Field Crops Research 115 (2010) 39–49

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Diverse no-till irrigated crop rotations instead of burning and plowing continuous wheat

William F. Schillinger [a,*], Douglas L. Young [b], Ann C. Kennedy [c], Timothy C. Paulitz [d]

[a] Department of Crop and Soil Sciences, Washington State University, Dryland Research Station, P.O. Box B, Lind, WA 99341, USA
[b] School of Economic Sciences, Washington State University, 101 Hulbert Hall, Pullman, WA 99164, USA
[c] Land Management and Water Conservation Research Unit, USDA-ARS, 217 Johnson Hall, Pullman, WA 99164, USA
[d] Root Disease and Biological Control Research Unit, USDA-ARS, 363 Johnson Hall, Pullman, WA 99164, USA

ARTICLE INFO

Article history:
Received 12 August 2009
Received in revised form 29 September 2009
Accepted 1 October 2009

Keywords:
Canola
Crop residue management
Economics
Irrigated cropping systems
No-till
Root diseases
Soil quality
Spring barley
Weed management
Winter wheat

ABSTRACT

Field burning of residue is a traditional management tool for irrigated wheat (*Triticum aestivum* L.) production in the Inland Pacific Northwest of the United States (PNW) that can result in reduced air quality. A 6-year no-till field experiment to evaluate two complete cycles of a 3-year irrigated crop rotation of winter wheat–spring barley (*Hordeum vulgare* L.)–winter canola (*Brassica napus* L.) was sown (i) directly into standing residue of the previous crop, (ii) after mechanical removal of residue and, (iii) after burning of residue. The traditional practice of continuous annual winter wheat sown after burning residue and inverting the topsoil with a moldboard plow was included as a check treatment. Over-winter precipitation storage efficiency (PSE) was markedly improved when residue was not burned or burned and plowed after grain harvest. Grain yield of winter wheat trended higher in all no-till residue management treatments compared to the check treatment. Average grain yields of spring barley and canola were not significantly different among the no-till residue management treatments. Winter canola failed in 5 of 6 years due to a combination of a newly identified Rhizoctonia damping-off disease caused by *Rhizoctonia solani* AG-2-1 and cold temperatures that necessitated replanting to spring canola. Six-year average net returns over total costs were statistically equal over all four systems. All systems lost from \$358 to \$396 ha^{-1}. Soil organic carbon (SOC) increased linearly each year with no-till at the 0–5 cm depth and accumulated at a slower rate at the 5–10 cm depth. Take-all of wheat caused by *Gaeumannomyces graminis* var. *tritici* was most severe in continuous annual winter wheat. The incidence and severity of Rhizoctonia on roots of wheat and inoculum of *R. solani* AG-8, was highest in the no-till treatments, but there was no grain yield loss due to this disease in any treatment. Residue management method had no consistent effect on Rhizoctonia root rot on barley. The annual winter grass downy brome (*Bromus tectorum* L.) was problematic for winter wheat in the standing and mechanically removed residue treatments, but was controlled in the no-till residue burned and the burn and plow check. Another winter annual grass weed, rattail fescue (*Vulpia myuros* L.), infested all no-till treatments. This was the first comprehensive and multidisciplinary no-till irrigated crop rotation study conducted in the Pacific Northwest.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Many deep-well irrigators in east-central Washington grow continuous annual winter wheat. Irrigated wheat grain yields average 6700 kg ha^{-1} with residue production of 9400 kg ha^{-1} or more. After grain harvest in August, the traditional practice is to burn the residue and completely invert the surface soil with moldboard plow tillage in preparation for planting the next winter wheat crop in September. Growers generally feel they need to burn and moldboard plow winter wheat residue to control downy brome and because high residue levels hamper planting. Previous grower experience and research (Moyer et al., 1994) showed that long-term control of downy brome is very difficult in continuous irrigated winter wheat using no-till. Therefore, new crop rotation and residue management strategies and an "agro-ecosystem approach" are required to make

Abbreviations: Db, bulk density; CV, coefficient of variation; DEA, dehydrogenase enzyme activity; EC, electrical conductivity; PNW, Inland Pacific Northwest of the United States; PSE, over-winter precipitation storage efficiency; SOC, soil organic carbon; SD, standard deviation.

* Corresponding author. Tel.: +1 509 235 1933; fax: +1 509 235 1934.
E-mail address: schillw@wsu.edu (W.F. Schillinger).

0378-4290/\$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2009.10.001

no-till (without burning) feasible. Alternatives to field burning are needed to reduce smoke emissions and maintain air quality. Reduction or elimination of tillage will also improve air quality by controlling dust, reduce soil erosion and improve soil quality (Doran et al., 1996). Surface residue management systems improve soil quality by increasing SOC, fungal biomass, earthworm populations, and microbial enzyme activity (Holland and Coleman, 1987; Karlen et al., 1994; Kennedy et al., 2004).

A group of deep-well irrigators from the Odessa, Washington area approached the authors in 1998 concerning the future of their farming operations. The growers were concerned about potential regulations to reduce or eliminate wheat residue burning and desired research on how to farm profitably in the future without field burning. Grower advisors and scientists designed the experiment jointly. The objective of the experiment was to assess the agronomic, plant health, economic viability, and the soil quality benefits of a diversified no-till crop rotation with various residue management practices compared to the burn and plow system for producing continuous winter wheat.

2. Materials and methods

2.1. Treatments

A 6-year irrigated cropping systems study was conducted at the Washington State University Dryland Research Station near Lind from 2000 to 2006. The soil at this site is a Shano silt loam (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids). To obtain baseline residue levels to begin the experiment, the entire 4-ha experiment area was sown uniformly to 'Madsen' winter wheat in September 1999. The irrigated winter wheat grain yield in August 2000 was 7400 kg ha^{-1} and straw production was 12,000 kg ha^{-1}. Beginning in August 2000 (the 2001 crop year), a 3-year crop rotation of winter wheat–spring barley–winter canola was practiced under three residue management methods. Crops were sown: (i) directly into standing residue, (ii) after mechanical removal of residue, and (iii) after burning the residue. A check treatment of continuous annual winter wheat sown after residue burning and moldboard plowing was also included. With "mechanically removed" residue management, the residue was swathed, baled, and bales removed from the field immediately after grain harvest in early August. Burning in the "burned" residue management treatment was conducted in early August after making a 2-m-wide pass with a tandem disc around each of the burn blocks to bury residue to contain the fire.

The experimental design was a split block (Steel and Torrie, 1980) with four replications. Main plots (15 m × 150 m) were crops and subplots (15 m × 50 m) were residue management. Crops were planted in a direction perpendicular to the residue management treatments. Each phase of the 3-year no-till crop rotation in each residue management method was sown each year. Thus, there were 40 plots (3 crops × 3 residue management practices × 4 replications = 36 plots + 4 replications of the check treatment of continuous winter wheat after burning and plowing). The burn and plow check plots were 15 m × 150 m in size. The experiment area had been in a 2-year tillage-based dryland winter wheat–summer fallow rotation for at least 30 years prior to initiation of the experiment.

2.2. Inputs and field operations

All no-till treatments were sown and fertilized in one pass with a low disturbance Cross Slot™ (Baker et al., 1996) no-till drill with 20 cm row spacing. In the check treatment, after burning the residue, a moldboard plow was used to invert the soil to a depth of 15 cm, the inverted soil was packed with a roller, and winter wheat then sown with a conventional double-disc drill with 15 cm row spacing.

The timing of irrigation varied somewhat from year to year, but the entire experiment received 380 mm of irrigation water every year with 150 mm applied in the fall and 230 mm in the spring. Water was applied via hand-line sprinklers. As all treatments were randomized throughout the experiment, all crops received irrigation water at the same time. The optimum irrigation timing for canola, spring barley, and winter wheat differ, but crop-specific tailoring of irrigation for individual crops was not possible. Average annual precipitation during the 6-year study period was 221 mm. Consequently, all treatments received an average of 601 mm of water annually.

