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Eight years of annual no-till cropping in Washington's winter wheat-summer fallow region

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Abstract

The tillage-based winter wheat (*Triticum aestivum* L.)-summer fallow (WW-SF) cropping system has dominated dryland farming in the Pacific Northwest USA for 125 years. We conducted a large-scale multidisciplinary 8-year study of annual (i.e., no summer fallow) no-till cropping systems as an alternative to WW-SF. Soft white and hard white classes of winter and spring wheat, spring barley (*Hordeum vulgare* L.), yellow mustard (*Brassica hirta* Moench), and safflower (*Carthamus tinctorius* L.) were grown in various rotation combinations. Annual precipitation was less than the long-term average of 301 mm in 7 out of 8 years. Rhizoctonia bare patch disease caused by the fungus *Rhizoctonia solani* AG-8 appeared in year 3 and continued through year 8 in all no-till plots. All crops were susceptible to rhizoctonia, but bare patch area in wheat was reduced, and grain yield increased, when wheat was grown in rotation with barley every other year. Remnant downy brome (*Bromus tectorum* L.) weed seeds remained dormant for 6 years and longer to heavily infest recrop winter wheat. There were few quantifiable changes in soil quality due to crop rotation, but soil organic carbon (SOC) increased in the surface 0–5 cm depth with no-till during the 8 years to approach that found in undisturbed native soil. Annual no-till crop rotations experienced lower average profitability and greater income variability compared to WW-SF. Yellow mustard and safflower were not economically viable. Continuous annual cropping using no-till provides excellent protection against wind erosion and shows potential to increase soil quality, but the practice involves high economic risk compared to WW-SF. This paper provides the first comprehensive multidisciplinary report of long-term alternative annual no-till cropping systems research in the low-precipitation region of the Pacific Northwest.

1. Introduction

An agroecosystem approach to dryland farming is needed in the low-precipitation (<340 mm annual) dryland cropping zone of the inland Pacific Northwest because the widespread practice of growing only one crop every 2 years in a tillage-intensive WW-SF rotation has degraded soils and contributed to environmental problems. Blowing dust from excessively tilled soil is the major soil loss and agricultural environmental concern in the 1.5 million hectare WW-SF region.

Soils in the region are particularly vulnerable to wind erosion due to the dry environment, limited vegetation, high winds, intensive tillage, and because they contain substantial quantities of readily erodible and suspendible fine particulates (Papendick, 2004). Fine particulate emissions during dust storms are hazard to motorists due to lack of visibility

Table 1

Plant available soil water in the 1.8 m soil profile in the continuous annual soft white spring wheat treatment at time of sowing in late March or early April, September–March precipitation, growing season precipitation, and 12-month total precipitation during the 8-year experiment as well as the 30-year average near Ritzville, Washington

Year	Available soil water[a]	Precipitation (mm)						
		September–March	April	May	June	July	August	12-month total
1997	257	389	35	34	20	6	2	486
1998	133	195	7	36	12	25	7	282
1999	122	170	6	4	9	2	8	199
2000	123	164	18	13	24	11	0	230
2001	81	144	19	22	5	2	12	204
2002	115	182	12	21	19	7	1	242
2003	146	221	31	12	2	0	3	269
2004	89	126	20	34	1	0	7	188
8-year average	134	199	18	22	11	7	5	262
30-year average[b]		212	23	26	18	11	11	301

[a] Available soil water for cereals was calculated as total volumetric soil water (%) in the 1.8 m soil profile minus 6.0%.

[b] The 30-year (1974–2004) average precipitation is for the city of Ritzville located 7 km east of the experiment site.

and are a health concern when inhaled into lungs (Saxton et al., 2000). These soils have lost 50% of their original SOC in the surface 10 cm from topsoil erosion and oxidation since the onset of farming (Kennedy et al., 2004). Options for maintaining and improving soil quality are to increase the cropping intensity and reduce or eliminate tillage.

The WW-SF system is popular with farmers because it provides relatively stable grain yields and poses less economic risk compared to wheat or barley grown on an annual basis (i.e., one crop each year) (Young et al., 1999). Tillage practices for the WW-SF system frequently involving eight or more passes with various tillage implements during the 13-month fallow period. Conservation-till and no-till farming methods have become increasingly popular with farmers in many areas of the world, but adoption of such practices in the low-precipitation dryland zone in the Pacific Northwest has been limited (Schillinger et al., 2006).

The objective of our experiment was to evaluate the agronomic and economic feasibility of long-term no-till annual crop production in a typical WW-SF production region. A further objective was to document soil quality changes and benefits that may occur during the transition period from intensively tilled WW-SF to no-till annual cropping.

2. Materials and methods

2.1. Treatments

An 8-year field study of no-till annual cropping systems was conducted from 1997 to 2004 at the Ronald Jirava farm near Ritzville, Washington. The soil at the experiment site is a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll) (US classification system), also known as a Haplic Kastanozems (FAO/UNESCO, 1990). Soil is more than 2 m deep with no rocks or restrictive layers

and slope is less than 1%. The bulk density of native (i.e., never been farmed) soil is 1.09 and 1.10 g cm^{-3} in the 0–5 and 5–10 cm depths, respectively, whereas bulk density at the cropped experiment site averaged 1.09 g cm^{-3} in the 0–5 cm depth and 1.23 g cm^{-3} in the 5–10 cm depth.

Thirty-year average annual precipitation for the site is 301 mm (Table 1). The field where the experiment was conducted had been planted to soft white spring wheat (SW) in 1996 following decades of WW-SF. In Phase I (1997–2000) of the experiment, cropping systems were: (i) a 4-year safflower (SAF)-yellow mustard (YM)–SW–SW crop rotation, (ii) a 2-year SW-spring barley (SB) rotation and, (iii) continuous annual SW (Table 2). Experimental design was a randomized complete block with four replications. Each crop in all rotations occurred each year in 20 m × 150 m plots, making a total of 28 plots. The 4-year rotation was designed primarily to test the effects of back-to-back broadleaf crops on the epidemiology of soil fungal diseases that plague monoculture wheat.

In Phase II (2001–2004) of the experiment, existing plots were split along the long axis (i.e., from 20 m × 150 m to 10 m × 150 m for a total of 56 plots) to introduce the

Table 2

Crop rotations during Phase I (1997–2000) and Phase II (2001–2004) of a no-till annual cropping systems study near Ritzville, Washington

Years 1997–2000	Years 2001–2004
Four-year rotations	
SAF–YM–SW–SW	WW–WW–SW–SW
	WW–SB–YM–SW
Two-year rotations	
SW–SB	SW–SB
	HW–SB
Continuous spring wheat	
Continuous SW	Continuous SW
	Continuous HW

HW, hard white spring wheat; SAF, safflower; SB, spring barley; SW, soft white spring wheat; WW, soft white winter wheat; YM, yellow mustard.

following cropping systems: (i) a 4-year WW–WW–SW–SW rotation, (ii) 4-year WW–SB–YM–SW rotation, (iii) a 2-year SW–SB rotation (retained from Phase I), (iv) a 2-year hard white spring wheat (HW)–SB rotation, (v) continuous annual SW (retained from Phase I) and, (vi) continuous annual HW (Table 2). Both phases of the experiment were designed in consultation with an advisory group of 15 regional dryland wheat farmers.

