

Agronomics and economics of no-till facultative wheat in the Pacific Northwest, USA

L.S. Bewick^{a,*}, F.L. Young^b, J.R. Alldredge^c, D.L. Young^d

^aDepartment of Crop and Soil Sciences, Washington State University, Pullman, WA 99164, USA

^bLand Management and Water Conservation Research Unit, USDA-ARS, Washington State University, Pullman, WA 99164, USA

^cDepartment of Statistics, Washington State University, Pullman, WA 99164, USA

^dSchool of Economic Sciences, Washington State University, Pullman, WA 99164, USA

Received 25 September 2007; accepted 16 November 2007

Abstract

Winter wheat (*Triticum aestivum* L.) (WW) rotated with dust-mulch summer fallow (WW/SF) has been the dominant production practice in the low-precipitation zone (<300 mm annual precipitation) of the Pacific Northwest (PNW) since the early 1900s. Over time, WW/SF has experienced several problems including severe wind erosion, increased pest problems and costs of production, and reduced crop yields. Producers need system alternatives to replace or modify the traditional WW/SF system. One proposed alternative is production of no-till facultative wheat (*T. aestivum* L.) (FW). Generally, FWs have less cold tolerance, a shorter but distinct period required for vernalization, and start growing and initiate flowering earlier compared with true WWs. This study compares agronomic, economic, and soil moisture components of FW/chemical fallow (FW/ChF), FW/spring wheat (*T. aestivum* L.) (FW/SW), and WW/reduced tillage SF (WW/RSF) rotations as part of an inter-disciplinary, multi-component research trial conducted near Ralston, Washington, USA. Over the 4-year study period, spring soil water content (SWC) was greater for ChF compared with RSF at all depths except 0.3–0.6 m. In the fall, difference in SWC between ChF and SF disappeared at depths below 0.6 m but was less for ChF from the soil surface to 0.6 m. WW/RSF and FW/ChF were more productive, both economically and agronomically, than FW/SW, with WW/RSF being more productive than either FW rotation by a wide margin. The FW/SW rotation produced lower yields that were more susceptible to fluctuations in crop year precipitation, contained more weeds, cost more to produce, and was less profitable than either WW/RSF or FW/ChF. The FW/ChF rotation was less variable than WW/RSF; however, net returns over total cost were consistently negative for FW/ChF and averaged \$69.00 rotational ha⁻¹ less than WW/RSF. Even though FW/ChF yielded and earned less than WW/RSF, the FW/ChF rotation may be a viable conservation system with cost sharing and/or further research. The yield of FW following ChF was excellent in 2002 in large-scale demonstration plots, in 2003 in the main study where it out-yielded WW, and in 2006 when FW was planted into ChF without sulfentrazone herbicide. The advantages of FW/ChF include (1) spread-out fall planting and summer harvesting operations; (2) opportunities to control problem winter-annual weeds; (3) better competition with summer annual weeds than spring wheat; and (4) a late planting date that does not rely on seed-zone soil water like WW.

Published by Elsevier Ltd.

Keywords: Chemical fallow; Reduced tillage summer fallow; Winter wheat; Spring wheat; Low precipitation; Soil moisture

1. Introduction

Since the early 1900s the dominant production practice in the low-precipitation zone (<300 mm annual precipitation) of the inland Pacific Northwest (PNW) has been to alternate winter wheat (*Triticum aestivum* L.) (WW) with

dust-mulch summer fallow (WW/SF), resulting in one crop every 2 years (Papendick, 2004). During the summer fallow period, a weed-free dust-mulch is maintained to a depth of 100–150 mm by multiple tillage operations (Thorne et al., 2003) and serves as a barrier that reduces evaporation of soil moisture below the tillage line. The summer fallow period maximizes soil water storage and reduces the risk of crop failure or uneconomical yields (Peterson et al., 1996). The WW/SF system remains the major rotation in this

*Corresponding author. Tel.: +1 509 335 2451.

E-mail address: bewicls205dn@wsu.edu (L.S. Bewick).

region today because of the adaptation of WW to the area, its time-proven yield and economic stability compared with other small grain production systems, and uniform seasonal demand on farm machinery and labor.

The low-precipitation zone of the PNW is characterized by cool, moist winters with warm, dry summers, occasional drought cycles, and frequent winds that may reach speeds in excess of 80 km/h. Almost 70% of the annual precipitation is received from November to April (Young, 2004; Leggett et al., 1974). The climate, combined with the WW/SF system and poorly aggregated soils, results in significant dust storms that are most prevalent in the early spring, late summer, and fall (Papendick, 2004). The dust storms can result in significant topsoil losses (240–600 Mg ha⁻¹ annually) (Papendick, 1996) and PM10 (particulates of dust 10 µm and smaller) emissions that negatively affect human respiratory health (Upadhyay et al., 2003).

Several studies have examined the economic performance of alternative conservation tillage cropping systems in the low-precipitation zone of the PNW. Two studies examined the performance of a no-till annual hard red spring wheat (*T. aestivum* L.) (HRSW) cropping system in two precipitation zones (Juergens et al., 2004; Schillinger and Young, 2004). At a site in Benton County, Washington (<200 mm annual precipitation), one of the driest wheat production areas in the world, annual net returns over total costs before government farm payments were negative for both no-till continuous HRSW and WW/SF, with HRSW returning \$95.35 rotational ha⁻¹ less than WW/SF (Schillinger and Young, 2004). A rotational ha of a given 2-year system, for example WW/SF, would include 0.5 ha of WW and 0.5 ha of SF. At a second site in Adams County, Washington (200–300 mm annual precipitation), WW/SF returned \$113.00 rotational ha⁻¹ more than no-till continuous HRSW. The HRSW system also demonstrated more annual income risk than WW/SF. Similarly, an 8-year study conducted in Adams County found WW/SF to be most profitable compared with six other alternative rotations examined (Young, 2005). Over the first 5 years of the study, during which time record-high precipitation was received, continuous no-till soft white spring wheat (*T. aestivum* L.) (SWSW) was economically competitive with WW/SF. However, over the complete 8-year study, profitability of continuous no-till SWSW lagged conventional WW/SF by \$60.00 rotational ha⁻¹ (Young, 2005). Juergens et al. (2004) compared the economics of two additional alternative crop rotations with WW/SF. They included a 4-year rotation of safflower (*Carthamus tinctorius* L.)/yellow mustard (*Brassica hirta* Moench.)/SWSW/SWSW, and a 2-year rotation of SWSW/spring barley (*Hordeum vulgare* L.). The two alternative rotations were not economically competitive with WW/SF. The lower average returns and higher risk of spring crops in comparison with the traditional WW/SF system have deterred many growers from annual spring cropping in the low-rainfall region of the PNW.

One crop that has not been examined in a rotation system in the PNW or other locations in the United States is facultative wheat (*T. aestivum* L.) (FW). To date, no clear definition of FW exists and the genetic properties to distinguish it from WW and spring wheat (SW) are not clear. FWs, often derived from SW by WW crosses (Braun, 1997), are usually characterized by strong photosensitivity and partial sensitivity to vernalization (Stelmakh, 1998). In addition, FWs have less cold tolerance, a shorter but distinct vernalization period, and initiate spring growth and flowering earlier compared with true WWs (Braun and Săulescu, 2002; Hodson and van Ginkel, 2004).

Interest in FW as an alternate crop in the PNW was sparked by research conducted by Young (2004) in 1996 and 1997 in Adams County, Washington. The study evaluated the response of specifically chosen fall-planted SW varieties for grain and biomass production and to suppress spring weed growth, especially of *Salsola tragus* Sennen & Pau. Three SW varieties and a WW variety were planted at four different dates ranging from early November to late March. Spring wheat varieties were chosen based on their facultative tendencies and other agronomic and adaptive qualities. In general, the yield of FW planted in November was similar to WW planted in November and to the same variety of SW planted at the normal mid-March planting date. In May, FW planted in November was 50% taller than FW planted in March, which indicated promise for weed suppression. Of the three spring wheat varieties planted ‘Alpowa’ performed best, and yielded higher with greater biomass production. Based on these results a pilot study was conducted to determine how ‘Alpowa’ planted in November of 2001 would perform in a large (9 × 152 m), single-strip demonstration plot previously managed under chemical fallow (ChF). Yield of FW exceeded SW (planted at normal mid-March planting date) following ChF and was similar to WW following reduced tillage SF (RSF). The success of the two FW studies indicated promise for FW as a potential alternative crop for growers.