All treatments received 190 kg N, 34 kg P, and 22 kg S ha^{-1} each year. Burn and plow continuous annual winter wheat received all fertilizer in granular form with 135 kg N, 34 kg P, and 22 kg S ha^{-1} applied with a spreader in September after burning but prior to plowing and planting. The sources that made up this mix were urea (46-0-0-0), monoammonium phosphate (11-52-0-0), and ammonium sulfate (21-0-0-24). The remaining 55 kg ha^{-1} N was applied as granular urea to the growing wheat crop in April. The soil contained >450 kg ha^{-1} of extractable potassium, thus potassium fertilizer was not required. For the no-till residue management treatments, winter wheat received 135 kg N, 34 kg P, and 22 kg S ha^{-1} as liquid slightly below and to the side of the seed at time of planting with the Cross Slot™ no-till drill. The liquid fertilizer mix was Solution 32 (32-0-0-0) + ammonium phosphate (10-34-0-0) + thiosul (12-0-0-26). The remaining 55 kg N ha^{-1} was applied as granular urea to the growing wheat crop in April. Winter canola received the same fertilizer regime as the no-till winter wheat. However, winter canola was killed by disease and cold in 5 of 6 years, therefore, 55 kg ha^{-1} of liquid Solution 32 N was applied at sowing of spring canola in those 5 years. Spring barley received 190 kg N, 34 kg P, and 22 kg S ha^{-1} as Solution 32 + ammonium phosphate + thiosul at time of sowing with the Cross Slot™ drill.

Winter wheat (cv. Madsen) and spring barley (cv. Baronesse) were sown at a rate of 112 kg ha^{-1} during all years. Winter canola (cv. Olsen and Inca) and spring canola (cv. Hyola and Rapa) were sown at a rate of 5.6 kg ha^{-1}. Additional details on field operations, inputs, and rates are reported by Zaikin et al. (2008).

Weeds were controlled with several groups of herbicides with different modes of action that are commonly used by growers in the region. Assure II™ (quizalofop-p-ethyl) was used to control grass weeds in canola. Glyphosate [N-(phosphonomethyl)glycine] was applied to winter wheat residue in March prior to planting spring barley (and prior to replanting canola in the spring in 5 of 6 years). Broadleaf weeds in winter wheat and spring barley were controlled with an in-crop application of Bronate™ (bromoxynil + MCPA). Paraquat was used to control volunteer spring barley in barley residue in late August prior to planting winter canola. Herbicides and their application rates used throughout the experiment are reported by Zaikin et al. (2008).

2.3. Measurements and assessments

2.3.1. Soil water content and precipitation

Soil water content in the 1.8-m soil profile was measured in all 40 plots in late March and again after grain harvest in early August. Soil volumetric water content in the 0–0.3-m depth was determined from two 0.15-m core samples using gravimetric procedures (Topp and Ferre, 2002) and in the 0.3–1.8-m depth in 0.15-m increments by neutron attenuation (Hignett and Evett, 2002). Precipitation was measured at an official U.S. Weather Bureau recording site located 150 m from the experiment.

2.3.2. Plant stand and grain yield

Crop plant stand establishment was determined by counting individual plants in a 1-m-long row segments 21 days after planting. Measurements were obtained from three areas in each plot and the numbers then averaged taking into account the difference in row spacing between the no-till (20 cm) and conventional double-disc (15 cm) drills.

Grain yield was determined by harvesting the grain from plants in a swath through each plot with a Hege™ 140 plot combine with 1.5-m-wide cutting platform operated 35 cm above the soil surface, collecting grain in a sack, and weighing grain on a digital scale. Mowing 0.3-m-wide alleys just before grain harvest delineated borders between residue management treatments. The plot combine was equipped with a custom-built chaff and straw spreader (Schillinger et al., 2008) to uniformly spread residue along the width of the cutting platform. A farm-scale combine, with cutting bar operated slightly lower than that of the plot combine, was then used to harvest remaining grain within each plot and further distribute chaff and straw. The farm-scale combine was also equipped with a chaff spreader and straw spreader, thus all residue was evenly distributed across the plots at harvest every year.

2.3.3. Economic assessment

Detailed cost of production budgets were generated for each crop and residue management system. Production costs are categorized as either fixed or variable. For a given land and machinery base, fixed costs do not vary with the number of hectares planted. Machinery fixed costs include depreciation, interest, taxes, housing, and insurance. Variable costs are those that vary with number of hectares planted such as machinery repairs, fuel, labor, custom services, seed, fertilizer, pesticides, and crop insurance.

Many budgets were similar in terms of cultural practices and costs. There were no costs for some residue management practices and only minor costs for others. There was no charge for baling of wheat and barley residue because mushroom growers or others will bale and haul away residue in return for the product. The costs for burning of residue covered the burning permit and low burning operation costs. The utilized soft white wheat price of \$128.96 Mg^{-1} and spring barley price of \$98.28 Mg^{-1} were based on the average prices over the era of the experiment (Union Elevator, Lind, Washington, 2001–2006). The average price for canola was \$264.55 Mg^{-1}.

Net return per rotational ha was used to measure the profitability of different crop rotations. For example, a rotational ha of winter wheat–spring barley–spring canola includes 1/3 ha of winter wheat, 1/3 ha of spring barley and 1/3 ha of winter canola. Such diversification usually reduces annual income risk. It also typically permits more efficient use of machinery and labor based on varying seasonal demands by different crops.

Net return or profit in this study includes only market returns, excluding government payments and crop insurance indemnities. Although government payments are an important source of farm income, the purpose of this study was to compare the market profitability of different rotations, not to measure the total farm income of individual growers. Including government payments would require assumptions on historical yields and base areas, which vary from farm to farm. Furthermore, Nail et al. (2007) showed that adding government subsidies and crop insurance effects did not change the economic ranking of cropping systems in other experiments in the region.

2.3.4. Soil quality

Soil samples for laboratory analysis were obtained by first removing all surface residue and sampling from 0 to 5, 5 to 10 and 10 to 20 cm depths in the fall each year. Soil samples, each a composite of seven cores, were taken randomly in each of the 40 plots using a king tube with a 5 cm core diameter. Samples were stored at 4 °C until analysis, which occurred within two 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). Total C was determined with a LECO CNS analyzer (LECO, St. Joseph, MI) using soil that was oven dried, then all visible residue was removed and the soil was ground to pass a 1 mm sieve. Soil organic carbon was assumed to be equivalent to total C for those soils with pH < 7.0. Soils with pH > 7.0 were brought to pH 7.0 with 0.1N HCl to remove carbonates as CO_2, then dried prior to total C analysis. Additionally, in the soils with pH > 7.0, carbonates were determined as described by El Mahi et al. (1987) and SOC was calculated by subtraction of carbonates from total *C* values to confirm. No carbonates were present in these soils. Dehydrogenase enzyme activity, presented as μg tryphenyl formazan (TPF) g soil^{-1} h^{-1}, was determined as described by Tabatabai (1994). Soil bulk density (Db) was determined at the 0–20 cm depth using intact soil cores as described by Doran and Mielke (1984). For this manuscript, soil data from only the winter wheat plots and from the top two depths (0–5 cm and 5–10 cm) is presented; however, all data were included in the ANOVA.

2.3.5. Diseases

Samples from wheat plots were assessed for take-all (caused by *Gaeumannomyces graminis* var. *tritici*) and wheat and barley were assessed for Rhizoctonia root rot (caused by *Rhizoctonia solani* AG-8 and *R. oryzae*). In late April, three samples were taken within each plot, approximately 15 m apart walking along a transect near the center of the plot. Each consisted of a shovel full of plants and soil with about five plants per sample. Three plants were chosen from each sample, for a total of nine plants per plot. Plants were kept at 4 °C until the roots were washed, examined, and rated.