2.2. Field operations

In the first 3 years (1997–1999), all plots were planted and fertilized in one-pass directly into the undisturbed soil and residue left by the previous crop using the cooperating farmer's Flexi-Coil[TM] 6000 air-delivery no-till drill equipped with Barton II[TM] dual-disk openers on 19 cm row spacing. Thereafter, all plots were planted and fertilized in one-pass using a custom-built no-till drill equipped with Cross-slot[TM] notched-coulter openers on 20 cm row spacing. Both drills cause little soil disturbance and provide simultaneous and precise placement of seed and fertilizer, with the fertilizer placed beneath and slightly to one side of the seed.

In early March, glyphosate [N-(phosphonomethyl)glycine] herbicide was applied 2–4 weeks before planting spring crops at a rate of 0.43 kg acid equivalent (a.e.) ha^{-1} to control weeds and limit the buildup of fungal inoculum on living hosts between harvest and planting (Smiley et al., 1992). Spring crops were planted in a 2-day period during the last week in March or first week of April each year. In Phase II, winter wheat was planted in late October or early November after the onset of fall rains. Seeding rate over the years was held constant at: (i) 34 kg ha^{-1} for safflower, (ii) 8 kg ha^{-1} for yellow mustard, (iii) 78 kg ha^{-1} for SW, HW, and SB, and (iv) 65 kg ha^{-1} for WW (Table 2). Solution 32 (NH$_4$NO$_3$ + urea) provided the base for liquid fertilizer to supply an average of 39 kg N, 8 kg P (aqueous solution of NH$_4$H$_2$PO$_4$), and 11 kg S (aqueous solution of (NH$_4$)$_2$S$_2$O$_3$) ha^{-1}. Fertilizer rate was kept the same for all spring crops during each year. Soil water content and residual soil N, P, and S was measured in all rotations in mid-March to determine fertilizer needs for spring crops based on a yield goal. For WW, fertilizer rate was determined by measuring residual soil N, P, and S, but not soil water as soils were dry at the time of fall planting. Thus, the fertilizer rate for WW differed slightly from that of spring crops (Tables 3a and 3b). The cultivars used were 'Alpowa' SW, '377S' HW, 'Baronesse' barley, 'Eltan' WW, 'Ida Gold' yellow mustard, and 'Common' safflower.

Between the tillering and jointing plant development growth stage of wheat and barley (Large, 1954), in-crop broadleaf weeds were controlled with 2,4-D (2,4-dichlorophenoxyacetic acid) ester, dimethylamine salt of dicamba (3,6-dichloro-2-methoxybenzoic acid) and other herbicides as shown in Tables 3a and 3b. No in-crop herbicides were labeled/legally available for safflower and yellow mustard.

Table 3a
Generalized field operations and inputs for spring-planted wheat, barley, yellow mustard, and safflower at Ritzville, Washington, 1997–2000

Date	Wheat	Barley	Yellow mustard	Safflower
15 March	Herbicide: 0.43 kg a.e. ha^{-1} glyphosate	Herbicide: 0.43 kg a.e. ha^{-1} glyphosate	Herbicide: 0.43 kg a.e. ha^{-1} glyphosate	Herbicide: 0.43 kg a.e. ha^{-1} glyphosate
4 April	Planted at 78 kg ha^{-1} and fertilized at 40 kg N, 10 kg P, and 10 kg S ha^{-1}	Planted at 76 kg ha^{-1} and fertilized at 40 kg N, 10 kg P, and 10 kg S ha^{-1}	Planted at 8 kg ha^{-1} and fertilized at 40 kg N, 10 kg P and 10 kg S ha^{-1}. Replanted on 29 April in 1998 and 1999 after killing frost	Planted at 34 kg ha^{-1} and fertilized at 50 kg N, 11 kg P, and 11 kg N ha^{-1}. Safflower was discontinued in 2001
18 May	In-crop broadleaf herbicide: 0.46 kg a.e. ha^{-1} 2,4-D in 1999 and 2000. 2,4-D plus 0.02 L ai ha^{-1} thrifensulfuron + tribenuron in 1998 and 2000. 2,4-D plus 0.08 kg a.e. ha^{-1} dicamba in 2001	In-crop broadleaf herbicide: 0.46 kg a.e. ha^{-1} 2,4-D in 1999 and 2000. 2,4-D plus 0.02 L ai ha^{-1} thrifensulfuron + tribenuron in 1998 and 2000. 2,4-D plus 0.08 kg a.e. ha^{-1} dicamba in 2001		
9 August	Harvest	Harvest	Harvest	
18 August	Post-harvest herbicide: 0.42 kg ai ha^{-1} paraquat + 0.21 kg ai ha^{-1} diuron in 1999 and 2000	Post-harvest herbicide: 0.42 kg ai ha^{-1} paraquat + 0.21 kg ai ha^{-1} diuron in 1999	Post-harvest herbicide: 0.42 kg ai ha^{-1} paraquat + 0.21 kg ai ha^{-1} diuron	
3 September				Harvest
11 September				Post-harvest herbicide: 0.42 kgai ha^{-1} paraquat + 0.21 kg ai ha^{-1} diuron

Table 3b
Generalized field operations and inputs for winter wheat, spring wheat, spring barley, and yellow mustard at Ritzville, Washington, 2001–2004

Date	Winter wheat	Spring wheat	Spring barley	Yellow mustard
30 October	Planted at 65 kg ha^{-1} and fertilized at 34 kg N, 8 kg P, and 8 kg S ha^{-1}			
16 March	Herbicide: 0.035 kg ai ha^{-1} sulfosulfuron applied to second-year winter wheat to control downy brome in 2002–2004	Herbicide: 0.39 kg a.e. ha^{-1} glyphosate	Herbicide: 0.39 kg a.e. ha^{-1} glyphosate	Herbicide: 0.39 kg a.e. ha^{-1} glyphosate
1 April	Planted at 73 kg ha^{-1} and fertilized at 37 kg N, 5 kg P, and 6 kg S ha^{-1}	Planted at 73 kg ha^{-1} and fertilized at 37 kg N, 5 kg P, and 6 kg S ha^{-1}	Planted at 73 kg ha^{-1} and fertilized at 37 kg N, 5 kg P, and 6 kg S ha^{-1}	Planted at 8 kg ha^{-1} and fertilized at 37 kg N, 5 kg P, and 6 kg S ha^{-1}. Replanted twice in 2002 and once in 2004 after earlier plantings were killed by frost
28 April	In-crop broadleaf herbicide: 0.68 kg a.e. ha^{-1} 2,4-D ester + 0.12 kg ha^{-1} dicamba			
17 May		In-crop broadleaf herbicide: 0.52 kg a.e. ha^{-1} 2,4-D ester + 0.10 kg a.e. ha^{-1} dicamba	In-crop broadleaf herbicide: 0.52 kg a.e. ha^{-1} 2,4-D ester + 0.10 kg a.e. ha^{-1} dicamba	
1 August	Harvest	Harvest	Harvest	Harvest. There was no harvest of yellow mustard in 2002 as both plantings were killed by frost
12 August	Post-harvest herbicide: 0.42 kg ai paraquat + 0.21 kg ai ha^{-1} diuron	Post-harvest herbicide: 0.42 kg ai paraquat + 0.21 kg ai ha^{-1} diuron	Post-harvest herbicide: 0.42 kg ai paraquat + 0.21 kg ai ha^{-1} diuron	Post-harvest herbicide: 0.42 kg ai paraquat + 0.21 kg ai ha^{-1} diuron

Russian thistle (Salsola iberica), a major broadleaf weed of spring-planted crops, was present at time of grain harvest in late July in 6 of 8 years. When present, Russian thistle was controlled 7–10 days after grain harvest with paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) plus diuron [N'-(3,4-dichlorophenyl)-N,N-dimethylurea] (Tables 3a and 3b).