Considerable research has been published on ChF, although little has been conducted in the PNW. The efficiency of ChF to store soil moisture has varied by location. Several studies have found that, contrary to the effectiveness of ChF to increase total soil water storage in high-rainfall areas (Greb et al., 1967; Smika and Wicks, 1968), ChF was often only equivalent in total water storage to conventional SF in low-rainfall environments (Al Mulla, 2004; Pannkuk et al., 1997; Incerti et al., 1993; Overson and Appleby, 1971; Wiese et al., 1960). These studies also showed that the efficiency of ChF to store soil water when compared with SF varied by time of year. Rainfall distribution over the fallow period (Incerti et al., 1993; Lindstrom et al., 1974), amount of soil surface residue (Pannkuk et al., 1997; Incerti et al., 1993), and soil texture, which influences the thermal and hydraulic properties of the soil (Hammel et al., 1981), affects the efficiency of ChF to store soil water and may explain the variability in results

among different studies and regions. Research conducted by Incerti et al. (1993) in Australia showed that both soil water storage and subsequent WW yield were similar in both ChF and SF; however, the cost of herbicides to maintain effective weed control needed in ChF was not economical for growers. The author stated that the development and use of residual herbicides may overcome this handicap of ChF. This conclusion was also reached by researchers in the USA (Pannkuk et al., 1997). In semi-arid areas, where less crop residue is accumulated and the evaporative potential is greater, the moisture line in ChF is generally deeper in the soil than in SF (Gibson et al., 1992; Lindstrom et al., 1974). No research has been published on the use of ChF in rotation with FW. In addition, no recent research has been conducted to assess the economic competitiveness of ChF with conventional SF, taking into account the recent higher petroleum prices, lower cost of non-selective contact herbicides, and the availability of residual herbicides.

FW, with its late planting date and early spring emergence, merits examination as a potentially agronomically, economically, and environmentally acceptable crop. The objective of this research was to examine performance of FW in two rotations (FW/SW and FW/ChF) compared with WW/RSF. This manuscript focuses on and uses both agronomic and economic performance to assess the overall performance of the three systems. Agronomic performance of the systems was evaluated using residue production, yield, test weight, and soil moisture. Economic performance of the systems was assessed using standard enterprise budgeting techniques to determine system production costs and profitability.

2. Materials and methods

2.1. Plot history and establishment

This study was part of the first long-term, multi-, interdisciplinary project designed to develop conservation tillage, spring cropping systems in the low-precipitation zone of the PNW. The study site was located in Adams County (T 17N, R 35E) southwest of Ralston (46°54'N, 118°24'W), Washington (Young, 2004; Young and Thorne, 2004), on a Ritzville silt loam soil (coarse-silty, mixed, mesic, Calcic, Haploxeroll) with 30% sand, 62% silt, and 8% clay. Soil depth was >2 m with no restrictive layers and slopes <1%.

The long-term project consisted of three phases; Phase I (1995–2000), Phase II (2000–2002), and Phase III (2002–2007). The general field layout, experimental design, Phase I crop rotations (1995–2000), and field operations have been published previously (Thorne et al., 2003; Young and Thorne, 2004). During Phase I there were 32, 152 × 9 m plots. In the beginning of Phase II (2000–2002), plots were split in half forming 64, 76 × 9 m plots.

Phase III (2002–2007) contained four rotation systems that included two crop rotations per rotation system. The

rotation systems were designed so comparisons could be made either within or among any of the systems. This manuscript addresses three crop rotations in two of the rotation systems in Phase III, no-till FW/ChF, no-till FW/SW, and WW/RSF. The plot histories of the FW/ChF and FW/SW crop rotations were SW/ChF (1995–2000) and FW/ChF (2001–2002). The WW/RSF crop rotation was maintained on plots dedicated to this rotation since 1995. Within each crop rotation, each crop or fallow treatment was present every year, with the exception of the 2002–2003 crop year where no FW following SW was produced. One side of each plot (3 × 76 m) was designated as a sample area, where all data other than crop yield were collected, while the other side (6 × 76 m) was designated as the harvest area. Generally, all field operations were conducted with commercial-size machinery.

2.2. Systems maintenance and management

In each crop year (1 September–31 August), WW was planted in early September, FW was planted in early November, and SW was planted the following March. FW and SW plots were planted with 'Alpowa' SWSW and fertilized using a 3.0-m wide John Deere[®] 9400 hoe-opener drill with rows spaced 17.8 cm apart. Additional fertilizer was applied to FW in the spring with a 4.6-m wide spoke-wheel injector. WW plots were planted with 'Finch' in 2002 and 2003 and 'Tubbs' in 2004 and 2005 using a 2.4-m wide John Deere[®] HZ 616 deep-furrow drill with rows spaced 40.0 cm apart. Fertilizer was applied in the spring of the RSF period with a 9.8-m wide Haybuster[®] 3200 Under-cutter with 60 cm v-shaped sweeps.

Seed and fertilizer rates varied by year and crop. Generally, seeding rates varied from 86 to 98, 75 to 91, and 38 to 50 kg ha⁻¹ for FW, SW, and WW, respectively. All seed was pre-treated with Dividend Extreme[®] (difenoconazole + mephenoxam, at 1.3 ml kg⁻¹ seed) and Raxil[®] XT (tebuconazole + metalaxyl, at 0.10 ml kg⁻¹ seed) fungicides. Fertilizer rates were calculated based on soil test results and projected yields for the area. Nitrogen (N), phosphorus (P), and sulfur (S) were applied to FW and SW, while only N and S were applied to WW. Nitrogen rates ranged from 17 to 62, 25 to 45, 40 to 79, and 73 to 84 kg ha⁻¹ for FW following ChF (FW_(ChF)), FW following SW (FW_(SW)), SW, and WW, respectively. The lowest N rates for the FW and SW were for a year where residual N was high. Phosphorus rates were 6 kg P ha⁻¹ for both FW treatments and ranged from 13 to 16 kg P ha⁻¹ for SW. In general, sulfur was applied at 11 kg S ha⁻¹ for all crops. An additional 20 kg N ha⁻¹ was applied to FW plots in the spring.

2.3. Precipitation and soil moisture

Precipitation was measured daily by an on-site weather station over the duration of the study. Precipitation by snow was not measured by the on-site weather station;

however, the grower, located 1.6 km north of the site, measured all precipitation including that from snow. Snow data obtained from the grower was combined with on-site precipitation data.

Soil moisture and nutrient content was measured bi-annually in early spring and in August following crop harvest using a tractor-mounted Giddings[®] soil probe. Three, 1.8-m deep cores were collected from each plot using a 32-mm diameter soil probe. Cores from the same plot were combined by 0.3-m depth increments. Samples were transported from the field site in coolers and stored in freezers at 0 °C until processing for gravimetric water content (Top and Ferre, 2002) and nutrient analysis.

Soil water storage efficiency (WSE) was calculated for fallow treatments by determining the ratio of stored soil water in the full 1.8-m soil profile to the total precipitation during the fallow period (Pannkuk et al., 1997). The fallow period for ChF was 18 months, while the fallow period for RSF was 12 months. The longer fallow period for ChF was because FW, although planted in November, does not emerge and begin actively growing until late February to early March.