Take-all severity was assessed on winter wheat using a 0–5 scale (Moore and Cook, 1984), based on black discoloration of roots and crowns caused by *G. graminis* var. *tritici*. Rhizoctonia root rot was rated on spring barley using a 0–8 scale, based on typical symptoms of brown root tips, spear-tipping and constricted brown lesions on the root (Kim et al., 1997). The incidence of Rhizoctonia on seminal and crown roots of barley and wheat were also assessed. Canola plots were surveyed each year in the fall and spring. Plants were randomly taken from each plot and examined for above ground disease symptoms (stem rots and leaf spots).

2.3.6. Weeds

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

2.4. Statistical analysis

Analysis of variance was conducted for over-winter PSE, plant stand establishment, weed population, weed dry biomass, grain yield, economics, soil quality properties, and diseases (SAS, 2008). Year, crop species, and residue management method were considered main effects. Soil depth was considered a repeated measure. The Bonferroni method was used to control the experimentwise error rate for multiple comparisons. All analysis of variance tests were done at the 5% level of significance. Pearson's

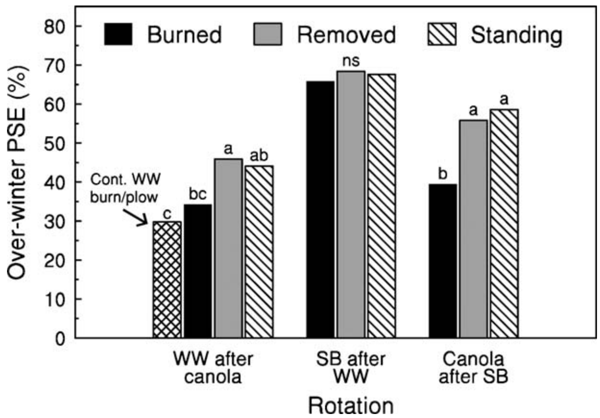

Fig. 1. Over-winter precipitation storage efficiency in the soil as affected by crop rotation and three residue management practices as well as with continuous annual winter wheat after burning and plowing. Data are the average over the 6-year experiment. Within-crop means followed by the same letter are not significantly different at $P < 0.05$. Abbreviations are: SB, spring barley; WW, winter wheat.

correlation coefficients were calculated to determine the relationships among soil characteristics (pH, EC, DEA, SOC, Db).

3. Results and discussion

3.1. Soil water dynamics

Residue management had a significant effect on over-winter PSE (Fig. 1). Winter wheat following canola had the lowest PSE because the crop transpired water during active growth in the fall and late winter. Within winter wheat residue management treatments, over-winter PSE was only 30 and 36% in the burn and plow and the burned no-till treatments, respectively, compared to >45% for the mechanically removed and standing residue treatments (Fig. 1).

There were no differences in over-winter PSE in those plots going into spring barley following winter wheat (Fig. 1) because all winter wheat residue was left standing from grain harvest until early spring. Residue burning was conducted just prior to planting of spring barley. The plots going into spring barley had the highest average over-winter PSE (average 66–69%) of the three crops in rotation due to the high quantities of standing residue.

August burning dramatically reduced over-winter PSE to an average of 41% in canola following spring barley compared to over-winter PSE values > 58% in the standing residue and residue mechanically removed treatments (Fig. 1). Although spring barley produces less residue than winter wheat, average over-winter PSE values were greater in fall-sown canola compared to fall-sown wheat because the wheat grew vigorously throughout the fall whereas winter canola was killed by a combination of disease and cold during the fall in 5 of 6 years (see Section 3.6).

There was a residue management × crop species interaction for over-winter PSE (Table 1A, Fig. 1) because winter wheat residue remained standing over winter in all no-till treatments whereas spring barley and canola residue was burned in August. Data from this experiment are in agreement with other studies in Mediterranean-like (i.e., winter precipitation) environments that conclusively show benefits of surface residue on over-winter PSE compared to the negative consequences of residue burial with moldboard plow tillage and/or burning (Bescansa et al., 2006; Papendick, 1987; Ramig and Ekin, 1976).

3.2. Plant stand establishment

Significant differences in plant population as affected by residue management were measured for all three crops (Fig. 2). The highest density of winter wheat occurred in the burn and plow check, followed by the no-till burn treatment. There were no differences in plant stand between the mechanically removed and standing residue treatments.

The tendency for spring barley stands was burn > residue removed > standing residue (Fig. 2). High quantities (i.e., >8 Mg ha^{-1}) of winter wheat residue can present a formidable obstacle to successful establishment of crops and is a major reason why a relatively low percentage of irrigated and high-precipitation-zone farmers in the PNW have adopted no-till practices compared to other regions of the USA (Kok et al., 2009). The lesser number of spring barley plants in the standing residue treatment was due to a heavy mat of residue and duff that somewhat hindered seedling emergence. Still, an average stand of 150 plants m^{-2} was achieved, which is considered satisfactory.

Canola stands averaged 50 plants m^{-2} with the burn > residue removed = standing residue (Fig. 2). Newly harvested spring barley residue did not present a problem for sowing winter canola.

Table 1

(A) Analysis of variance for plant stand, over-winter precipitation storage efficiency (PSE), weed population, weed dry biomass and grain yield for three crops as affected by year and residue management methods and their interactions at Lind, WA

Source	df	Plant stand	Over-winter PSE	Weed population	Weed dry biomass	Grain yield
Year (Y)	5	***	***	***	*	***
Crop (C)	2	***	***	***	*	***
Residue (R)	2	***	***	***		*
Y × C	10	***	***	***		***
Y × R	10		*			
C × R	4	*	**	***		
Y × C × R	20					

(B) Analysis of variance for pH, electrical conductivity (EC), dehydrogenase (DEA), soil organic carbon (SOC), and bulk density (dB) as affected by year, depth of soil, and residue management methods and their interactions at Lind, WA

Source	df	pH	EC	DEA	SOC	dB
Year (Y)	5	***	***	***	**	***
Depth (D)	2	**	***	***	***	Nd
Residue (R)	3	***	*		**	
Y × D	10	**		**		Nd
Y × R	15					**
R × D	6			***	*	Nd
Y × D × R	30			*		Nd

(*), (**), (***) Significant at the 0.05, 0.01 and 0.001 levels, respectively. Blank values indicate no significant difference. Nd, Not determined.

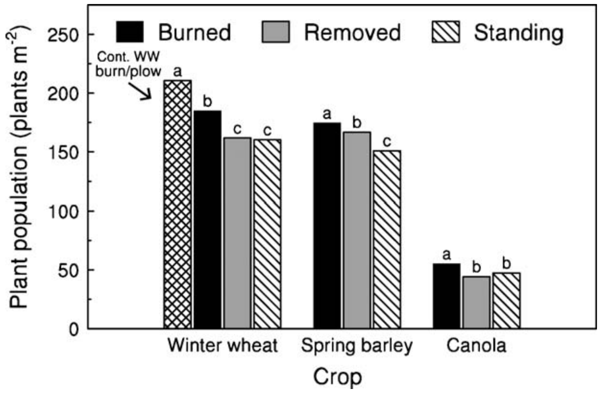

Fig. 2. Plant stand establishment of three crops as affected by three no-till residue management practices plus continuous annual winter wheat after burning and plowing. Data are averaged over the 6-year experiment. Within-crop means followed by the same letter are not significantly different at $P < 0.05$.

Adequate winter canola stands were consistently achieved in all residue management treatments.

There was a significant crop species × residue management interaction for plant stand establishment (Table 1A). This interaction is explained by the fact that spring barley plants in the standing residue treatment were fewer than with residue mechanically removed, whereas winter wheat and canola stands in these two residue management methods were equal (Fig. 2).

3.3. Grain yield

The 6-year average grain yields for winter wheat, spring barley, and canola are shown in Table 2. Winter wheat grain yield differed between the low (5685 kg ha^{-1}) burn and plow treatment and high (6241 kg ha^{-1}) residue burned treatment, with grain yields for the standing residue and residue mechanically removed treatments falling in the middle (Table 2). Grain yield for continuous annual winter wheat was much lower than winter wheat in the crop rotation treatments in 2003 due to documented take-all root disease (Cook and Veseth, 1991, see Section 3.6) and also trended lower in 2005, probably due to water stress because of low over-winter PSE (Fig. 1). The coefficient of variation (CV) for winter wheat grain yield over the six years averaged among treatments was 17%.