2.3. Survey of winter wheat grain yield from neighboring farms

Although WW-SF was not included in the replicated experiments in Phase I or II, grain yield of this traditional system was determined by conducting two multiple-year surveys of WW grain yields after summer fallow. The surveys covered 1997–2000 and 2001–2004 and included WW-SF farmers within a 7 km radius of the experiment. All farmers in the survey area practiced the traditional tillage-based method of WW-SF farming. The climate and soils of the neighboring farms of survey area are similar to the experiment site. A one-page mailed questionnaire was used. Multiple-year winter wheat grain yield data were obtained from 10 and 9 farms in the first and second surveys, respectively, corresponding to 59% and 53% response rates. Further details on the survey methods and approach are found in Juergens et al. (2004).

2.4. Measurements

2.4.1. Soil water content

In Phase I, water content in a 1.8 m soil profile was measured in all 28 plots each spring before planting and again after grain harvest. Soil volumetric water content in the 0–0.3 m depth was determined from two 0.15 m core samples using gravimetric procedures and in the 0.3–1.8 m depth in 0.15 m increments by neutron attenuation (Gardner, 1986). In Phase II, soil water content was measured, using the procedures described above, in 44 of 56 plots. Because of labor and time constraints, soil water content was not measured in the 2-year HW–SB rotation or in continuous annual HW because we felt data would be similar to those measured in the 2-year SW–SB rotation and in continuous annual SW. Precipitation was measured on site during all years with a computerized weather station.

Available soil water for spring cereals was calculated as average volumetric soil water (%) in the 1.5 m soil profile minus 6.0%, whereas available water for winter wheat was considered volumetric soil water (%) in the 1.8 m profile minus 4.5%. These formulas were developed from experiments that showed winter wheat develops a deeper root system and extracts soil water to a greater degree compared to spring cereals (Leggett, 1959).

2.4.2. Rhizoctonia bare patch disease

Rhizoctonia bare patches first appeared during year 3 of the experiment in 1999 and were present every year thereafter. The location, size, and area of patches were

determined with a Pathfinder Pro XR[TM] global positioning system (GPS) equipped with mapping software. Measurements were obtained by circling each clearly visible rhizoctonia patch with the backpack-mounted GPS mapping unit. Rhizoctonia bare patch areas were mapped every year from 1999 to 2004, except in 2001 when drought made it difficult to discern the border areas between rhizoctonia bare patches and severely water-stressed wheat and barley.

2.4.3. Weeds

Weeds species were identified, counted, and collected just before grain harvest within a 3 m^2 sample 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 them on a digital scale accurate to 0.01 g.

2.4.4. Plant stand and grain yield

Crop plant stand establishment was determined by counting individual plants in a 1 m^2 area 21 days after planting. Measurement were obtained from three areas in each plot and the numbers then averaged. Grain yield was determined using a commercial combine to harvest a 6.1 m × 150 m area in each plot and weighing the grain in a weigh wagon. The combine was equipped with a chaff spreader and straw chopper to evenly distribute chaff and straw along the width of the combine cutting platform.

2.4.5. Soil quality

Soil samples for laboratory analysis were obtained from 0–5 and 5–10 cm depths in October of 1997, 1999, and November of 2002 and 2005. Seven soil samples, each a composite of seven cores, were taken randomly across the plots or nearby native sites using a king tube having a 5 cm core diameter. Native sites were three rural cemeteries where farming or other soil disturbance had never occurred. Soils were stored at 4 °C until analysis, which occurred within 2 weeks after sampling.

The pH and electrical conductivity (EC) were determined by preparing a 1:1 soil to water slurry and allowing samples to reach equilibrium at room temperature (Smith and Doran, 1996). The pH was determined with an Orion Research 811 (Boston, MA) pH meter. Electrical conductivity was measured using a digital conductivity meter (VWR International, Bristol, CT). Dehydrogenase enzyme activity (DEA) was determined as described by Tabatabai (1994). Total soil C was determined with a LECO CNS analyzer (LECO, St. Joseph, Michigan) using soil that was oven dried and ground to pass a 1 mm sieve.

2.5. Economic assessment

Standard enterprise budgets were used to assess the profitability of the no-till cropping systems and the surveyed traditional WW-SF system in both Phases I and II of the experiment (Juergens et al., 2004). Costs were based on the actual sequence of operations in the research plots and those of the surveyed WW-SF farmers. Fertilizer, herbicide, seed and other input rates for each rotation were averages used during the experiment and on the surveyed farms. Experiment systems assumed typical farm-scale machinery for the region. Total costs, including cash and non-cash costs, were enumerated for each practice and crop. These costs include a fair market return for the farmer's land, machinery, and labor. Under such total cost budgeting, a "fair or normal profit" would be zero. Anything less than zero implies the farmer is receiving less than market returns for his/her labor, land, and other resources. Grain yields were those measured from the experiment or enumerated from the survey. All cost and revenue figures are presented on a rotational hectare basis; for example, WW-SF includes one half hectare of WW and one half hectare of SF. This ensures comparability on a standard $ ha^{-1} basis for differing crop rotations.

To reflect changing market conditions and the inclusion of different crops, separate current crop and input prices were used for Phases I and II of the experiment. In Phase I, soft white wheat and feed barley prices used are $123.46 and $92.70 Mg^{-1}, respectively. These are the regional average 1997–2001 farm gate prices (Washington Agricultural Statistics Service, various issues). Safflower and yellow mustard price of $264.55 Mg^{-1} was the average contract price that regional farmers received during the period. Whenever possible, 5-year average farm gate commodity prices were used to compute gross revenue for each crop in each rotation. For Phase II, the 2001–2004 annual average farm gate commodity prices for soft white wheat, feed barley, and yellow mustard were $116.88, $99.03, and $326.28 Mg^{-1}, respectively. The 2002–2004 3-year average farm gate commodity price for hard white wheat was $116.88 Mg^{-1}.

2.6. Statistical procedures

Analysis of variance was conducted for soil water content, crop plant stand establishment, rhizoctonia bare patch area, weed populations, grain yield, various soil properties, and net returns over total costs (SAS, 1999). The Bonferroni method was used to control the experiment wise error rate for multiple comparisons. All analysis of variance tests were done at the 5% level of significance.