2.4. Grain yield and crop residue

Grain was harvested with a John Deere 7720 combine equipped with a 5-m header, on-board electronic weigh scale, and a straw chopper and spreader to evenly distribute plant residue. A subsample of grain (approximately 400 g) was collected from each plot, cleaned to determine total percent dockage, and then test weights were obtained. The clean subsamples were dried at 49 °C for 48 h or until grain reached approximately zero percent moisture and weighed again. Grain yield was reported at zero percent moisture and dockage.

In the 2005–2006 crop year, a small study was conducted in response to scientists', extension agents', and the growers' concern that carry-over from sulfentrazone (*N*-[2,4-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazolo-1-yl]methanesulfonamide), used for broadleaf weed control in ChF, reduced subsequent FW yields. In the fall of 2005, FW was planted into plots that had never received an application of sulfentrazone. Grain yields were collected as described above.

Crop biomass samples were collected annually when plants were physiologically mature prior to crop harvest. Biomass was sampled from all rows within each of three, 1-m² areas per plot. Plants were cut just above the soil surface, placed in large paper bags, and weighed after drying in ovens at 49 °C for at least 48 h. Grain weights were subtracted from crop biomass to determine crop residue values.

2.5. Economic assessment

Standard enterprise budgeting techniques were used to assess system production costs and profitability.

Production costs were categorized as fixed or variable. Fixed costs do not vary with the number of hectares planted for a fixed farm size and machinery complement. However, variable costs vary proportionately with the area planted. Machinery fixed costs included depreciation, interest, taxes, housing, and insurance. Land fixed costs include only property taxes and net land rent (actual rent). Net land rent is an opportunity cost, which reflects the money forgone by using owned land rather than renting it to another grower. Net rent is based on rental agreements typical of the area. The typical small grain lease is 1/3 landlord and 2/3 tenant crop shares and a similar split for fertilizer and crop insurance costs. The landlord pays the property taxes, while the tenant is responsible for personal taxes on equipment and other non-real estate assets. For both wheat–fallow treatments (WW/RSF and FW/ChF), the previous year's fallow costs, plus interest, are included as part of the fixed costs of raising WW or FW. Other fixed costs include legal and accounting services, overhead expenses, and farm-wide insurance. Both fixed and variable costs must be covered by wheat sales if the enterprise is to remain profitable in the long run.

Variable costs include hire of custom services, seed, fertilizer, herbicides, crop insurance, machinery repairs, fuel, lubrication, and labor, and interest on operating capital. Costs were based on the actual sequence of operations conducted on the experimental plots during the 4-year study. Input rates were a 4-year average from each cropping system. Year 2006 input prices and a 2006 interest rate on average investment of 8% were used (Zaikin et al., 2007). The machinery complement reflects machinery used on typical farms in the region with comparable crop rotations. The machinery includes a 12-m John Deere[®] 9400 hoe-opener drill equipped for fertilizer application; 12-m John Deere[®] HZ 616 deep-furrow drill; 9-m offset finishing disk; 10-m undercutter equipped for fertilizer application; 22-m rodweeder; 24-m pesticide applicator; 223710 W Challenger[®] four-wheel drive tractor; John Deere[®] hillside combine (8-m header); grain truck; and farm pickup. It should be noted that even with the smaller farm size of 809 ha assumed for these budgets, many growers would own at least a second smaller tractor to optimize fuel efficiency, to serve as a replacement in case of breakdowns, and to permit simultaneous operations during key periods. To account for the high annual hours of use of the sole tractor in this study, the tractor is assumed to have a shorter life and a greater annual repair cost.

Machinery purchase price, salvage value, years of use, and repair costs were derived from Zaikin et al. (2007), Nail et al. (2005), Hinman and Esser (1999), local equipment dealers, and the grower cooperator. Annual hours of use were derived from Platt et al. (2004), Esser et al. (2003), and Juergens et al. (2003) with a similar farm size and location. Other budgets referenced include Nail et al. (2005) as a small farm size example and Young et al. (2000), Zaikin et al. (2007), and Hinman and Esser (1999)

as large farm size examples. Most equipment purchase prices assume used machinery.

It should be noted that the purchase price of a used 12-m hoe-opener drill (\$17,600–25,600), similar to the one used to plant spring no-till crops in this study, is much less than most traditional no-till drills. The average purchase price of a new 9–11-m hoe-opener no-till drill with an air cart is \$82,000 (Esser et al., 2003). The cost difference in part reflects the vast changes in no-till technology over the years. The new no-till drills are generally much heavier than conventional drills and have more sophisticated fertilizer delivery, openers, and other systems. The JD 9400 hoe-opener drill is lighter than most no-till drills putting it at an advantage in low-annual rainfall regions like the study area. The JD 9400 hoe-opener drill has been used since 1995 by the long-term project to plant no-till crops.

Net returns to management include only market returns and exclude government payments and crop insurance indemnities. Gross annual receipts for each system were based on actual yields of WW, FW_(ChF), FW_(SW), and SW during the study period and the regional 5-year (2002–2006) average farm gate price of \$0.1290 kg⁻¹ (\$3.51 bu⁻¹) for soft white wheat (Ritzville Warehouse, Ritzville, Washington) rather than annual wheat prices. This means that the actual performance of each system is not confounded by fluctuations in the wheat market, which might be correlated over time with production performance of particular systems. During the 2002–2003 crop year FW_(SW) was not produced and therefore net returns were not calculated for the FW/SW cropping system in that year. Net returns for each system were computed per rotational ha (for example, WW/RSF includes 0.5 ha of WW and 0.5 ha of RSF). This correctly portrays the average annual income per cropped ha for growers who allocate 1/*n* of their land to each crop in an *n*-year rotation. This approach ensures comparability on a standard dollar ha⁻¹ basis for different crop rotations. Standard deviations of net returns were calculated and, although they cannot be statistically compared, provide a useful measure of the economic variability of the different cropping systems.

2.6. Statistical analysis

The experimental design was a randomized complete block (RCB) with all crop rotation systems present in each of four blocks each year. Analysis of variance (ANOVA) was used to examine effects on grain yield, grain test weight, crop residue, soil moisture, soil WSE, and economic net returns. Repeated measures analysis, with year being treated as the repeated factor, was used for grain yield, grain test weight, crop residue, soil moisture, soil WSE, and for looking within years at economic net returns. Soil moisture values were log transformed before analysis to improve homoscedasticity, although all tables present original values. A mixed effects ANOVA without a

repeated factor was used when examining effects on economic net returns across all years (Little et al., 1996) both including and excluding 2003. The outcomes of the two analyses were not different so values were examined across all years. The Bonferroni method was used for pre-planned comparisons of treatment means with an overall level of significance of 0.05 (Dean and Voss, 1999). All analyses had a significant year by treatment interaction, which indicated that comparisons should be made within years only. However, the systems were compared across all years to obtain an indication of each rotation's overall performance during the study period and also because this was one of the original pre-planned comparisons.

3. Results

3.1. Precipitation and soil moisture

The 30-year average annual crop year precipitation at the site is approximately 292 mm (including precipitation by snow). The traditional crop year begins 1 September and ends 31 August the following year. Crop year precipitation including snow was below the historic average the year preceding the study (2001–2002) as well as the second (2003–2004) and third (2004–2005) crop years (Fig. 1). The first crop year (2002–2003) was slightly above average, while the fourth crop year (2005–2006) was almost 100 mm above average.