Spring barley grain yields averaged 5272, 5520, and 5686 kg ha^{-1} for the standing, mechanically removed, and residue burned treatments, respectively (Table 2). Spring barley yields were consistent from year to year (6-year CV averaged among residue treatments was 11%) and there were no significant grain yield differences among treatments when averaged over the six years.

Canola grain yields fluctuated widely across years (Table 2) as indicated by a 6-year CV of 50% averaged over residue management treatments. Winter canola was successfully grown only during the 2002 crop year. Spring canola was successful in 2001 (average grain yield = 2750 kg ha^{-1}) when June air temperatures were mild, but in other years spring canola grain yield was reduced (Table 2) when June air temperatures exceeded 33 °C for one day or more. These high air temperatures caused flowering spring canola plants to abruptly abort their florets (Angadi et al., 2000). Average maximum air temperatures of 33 °C during a 3-day period in late May were especially detrimental to spring canola grain yields in 2005 (Table 2). The mechanically removed and standing residue management treatments trended towards greater grain yields than the residue burned treatment in the final two years of the experiment (most likely due to greater soil water availability), but the 6-year average grain yields among residue treatments were the same.

Canola yields were dramatically lower than expected. A cooperating grower near Odessa, Washington using traditional (i.e., tillage based) practices reported average winter canola yields of 3360 kg ha^{-1} during 2001–2006 with no winterkill problems. Winter canola in the experiment was killed by a combination of Rhizoctonia root rot fungal disease and cold temperatures in 5 of 6 years. This fungal pathogen is more severe in no-till farming and can be reduced with tillage (Rovira, 1986). Winter canola appears to be quite vulnerable to winterkill when infected by Rhizoctonia.

3.4. Economics

Table 3 displays 6-year average fixed costs, variable costs, total costs, gross returns, and net returns by crop rotation and residue management treatment. Total costs ranged from \$976 to \$990 ha^{-1} for the 3-year crop rotation to \$1091 ha^{-1} for continuous annual winter wheat. As shown in Zaikin et al. (2008), fertilizers contributed strongly to high variable costs. At 2001–2006 average crop prices and experiment yields and production costs, all four cropping systems treatments incurred annual average losses of over \$358 ha^{-1}. Average net returns were statistically equal for all four systems. The net returns of no-till residue management systems were similar (−\$382 to −\$396 per rotational ha). Continuous annual winter wheat earned only \$24 ha^{-1} more, or lost \$24 ha^{-1} less, than the best no-till residue management rotation (Table 3). Although these net returns exclude government payments as discussed earlier, government payments typical for this period and region would have been inadequate by a wide margin to generate positive returns.

Table 2
Grain yields from 2001 to 2006 for three crops produced under three residue management systems plus continuous winter wheat produced in the burn and plow check treatment.

Rotation	2001	2002	2003	2004	2005	2006	6-year avg.
Winter wheat (kg/ha)							
Burned	5285	7133	7619 a*	6884	4872	5650 ab	6241 a
Mech. removed	4441	7381	6466 a	6446	5429	4677 b	5806 ab
Standing	5123	7206	6766 a	6197	6406	5066 ab	6128 ab
Burn–plow	5022	6528	5014 b	6625	4600	6326 a	5685 b
Spring barley (kg/ha)							
Burned	6457	4956	5360	5851	5382	6114 a	5686
Mech. removed	6793	5214	5008	5714	5057	5339 ab	5520
Standing	6446	5057	4659	5672	4883	4918 b	5272
Canola (kg/ha)							
Burned	2895	2803	1150	1249	459 b	1655 b	1701
Mech. removed	2796	2493	1271	1278	732 a	1669 b	1706
Standing	2566	2451	1486	1177	550 ab	1880 a	1684

* Within-crop and within-year grain yields followed by the same letter are not significantly different at $P < 0.05$.

Table 3
Average production cost, gross return, and net return over total cost ($/rotational ha) from 2001 to 2006 for three crops produced under three residue management systems plus continuous winter wheat produced in the burn and plow check treatment.

Crop and treatment	Fixed costs	Variable costs	Total costs	Gross return	Net returns over total costs
No-till WW, SB, Canola					
Residue burned	230	759	990	608	−382 [a]
Residue baled	216	759	976	582	−393 [a]
Residue standing	225	764	977	581	−396 [a]
Cont. WW burn and plow	209	882	1091	733	−358 [a]

Notes: Rotational ha equals 1/3 ha wheat + 1/3 ha barley + 1/3 ha canola for the 3-crop rotation. Net returns over total costs are based on average crop prices of $128.96 Mg^{-1} for wheat, $98.28 Mg^{-1} for barley, and $264.55 Mg^{-1} for canola. Average net returns over total costs followed by the same lower case letter are not significantly different at $P < 0.05$. Abbreviations are: SB, spring barley; WW, winter wheat.

The relatively low canola yields explain part of the uncompetitive net returns. Low crop prices coupled with rising input costs during this time period also contributed to the low net returns. Prices for all crops increased from 2007 to early 2009 compared to the experiment period. As long as growers are covering variable costs they will continue producing in the short run; however, gross returns fall below variable costs in Table 3. Other non-crop returns, such as long-term appreciation in land value, or the non-monetary value of a rural agricultural lifestyle, may also persuade growers to continue farming in the short-term as long as they cover variable costs.

Table 4 displays net returns by individual crop and residue management treatment during the 6-year experiment. These annual net returns are important because farmers (and their bankers) are very concerned about income stability as well as with average income. Annual losses for winter wheat ranged from $54 to $453 ha^{-1} over all systems and years. Spring barley losses spanned $290 to $443 ha^{-1} over systems and years. As expected, the high production costs and low yields for canola combined to generate exceptionally large annual losses ranging from 334 to $875 ha^{-1} (Table 4). Replanting to spring canola in 5 of 6 years added $148 ha^{-1} to costs. Canola seed alone cost $8.82 kg^{-1}. Replanting canola also added to machinery, labor, and other costs (Zaikin et al., 2008). It is not surprising that net returns for canola were more favorable in 2002, the single year that it was not necessary to replant winter canola to spring canola. The losses for canola listed in Table 4 are unsustainable and farmers would abandon no-till canola unless yields were increased, costs reduced, prices elevated, and/or this crop provided an exceptional rotation benefit to the subsequent crop. Annual variability in net returns as measured by the standard deviation (SD) is relatively similar within crops over residue management practices (Table 4). Canola not only incurs greater average losses than the other crops, its profit risk is much greater. The average SD of net returns for canola exceeds that for winter wheat and spring barley by 78 and 271%, respectively (Table 4).

3.5. *Soil quality*

Soil quality assessments can be used to determine the effects of management practices on the soil. We include here data from the winter wheat plots for each year of the study and information on the 0–5 and 5–10 cm depths only. Treatments varied with year for all variables (Table 1B). All soil quality values varied with depth, except Db, which was combined over the two depths. The pH, EC, and SOC varied with residue treatment, while DEA and Db were not affected by residue treatment. Interactions among treatments included year × depth for pH and DEA and residue × depth for SOC and DEA. There were no significant year × residue × crop interactions, except for DEA. Variability in some of the soil quality data can be explained by the fact that residue management treatments were maintained on the same plots during the entire experiment and the effect of the residue management practice on soil values was often greater with time.

Initial pH was slightly below neutral at 6.6 for the 0–5 cm depth and 6.2 for the 5–10 cm depth (Fig. 3a). By the end of the experiment the overall mean soil pH was 6.5 for the 0–5 cm depth with a range from 6.2 to 6.7 among treatments. The pH ranged from 6.6 to 6.8 at the 5–10 cm depths by 2006 (Fig. 3b). Soil pH for these treatments was within the range considered adequate for plant growth. The pH of the burn and plow treatment in the surface sample decreased with time to 6.2 and was often less than other treatments in the 5–10 cm depth. Hamman et al. (2007) found the intensity of the burning of residue affects soil characteristics, and that soil pH decreased with burning. The pH in the burn and plow treatment was often lower than the no-till treatments at both depths. At the 5–10 cm depth, pH of all the treatments increased over time to a mean 6.6.