3. Results and discussion

3.1. Precipitation and soil water

Crop year (1 September–31 August) precipitation during the 8-year period ranged from 188 to 486 mm and averaged 262 mm (Table 1). Long-term (30-year) precipitation for the
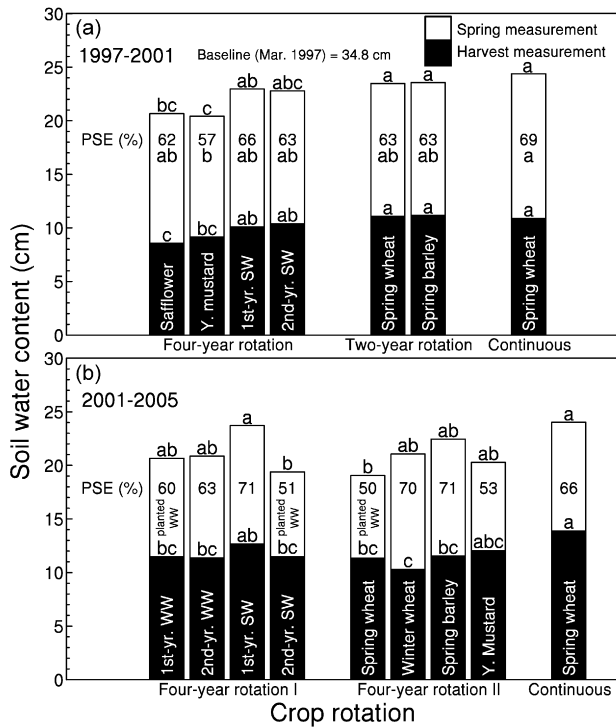
Fig. 1. Soil water content measured after grain harvest in July/August (black bars) and again in mid-to-late March (white bars) during Phase I (A) and Phase II (B) of an 8-year cropping systems experiment near Ritzville, Washington. Precipitation storage efficiency (PSE) is the percentage of over-winter precipitation that was stored in the soil. Soil water content means among crop rotations for each sampling date followed by the same letter are not significantly different at $P < 0.05$.

site averages 301 mm. Below average precipitation occurred in seven of the eight crop years.

Plant available soil water in late winter/early spring (measured just before planting) for the continuous annual soft white spring wheat treatment ranged from 81 to 257 mm and averaged 134 mm over the 8 years (Table 1). Wheat farmers in the Inland PNW generally will not consider planting spring cereals unless there is a minimum of 125 cm of available soil water at the time of planting (Schillinger, 2005).

Average soil water content at time of grain harvest in July/August and in mid-to-late March is shown for all crops in all rotations for Phases I (Fig. 1a) and II (Fig. 1b). Safflower and yellow mustard tended to use more water by harvest than spring wheat or spring barley during Phase I, resulting in significantly less soil water in the soil profile for crops following safflower and yellow mustard compared to after spring cereals (Fig. 1a). Over-winter precipitation storage efficiency (PSE), the percentage of precipitation occurring between summer harvest and spring planting that was stored in the soil, ranged from 57 to 69% and was lowest following yellow mustard, presumably because little residue remained on the soil after harvest of this crop. The benefits of crop residue for enhancing over-winter PSE in a Mediterranean climate have been described by Papendick and McCool (1994). There were no differences between spring wheat and spring barley in soil water use or soil over-winter PSE (Fig. 1a).

In Phase II, soil water used by the time of grain harvest tended to be slightly greater for winter wheat compared to

Table 4
Percentage plot area with bare patches caused by *Rhizoctonia solani* AG8 from 1999 to 2004[a]

Rotation	1999	2000	Rotation	2002	2003	2004
Four year			Four year I		[b]	
Spring wheat	4.2	4.5	Winter wheat	9.6	6.3 cd	8.6 cde
Spring wheat	9.9	9.2	Winter wheat	13.6	8.8 bcd	8.4 cde
Safflower		7.3	Spring wheat	11.7	17.6 a	19.7 a
Yellow mustard		11.1	Spring wheat	10.2	10.2 bcd	14.6 ab
Two year			Four year II			
Spring wheat	4.8	5.8	Winter wheat	10.5	8.6 bcd	8.8 cde
Spring barley	10.1	9.1	Spring barley	14.4	11.0 bcd	18.8 a
Continuous			Yellow mustard	[c]	18.1 a	14.6 ab
Spring wheat	8.5	11.9	Spring wheat	12.3	5.2 d	9.7 bcde
Average	7.5	8.4	Two year I			
			Spring wheat	7.2	5.7 d	7.3 de
			Spring barley	11.1	12.3 abc	10.3 bcde
			Two year II			
			HW spring wheat	7.9	6.1 cd	5.3 e
			Spring barley	7.4	12.0 abc	6.7 de
			Continuous spring wheat			
			SW spring wheat	17.7	13.7 ab	12.9 bc
			HW spring wheat	18.0	14.6 ab	12.0 bcd
			Average	11.7	10.7	11.3

Within-year means followed by the same letter are not significantly different at $P < 0.05$.

[a] Rhizoctonia bare patch area was not mapped in 2001 when drought made it difficult to discern the border areas between rhizoctonia bare patches and severely water-stressed crops.

[b] Within-column means followed by the same letter are not significantly different at $P < 0.05$.

[c] Yellow mustard was planted twice and killed both times by frost in 2002. Yellow mustard plots were thereafter left in chemical summer fallow for the 2002 crop year, thus rhizoctonia bare patches were not present.

spring cereals (Fig. 1b). The soil profile was driest after yellow mustard during 3 of 4 years in Phase II, but this is not reflected in the 4-year average in Fig. 1b. Yellow mustard was planted twice and seedlings killed both times by frost in April 2002, therefore this treatment was left fallow in the 2002 crop year, resulting in 81 mm of available water remaining in the soil when the other treatments were harvested. Over-winter PSE ranged from 50 to 71% in Phase II. The lowest over-winter PSE was generally in treatments planted to winter wheat (i.e., water used by winter wheat seedlings during the late fall and winter) and, as in Phase I, following yellow mustard.

3.2. Rhizoctonia bare patch disease

Rhizoctonia bare patch caused by *Rhizoctonia solani* AG-8 first appeared in year 3 (1999) of the experiment (Cook et al., 2002) and continued through year 8. This fungal pathogen is unique to no-till farming and can be eliminated with tillage (Rovira, 1986). Rhizoctonia infected all crops in all rotations. Total bare patch area averaged across crops ranged from 7.5 to 11.7% of total plot area between 1999 and 2004 (Table 4). There were no differences in the total area of bare patches among treatments from 1999 to 2002, but in 2003 and 2004, bare patch area tended to be greatest in crops following winter wheat (Table 4), presumably due to increased water stress. Significantly lower levels of rhizoctonia bare patch were measured in 2003 and 2004 for both soft white and hard white classes of wheat in the 2-year SW–SB rotation compared to continuous annual monoculture of these two wheat classes (Table 4); thus providing the first documentation of suppression of rhizoctonia bare patch disease in low-disturbance no-till systems with rotation of cereal crops (Schillinger and Paulitz, 2006).

