No-tillage Cropping Systems can Replace Traditional Summer Fallow in North-Central Oregon

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ABSTRACT

The traditional winter wheat (*Triticum aestivum* L.)-summer fallow (WW-SF) using conventional tillage (CT), the predominant cropping system in eastern Oregon, has been shown increase soil erosion and to deplete soil organic carbon (SOC). This research evaluates alternative no-tillage (NT) cropping systems designed to reduce these negative impacts on the soil and environment. In this long-term experiment (2004-05 to 2009-10 crop-years), WW-SF using CT was compared with annual winter wheat (WW-WW), annual spring wheat (SW-SW), annual spring barley (*Hordeum vulgare* L.) (SB-SB), winter wheat-chemical fallow (WW-CF), winter wheat-winter pea (*Pisum sativum* L.) (WW-WP), and winter wheat-spring barley-chemical fallow rotation (WW-SB-CF), all using NT. Measurements included, phenology, plant population, plant height, yield components, grain yield, crop residues, SOC, soil moisture, and precipitation. Water-use efficiency (WUE) was derived from precipitation, phenology, and grain yield data. In annual cropping, grain yield under WW-WP and SB-SB was greater than under WW-WW and SW-SW. Grain yields among crop rotations with fallow (WW-SF, WW-CF, and WW-SB-CF) were not significantly different. On an annual basis, SB-SB rotation produced the highest yield and WW-WP rotation produced the lowest yield. The WUEs of all fallow rotations, SB-SB, and SW-SW were not different but were all higher than WUEs of WW-WP and WW-WW. Residue cover and SOC were highest under annual cropping systems and lowest following peas in WW-WP and SF in WW-SF system. Based on results from the six year study rotations with fallow using NT (WW-CF, and WW-SB-CF) can replace the traditional WW-SF system without yield penalty.

Abbreviations: CBARC, Columbia Basin Agricultural Research Center; CF, chemical fallow; CT, conventional tillage; HI, harvest index; INPNW Inland Pacific Northwest; LTE, long-term experiment; NIS, nonionic surfactant; NT, no-tillage; OSU, Oregon State University; SB, spring barley; SF, summer fallow; SOC, soil organic carbon; SOM, soil organic matter; SP, spring pea; SW, spring wheat; WP, winter pea; WUE, water use efficiency; WW, winter wheat

INTRODUCTION

Winter wheat-summer fallow rotation (WW-SF) is the predominant cropping system in the low precipitation regions of north-central Oregon and south-central Washington of the Inland Pacific Northwest (IPNW) where precipitation is considered inadequate to produce a crop every year. The region covers about 1.6 million ha and receives less than 305 mm per crop-year (Schillinger et al., 2003). Fallowing is used primarily to store winter precipitation, allow mineralization of nutrients (N, S), control weeds, and is economical where rainfall is less than 330 mm (Leggett et al., 1974; Bolton and Glen, 1983). The WW-SF system, however, depletes SOC, exacerbates soil erosion and it is not biologically sustainable (Rasmussen and Parton, 1994; Williams, 2003; 2008). Current WW-SF systems involve intensive tillage using a cultivator, chisel, and disk plough. Breeding efforts to develop high yielding semi-dwarf wheat varieties with high water-use efficiency and disease resistance have not been able to stem the decline in biological sustainability in the IPNW (Duff et al, 1995). Economic sustainability was also declining in the IPNW fallow cropping systems because costs continued to rise while wheat prices remained static (Duff et al., 1995) until recently when wheat prices increased from \$0.15 kg^{-1} in the 1990s to \$0.26 kg^{-1} in the late 2000s (Portland Wheat Exchange, 2013). Future wheat prices are not certain and largely determined by global market forces. Conservation tillage practices such as NT, modified fallow, annual cropping, and the introduction of alternative crops into wheat-based rotations are potential ways to improve biological and economical sustainability of cropping systems in the region (Kassam et al., 2009).

