insufficient for seedling emergence (Fig. 1). Instead, WW was planted shallow (2 cm deep) in late October or early to mid-November after the onset of fall rains.

Grain Yield, Yield Components, and Straw Production

Grain yield averaged over years was 530 kg ha^{-1} for annual HRSW and 1190 kg ha^{-1} for WW after SF (Fig. 2). Record-setting high WW grain yield for the Rowell farm of 2770 kg ha^{-1}, and also the 6-yr high grain yield for annual HRSW of 1210 kg ha^{-1} (Fig. 2), was achieved in 1998 largely due to 36 mm of rain during a 2-d period in late May. During the ensuing drought years (1999–2002), WW produced economically viable yield in 2000, but otherwise WW and HRSW yields ranged from 42 to 570 kg ha^{-1} (Fig. 2); these are viewed by farmers as crop failures.

Spikes per unit area for WW and HRSW were significantly different in 1998 but not in the drought years that followed (Fig. 3A). Conversely, WW produced more kernels per spike than HRSW from 1999–2002, but in 1998, there were no differences (Fig. 3b). Small but significant differences in kernel weight were found between WW and HRSW in 1998 and 1999 but not in the other years (Fig. 3C). These data agree with Arnon (1972) and Garcia del Moral et al. (2003), who reported that spikes per unit area is the most important yield component for rainfed wheat in nondrought years, but

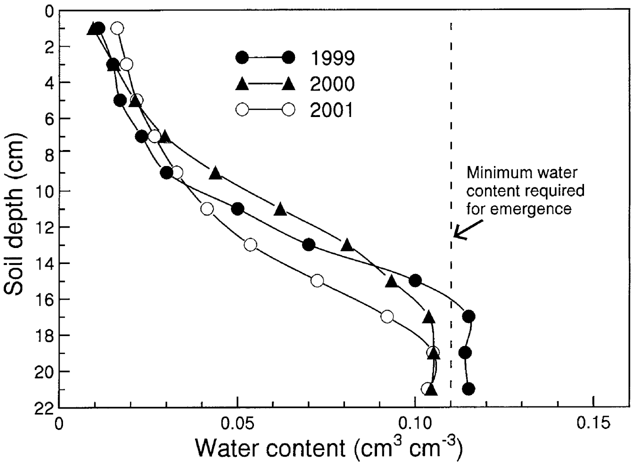

Fig. 1. Seed-zone soil water content in summer fallow in late August during three drought years.

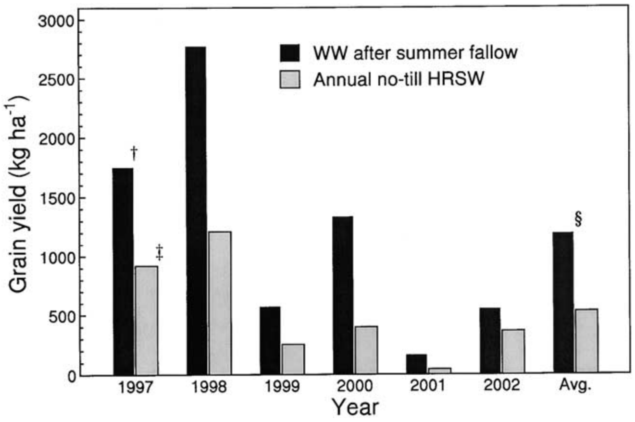

Fig. 2. Grain yield of winter wheat (WW) after summer fallow (one crop every 2 yr) compared with continuous annual no-till hard red spring wheat (HRSW) during 6 yr in the Horse Heaven Hills, Washington. † = WW yield in 1997 is the average from several neighboring fields, not from replicated plots, and thus statistical analysis is not possible in 1997. ‡ = HRSW grain yield is from replicated plots during all 6 yr. § = statistical comparison of average grain yield is for 5 yr (1998 to 2002). Grain yield of WW after summer fallow was significantly ($P < 0.05$) greater than grain yield of annual HRSW each year and when averaged over the 5 yr.