The severity of rhizoctonia bare patch disease was strikingly evident from photos taken by airplane as well as from the GPS-based maps (Fig. 2). An overlay of maps over
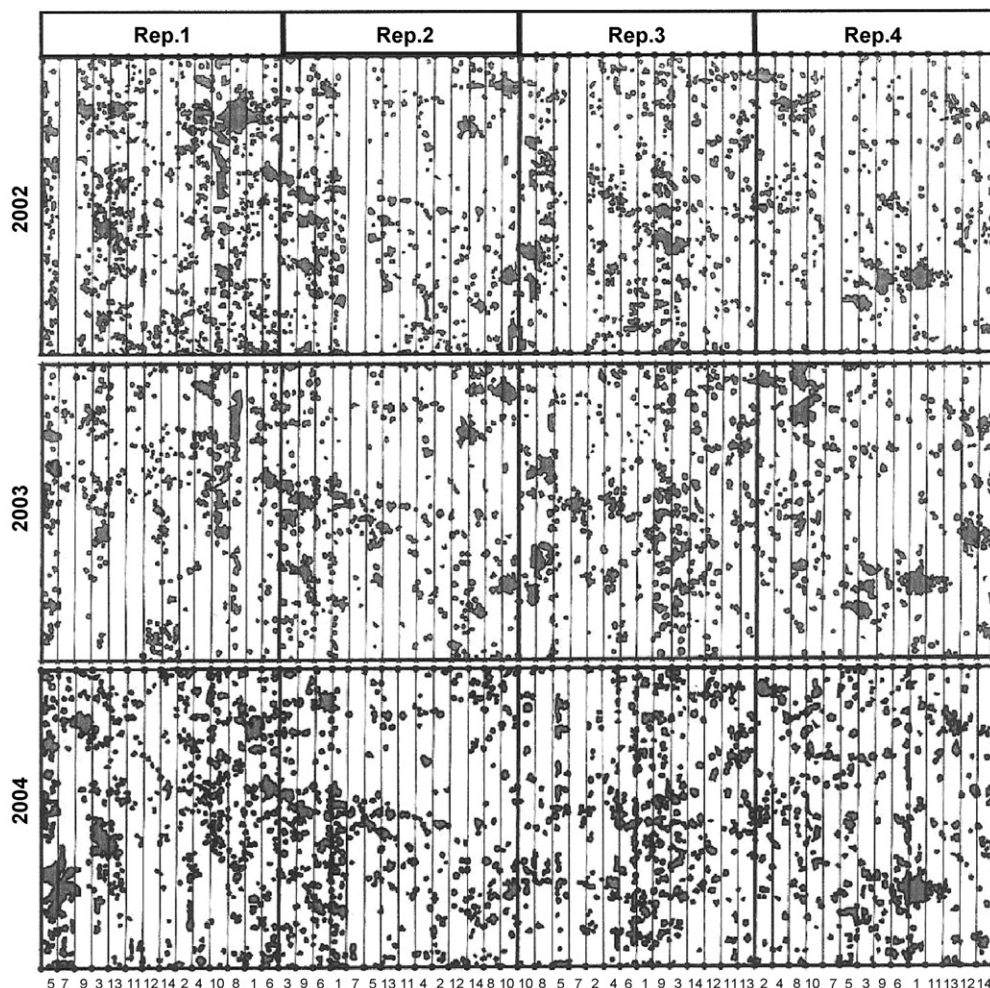

Fig. 2. Distribution of rhizoctonia bare patches mapped with a backpack-mounted global positioning system in June 2002–2004 in the long-term no-till cropping systems study near Ritzville, Washington. There are no rhizoctonia bare patches in plots marked number 7 in 2002 because yellow mustard was killed by frost and these plots were then left fallow for the remainder of the 2002 crop year.

years showed that some bare patches persisted with the same size and shape from year to year while in other areas new patches appeared and others had disappeared.

3.3. Weeds

3.3.1. Phase I (1997–2000)

Russian thistle (Holm et al., 1997) was by far the most troublesome broadleaf weed throughout the experiment. Russian thistle produces a prolific number of seeds in late summer that germinate in repeated flushes the next spring after rainfall events of 3 mm or more. The most severe infestations occur when Russian thistle seedlings become established before crop canopy closure. During Phase I, Russian thistle produced an average of 16 plants m^{-2} or more in safflower and yellow mustard (Table 5a) because there were no herbicides labeled for in-crop control of broadleaf weeds in these broadleaf crops. Both the number of plants and dry biomass produced by Russian thistle at time of grain harvest were significantly greater in safflower and yellow mustard compared to spring-sown wheat and barley (Table 5a).

Horseweed (Conyza canadensis L.), prickly lettuce (Lactuca serriola L.), common lambsquarters (Chenopodium album L.), tumble mustard (Sisymbrium altissimum L.), and tansy mustard (Descurainia pinnata Walt.) are broadleaf weeds that were present, but were much less problematic compared to Russian thistle (Table 5a). With the

exception of horseweed and Russian thistle, all the other broadleaf weeds mentioned above were found only in safflower and yellow mustard. This indicates that minor broadleaf weeds can be effectively controlled following back-to-back broadleaf crops when the rotation reverts to cereals.

Downy brome, a winter annual with a growth cycle similar to winter wheat, is the most problematic grass weed in the traditional 2-year WW-SF rotation because of the high frequency of winter wheat. Although remnant downy brome seeds germinated and established in late fall and winter, this weed was effectively controlled with glyphosate herbicide prior to planting spring crops. Downy brome seed production was essentially non-existent in all crop rotations during all years in Phase I.

3.3.2. Phase II (2001–2004)

The major weeds in Phase II of the experiment were Russian thistle and downy brome. Prickly lettuce, horseweed, lambsquarters, and tansy mustard were also present but at very low levels. The population of Russian thistle was significantly greater in yellow mustard than in any of the cereal crops (Table 5b). Continuous annual hard white wheat had a higher population of Russian thistle than any other cereal, presumably due to the greater-than-average rhizoctonia bare patch area in this treatment. Although all Russian thistle seedlings within the bare patches caused by Rhizoctonia solani AG-8 were stunted and many Russian

Table 5a

Average population and dry biomass of five weeds, as well as total weeds, from 1997 to 2000 as affected by crop and crop rotation

	Russian thistle	Horse-weed	Prickly lettuce	Lambs-quarterss	Tumble mustard	Tansy mustard	Total[a] weeds
Population (plants m^{-2})							
Four-year rotation[b]							
Safflower	16 a[c]	1	1 a	1 a	1 a	1 a	21 a
Yellow mustard	18 a	1	1 a	1 a	1 a	1 a	23 a
First-year wheat	5 b	0	0 b	0 b	0 b	0 b	6 b
Second-year wheat	2 b	1	0 b	0 b	0 b	0 b	5 b
Two-year rotation							
Wheat	3 b	1	0 b	0 b	0 b	0 b	5 b
Barley	3 b	1	0 b	0 b	0 b	0 b	4 b
Continuous s. wheat	4 b	1	0 b	0 b	0 b	0 b	5 b
Dry biomass (kg ha^{-1})							
Four-year rotation							
Safflower	851 a	66 a	81 a	11 ab	80 a	118 a	1229 a
Yellow mustard	961 a	32 ab	28 b	32 a	62 a	135 a	1250 a
First-year wheat	179 b	0 b	0 b	0 b	0 b	0 b	184 b
Second-year wheat	158 b	20 b	0 b	0 b	0 b	0 b	178 b
Two-year rotation							
Wheat	86 b	6 b	0 b	0 b	0 b	0 b	98 b
Barley	54 b	4 b	0 b	0 b	0 b	0 b	63 b
Continuous s. wheat	140 b	10 b	0 b	0 b	0 b	0 b	161 b

[a] Total weeds also includes small quantities of Canada thistle (Cirsium arvense L. Scop.), prostrate knotweed (Polygonum aviculare L.), and redroot pigweed (Amaranthus retroflexus L.).