The 2004–2005 crop year was the driest crop year (Fig. 1) since the cropping systems project was initiated in 1995. In addition, this year also experienced the most abnormal

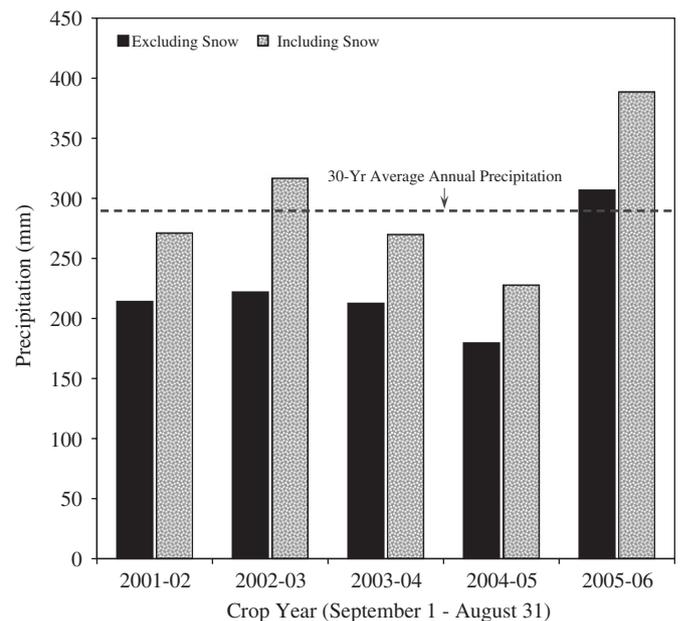


Fig. 1. Crop year (1 September–31 August) precipitation (excluding and including snow) for the year preceding the study and over the 4-year study period in the low-precipitation winter wheat-producing region of the Pacific Northwest, USA. The dashed line represents the 30-year average annual precipitation (including snow) for the study area.

precipitation pattern of the 5 years (data not shown). Normally there is a major period of appreciable precipitation, occurring in late fall to late winter (October–January), that receives between 50 and 90 mm and accounts for the majority of soil water recharge (Fuentes et al., 2003). During the 2004–2005 crop year, precipitation for this late fall to late winter period did not exceed 35 mm and approximately half of the crop year precipitation was received between February and June, resulting in less than average soil water recharge.

The 4-year average total soil water content (SWC) in the 0–1.8-m profile for the four crops was similar (Fig. 2) and ranged between 1.058 and 1.136 mm³ mm⁻³ in the spring. In the fall, total SWC ranged from 0.473 to 0.564 mm³ mm⁻³ and was greatest in SW and least in WW. Average spring total SWC in the 0–1.8-m profile was 1.110, 1.120, 1.058, and 1.136 mm³ mm⁻³ for FW_(ChF), FW_(SW), SW, and WW, respectively. In the fall, average total SWC in the 0–1.8-m profile was 0.546, 0.555, 0.564, 0.473 mm³ mm⁻³ for FW_(ChF), FW_(SW), SW, and WW, respectively. Average total SWC for WW and SW differed, but both were similar to FW_(ChF) and FW_(SW) (Fig. 2).

In the spring, SWC at the 0–0.3-m depth was least for WW and greatest for FW_(SW) and SW (Fig. 2); however, there was no difference at the 0.3–0.9-m depths. At the 0.9–1.2-m depths, no difference was found between the two FW treatments and WW, but SWC for SW was less than WW. At the 1.2–1.8-m depth, SWC was least for SW compared with any of the other three crop treatments, which were all similar to each other. In the fall, SWC was similar for all crop treatments to a depth of 0.9 m (Fig. 2). At the 0.9–1.2-m depth SWC was less for WW than for FW_(SW); however, SW did not differ from either FW treatment. WW had the least SWC at the 1.2–1.8-m depth

compared with SW or either FW, with all three non-WW treatments being similar.

In the spring of the fallow year, following soil water recharge, SWC was greater for ChF compared with RSF at all depths except 0.3–0.6 m (Fig. 3). In the fall, SWC was less in ChF than in RSF from the soil surface to 0.6 m (Fig. 3). The two fallow treatments were similar from 0.6 to 1.8 m depth. The 4-year average WSE was greater for ChF (42%) than RSF (30%) (data not shown). Over the study period average WSE ranged from 31% to 54% for ChF and 25% to 35% for RSF.

3.2. Grain yield and test weight

Average yield and grain test weight over the study period was used as indicator of cropping system performance, which was one of the pre-planned comparisons. Average yields over the study period were 2395, 1777, 1753, and 3083 kg ha⁻¹ for FW_(ChF), FW_(SW), SW, and WW, respectively (Fig. 4). Overall, the two wheat–fallow treatments (FW_(ChF) and WW) yielded higher and were more stable across years than either annual crop treatment (FW_(SW) and SW). Looking at each year individually, in 2003, yield of FW_(ChF) was greater than either SW or WW, with SW having the least. In 2004, WW produced the greatest yield compared with the other treatments, which did not differ from each other. WW also produced the highest yield compared with the other crops in 2005 and 2006. In 2005, FW_(ChF) yielded more than both FW_(SW) and SW, which were similar, while in 2006 yields of SW and both FWs were similar.

The minimum test weight required for USA grade #1 wheat is 78.9 kg hl⁻¹ (USDA Federal Grain Inspection Service). Average test weights over the study period were

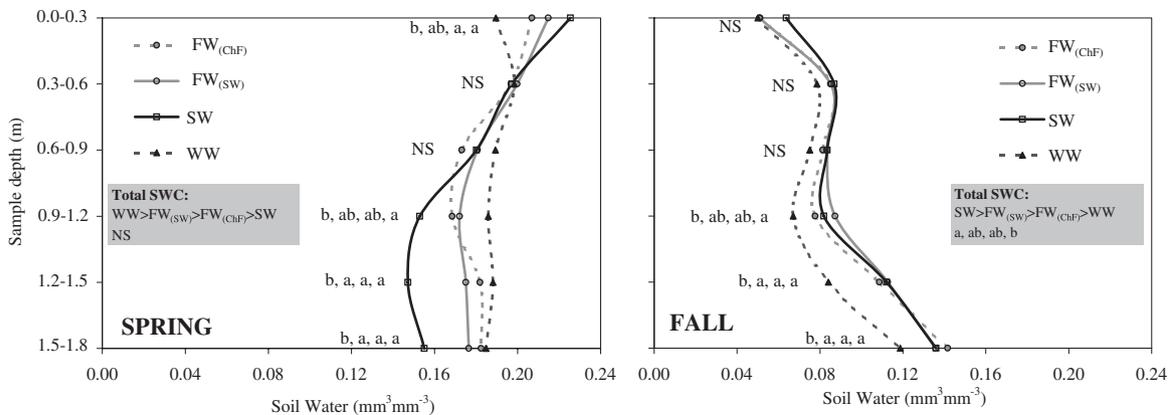


Fig. 2. Spring (left) and fall (right) soil water content (SWC) comparisons by depth for crop treatments averaged over the 4 years of the study in the low-precipitation winter wheat-producing region of the Pacific Northwest, USA. Means within the same depth-increments followed by the same letter are not significantly different (overall $P < 0.05$) based on the Bonferroni method for pre-planned comparisons. At each depth, letters are arranged from highest to lowest SWC (right to left). Below the legend, comparisons of total SWC (entire 1.8 m profile) for each crop and their respective letters of significance are listed. The letters are arranged from highest to lowest (left to right) SWC. Soil moisture values were log transformed before analysis to improve homoscedasticity, although original values are presented in the figures. Crops are abbreviated as follows: FW_(ChF) = facultative wheat following chemical fallow, FW_(SW) = facultative wheat following spring wheat, SW = spring wheat following facultative wheat, and WW = winter wheat following reduced tillage dust-mulch summer fallow. No FW_(SW) was grown in 2003. Average SWC over the 4-year study period is used as an indicator of cropping systems performance, which was one of the pre-planned comparisons.