Table 4
Net return ($/ha) from 2001 to 2006 for three crops produced under three residue management methods plus continuous winter wheat produced in the burn and plow check treatment.

Treatments	2001	2002	2003	2004	2005	2006	Average	SD
Winter wheat								
Residue burned	−216	−95	−54	−118	−288	−222	−166	90
Residue baled	−314	−66	−147	−147	−233	−297	−201	97
Residue standing	−303	−83	−118	−170	−152	−268	−182	86
Burn and plow	−413	−286	−419	−274	−453	−303	−358	79
Spring barley								
Residue burned	−319	−417	−378	−359	−389	−341	−367	35
Residue baled	−290	−393	−413	−360	−403	−385	−374	45
Residue standing	−312	−403	−443	−363	−415	−413	−392	47
Canola								
Residue burned	−527	−334	−692	−666	−875	−588	−614	181
Residue baled	−544	−389	−660	−659	−803	−585	−607	139
Residue standing	−584	−396	−618	−685	−851	−548	−614	151

Note: Net returns over total costs are based on average crop prices of $128.96 Mg^{-1} for wheat, $98.28 Mg^{-1} for barley, and $264.55 Mg^{-1} for canola.

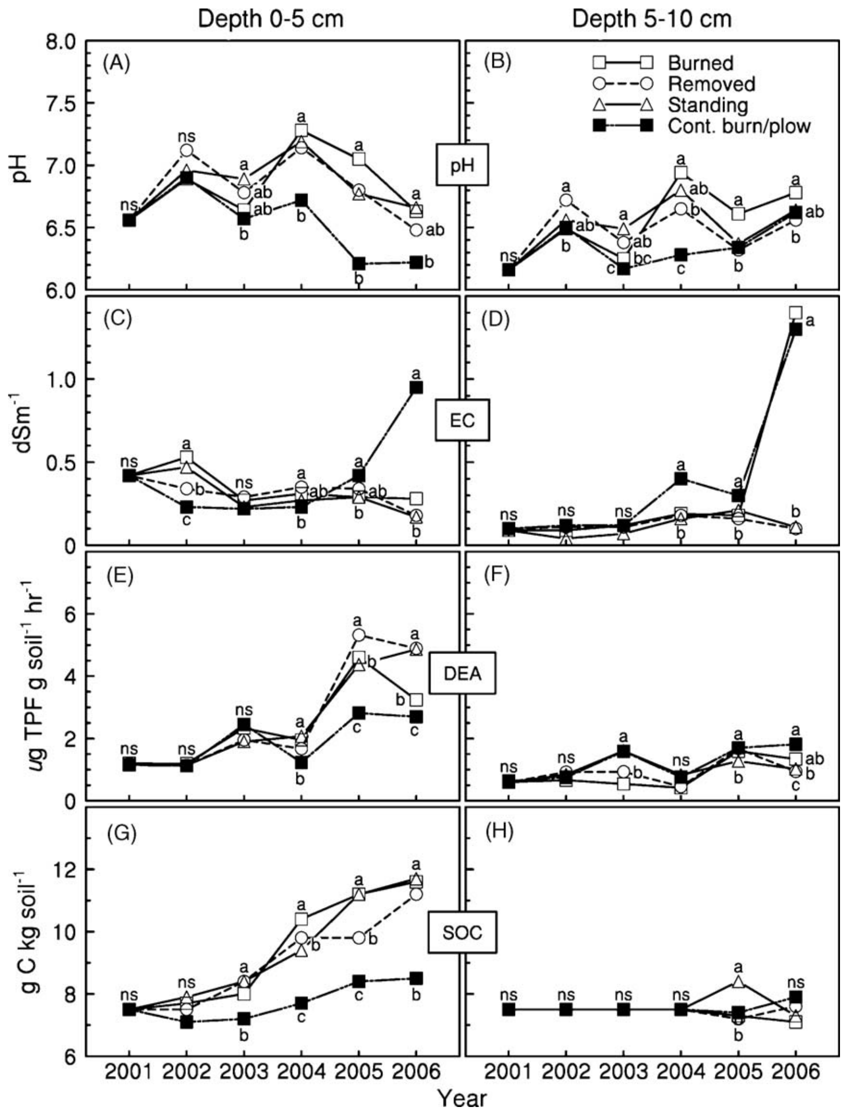

Fig. 3. Soil parameters of pH, electrical conductivity (EC), dehydrogenase (DEA), and soil organic carbon (SOC) at two depths from 2001 to 2006 for winter wheat produced in three no-till residue management systems and in the burn and plow check. Within-year means followed by the same letter are not significantly different at $P < 0.05$.

Electrical conductivity was 0.42 and 0.10 dS m^{-1} at the 0–5 cm and 5–10 cm depths, respectively, at the beginning of the experiment (Fig. 3c and d). Surface EC differed among treatments in 2002, 2005 and 2006, with burn and plow having the highest EC values in 2005 and 2006. Soil EC often increases with the addition of high levels of residue (Brye et al., 2006), but can also be affected by the ash. These increases in EC, while interesting and statistically significant are not approaching levels that would be detrimental to soil or plant health. At the 5–10 cm depth, there were no differences in EC until 2004 when the burn and plow values were higher than in the no-till treatments. Electrical conductivity is an important soil quality indicator with levels between 0 and 1.5 dS m^{-1} considered acceptable for plant and microbial growth (Smith and Doran, 1996). The EC values for all plots in our study were within a reasonable range. While EC varied among treatments, there were no consistent differences across time.

Initially DEA values were 1.2 μg TPF g $soil^{-1}$ h^{-1} at the 0–5 cm depth and 0.60 μg TPF g $soil^{-1}$ h^{-1} at the 5–10 cm depth (Fig. 3e and f). The DEA values began to differentiate among treatments beginning in 2003 and became especially noticeable beginning in 2005 and 2006 at the 0–5 cm depth with burn and plow being much lower than the no-till treatments. In 2006, DEA at the 0–5 cm depth ranged from 4.89 to 2.70 μg TPF g $soil^{-1}$ h^{-1}, while at the 5–10 cm depth the range was 1.81–0.94 μg TPF g $soil^{-1}$ h^{-1}. The DEA generally increased with greater SOC inputs (Acosta-Martinez et al., 2003).

The initial Db of the 0–10 cm depth was 1.2 g cm^{-3} and in 2006 Db averaged 1.35 g cm^{-3} across treatments (data not shown). By 2006, the highest Db (1.40 g cm^{-3}) was found in the standing residue treatment. Our findings are in partial agreement with others who showed that Db often increases with no-till (Grant and Lafond, 1993; Álvaro-Fuentes et al., 2008).

At the start of the study, SOC was 7.5 g C kg $soil^{-1}$ at both the surface at the 5–10 cm depth (Fig. 3g and h). The SOC increased in a near linear fashion with time and the rate of increase was by far greatest at the 0–5 cm depth in the no-till treatments (Fig. 3g). The highest SOC (11.7 g C kg $soil^{-1}$) was in standing residue treatments at 0–5 cm. At the 5–10 cm depth, the highest SOC value was 7.9 g C kg $soil^{-1}$ and the lowest was 7.1 g C kg $soil^{-1}$ for the burn and plow treatment. Soil organic carbon may be one of the best indicators of soil health, although measurable changes in SOC do not occur until after several years. As seen in this study and in other field studies, no-till eventually leads to increased SOC in both irrigated and dryland cropping systems (Campbell et al., 2000; Schillinger et al., 2007). Increased SOC in the no-till treatments compared with the burn and plow indicates that not tilling the soil enhanced SOC content more than did management of surface residues (Fig. 3g). However, the SOC content increased with time for treatments with residue left on the soil surface (Fig. 3g).