Despite concerns of decline in soil resources and sustainability, growers in the low rainfall regions of the IPNW remain skeptical about alternative production systems primarily due to lack of long-term information on the biological and economical sustainability of alternative cropping systems, particularly intensive cropping and NT cropping systems in this region. Indeed under NT there are production problems that include poor seed emergence and slow seedling growth due to cooler and wetter soils compared with CT soils (Allmaras et al., 1973; Ramig et al., 1983; Schillinger and Bolton, 1993; Reicoskey et al., 1995; Wuest et al., 2000), N deficiency due to N immobilization (Allmaras et al., 1973; Ramig et al., 1983; Rice and Smith, 1983; Rasmussen and Douglas, 1992; Franzluebbers, 2004), pest problems (Allmaras et al., 1973; Ramig et al., 1983; Reicoskey et al., 1995; Smiley, 1996), and, sometimes, reduced yields under terminal drought conditions particularly if the crop under NT does not compensate for the slower start caused by N deficiency and low soil temperature. While yield and profitability are usually top priority in the short run, ensuring that NT cropping systems are sustainable in long run should be the main goal particularly in the context of changing global climate. No-tillage systems have many advantages over CT systems. In NT systems, crop residues remain on the surface and protect the soil from erosion (Allmaras et al., 1973; Ramig and Ekin, 1987; Thorne et al., 2003). No-tillage systems sequester more C than conventional systems (Reicosky et al., 1995; Williams et al., 2004; Abreu et al., 2011) and increase soil aggregation (Denef et al., 2004). Soil macropores that remain intact in NT systems (Logsdon et al., 1990; Franzluebbers, 2004) facilitate rapid water infiltration. Surface residues form a mulch layer that aids water infiltration and reduces evaporation (Schillinger and Bolton, 1993; Franzluebbers, 2002; Lenssen et al., 2007). Increased water infiltration and reduced evaporation increase soil available water (Ramig et al., 1983; Schillinger and Bolton, 1993; Bonfil et al., 1999; Halvorson et al., 1999; Franzluebbers, 2002; Lenssen et al., 2007) and crop productivity under dryland conditions. Despite these advantages many growers haven’t fully embraced NT and annual cropping systems in the north central Oregon and south central Washington. In these regions NT represented 15 to 20% of spring-planted small grain acreage and 10 to 20% of fall-planted small grain acreage (Smiley et al., 2005). Winter wheat – summer fallow using CT is still the predominant summer fallow system. However, there has been a steady increase in growers interested in and experimenting with NT cropping but information on the productivity and reliability of these systems in this low precipitation zone remains inadequate.

Of the long-term experiments that have been conducted in the IPNW, the earliest were started in 1912 (and lasted for 49 years) at the Oregon State University (OSU) Columbia Basin Agricultural Research Center (CBARC) at Moro in north central Oregon (Hall, 1955; 1960; 1963) where mean annual precipitation is 280 mm. Another set of long-term experiments, initiated in 1931 at the CBARC near Pendleton (with 406 mm of annual precipitation) are still on-going. All these experiments evaluated crop rotations under different fallowing frequencies, annual cropping, fertilization, and reduced tillage practices. However, none of these experiments evaluated NT cropping systems until recently (1982 and 1997) when the NT treatments were added to the experiments near Pendleton. Other long-term experiments evaluating NT cropping systems in the IPNW were initiated at Moscow, ID with mean annual precipitation of 690 mm (Guy, 2005, 2006) and at Lind, WA with mean annual precipitation of 203 mm (Schillinger, 2004). The results from these experiments, however, are not directly applicable to the Moro area with 280 mm of annual precipitation where the recent and on-going experiment is located. Information on NT cropping systems for this area was lacking.