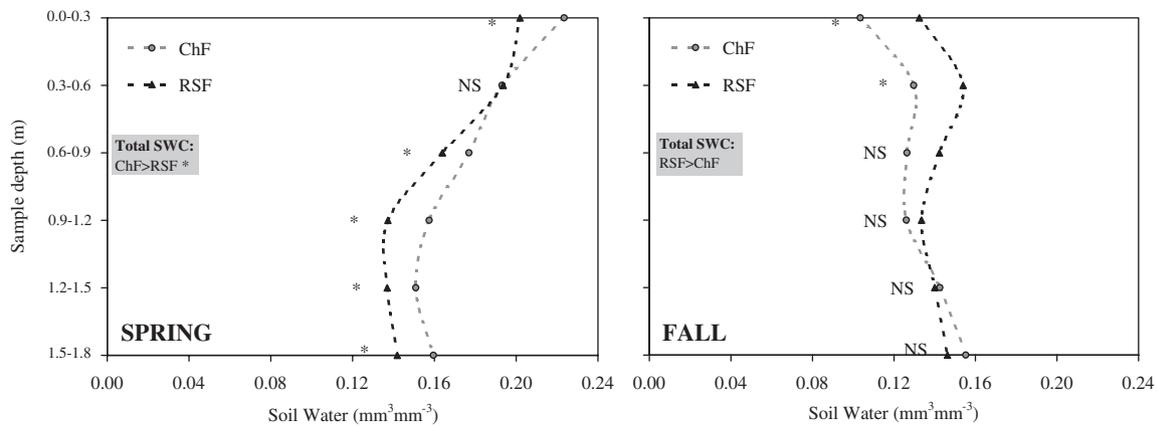


Fig. 3. Spring (left) and fall (right) soil water content (SWC) comparisons by depth for both fallow treatments over the 4 years of the study in the low-precipitation winter wheat-producing region of the Pacific Northwest, USA. Means within the same depth increments followed by (NS) are not different (overall $P < 0.05$) based on the Bonferroni method for pre-planned comparisons. The "*" refers to a significant difference between values. Below the legend, comparisons of total SWC (entire 1.8 m profile) for both the two fallow treatments are listed. Soil moisture values were log transformed before analysis to improve homoscedasticity, although original values are presented in the tables. Fallow treatments are abbreviated as follows: ChF = chemical fallow, RSF = reduced tillage dust-mulch summer fallow. Average soil water content is used as an indicator of fallow system performance, which was one of the pre-planned comparisons.

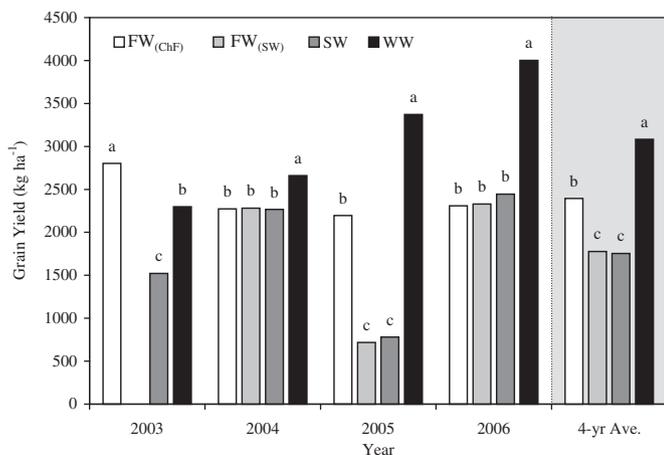


Fig. 4. Crop grain yield comparisons over the 4 years of the study in the low-precipitation winter wheat-producing region of the Pacific Northwest, USA. Means within years followed by the same letter are not significantly different (overall $P < 0.05$) based on the Bonferroni method for pre-planned comparisons. Crops are abbreviated as follows: FW_(ChF) = facultative wheat following chemical fallow, FW_(SW) = facultative wheat following spring wheat, SW = spring wheat, and WW = winter wheat. No FW_(SW) was grown in 2003. Average yield over the 4-year study period was used as an indicator of cropping systems performance, which was one of the pre-planned comparisons.

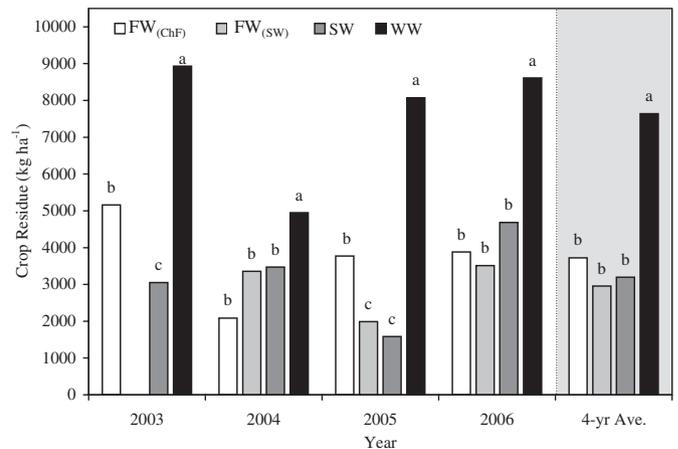


Fig. 5. Crop residue comparisons over the 4 years of the study in the low-precipitation winter wheat-producing region of the Pacific Northwest, USA. Means within years followed by the same letter are not significantly different (overall $P < 0.05$) based on the Bonferroni method for pre-planned comparisons. Crops are abbreviated as follows: FW_(ChF) = facultative wheat following chemical fallow, FW_(SW) = facultative wheat following spring wheat, SW = spring wheat, and WW = winter wheat. No FW_(SW) was grown in 2003. Average biomass over the 4-year study period was used as an indicator of cropping systems performance, which was one of the pre-planned comparisons.

80.0, 78.3, 77.1, and 74.7 kg hl⁻¹ for FW_(ChF), FW_(SW), SW, and WW, respectively. Overall FW_(ChF) had the heaviest test weight of all crops produced. FW/SW and SW had similar test weights and were greater than WW, which had the lightest test weight of all the crops. During the study, test weights ranged between 78.2 and 81.2, 75.3 and 81.9, 76.1 and 78.4, and 69.7 and 78.6 kg hl⁻¹ for FW_(ChF), FW_(SW), SW, and WW, respectively. Test weights were lightest in the 2004–2005 crop year and heaviest in the 2005–2006 crop year.

3.3. Crop residue

Average crop residue remaining after harvest over the study period was 3724, 2953, 3196, and 7641 kg ha⁻¹ for FW_(ChF), FW_(SW), SW, and WW, respectively (Fig. 5). Overall, WW produced more residue across years than SW or either FW. In general, within each year crop residue production mimicked grain yield. The exception was in 2003 when WW produced the most residue (Fig. 5) even though it did not have the greatest yield (Fig. 4). In the

remaining 3 years of the study, WW produced more residue than any other crop. In 2004 and 2006, both FW treatments and SW were similar, while in 2005 FW_(ChF) produced more residue than either FW_(SW) or SW.

3.4. Economics

Average variable costs were \$44.04, \$111.85, and \$236.36 rotational ha⁻¹, while average fixed costs were \$158.08, \$115.15, and \$92.15 rotational ha⁻¹ for WW/RSF, FW/ChF, and FW/SW, respectively (Table 1). Average gross revenue for WW/RSF, FW/ChF, and FW/SW was \$198.82, \$154.43, and \$232.64 rotational ha⁻¹, respectively (Table 1).

Over the study period, WW/RSF averaged the highest net return over variable cost, followed by FW/ChF and then FW/SW (Table 2). Both FW/ChF and FW/SW averaged negative net returns over total cost in all 4 years. From 2003 to 2006, net returns over total cost per rotation ha⁻¹ was -\$3.29, -\$72.56, and -\$95.87 for WW/RSF, FW/ChF, and FW/SW (Table 2). The total cost for the WW/RSF system implies a production cost per kg of wheat of \$0.1311 (\$3.57 bu⁻¹), slightly higher than

the 5-year (2002–2006) average price of \$0.1290 kg⁻¹ (\$3.51 bu⁻¹). However, it is a profitable production cost compared with the 2007 soft white wheat price, which has ranged between \$0.1800 kg⁻¹ (\$4.90 bu⁻¹) and \$0.2940 kg⁻¹ (\$8.00 bu⁻¹).