The ongoing increase in SOC in this study illustrates the impact of available water. Increases in SOC are usually not evident for 6–8 years after adoption of no-till in dryland cropping systems (Schillinger et al., 2007). Long-term research on conservation-till and no-till cropping systems is needed to understand the dynamics of soil quality, optimize available water use, and reduce soil erosion (Karlen et al., 1994; Rasmussen et al., 1998). Using Pearson's correlations, SOC was positively correlated with pH (r = 0.298; P = 0.0006) and DEA (r = 0.63; $P < 0.0001$) and inversely correlated with Db (r = −0.73; $P < 0.0001$).

3.6. Diseases

Take-all of wheat was highest in continuous annual winter wheat in all years (Fig. 4). There was a trend of increasing take-all in this treatment for the first three years, but disease levels in 2006 had decreased to similar levels seen in 2002. This increase in take-all with monocrop irrigated wheat is expected because inoculum builds up when wheat is grown continuously, and the disease is reduced by a break with a non-susceptible rotation crop, such as canola (Hornby, 1998). The yield reduction in the continuous annual winter wheat treatment during the first several years compared to winter wheat in crop rotation was probably due to the high disease levels of take-all. Barley can also support this pathogen, but it is not as susceptible as wheat (Wiese, 1987). The no-till residue management treatments did not have a consistent effect on take-all. In 2003 and 2004, there were no significant differences in take-all among the no-till residue management treatments, but in 2002 and 2006, higher disease levels were found in the residue burned treatment.

In the last year of the experiment, continuous annual winter wheat experienced take-all decline. This phenomenon is manifested by a decline in take-all disease after a few years of disease increase in monoculture wheat and is caused by increased populations of antagonistic *Pseudomonas* spp. that produce antifungal compounds such as 2,4-diacetylphloroglucinol and phenazine (Hornby, 1983; Weller et al., 2002). These bacteria colonize the lesions of the take-all pathogen on the roots, and disease is required for the buildup of bacterial populations. Inoculum levels of Rhizoctonia, as determined by quantification of Rhizoctonia DNA in soil, was almost 100 times higher in continuous annual winter wheat compared to no-till winter wheat in the 3-year rotation (Paulitz et al., in press). The DNA inoculum levels declined over 10-fold from 2003 to 2006, further evidence of take-all decline.

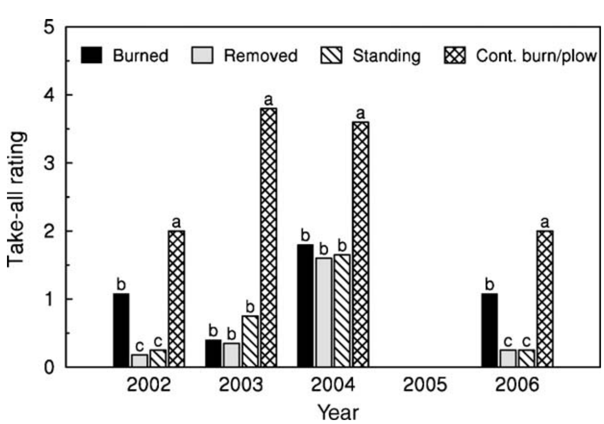

Fig. 4. Severity of take-all disease caused by *Gaeumannomyces graminis* var. *tritici* on winter wheat in four production systems. Take-all ratings were based on a 0–5 scale, with 0 being no disease. Treatments with the same letters within each year are not significantly different at $P < 0.05$. Data were not collected in 2005.

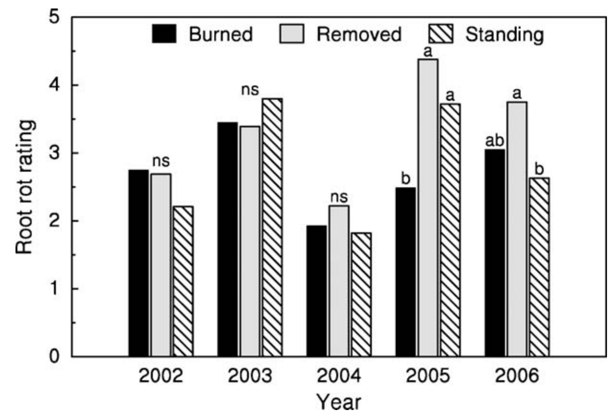

Fig. 5. Severity of Rhizoctonia root rot on spring barley with three no-till residue management methods. Rhizoctonia ratings were based on a 0–8 scale, with 0 being no disease. Treatments with the same letters within each year are not significantly different at $P < 0.05$.

Residue management method had no significant effect on Rhizoctonia root rot in the first three years of the experiment (Fig. 5). However, in 2005 and 2006, the burned residue and standing residue treatments had the lowest disease ratings, respectively. This lack of consistent effects may reflect the fact that *Rhizoctonia* does not survive in the upper crowns and above ground debris, but rather in the intact roots as thick walled monilioid hyphae. Therefore, unlike other diseases such as Fusarium crown rot, removal of residue will have little effect (Davis et al., 2008). Burning will not affect the survival in the roots, since the soil provides a thermal buffer for burning, and temperatures just a few cm below the surface will not reach lethal temperatures.

Tillage had an effect on *Rhizoctonia* in winter wheat. In 2003 and 2006, significantly lower levels of seminal and crown root infection were found in the burn and plow continuous annual wheat (data not shown). In addition, 10-fold higher levels of *Rhizoctonia* inoculum were seen in all the no-till residue management winter wheat compared to the burn and plow continuous annual winter wheat (Paulitz et al., in press). This increase of *Rhizoctonia* in no-till systems has been well documented in Australia and the US (Rovira, 1986; Weller et al., 1986). Despite the higher levels of *Rhizoctonia* in the no-till treatments, there was no grain yield loss compared to burn and plow continuous wheat (Table 2) and no bare patches were observed. Irrigation may have compensated for root loss, or may make the soil less conducive for bare patch formation.

The only major impact of *Rhizoctonia* was seen with winter canola. The crop failed in 5 out of 6 years, probably due a combination of *Rhizoctonia* and cold air temperature. Examination of seedlings in the fall showed a hypocotyl rot and collapse of the stem. *R. solani* AG-2-1 was isolated, and its pathogenicity verified in the greenhouse (Paulitz et al., 2006). This pathogen causes post-emergence damping-off (wirestem) on brassicas (Kataria and Verma, 1992; Yibarek et al., 1987). Despite controlling the greenbridge (Smiley et al., 1992), winter canola failed to survive the winter. This suggests that *Rhizoctonia* may weaken seedlings, reducing their ability to survive winter temperatures.

3.7. Weeds

Downy brome and rattail fescue, both winter annual grasses, were by far the most troublesome weeds throughout the study.

Table 5
Population and dry biomass of four weed species as well as total weeds collected in late July just before grain harvest. Data are the average from the 6-year experiment.

	Russian thistle	Downy brome	Prickly lettuce	Horseweed	Total[*] weeds
Population (plants 3m^{-2})					
Winter wheat					
Residue burned	0	1 c[**]	1	3	9 c
Residue removed	0	38 a	1	2	53 a
Residue standing	0	22 b	1	1	29 b
Burn and plow	0	1 c	0	1	6 c
Spring barley					
Residue burned	0	0	1	0	2
Residue removed	0	1	2	3	5
Residue standing	0	2	1	1	4
Canola					
Residue burned	2	0	1	2	8 b
Residue removed	3	1	2	2	20 a
Residue standing	4	0	2	1	14 ab
Dry biomass (g 3m^{-2})					
Winter wheat					
Residue burned	0	2	21	4	47 b
Residue removed	0	78	12	2	152 a
Residue standing	0	49	15	39	130 a
Cont. burn/plow	0	3	0	5	17 b
Spring barley					
Residue burned	0	0	26	0	39
Residue removed	0	1	12	3	29
Residue standing	0	3	11	4	21
Canola					
Residue burned	31	0	25	13	125
Residue removed	32	9	49	9	158
Residue standing	65	0	53	4	180

[*] Total weeds also includes small quantities of tumble mustard (*Sisymbrium altissumum* L.), pinnate tansymustard (*Descurainia pinnata* Walt.), prostrate knotweed (*Polygonum aviculare* L.), mayweed chamomile (*Anthemis cotula* L.), tumble pigweed (*Amaranthus albus* L.), yellow starthistle (*Centaurea solstitialis* L.), annual sowthistle (*Sonchus olearaceus* L.), field pennycress (*Thlaspi arvense* L.), and lambsquarters (*Chenopodium berlandieri* Moq.).
[**] Means in groups in columns followed by the same letter are not significantly different at $P < 0.05$.