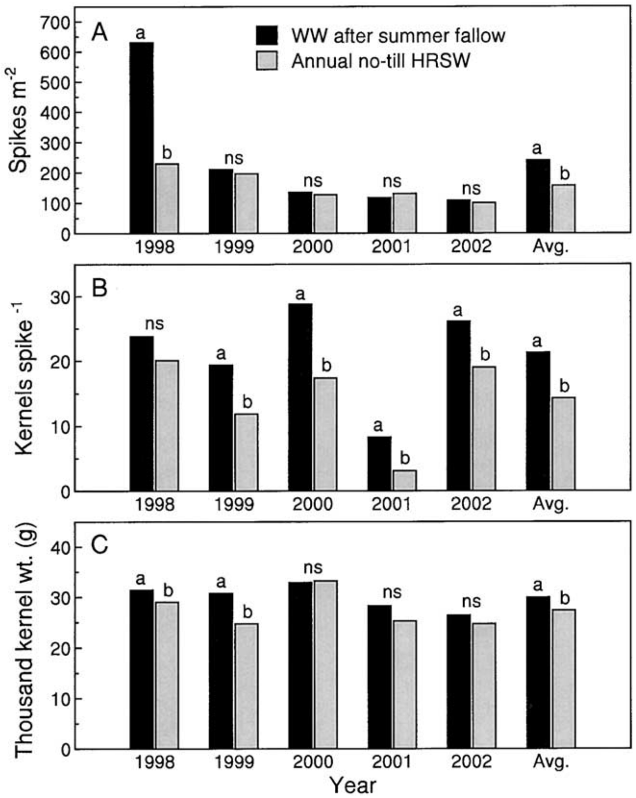

Fig. 3. Grain yield components [(A) spikes per square meter, (B) kernels per spike, and (C) thousand-kernel weight] of winter wheat (WW) after summer fallow compared with continuous annual no-till hard red spring wheat (HRSW) during 5 yr. Within-year means followed by a different letter are significantly different at $P < 0.05$. ns = no significant difference.

under conditions of extreme water stress, the number of kernels per spike has the greatest effect on yield.

Straw production for annual HRSW ranged from 800 (2001) to 2130 (1998) kg ha^{-1} and averaged 1350 kg ha^{-1} during the 6 yr. For WW after SF, straw production ranged from 1130 (2002) to 6410 (1998) kg ha^{-1} and averaged 2650 kg ha^{-1}. Thus, total straw production between the two systems over the 6 yr was about the same.

Economics

Table 3 shows market gross returns, total costs, and net returns for the WW-SF and annual HRSW systems for 1997–2002. Over 6 yr, HRSW averaged a loss of −\$109 ha^{-1} yr^{-1} while WW-SF lost only −\$14 ha^{-1} yr^{-1}. The returns reflect appropriate protein premiums or discounts for HRSW each year. Annual net returns ranged from −\$148 to −\$61 ha^{-1} yr^{-1} for HRSW and from −\$56 to +\$40 ha^{-1} yr^{-1} for WW-SF. Farm-specific government payments might add another \$25 ha^{-1} yr^{-1} return for both cropping systems. These payments put WW-SF in the black on average but not annual HRSW.

Production costs for annual HRSW averaged \$180 ha^{-1} yr^{-1} and were double those for WW-SF at \$90 ha^{-1} yr^{-1} (Table 3). Although the annual HRSW production costs are low compared with higher-precipitation regions of the Pacific Northwest, the regular use of fertilizer, two or three herbicide applications annually (see Table 1), plus planting and harvesting every hectare every year elevates these costs relative to WW-SF. Costs for the WW-SF system, which were computed using Doug Rowell's practices, are among the lowest wheat production costs observed in the USA (Young et al., 2001). During dry years, no fertilizer is applied. In-crop broadleaf weed control is limited to inexpensive 2,4-D herbicide. Farm-grown grain is kept and treated for seed.