Standard deviation of net returns was greatest for FW/SW, followed by WW/RSF and then FW/ChF (Table 1). Total cost of production was greatest for SW (\$346.92 rotational ha⁻¹), followed by FW_(ChF) (\$346.92 rotational ha⁻¹), FW_(SW) (\$310.10 rotational ha⁻¹) and then WW (\$281.71 rotational ha⁻¹). ChF (\$135.37 rotational ha⁻¹) costs more to maintain than RSF (\$106.13 rotational ha⁻¹).

4. Discussion

Using a reduced-tillage summer fallow system similar to the one used in this study, the cooperating grower's long-term WW yield was 3700 kg ha⁻¹. In our research, over the 4-year study period, WW averaged 3083 kg ha⁻¹ and was the greatest yielding crop compared with SW or either FW (Fig. 4). With the exception of the 2002–2003 growing season, WW produced the greatest amount of grain

Table 1
Costs^a and gross receipts^b per rotational ha for FW/ChF, FW/SW, and WW/RSF rotations, Ralston, WA, 2003–2006

Rotation	Variable cost (\$ rotational ha ⁻¹)	Fixed cost (\$ rotational ha ⁻¹)	Total cost (\$ rotational ha ⁻¹)	Gross receipts	S.D. ^c
FW/ChF	111.85	115.15	227.00	154.43	17.75
FW/SW	236.36	92.15	328.51	232.74	117.81
WW/RSF	44.04	158.08	202.11	198.82	48.80

^aAll costs were valued at the 2006 point in time during the study.

^bGross receipts for crop sales were calculated from actual annual wheat yields and the 5-year average farm gate price for soft white spring wheat of \$0.1290 kg⁻¹ (\$3.51 bu⁻¹). Gross receipts are shown on a \$0.5 ha⁻¹ basis because a rotational ha of WW/RSF for example will consist of 0.5 ha of WW and 0.5 ha of RSF.

^cStandard deviations for gross receipts show the variability in each system and are used as an indicator of system riskiness.

Table 2
Net returns^a over variable and total cost per rotational ha for FW/ChF, FW/SW, and WW/RSF rotations, Ralston, WA, 2003–2006

Rotation	Net returns (\$ rotational ha ⁻¹)					S.D. ^b
	Year					
	2003	2004	2005	2006	4-yr Ave.	
<i>Over variable cost</i>						
FW/ChF	68.82 b	34.69 c	29.78 b	37.03 c	42.58 b	17.8
FW/SW	NA	56.98 b	-139.69 c	71.55 b	-3.72 c	118
WW/RSF	104.24 a	127.57 a	173.37 a	213.96 a	154.78 a	48.8
<i>Over total cost</i>						
FW/ChF	-46.32 a	-80.46 b	-85.36 b	-78.11 c	-72.56 b	17.8
FW/SW	NA	-35.17 a	-231.84 c	-20.60 b	-95.87 b	118
WW/RSF	-53.84 a	-30.50 a	15.29 a	55.88 a	-3.29 a	48.8

^aFor net returns over variable and total cost, means within years followed by the same letter are not significantly different (overall $P < 0.05$) based on the Bonferroni method for pre-planned comparisons. Crop rotations are abbreviated as follows: FW/ChF = facultative wheat rotated with chemical fallow, FW/SW = facultative wheat rotated with spring wheat, WW/RSF = winter wheat rotated with reduced tillage dust-mulch summer fallow.

^bVariability within each system is expressed by standard deviation (S.D.) and is used as an indicator of system riskiness.

compared with the other three crops annually (Fig. 4) and was likely a result of better utilization of soil moisture below 1.2 m (Fig. 2). However, in 2003, WW yielded 2299 kg ha^{-1} , 25% less than the 4-year average. This was likely attributable to two factors, below normal precipitation (Fig. 1) and a less productive WW variety. From 1 May to 1 August, which includes anthesis and grain fill, precipitation was 7.6 mm (42.9 mm below the average). Secondly, the WW variety ‘Finch’ had uneven and incomplete emergence by late winter (February) of 2003, leaving approximately 20% of the plants yet to emerge in the spring (personal observation). Previous research in the PNW has shown that late winter or early spring germination of WW results in little to no grain production because of insufficient time for vernalization (Young, 2004; Young et al., 1994). If incomplete vernalization occurred, this may also explain why the 2003 WW crop residue production was high compared with its yield, when in all other years and for all other crops, crop residue production mimicked crop yield (Figs. 4 and 5). Furthermore, the 2003 spring followed the driest fall on record and was cold and wet, which would slow plant growth (John Burns, personal communication). In the 2003–2004 crop year, WW yielded only 17% more than the other three crops. Again ‘Finch’ WW was planted to maintain the consistency through two WW growing seasons. During the next 2-year cycle (2004–2006), ‘Tubbs’ WW was planted and WW yield improved even in the 2004–2005 drought year (Fig. 4). WW produced 54% and 64% more grain compared with the second highest yielding crop during the 2004–2005 and 2005–2006 growing seasons, respectively. It appears that ‘Tubbs’ compared with ‘Finch’ was better adapted to the semi-arid wheat-producing region of the PNW.

Previous research in the region with FW production (Young 2004) has indicated potential for FW as a component of the current WW cropping system. Over the 4-year study period, $\text{FW}_{(\text{ChF})}$ was the second highest yielding crop producing 20% less than WW and approximately 26% more than $\text{FW}_{(\text{SW})}$ or SW (Fig. 4). During the 2002–2003 growing season, $\text{FW}_{(\text{ChF})}$ yielded 22% more grain than WW and 84% more grain than SW (Fig. 4). The yield reduction that occurred in $\text{FW}_{(\text{ChF})}$ during the 2003–2004 crop year was likely due to poor weed control in the preceding ChF year. Herbicides were applied three times during the 2002–2003 ChF period to control *Bromus tectorum* L., *Salsola tragus* Sennen & Pau, and *Lactuca serriola* L. Weed control was poor, especially by the third application because of high temperatures and dusty field conditions, which likely reduced herbicide efficacy. As a final attempt to prevent weed seed production and further depletion of soil moisture the ChF plots were mowed and subsequently disked lightly.

The impact of poor weed control in ChF was evident when fall and spring total SWC (0–1.8 m profile) of FW/ChF and WW/RSF were compared for the 2002–2003 crop year. In the fall prior to planting, total SWC was less in ChF ($0.601 \text{ mm}^3 \text{ mm}^{-3}$) compared with RSF

($0.862 \text{ mm}^3 \text{ mm}^{-3}$). Furthermore, SWC was less for ChF compared with RSF at individual depths down to 1.2 m. In addition, this depletion carried over to the subsequent FW crop. Total spring SWC was significantly less for $\text{FW}_{(\text{ChF})}$ compared with WW and at individual depths between 0.3 and 1.5 m. Consequently, the 2004 FW yield was reduced.

Over the 4-year study period, spring SWC was greater for ChF compared with RSF at all depths except 0.3–0.6 m. This is in contrast to Fuentes et al.’s. (2003) findings that conventional SF had slightly higher soil water content than ChF. The authors noted that differences in crop rotations and ChF management may have confounded the results. In the fall, the difference in SWC between ChF and RSF disappeared at depths below 0.6 m but was less for ChF from the soil surface to 0.6 m. These findings are similar to research by Fuentes et al. (2003).

In 2005, the driest year of the study, $\text{FW}_{(\text{ChF})}$ yielded higher than either $\text{FW}_{(\text{SW})}$ or SW (Fig. 4). In 2006, when precipitation was slightly above normal (Fig. 1), $\text{FW}_{(\text{ChF})}$ yield was not different from either $\text{FW}_{(\text{SW})}$ or SW (Fig. 4). With sufficient precipitation and a well-maintained ChF period to store moisture, $\text{FW}_{(\text{ChF})}$ should have yielded more than $\text{FW}_{(\text{SW})}$ or SW. We hypothesized that $\text{FW}_{(\text{ChF})}$ was injured by sulfentrazone carry-over from application to ChF during the previous 2003–2004 and 2004–2005 crop years. A comparison of sulfentrazone and non-sulfentrazone-treated areas in 2006 confirmed that the yield of $\text{FW}_{(\text{ChF})}$ without sulfentrazone (2886 kg ha^{-1}) was 20% higher than $\text{FW}_{(\text{ChF})}$ with sulfentrazone (2309 kg ha^{-1}).