Prickly lettuce (*Lactuca serriola* L.), horseweed (*Conyza canadensis* L.) and Russian thistle (*Salsola tragus* L.), were the most common broadleaf weeds.

Downy brome was only a problem in winter wheat as it was readily controlled with a grass weed herbicide in canola and with glyphosate prior to planting spring barley. Therefore, the designers of the experiment thought a 3-year rotation that included spring barley and canola would control downy brome. The continuous annual winter wheat after burning and plowing and the no-till residue burn winter wheat had essentially no downy brome (Table 5), thus at least partially disproving growers' conception that both burning and plowing are required for control of this weed. High levels of downy brome were measured in the residue removed and standing residue treatments during the winter wheat phase of the rotation. The residue removed treatment had almost doubled the downy brome infestation of the standing residue treatment (Table 5) due, we feel, to weed seed dispersal during the swathing, baling, and removal of the straw from these plots just after grain harvest.

Rattail fescue has a shallow root system and can easily be controlled with tillage, but this weed has become a concern in the Pacific Northwest as more farmers convert to no-till practices (Ball et al., 2008). Patches of rattail fescue first appeared in winter wheat of all no-till residue management treatments in year three and patches expanded rapidly thereafter. Although glyphosate, paraquat, and quizalofop-p-ethyl herbicides initially appeared to effectively control rattail fescue, flushes occurred in the seed rows of the no-till plots throughout the winter and well into the spring, apparently re-tillering from crowns. A study of rattail fescue biology conducted at several locations in Oregon showed that seed production did not occur when emergence occurred after 28 January, presumably due to lack vernalization requirement (Ball et al., 2008). In our study, rattail fescue seedlings that were first visible above ground in April still produced seed. By year six, large patches of rattail fescue were present in all no-till plots. Burning had no apparent beneficial effect on controlling rattail fescue. Rattail fescue population was not measured due to the time and difficulty to gather biomass from solid "sodded in" stands of this weed within a crop canopy.

Broadleaf weeds were of minor concern compared to winter annual grass weeds. Russian thistle was somewhat problematic in canola, but was completely controlled in winter wheat and spring barley (Table 5) due to crop competition and in-crop application of broadleaf herbicide. Small, but consistent, populations of prickly lettuce and horseweed were present in all crops regardless of residue management. Several other minor broadleaf weeds were recorded during the study and are listed at the bottom of Table 5.

The lowest overall weed population and weed biomass occurred in spring barley due to its rapid and vigorous establishment of crop canopy. There was a significant crop × residue management interaction for weed population, but not weed biomass (Table 1). This interaction occurred because there were no weed differences in either spring barley or canola as affected by residue management, whereas in winter wheat, downy brome population was much greater with mechanically removed and standing residue compared to the burn and burn and plow treatments (Table 5).

4. Summary and conclusions

1. Burning residue after grain harvest (or burning residue plus moldboard plowing) in August significantly reduced over-winter PSE compared to standing residue and residue removed treatments, causing more crop water stress in certain years.
2. Winter wheat grain yield trended higher in all no-till residue management treatments compared to the burn and plow check. There were no differences in the 6-year average grain yield for either spring barley or canola among residue management treatments.
3. Six-year average net returns over total costs were statistically similar over all four cropping systems. All systems lost from $358 to $396 per rotational ha.
4. It took three or more years for soil quality parameters to differentiate among treatments. The pH in the burn and plow treatment declined with time, while pH in the no-till treatments increased over time in the 0–5 cm depth. The EC values were higher in the burn and plow check compared to the no-till treatments during the last three years. While these EC values are low and potentially not biologically significant, the increase may have occurred due to the plowing in of the burned residue ash containing Ca, K, and Mg. At the 0–5 cm depth, DEA was greater in all no-till treatments compared to the burn and plow check whereas the opposite trend was observed at the 5–10 cm depth. Soil organic carbon in the 0–5 cm depth increased at a faster rate in all no-till treatments compared with the burn and plow check. Tillage had a more negative effect on SOC accumulation than did residue burning. The Db values varied, but there were no consistent differences due to treatment.
5. The major disease problem in continuous annual winter wheat with burning and plowing was take-all, which significantly reduced grain yield in the early years of the experiment. However, take-all declined over the last years of the experiment,

due to natural microbial suppression of the disease. Despite the buildup of *Rhizoctonia solani* AG-8 in the no-till residue management treatments, Rhizoctonia did not become a major disease in wheat or barley. However, another group of *Rhizoctonia solani* AG-2-1, caused post-emergence rotting of seedlings and winterkill of winter canola, and could pose a serious problem for no-till winter canola production.

6. Two winter annual grasses, downy brome and rattail fescue, were by far the most problematic weeds in the study. Although downy brome was only a problem in winter wheat (i.e., once every three years) in the no-till crop rotation treatments, the populations of this weed increased each year in the standing residue and residue removed treatments. There was essentially no downy brome in the no-till burned and burn and plow treatments. Patches of rattail fescue grew rapidly in all no-till plots in all crops despite timely application of herbicides. Burning was not effective in controlling rattail fescue. With today's technology, it appears that periodic tillage or a no-till fallow period is needed to control rattail fescue.

In conclusion, this experiment was the first long-term effort to develop cropping systems for no-till irrigated farming in the Pacific Northwest. Valuable information was obtained on soil quality, agronomy, economics, diseases, weed ecology, and other factors under various no-till residue management scenarios. We recommend that concerned land grant universities and the USDA-ARS devote more resources for research on high residue farming in diverse irrigated cropping systems.

Acknowledgements

The authors appreciate the excellent support provided by Bruce Sauer, Harry Schafer, Timothy Smith, Steven Schofstoll, Brian Fode, and Cindy Warriner from the WSU Dryland Research Station at Lind, WA. We thank Kurtis Schroeder, Karen Adams, Chasity Watt, Jeremy Hansen, and Tami Stubbs with USDA-ARS and WSU at Pullman, WA for assistance with the soil quality and disease work. We gratefully acknowledge grower advisors Jeff Schibel, Neil Fink, Clark Kagele, Keith Schafer, and Gary Schell for their active collaboration in the design of the experiment and participation in annual progress review meetings. Funding for the study was provided by Washington State University, USDA-ARS, the Columbia Plateau PM_{10} Project, the Washington Department of Ecology, and the Solutions to Economic and Environmental Problems (STEEP) Project.