[b] First- and second-year wheat after broadleaf crops began in 1998 and 1999, respectively.

[c] Within-column means followed by the same letter are not significantly different at $P < 0.05$.

Table 5b
Average population and dry biomass of Russian thistle and downy brome, as well as total weeds, from 2001 to 2004 as affected by crop and crop rotation

	Population (plants m^{-2})			Dry biomass (kg ha^{-1})		
	Russian thistle	Downy[a] brome	Total[b] weeds	Russian thistle	Downy brome	Total weeds
Four-year rotation I						
Spring wheat	1 c[c]	4 b	5 bc	31 c	29 b	60 c
Spring wheat	2 c	0 c	2 cd	36 c	0 c	36 cd
Winter wheat	2 c	8 b	10 b	19 c	35 ab	54 c
Winter wheat	1 c	20 a	21 a	13 c	54 a	67 c
Four-year rotation II						
Spring wheat	3 c	0 c	3 cd	42 c	0 c	42 cd
Winter wheat	2 c	18 a	20 a	56 c	35 ab	91 c
Spring barley	1 c	0 c	1 d	12 c	0 c	12 d
Yellow mustard	11 a	0 c	13 ab	548 a	0 c	579 a
Two-year rotation I						
Spring wheat	1 c	0 c	1 d	3 c	0 c	3 d
Spring barley	1 c	0 c	1 d	3 c	0 c	3 d
Two-year rotation II						
Hard white SW	1 c	0 c	1 d	17 c	0 c	17 d
Spring barley	1 c	0 c	1 d	2 c	0 c	2 d
Continuous spring wheat						
Soft white	1 c	0 c	1 d	6 c	0 c	6 d
Hard white	6 b	0 c	6 bc	206 b	0 c	206 b

[a] Downy brome population was measured as the number of individual whole plants. Many individual downy brome plants had 20 or more productive tillers.
[b] Total weed biomass also includes small quantities of prickly lettuce, horseweed, lambsquarters and tansy mustard.
[c] Within-column means followed by the same letter are not significantly different at $P < 0.05$.

thistle seedlings killed by the fungus, some Russian thistle plants survived and ultimately flourished after their tap root was able to penetrate through the rhizoctonia-infected surface soil layer to reach available soil water below (Schillinger and Paulitz, 2006). The greatest Russian thistle infestations in cereal crops were always in rhizoctonia bare patch areas.

Similar to Phase I, remnant downy brome seeds (i.e., seeds produced before 1996) germinated and emerged each fall and winter but were effectively controlled with glyphosate herbicide prior to planting spring crops. The flush of downy brome seedlings each fall and winter was from seed present in the field prior to 1996 when the rotation was WW-SF as evidenced by the absence of downy brome plants (i.e., no seed production) measured in continuous annual spring-planted plots during the 8-year period (Tables 5a and 5b) and the fact that all fields within 400 m of the experiment area were planted to spring crops since 1996 (i.e., no contamination from neighboring fields). It is widely believed that few downy brome seeds remain viable under field conditions for longer than 2 years (Hulbert, 1955; Rydrych, 1974; Yenish et al., 1998). Anderson (2005) reported that weed seeds die rapidly if left on the soil surface and exposed to environmental extremes and predation and that no-till enhances this natural loss of weed seeds by maintaining seeds on the soil surface. This did not hold true in our study where data conclusively show that downy brome seeds can remain viable for 6 years and longer under field conditions before germinating in substantial flushes. Heavy infestations of downy brome

occurred in 2001 and subsequent years when winter wheat was introduced into the 4-year rotations (Table 5b).

3.4. Grain yield

Exceptionally high grain yields of all crops were obtained in 1997 (Table 6), the first year of the experiment, when an unusually high 486 mm of crop-year precipitation occurred. In the ensuing 7 years of less-than-average precipitation, grain yields of all crops plummeted. Grain yield of yellow mustard was particularly low and sporadic in the drought years in both Phases I and II (Table 6). Safflower (only grown in Phase I) was more resilient that yellow mustard because it has a large seed that emerged readily from the soil and seedlings tolerated early-spring frost. The 4-year-average grain yield for safflower was 32% greater compared to yellow mustard.

There were no significant differences in spring wheat grain yield as affected by crop rotation in Phase I (Table 6) even though first year spring wheat after two consecutive broadleaf crops had at least 20 mm less available soil water at time of planting each spring (data not shown) compared to the cereal-only treatments. This indicates that the broadleaf crops may have bestowed some rotation benefit to the subsequent wheat crop that compensated for less available soil water. Spring barley (in the 2-year rotation with SW) had the highest overall grain yield in Phase I and was the only treatment that had significantly greater yield than first year spring wheat after broadleaf crops (Table 6).

Due to ongoing drought, grain yields of crops in Phase II were considerably lower than in Phase I. In 2001, recrop

Table 6

Grain yield of crops in Phase I (1997–2000) and Phase II (2001–2004) of a long-term dryland cropping systems experiment near Ritzville, Washington

Rotation	Year (kg ha^{-1})				
	1997	1998	1999	2000	4-year average
Phase I					
Four year (kg ha^{-1})					
Safflower	1590[a]	737	1161	544	1008
Yellow mustard	1597	373	93	669	683
Spring wheat	4314 b	2759	1794	2665	2883 b
Spring wheat	4604 b	2789	1700	2561	2914 ab
Two year (kg ha^{-1})					
Spring wheat	4571 b	2707	1867	2956	3010 ab
Spring barley	5165 a	2530	1690	2914	3075 a
Continuous spring wheat	4345 b	2810	1805	2852	2953 ab

Rotation	Year (kg ha^{-1})				
	2001	2002	2003	2004	4-year average	8-year average
Phase II						
Four year I (kg ha^{-1})						
Winter wheat	446 bcd	1400 bc	2044 ab	1186 cde	1269 bcde	
Winter wheat	600 abcd	1433 ab	1952 abc	932 e	1229 cde	
Sprint wheat	558 abcd	1553 ab	1277 de	1544 bcd	1233 cde	
Spring wheat	642 abcd	1547 ab	1578 bcde	1788 ab	1389 abcd	
Four year II (kg ha^{-1})						
Winter wheat	321 d	1104 c	1966 abc	1071 cde	1115 de	
Spring barley	358 cd	1461 ab	1622 abcde	1625 bc	1267 cde	
Yellow mustard	392	[b]	164	390	315	
Spring wheat	823 ab	1441 ab	2091 a	1925 ab	1570 ab	
Two year I (kg ha^{-1})						
Spring wheat	781 abc	1670 ab	1751 abcd	2274 a	1619 a	2315
Spring barley	780 abcd	1681 ab	1791 abc	2347 a	1650 a	2362
Two year II (kg ha^{-1})						
Hard white	599 abcd	1502 ab	1787 abcd	1932 ab	1377 abc	
Spring barley	594 abcd	1737 a	1868 abc	2332 a	1633 a	
Continuous spring wheat						
Spring wheat	962 a	1460 ab	1497 cde	1037 de	1438 abc	2196
Hard white	432 bcd	1416 abc	1207 d	1834 ab	1023 d	

The class of wheat is soft white unless otherwise stated. Within-year and 4-year-average means followed by the same letter are not significantly different at $P < 0.05$.