The FW/SW rotation was the only annual crop rotation examined in this study. The 4-year average yield was similar for both $\text{FW}_{(\text{SW})}$ and SW but was less than either $\text{FW}_{(\text{ChF})}$ or WW (Fig. 4). For individual years, SW in 2003 and both $\text{FW}_{(\text{SW})}$ and SW in 2005 had the lowest yield compared with $\text{FW}_{(\text{ChF})}$ and WW (Fig. 4). The major factors affecting yield of the annual crops were noticeably greater weed populations (unpublished data), lack of precipitation during grain fill, and a lower spring SWC due to inadequate winter precipitation required to recharge the soil profile depleted by the previous crop. In addition, stripe rust (caused by *Puccinia triticina* Ericks.) severely infected SW in 2005. However, ‘Alpowa’ planted as FW was not injured by *P. triticina* compared with ‘Alpowa’ planted as SW because the more mature FW plants were protected by high-temperature adult plant resistance present in the ‘Alpowa’ variety. During the 2003–2004 and 2005–2006 growing seasons, when precipitation was either timely or plentiful, annual crop yields increased.

Based on previous research at this site (Thorne et al., 2003), crop residue values from this study likely met conservation compliance for each system in 3 out of the 4 years. The Alternative Conservation System minimum residue cover required for WW/SF is 390 kg ha^{-1} at the location of this research (Thorne et al., 2003). In 2004, $\text{FW}_{(\text{ChF})}$ and WW likely did not produce enough residue to maintain conservation compliance during the 2005 fallow periods. In 2005, the driest year of the study, the annual

crops, FW_(SW) and SW, produced only 1989 and 1582 kg residue, respectively, and may have only met conservation requirements due to the short period between growing crops. However, it is possible that these systems could contribute to biomass production for future bioenergy needs. More research is needed to determine the minimum residue requirement for each system to maintain conservation compliance and the consequences on soil carbon, nutrients, and general soil health and erodability.

Four-year average net returns over variable cost were positive for FW/ChF and WW/RSF and negative in 1 year for FW/SW (Table 2). Little emphasis, with the exception of the negative values, should be placed on this measure because it applies only to short-term economic viability. Average net returns over total cost, the generally accepted measure of long-term profitability and economic sustainability, were negative for FW/ChF and FW/SW in all years and negative for WW/RSF in 2 out of the 4 years (Table 2). Negative net returns over total cost means that crop returns were insufficient to pay market returns to all the farmer's resources, including his/her labor and investment in land and machinery. A normal or fair return over total cost would be zero. However, it is noteworthy that the WW/RSF rotation, which is similar to the wheat–fallow rotation used on virtually all the cropland in the region, nearly covered total costs with an average net return of $-\$3.29$ rotational ha^{-1} . In small grain production, negative net returns over total cost are not uncommon when government payments are excluded (Janosky et al., 2002). According to a recent study conducted in the same region, government commodity direct payments for wheat–fallow averaged $\$16.68$ rotational $\text{ha}^{-1}\text{year}^{-1}$ (Zaikin et al., 2007). If net returns over total cost were adjusted for the inclusion of government commodity direct payments, WW/RSF would be the only rotation to produce positive net returns. The least variable rotation was FW/ChF (S.D. of $\$17.75$ rotational ha^{-1}), followed by WW/RSF (S.D. of $\$48.79$ rotational ha^{-1}) and then FW/SW (S.D. of $\$117.98$ rotational ha^{-1}) (Table 2). However, if risk were defined as probability of an annual loss (net returns over total costs less than zero), WW/RSF would incur a 50% probability versus a 100% probability of annual loss for the other two systems (Table 2).

The economic advantage of WW/RSF over no-till spring cropping follows the pattern of past studies in the region. Schillinger et al. (2007) reported average net returns over total costs for 2001–2004 of $-\$109.34$ rotational ha^{-1} for continuous SWSW and $\$0.14$ rotational ha^{-1} for surveyed WW/SF. Additionally, the results of an 8-year cropping system study conducted near Ritzville, Washington, similarly found negative net returns over total cost for continuous SWSW ($-\$32.57$ rotational ha^{-1}) (Young, 2005). Comparatively, WW/SF provided positive 8-year average net returns over total cost of $\$27.43$ rotational ha^{-1} .

It is noteworthy to mention the total cost of production of each of the crops and fallow periods that make up the

three crop rotations. WW cost 7% and 19% less to produce than either FW or SW, respectively, and FW cost 12% less to produce than SW (data not shown). The cost to maintain ChF was 21% greater than RSF, supporting observations made by Incerti et al. (1993). The combination of higher cost of production of ChF compared with RSF, the higher production costs of both FW and SW, and the lower yields of these crops compared with WW underlies the lower net returns over total costs for the FW/ChF and FW/SW systems compared with WW/RSF.

5. Conclusion

Results from this 4-year study show the overall performance of the wheat–fallow systems to be more productive economically and agronomically than the annual crop rotation. The WW/RSF rotation was the most profitable by a wide margin. Overall, the annual crop rotation of FW/SW produced lower yields that were more vulnerable to fluctuations in crop year precipitation, contained more weeds, cost more to produce, and provided the lowest net returns over total cost compared with either WW/RSF or FW/ChF wheat–fallow treatment. When the wheat–fallow rotations were compared, even though FW/ChF was more stable than WW/RSF, the FW/ChF system consistently provided negative net returns over total cost. The FW/ChF fell short of WW/RSF by $\$69$ rotational ha^{-1} in 4-year average profitability. Nonetheless, yields of FW_(ChF) were excellent in 2002 in large-scale demonstration plots and in 2003 and 2006 when FW was planted into ChF without sulfentrazone. Even though FW_(ChF) yielded and earned less than WW/RSF on average, the FW/ChF rotation may be a viable conservation system with cost sharing and/or further research. Research is needed to identify and improve FW varieties, effective production strategies, and alternative crops compatible with ChF.

Even though WW/RSF is currently the most profitable conservation practice for the low-rainfall region of the PNW, the agronomic advantages of FW/ChF are numerous. These advantages include (1) reduced soil compaction because planting does not occur in the wet spring; (2) well spread-out fall planting and harvesting operations; (3) opportunities to control problem winter-annual weeds; (4) better competition with summer-annual weeds than spring wheat; and (5) a late planting date that does not rely on seed-zone soil water like WW.

References

- Al Mulla, Y.A., 2004. Flex-cropping and chemical fallow potential for dryland farming. Dissertation, Department of Biological Systems Engineering, Washington State University.
- Braun, H.J., 1997. Winter hardiness of bread wheats derived from spring by winter crosses. *Acta Agron. Hung.* 45, 317–327.
- Braun, H.J., Săulescu, N.N., 2002. Breeding winter and facultative wheat. In: Curtis, B.C., Rajaram, S., Gómez, H., Macpherson, H.G. (Eds.), *Bread Wheat Improvement and Production*. Plant Production and