Table 3. Annual costs and market returns for winter wheat–summer fallow (WW-SF) compared with continuous annual no-till hard red spring wheat (HRSW) from 1997 to 2002.

Year	Rotation	Gross returns	Total costs	Net returns†
		\$ ha^{-1}		
1997	WW-SF	112.63	97.63	15.00
	HRSW	98.84	206.60	−107.76
1998	WW-SF	175.10	135.46	39.64
	HRSW	157.90	218.76	−60.86
1999	WW-SF	36.13	73.66	−37.53
	HRSW	39.98	172.82	−132.84
2000	WW-SF	84.16	83.77	0.39
	HRSW	60.93	155.38	−94.45
2001	WW-SF	10.11	66.20	−56.09
	HRSW	6.92	154.66	−147.74
2002	WW-SF	36.55	81.47	−44.92
	HRSW	58.98	170.94	−111.96
6-yr avg.	WW-SF	75.78	89.70	−13.92 a
	HRSW	70.59	179.86	−109.27 b

† The 6-yr average net returns for WW-SF and continuous annual HRSW followed by a different letter are significantly different at $P < 0.05$ (LSD \$18.75 ha^{-1}) and $P < 0.001$ (LSD \$50.05 ha^{-1}).

Many farmers and businessmen define economic risk as "probability of loss." Annual no-till HRSW failed to cover total costs, exclusive of government payments, in all 6 yr whereas WW-SF covered total costs, without government payments, in 3 of the 6 yr (Table 3).

CONCLUSIONS

Lack of residue cover and surface roughness on summer-fallowed soils in the HHH frequently leads to wind erosion as well as poor air quality in downwind urban areas. No-till farming is widely recognized throughout the world for excellent control of wind and water erosion, energy savings, and improved soil quality (Doran et al., 1996). Despite these benefits, continuous annual no-till HRSW was not economically competitive with the WW–SF system during either the relatively wet years or the drought years in this study. Annual HRSW lagged WW-SF in profitability by an average of \$95 ha^{-1} yr^{-1}. On a 3000-ha dryland farm, production of continuous annual HRSW would result in a net loss of \$285,000 yr^{-1} compared with the standard WW-SF (1500 ha in WW, 1500 ha in SF) system and therefore is clearly not a viable alternative with current technology.

Future research efforts in the HHH as a result of this paper should focus on:

1. Chemical SF as a replacement for tilled SF. Some newly developed soil-residual broadleaf herbicides have shown excellent and extended control of Russian thistle in chemical SF. Although late-August planting of WW into chemical SF is not feasible due to accelerated drying of the seed zone com-

pared with tilled SF (Hammel et al., 1981), farmers in the HHH only have adequate seed-zone moisture for planting WW in August about 50% of the time with tilled SF. Chemical SF would be acceptable to many farmers in the HHH if government farm programs helped offset the cost of herbicides and the possible reduction in yield due to delayed planting compared with tilled SF.

2. Development of spring wheat cultivars with fast and early prostrate growth habit to compete against Russian thistle. Different market classes of spring wheat may provide more favorable economics than HRSW. For example, continuous annual no-till soft white spring wheat (no protein requirement and with higher yield potential than HRSW) has been economically competitive with WW-SF in a long-term cropping systems experiment in a 290-mm precipitation area in eastern Washington (Juergens et al., 2004).
3. Flexible cropping options that depend on the quantity of overwinter soil water storage.

Finally, although we commend farmers in the HHH for their existing conservation efforts and concerns, further soil-saving refinements in the tilled WW-SF can be made. Undercutter sweep implements with thin, 70-cm-wide, adjustable-pitch and overlapping V blades with excellent depth control and minimal soil lifting have been shown to retain maximum amounts of surface residue and roughness during SF, with no adverse agronomic or economic effects (Schillinger, 2001; Janosky et al., 2002). Further details on controlling wind erosion and air quality on Columbia Plateau croplands in the Pacific Northwest are described by Papendick (2004).

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