[a] Safflower and yellow mustard were not included in the analysis of variance for grain yield. The analysis of variance was conducted only for cereal crops.

[b] Yellow mustard was planted twice in 2002 and killed both times by frost. This treatment was thereafter left in summer fallow for the remainder of 2002. The relatively high grain yield (i.e., 2091 kg ha^{-1}) of spring wheat in 2003 that followed yellow mustard in the rotation can be attributed, in part, to greater available soil water (data not shown) compared to the other treatments.

winter wheat and spring cereal yields were among the lowest ever experienced by area farmers. The lowest 4-year-average grain yields in Phase II (other than for yellow mustard that essentially failed in all 4 years) were for recrop winter wheat and for spring cereals following winter wheat in the rotation (Table 6). Spring barley and soft white spring wheat following another spring crop, especially following barley, generally achieved the highest grain yield. When data from the 2-year SW–SB and continuous SW rotations were analyzed separately in Phase II (i.e., without the two 4-year rotations), there was a significant rotation benefit for both soft white and hard white spring wheat grown in rotation with barley compared to continuous annual monoculture (Schillinger and Paulitz, 2006). We feel that the poor grain yield performance of recrop winter wheat was strongly linked to the

high downy brome infestation in this crop. In a related long-term dryland cropping systems experiment at Lind, Washington, where downy brome is not a major problem, recrop winter wheat consistently produced higher grain yield than spring wheat (WF Schillinger et al., unpublished).

Winter wheat after summer fallow grain yield varied considerably over years and among farmers in the Phase II yield survey. The lowest average annual yield was 2560 kg ha^{-1} in 2001 and the highest was 3520 kg ha^{-1} in 2003. All but one farmer experienced the lowest yield in 2001. The greatest yield variation across farmers occurred in 2004 with a range of 2290–4290 kg ha^{-1}. The average WW grain yield across farms and years was 3090 kg ha^{-1}. Differences in precipitation across years and management style among farmers within years likely contributed to WW

grain yield variability. Similar yield variation occurred in the Phase I WW-SF survey though average yields were higher (Juergens et al., 2004).

3.5. Soil quality

The soil pH varied with depth with the surface values being higher than at the lower depth (Fig. 3a and b). At the 0–5 cm depth, pH of 6.5 for the native undisturbed soil was consistent across all years. The pH values of native soils were 0.13–0.75 units higher than those from the cropping system experiment. Surface pH ranged from 5.8 to 6.4 and varied with year, but not with cropping system. At the 5–10 cm depth, pH ranged from 5.6 to 6.1. In 2002 and 2005 the native soil pH was significantly higher than the cropped treatments at the 5–10 cm depth. The pH did not differ among any of the cropping systems treatments tested.

Electrical conductivity was similar for all treatments and years and with depth (Fig. 3c and d). The average EC values

were 10.5 dS m^{-1} for the 0–5 cm depth and 10.6 dS m^{-1} for the 5–10 cm depth. While EC values for the native sites tended to be lower than the cropped treatments, the difference was not statistically significant and, in our opinion, not great enough to inhibit crop yield.

Dehydrogenase enzyme activity ranged from 2.4 to 5.3 μg triphenyl formazan (TPF) g^{-1} soil h^{-1} in the 0–5 cm depth and 1.1–4.4 μg TPF g^{-1} soil h^{-1} in the 5–10 cm depth (Fig. 3e and f). The DEA was similar at both depths for the native samples. For the various cropping systems plots, DEA was 1.3–4.2 μg TPF g^{-1} soil h^{-1} higher in the 0–5 cm than the 5–10 cm depth. There were no differences in DEA due to cropping system in the 5–10 cm depth, but there were differences among cropping systems in 2002 and 2005 for the surface samples. These differences were not consistent with any one crop or rotation. The 2-year SW-SB rotation had the highest DEA in both 2002 and 2005. Soil enzymes are often site-specific and dependent on soil characteristics rather than management (Bergstrom et al., 1998).
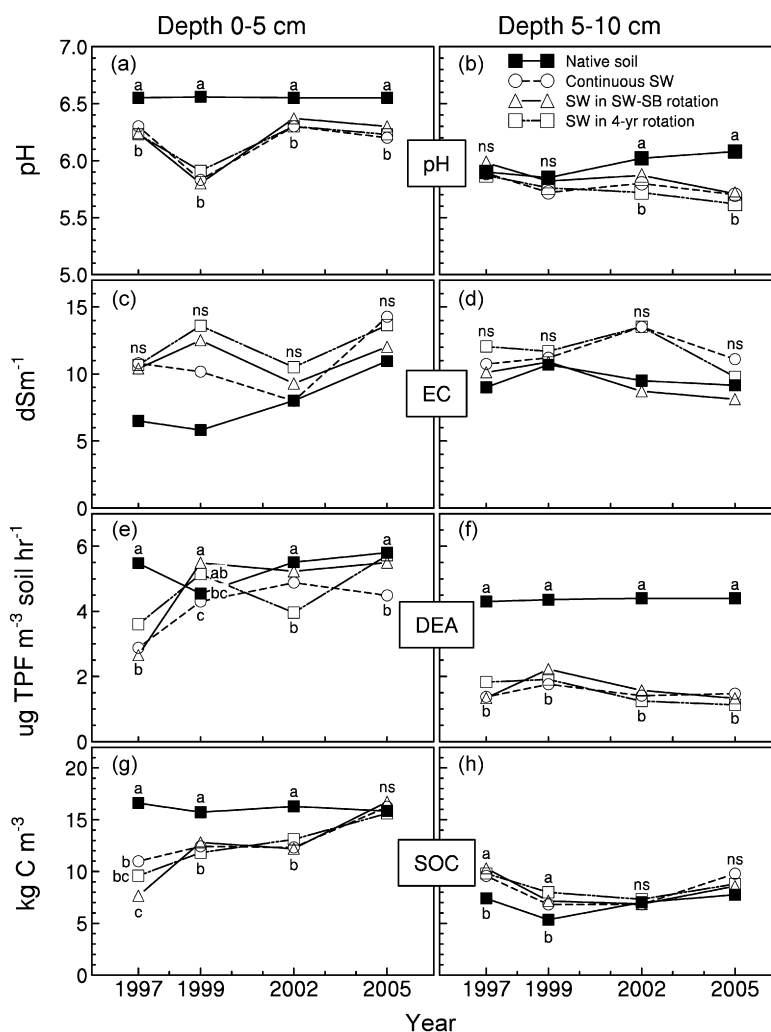

Fig. 3. The pH, electrical conductivity (EC), dehydrogenase enzyme activity (DEA), and soil organic carbon (SOC) of soils sampled from 0–5 and 5–10 cm depths from 1997 to 2005 of an 8-year cropping systems experiment. Within-year means followed by the same letter are not significantly different at $P < 0.05$. ns = not significant.