- Protection Series. United Nations Food and Agriculture Organization (FAO)FAO Corporate Documents Repository Available at <http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/006/y4011e0f.htm>, accessed 9/12/2007.
- Dean, A.M., Voss, D.T., 1999. Inferences for contrasts and treatment means. In: Casella, G., Fienberg, S., Olkin, I. (Eds.), *Design and Analysis of Experiments*. Springer, New York, USA, pp. 79–83.
- Esser, A., Hinman, H., Platt, T., 2003. 2003 enterprise budgets for spring barley, spring wheat and winter wheat using direct seeding tillage practices, Washington State University Extension Bulletin. Farm Business Management Report no. EB1963E, Lincoln County, Washington. Available at <<http://pubs.wsu.edu>>, accessed 9/12/2007.
- Fuentes, J.P., Flury, M., Huggins, D.R., Bezdicsek, D.F., 2003. Soil water and nitrogen dynamics in dryland cropping systems of Washington State, USA. *Soil Tillage Res.* 71, 33–47.
- Gibson, G., Radford, B.J., Nielsen, R.G.H., 1992. Fallow management, soil water, plant-available soil nitrogen and grain sorghum production in south west Queensland. *Aust. J. Exp. Agric.* 32, 473–482.
- Greb, B.W., Smika, D.E., Black, A.L., 1967. Effects of straw mulch rates on soil water storage during summer fallow in the Great plains. *Soil Sci. Soc. Am. Proc.* 38, 556–559.
- Hammel, J.E., Papendick, R.I., Campbell, G.S., 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. *Soil Sci. Soc. Am. J.* 45, 1016–1022.
- Hinman, H.R., Esser, A.E., 1999. 1999 enterprise budgets, summer fallow, winter wheat rotations and hard red spring wheat annual cropping. Washington State University Extension Bulletin. Farm Business Management Report no. EB1883, Adams County, WA. Available at <<http://pubs.wsu.edu>>, accessed 9/12/2007.
- Hodson, D., van Ginkel, M., 2004. A map of the world for wheat breeding. *Integrated Maize and Wheat Improvement Center (CIMMYT)*. Available at <www.cimmyt.org/whatisimmyt/recent_ar/Amapof.htm>, accessed 9/12/2007.
- Incerti, M., Sale, P.W.G., O'Leary, G.J., 1993. Cropping practices in the Victorian Mallee 1. Effect of direct drilling and stubble retention on the water economy and yield of wheat. *Aust. J. Exp. Agric.* 33, 877–883.
- Janosky, J.S., Young, D.L., Schillinger, W.F., 2002. Economics of conservation tillage in a wheat–fallow rotation. *Agron. J.* 94, 527–531.
- Juergens, L.A., Young, D.L., Hinman, H.R., Schillinger, W.F., 2003. An economic comparison of no-till spring wheat and oilseed rotations to conventional winter wheat–fallow in Adams County, Washington, 2002. Washington State University Extension Bulletin. Farm Business Management Report no. EB1956E. Available at <<http://pubs.wsu.edu>>, accessed 9/12/2007.
- Juergens, L.A., Young, D.L., Schillinger, W.F., Hinman, H.R., 2004. Economics of alternative no-till spring crop rotations in Washington's wheat–fallow region. *Agron. J.* 96, 154–158.
- Lindstrom, M.J., Koehler, F.E., Papendick, R.I., 1974. Tillage effects of fallow water storage in the eastern Washington dryland region. *Agron. J.* 66, 312–316.
- Leggett, G.E., Ramig, R.E., Johnson, L.C., Masee, T.W., 1974. Summer fallow in the Northwest. In: *Summer Fallow in the Western United States*. USDA-ARS Conservation Research Report 17. US Government Print Office, Washington, DC, pp. 110–135.
- Little, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. *SAS System for Mixed Models*. SAS Institute, Cary, NC.
- Nail, E.L., Young, D.L., Hinman, H.R., Schillinger, W.F., 2005. Economic comparison of no-till annual crop rotations to winter wheat–summer fallow in Adams County, WA, 2001–2004. Washington State University Extension Bulletin. Farm Business Management Report no. EB1997E. Available at <<http://pubs.wsu.edu>>, accessed 9/12/2007.
- Overson, M.M., Appleby, A.P., 1971. Influence of tillage management on a stubble mulch fallow–winter wheat rotation with herbicides. *Agron. J.* 63, 19–20.
- Pannkuk, C.D., Papendick, R.I., Saxton, K.E., 1997. Fallow management effects on soil water storage and wheat yields in the Pacific Northwest. *Agron. J.* 89, 386–391.
- Papendick, R.I., 1996. Farming systems and conservation needs in the northwest wheat region. *Am. J. Altern. Agric.* 11, 52–57.
- Papendick, R.I., 2004. Farming with the wind II, wind erosion and air quality control on the Columbia Plateau and Columbia Basin. Washington State University College of Agriculture and Home Economics Report no. XB1042, Pullman, WA.
- Peterson, G.A., Schlegel, A.J., Tanaka, D.L., Jones, O.R., 1996. Precipitation use efficiency as affected by cropping and tillage systems. *J. Prod. Agric.* 9, 180–186.
- Platt, T., Hinman, H., Esser, A., 2004. 2003 Enterprise budgets for summer fallow–winter wheat, spring barley, and spring wheat using conventional tillage practices, Lincoln County, Washington. Washington State University Extension Bulletin. Farm Business Management Report no. EB1964E. Available at <<http://pubs.wsu.edu>>, accessed 9/12/2007.
- Schillinger, W.F., Young, D.L., 2004. Cropping systems research in the world's driest rainfed wheat region. *Agron. J.* 96, 1182–1187.
- Schillinger, W.F., 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.
- Smika, D.E., Wicks, G.A., 1968. Soil water storage during fallow in the central Great Plains as influenced by tillage with herbicide treatments. *Soil Sci. Soc. Am. Proc.* 32, 591–595.
- Stelmakh, A.F., 1998. Genetic systems regulating flowering response in wheat. *Euphytica* 100, 359–369.
- Thorne, M.E., Young, F.L., Pan, W.L., Bafus, R., Alldredge, J.R., 2003. No-till spring cereal cropping systems reduce wind erosion susceptibility in the wheat/fallow region of the Pacific Northwest. *J. Soil Water Conserv.* 58, 250–257.
- Top, G.C., Ferre, P.A., 2002. Methods for measurement of soil water content: thermogravimetric using convective oven-drying. In: Dane, J.H., Top, G.C. (Eds.), *Methods of Soil Analysis. Part 4, Physical Methods*. SSSA Book Ser. 5. SSSA, Madison, WI, pp. 422–424.
- Upadhyay, B.M., Young, D.L., Wang, H.H., Wandschneider, P.R., 2003. How do farmers who adopt multiple conservation practices differ from their neighbors? *Am. J. Altern. Agric.* 18, 27–36.
- Wiese, A.F., Bond, J.J., Army, T.J., 1960. Chemical fallow in the southeastern Great Plains. *Weeds* 8, 284–290.
- Young, F.L., 2004. Long-term weed management studies in the Pacific Northwest. *Weed Sci.* 52, 897–903.
- Young, D.L., 2005. Economics of wind erosion control. In: Schillinger, W.F., Sharratt, B. (Eds.), *Northwest Columbia Plateau Wind Erosion/Air Quality Project, 2005 Annual Report*. Department of Agriculture Agricultural Research Service Cooperative Project, Washington State University, USA, pp. 77–83. Available at <<http://pnw-winderosion.wsu.edu/>>, accessed 9/12/2007.
- Young, F.L., Thorne, M.E., 2004. Weed-species dynamics and management in no-till and reduced-till fallow cropping systems for the semi-arid agricultural region of the Pacific Northwest, USA. *Crop Prot.* 23, 1097–1110.
- Young, F.L., Ogg, A.G., Papendick, R.I., Thill, D.C., Alldredge, J.R., 1994. Tillage and weed management affects winter wheat yield in an integrated pest management system. *Agron. J.* 86, 147–154.
- Young, D.L., Hinman, H.R., Schillinger, W.F., 2000. Economics of winter wheat–summer fallow versus continuous no-till spring wheat in the Horse Heaven Hills, Washington. Washington State University Extension Bulletin. Farm Business Management Report no. EB1907. Available at <<http://pubs.wsu.edu>>, accessed 9/12/2007.
- Zaikin, A.A., Young, D.L., Schillinger, W.F., 2007. Economic comparison of undercutter and traditional tillage systems for winter wheat–summer fallow. Washington State University Extension Bulletin. Farm Business Management Report no. EB2022E. Available at <<http://pubs.wsu.edu>>, accessed 9/12/2007.