Recent climate models have predicted that temperatures and precipitation in the IPNW will increase by an average of 3.2ºC and 4.5% by 2050, respectively, (Climate Impacts Group, 2013). To this end, research is needed to develop cropping systems adaptable to the changing climate. With increase in precipitation, annual cropping of winter wheat would be possible and work to perfect this system should be conducted. Furthermore, given that agriculture contributes from 10 to 25% of greenhouse gases per year (Moreau et al., 2012), cropping systems that mitigate climate change should be developed. Robertson et al. (2000) and Six et al. (2004) showed that global warming potential mitigation is possible in the long run under annual NT systems. Developing viable annual cropping systems may help sequester excess CO_2 from the atmosphere. The main focus of this experiment, therefore, was to develop profitable and sustainable NT cropping systems for north-central Oregon that sequester CO_2 and reduce wind and water erosion. The main objective was to develop NT cropping systems to replace the traditional CT WW-SF system that was depleting SOC and exposing the soil to wind and water erosion.

MATERIALS AND METHODS

A long-term experiment (LTE) designed to evaluate and compare the traditional WW-SF cropping system using CT and alternate cropping systems using no-till (NT) was initiated in 2003-04 crop year at OSU CBARC near Moro, Sherman County, OR (45º 29.041’ N and 120º 43.127’ W, 575 m above sea level). Soil at the site is a Walla Walla silt loam (coarse, silty, mixed, superactive, mesic Typic Haploxeroll) with 5.7-7.5 pH, and 0.7-1.2% SOC. The location receives 282 mm mean annual precipitation, most of it from September to June. Mean daily air temperature is -1 ºC during January and 19 ºC during July and August.

Moro LTE Treatment Descriptions

A uniform crop of spring wheat was planted over the intended experimental area during 2003 in an effort to homogenize the experimental area. The experimental area was mapped into

42 plots of 15 × 105 m arranged as 14 treatments of eight crop rotations in a randomized complete block design with three replications. The treatments were randomized within each of the three replications. The experiment evaluated annual cropping of WW, SW, SB under NT, two-year rotations (WW-SF under CT; WW-CF under NT; WW-WP under NT), and a three –year rotation involving WW–SB-CF also under NT. All winter and spring wheat cultivars grown for this study were soft white types. For all the treatments, each phase of each rotation was present in each year so that data could be collected every year. Treatments are described below.

Annual Cropping

Winter Wheat (WW): After harvest, plots were sprayed with glyphosate [*N*-(phosphonomethyl) glycine] at a rate ranging from 1.2 to 1.9 kg a.e. ha^{-1} to control of summer weeds in late September or early October. The plots were then seeded at a seeding rate of 240 seeds m^{-2} and a depth of 5 to 8 cm using a hoe drill (Fabro Ltd., Swift Current, SK, Canada) that was 3.7 m wide with 30 cm row spacing. The cultivars planted included 'Tubbs" in 2004, 'Stephens' in 2005, ORCF-101 (Clearfield™) in 2006 and 2007. Fertilizer, as a blend of urea and $(NH_4)_2SO_4$), was banded 2.5 cm below seed during planting. The N rates ranged from 22 to 45 kg ha^{-1} and the S rates ranged from 4 to 13 kg ha^{-1}. Fertilizer rates were based on residual soil-NO_3 and a target yield of 2.5 to 3 Mg ha^{-1}. Soil was sampled to a depth of 30 cm at six locations, composited, and sent to a commercial testing service (AgSource Cooperative Services, Umatilla, OR) for nutrient analyses in August. In 2004, starter fertilizer (16-20-0-14), at the rate of 56 kg ha^{-1}, was applied with the seed instead of ammonium sulfate. Plots were sprayed for broadleaf control in winter wheat using 0.18 g a.i. ha^{-1} Harmony Extra® (Thifensulfuron-methyl:Methyl 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate) +