Table 7
Comparison of net returns over total costs by crop rotation and year and the 4-year average during Phase II (2001–2004) for six no-till crop rotations and winter wheat-summer fallow

Crop rotation[a]	$/rotational hectare/year				
	2001	2002	2003	2004	2001–004 average[b]
WW–WW–SW–SW	−175.31	−127.33	−85.09	−127.21	−128.73 ab
SW–SB–YM–SW	−170.30	−183.01	−107.11	−139.93	−150.09 b
SW–SB	−160.99	−113.46	−89.43	−66.99	−107.72 a
HW–SB	−170.94	−110.44	−77.63	−68.20	−106.80 a
Continuous SW	−141.78	−115.83	−90.62	−89.14	−109.34 a
Continuous HW	−186.35	−104.64	−108.49	−142.17	−135.41 ab
Survey: WW-SF average	−31.51	0.84	25.53	5.68	0.14

[a] HW, hard white spring wheat; SB, spring barley; SW, soft white spring wheat; WW, soft white winter wheat; YM, yellow mustard.

[b] Four-year average net returns for the cropping system treatments followed by the same letter are not significantly different at $P < 0.05$. The $LSD_{0.05}$ is $29.73 ha^{-1}.

Soil organic carbon was higher in the surface depth for all treatments and across all sampling years compared to the 5–10 cm depth (Fig. 3g and h). Soil organic carbon in the native sites was relatively constant for all sampling dates, averaging 14.6 g C kg^{-1} for the 0–5 cm depth and 6.9 g C kg^{-1}for the 5–10 cm depth. At the 0–5 cm depth, native values initially were higher than from the experiment site; however, SOC increased over time in no-till to approach the native SOC value (Fig. 3g). It is possible that the differences among cultivated and native soils are due, in part, to C and N depletion (Cavigelli and Robertson, 2000). With long-term cultivation, C and N pools are homogenized and C pools may be depleted more than 75% (Knops and Tilman, 2000). At the 5–10 cm depth, SOC values for the native sites were less than or equal to the cropped treatments. For the cropping system plots, SOC values ranged from 7.0 to 13.9 g C kg^{-1} in the 0–5 cm depth and 6.8–10.3 g C kg^{-1} at the 5–10 cm depth. There were essentially no differences in SOC among the cropping system treatments.

The positive effects of crop rotation on crop growth have been shown in numerous experiments and differences in the soil biology are thought to be mainly responsible (Shipton, 1977; Cook, 1981; Johnson et al., 1992). Crop rotation enhances beneficial microorganisms and microbial diversity, interrupts the cycle of pathogens, and reduces weed and insect populations. We did not find measurable changes in soil biological properties with diverse crop rotation in this study, most likely because these changes occur at a slow rate in such dry environments.

3.6. Economics

3.6.1. Phase I (1997–2000)

Economic results for Phase I were reported in Juergens et al. (2004) so they are summarized only briefly here to provide perspective on 8-year trends. The SAF–YM–SW–SW rotation ranked last among the three spring no-till rotations with negative returns over total costs of −$31.45 ha^{-1}. The 2-year SW–SB rotation also averaged losses of −$12.10 ha^{-1}. Continuous annual SW was the only spring no-till system to show positive net returns at

$12.11 ha^{-1}. The $LSD_{0.05}$ for the experiment systems was $31.16 ha^{-1} indicating significantly greater profitability for the top continuous annual SW system over the oilseed-based system. These results show a clear lack of economic viability for safflower and yellow mustard under the conditions of this experiment. During Phase I, WW-SF averaged a positive net return over total costs of $21.52 ha^{-1}. Surveyed WW-SF was not part of the experiment, but if one treated the WW-SF return as a fixed value for comparison, it would be statistically equivalent to continuous annual SW.

3.6.2. Phase II (2001–2004)

Table 7 shows economic results for the six no-till systems and for surveyed WW-SF in Phase II. None of the no-till annual rotations generated sufficient market returns to cover total costs during the drought conditions of 2001–2004. Average net returns ranged from −107.72 for SW–SB to −$150.09 for SW–SB–YM–SW (Table 7). As in Phase I, the rotation that included an oilseed ranked last in profitability. Five of the six rotations earned statistically equivalent negative returns over total costs. The HW–SB, SW–SB, and continuous annual SW rotations suffered slightly smaller, but still large, average annual losses of −$106.80, −$107.72, and −$109.34 ha^{-1}, respectively.

Returns over total costs for WW-SF averaged $0.14 per rotational hectare over 2001–2004. This result shows that the WW-SF farmers averaged market returns on their resources, despite the dry climatic conditions during Phase II. The economic advantage of WW-SF over all annual crop rotations substantially exceeded the $LSD_{0.05}$ of $29.73 ha^{-1} for the experiment (Table 7), providing statistical support for the profit superiority of WW-SF. The decreased profitability for all rotations in Phase II compared to Phase I can largely be attributed to yields reduced by diminished precipitation and soil water.

4. Summary and conclusions

1. The oilseed crops safflower and yellow mustard used more soil water by harvest compared to cereals, resulting

in significantly less available soil water for crops that followed in the rotation.

2. Rhizoctonia bare patch caused by *Rhizoctonia solani* AG-8 infected all crops in all rotations beginning in year 3 and continued through year 8. The area with bare patches averaged over all crops during these years ranged from 7.5 to 11.7% of total plot area.

3. Russian thistle was the most troublesome broadleaf weed in all spring-planted crops. Russian thistle was the only plant that flourished within rhizoctonia bare patch areas.

4. Some seeds of the winter annual grass weed downy brome remained dormant and viable for 6 years and longer to heavily infest winter wheat during Phase II of the experiment. To our knowledge, this is first conclusive documentation of downy brome seeds remaining viable under field conditions for such a long time period.

5. Crop rotations did not differ in their impact on soil quality indicators. The greatest differences in soil properties occurred in the 0–5 cm depth, but soil from the experiment was different from the native undisturbed soil in pH, SOC, and DEA at the 5–10 cm depth. There was a gradual increase in SOC over time in the experiment that approached that of native undisturbed soil, but improvement in overall soil quality with no-till appears to occur at a very slow rate in this low-precipitation region.

6. The traditional WW-SF system consistently dominated no-till annual cropping rotations in terms of higher average profitability and reduced economic variability during the 8-year experiment. Annual crop rotations that included yellow mustard and safflower were always the poorest economic performers.

Acknowledgements

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