References

Acosta-Martinez, V., Klose, S., Zobeck, T.M., 2003. Enzyme activities in semiarid soils under conservation reserve program, native rangeland and cropland. J. Plant Nutr. Soil Sci. 166, 699–707.
Álvaro-Fuentes, J., López, M.V., Cantero-Martinez, C., Arrúe, J.L., 2008. Tillage effects on soil organic carbon fractions in Mediterranean dryland agroecosystems. Soil Sci. Soc. Am. J. 72, 541–547.
Angadi, S.V., Cutforth, H.W., Miller, P.R., McConkey, B.G., Entz, M.H., Brandt, S.A., Volkmar, K.M., 2000. Response of three *Brassica* species to high temperature stress during reproductive growth. Can. J. Plant Sci. 80, 693–701.
Baker, C.J., Saxton, K.E., Ritchie, W.R., 1996. No-Tillage Seeding: Science and Practice. CAB International, Wallingford, UK.
Ball, D.A., Frost, S.M., Fandrich, L., Tarasoff, C., Mallory-Smith, C., 2008. Biological attributes of rattail fescue (*Vulpia myuros*). Weed Sci. 56, 26–31.
Bescansa, P., Imaz, M.J., Virto, I., Enrique, A., Hoogmoed, W.B., 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. Soil Till. Res. 87, 19–27.
Brye, K.R., Cordell, M.L., Longer, D.E., Gbur, E.E., 2006. Residue management practice effects on soil surface properties in a young wheat-soybean double-crop system. J. Sustain. Agric. 29, 121–150.
Campbell, C.A., Zentner, R.P., Liang, B.-C., Roloff, G., Gregorich, E.C., Blomert, B., 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan-Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80, 179–192.
Cook, R.J., Veseth, R.J., 1991. Wheat Health Management. American Phytopathological Society Press, St. Paul, MN.
Davis, R.A., Huggins, D., Cook, R.J., Paulitz, T.C., 2008. Can placement of seed away from relic stubble limit Rhizoctonia root rot in direct-seeded wheat? Soil Till. Res. 101, 37–43.
Doran, J.W., Mielke, L.N., 1984. A rapid low-cost method for determining soil bulk density. Soil Sci. Soc. Am. J. 48, 717–719.
Doran, J.W., Sarrantonio, M., Liebig, M.A., 1996. Soil health and sustainability. Adv. Agron. 56, 1–54.
El Mahi, Y.E., Ibrahim, I.S., Magid, H.M.A., Eltilib, A.M.A., 1987. A simple method for the estimation of calcium and magnesium carbonates in soils. Soil Sci. Soc. Am. J. 51, 1152–1155.
Grant, C.A., Lafond, G.P., 1993. The effects of tillage systems and crop sequences on soil bulk density and penetration resistance on a clay soil in southern Saskatchewan. Can. J. Soil Sci. 73, 223–232.
Hamman, S.T., Burke, I.C., Stromberger, M.E., 2007. Relationships between microbial community structure and soil environmental conditions in a recently burned system. Soil Biol. Biochem. 39, 1703–1711.
Hignett, C., Evett, S.R., 2002. Methods for measurement of soil water content: neutron thermalization. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4—Physical Methods. SSSA Book Series: 5, Soil Science Society of America, Madison, WI, pp. 501–521.
Holland, E.A., Coleman, D.C., 1987. Litter placement effects on microbial and organic matter dynamics in an agroecosystem. Ecology 68, 425–433.
Hornby, D., 1983. Suppressive soils. Annu. Rev. Phytopathol. 21, 65–85.
Hornby, D., 1998. Take-all of Cereals: A Regional Perspective. CAB International, Wallingford, UK.
Karlen, D.L., Varvel, G.E., Bullock, D.G., Cruse, R.M., 1994. Crop rotations for the 21st century. Adv. Agron. 53, 1–45.
Kataria, H.R., Verma, P.R., 1992. *Rhizoctonia solani* damping-off and root rot in oilseed rape and canola. Crop Prot. 11, 8–13.
Kennedy, A.C., Stubbs, T.L., Schillinger, W.F., 2004. Soil and crop management effects on soil microbiology. In: Magdoff, F., Weil, R.R. (Eds.), Soil Organic Matter in Sustainable Agriculture. CRC Press, Boca Raton, FL, pp. 295–326.
Kim, D.-S., Cook, R.J., Weller, D.M., 1997. *Bacillus* sp. L324-92 for biological control of three root diseases of wheat grown with reduced tillage. Phytopathology 87, 551–558.
Kok, H., Papendick, R.I., Saxton, K.E., 2009. STEEP: impact of long-term conservation farming research and education in Pacific Northwest wheatlands. J. Soil Water Conserv. 64, 253–264.
Moore, K.J., Cook, R.J., 1984. Increased take-all of wheat with direct drilling in the Pacific Northwest. Phytopathology 74, 1044–1049.
Moyer, J.R., Roman, E.S., Lindwall, C.W., Blackshaw, R.E., 1994. Weed management in conservation tillage systems for wheat production in North and South America. Crop. Prot. 12, 243–259.
Nail, E.L., Young, D.L., Schillinger, W.F., 2007. Government subsidies and crop insurance effects on the economics of conservation cropping systems in eastern Washington. Agron. J. 99, 614–620.
Papendick, R.I., 1987. Tillage and water conservation: experience in the Pacific Northwest. Soil Use Manage. 3, 69–74.
Paulitz, T.C., Okubara, P.A., Schillinger, W.F., 2006. First report of damping-off of canola caused by *Rhizoctonia solani* AG 2-1 in Washington State. Plant Dis. 90, 829.
Paulitz, T.C., Schroeder, K.L., Schillinger, W.F., Root diseases of cereals in an irrigated cropping system: effects of tillage, residue management and crop rotation. Plant Dis., in press.
Ramig, R.E., Ekin, L.G., 1976. Conservation tillage effects on water storage and crop yields in Walla Walla and Ritzville soils. Oregon Agric. Exp. Stn. Spec. Rep. 459.
Rasmussen, P.E., Goulding, K.W.T., Brown, J.R., Grace, P.R., Janzen, H.H., Korchens, M., 1998. Long-term agroecosystem experiments: assessing agricultural sustainability and global change. Science 282, 893–896.
Rovira, A.D., 1986. Influence of crop rotation and tillage on Rhizoctonia bare patch of wheat. Phytopathology 76, 669–673.
SAS Institute, 2008. SAS User's Guide: Statistics. SAS Inst, Cary, NC.
Schillinger, W.L., Kennedy, A.C., Young, D.L., 2007. Eight years of annual no-till cropping in Washington's winter wheat—summer fallow region. Agric. Ecosyst. Environ. 120, 345–358.
Schillinger, W.F., Smith, T.A., Schafer, H.L., 2008. Chaff and straw spreader for a plot combine. Agron. J. 100, 398–399.
Smiley, R.W., Ogg, A.G., Cook, R.J., 1992. Influence of glyphosate on Rhizoctonia root rot, growth, and yield of barley. Plant Dis. 76, 937–942.
Smith, J.L., Doran, J.W., 1996. Measurement and use of pH and electrical conductivity for soil quality analysis. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Science Society of America, Madison, WI, pp. 169–186.
Steel, R.G., Torrie, J.H., 1980. Principles and Procedures of Statistics: A Biometrical Approach, 2nd ed. McGraw-Hill Book Co., New York.
Tabatabai, M.A., 1994. Soil enzymes. In: Weaver, R.W., Angle, S., Bottomley, P., Bezdicek, D., Smith, S., Tabatabai, A., Wollum, A. (Eds.), Methods of Soil Analysis. Part II. Microbiological and Chemical Properties, 2nd ed. American Society of Agronomy, Madison, WI, pp. 820–823.
Topp, G.C., Ferre, P.A., 2002. Methods for measurement of soil water content: thermogravimetric using convective oven-drying. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Physical Methods. SSSA Book Series: 5, Soil Science Society of America, Madison, WI, pp. 422–424.

Wiese, M.V., 1987. Compendium of Wheat Diseases, 2nd ed. American Phytopathological Soc. Press, St. Paul, MN.
Weller, D.M., Cook, R.J., MacNish, G., Bassett, E.N., Powelson, R.L., Petersen, R.R., 1986. Rhizoctonia root rot of small grains favored by reduced tillage in the Pacific Northwest. Plant Dis. 70, 70–73.
Weller, D.M., Raaijmakers, J.M., McSpadden-Gardener, B.B., Thomashow, L.S., 2002. Microbial populations responsible for specific soil suppressiveness to plant pathogens. Annu. Rev. Phytopathol. 40, 309–348.
Yibarek, S.M., Verma, P.R., Morrall, R.A.A., 1987. Anastomosis groups, pathogenicity, and specificity of *Rhizoctonia solani* isolates from seedling and adult rapeseed/canola plants and soils in Saskatchewan. Can. J. Plant Pathol. 9, 6–13.
Zaikin A.A., Young, D.L., Schillinger, W.F., 2008. Economics of an irrigated no-till crop rotation with alternative residue management practices versus continuous irrigated winter wheat with burning and plowing of stubble. Washington State Univ. Ext. Bull. EB2029E.