Tribenuron-methyl: (Methyl 2-[[[[N-(4-methoxy-6-methyl-1,3,5-triazin-2- l)methylamino] carbonyl] amino] sulfonyl] benzoate) and 0.7 kg ha^{-1} Bronate Advanced™ (bromoxynil: (3,5-dibromo-4-hydroxybenzonitrile + MCPA: 2-Methyl-4chlorophenoxyacetic acid) with 0.25% v/v nonionic surfactant (NIS) in mid-April in 2004 and in March in 2005. From 2006 to 2010, treatments plots were sprayed with 0.18 g a.i. ha^{-1} Harmony Extra®, 0.21 kg a.i. ha^{-1} Sencor™ (Metribuzin: (4-Amino-6-(1,1 dimethylethyl)-3-(methylthio-1,2,4-triazin-5(4H)-one), 0.41 kg a.e. ha^{-1} 2,4D (2,4-Dichlorophenoxyacetic acid) in mid-April. In 2007, plots with imazamox tolerant Clearfield® wheat (ORCF-101) were sprayed with 0.5 kg a.e. ha^{-1} Clearmax herbicide (imazamox: 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid) + (4-chloro-2-methylphenoxy) acetic acid) in March. In May, 2005 winter wheat was sprayed with 224g a.i. ha^{-1} of Osprey™ (Mesosulfuron-Methyl) and 21.04 g a.i. ha^{-1} of Olympus™ (Sulfonyl-amino-carbonyl-triazolinone) and 0.5 % v/v nonionic surfactant (NIS) to control cheatgrass (*Bromus tectorum* L.). Wheat was harvested at the end of July or the beginning of August.

Spring Wheat (SW) and Spring Barley (SB): After harvest, plots were sprayed with glyphosate at a rate ranging from 0.84-1.26 kg a.e. ha^{-1} for controlling summer weeds towards the end of September or early October. In early March of the following year, the plots were sprayed with 1.26 kg a.e. ha^{-1} glyphosate to kill weeds before planting spring crops. In April, the plots were then seeded using a Fabro® drill in rows spaced 30 cm apart. For spring wheat cultivars ‘Zak’ (in 2004 and 2005), and ‘Louise’ (in 2006 and 2007) were seeded at a seeding rate of 270 seeds m^{-2}. For spring barley the cultivar ‘Camas’ was seeded at a seeding rate of 280 seeds m^{-2} from 2004 to 2007 and from 2009 and 2010. In 2008 the barley cultivar Haxby was seeded. Fertilizer, as a blend of urea and ammonium sulfate, was banded 2.5 cm below the seed during planting. Nitrogen rates ranged from 28 to 38 kg ha^{-1} and S rates ranged from 7 to 13 kg ha^{-1} for both crops. Fertilizer rates were based on residual soil nitrate in the top 30-cm soil depth (determined from soil analyses as described for WW-WW) and a target yield of 2.5 Mg ha^{-1} for both spring wheat and spring barley. Soil analyses were conducted about two weeks before seeding. In May spring wheat was sprayed with 0.7 kg ha^{-1} Bronate Advanced, 0.18 g a.i. ha^{-1} Harmony Extra, and 0.5 % v/v NIS to control broadleaf weeds. Wheat and barley were harvested between the last two weeks of July and first two weeks of August.

Two-year Rotations

Conventional Tillage Winter Wheat-Summer Fallow (WW-SF)

Fallow Phase: After harvest, the field was left untilled from September of the harvest year to mid-April of the following (fallow) year. Glyphosate was applied as needed in the fall and spring at rates ranging from 0.84-1.26 kg a.e. ha^{-1} to control weeds during this period. In April plots were flail mowed and primary tillage was conducted to a depth of 15 cm using a chisel plow (John Deere (JD) 1600, John Deere, Moline, IL) and followed by sweep cultivation to a depth of about 13 cm using the same JD 1600 equipment but now fitted with 30 cm wide sweeps. From May to August, the plots were rod-weeded as needed at a depth of 8 to 10 cm to control weeds. On average, the plots were rod-weeded two or three times per season. In August soil was sampled to a depth of 30 cm at six locations, composited, and sent to AgSource Laboratories for nutrient analyses. Using this information, the plots were fertilized with anhydrous ammonia (NH_3) to bring soil N levels to 90 kg ha^{-1} at the beginning of September using shank applicators.

Gypsum was also applied to maintain sulfur levels above 10 ppm. Fertilizer rates were based on residual soil nitrate (NO_3) and a target yield of 5 Mg ha^{-1}

Crop Phase: Wheat, at a seeding rate of 230 seeds m^{-2}, was seeded at a depth of about 10 to 15 cm in mid-September using a deep furrow drill (JD 7616 HZ, John Deere, Moline, IL) with 12 rows at 40 cm spacing. Seeding rates were increased to 244 seeds m^{-2} if seeding was delayed to the end of September. Wheat cultivars grown included 'Tubbs' in 2004, 'Stephens' in 2005, ORCF-101 (Clearfield^{TM}) in 2006, 2007, and 2008, "Tubbs 06" in 2009, and ORCF-102 in 2010. During 2004 and 2005, winter wheat plots were sprayed for broadleaf control using 0.18g a.i. ha^{-1} Harmony Extra® and 0.7 kg a.i.ha^{-1} Bronate Adavanced with 0.25% v/v nonionic surfactant in mid-April. From 2006 to 2010 the plots were sprayed with 0.18 g a.i. ha^{-1} Harmony Extra®, 0.21 kg a.i.ha^{-1} Sencor® and 0.41 kg a.e. ha^{-1} 2,4D in mid-April. In March of 2007 Clearfield^{TM} wheat (ORCF-101) was sprayed with 0.5 kg a.e. ha^{-1} Clearmax® herbicide and 0.5 % v/v NIS. Wheat was harvested at the end of July or the beginning of August.

No-Till Winter Wheat-Chemical Fallow (WW-CF)

Fallow Phase: Glyphosate was applied in the fall of the harvest year and in the spring of the following year (during fallow) as needed (three to four times) at rates ranging from 0.84-1.26 kg a.e. ha^{-1} for weed control. Soil was sampled to a depth of 30 cm in the fall of the fallow year at six locations, composited, and soil samples analyzed to determine fertilizer recommendations for the following crop.

Crop Phase: The plots were seeded with a hoe drill (Fabro Ltd., Swift Current, SK, Canada) in rows spaced 30 cm apart at a seeding rate of 240 seeds m^{-2} either at the end of September or October of the fallow year. The cultivars planted include 'Tubbs" in 2004, 'Stephens' in 2005, ORCF-101 (Clearfield^{TM}) in 2006, 2007, and 2008, "Tubbs 06" in 2009, and ORCF-102 in 2010. Fertilizer, in the form of urea, was banded 2.5 cm below the seed during planting. Ammonium sulfate was applied with the seed during planting. Fertilizer recommendations that ranged from 65 to 90 kg ha^{-1} for N and 4 to 7 kg ha^{-1} for S were based on soil analysis to a depth 30 cm and were applied to bring up soil N levels to 90 kg ha^{-1}. Plots were sprayed for broadleaf control in winter wheat using 0.18 g a.i. ha^{-1} Harmony Extra® and 0.70 kg a.i. ha^{-1} Bronate Advanced with 0.25% v/v NIS in mid-April in 2004 and in March in 2005. From 2006 to 2010, plots were sprayed with 0.18 g a.i. ha^{-1} Harmony Extra®, 0.21 kg a.i. ha^{-1}, Sencor® and 0.41kg ha^{-1} 2,4-D in mid-April. In March of 2007 Clearfield^{TM} wheat (ORCF-101) was sprayed with 0.5 kg a.e. ha^{-1} Clearmax® herbicide for cheatgrass control. Included was 0.5 % v/v NIS and 2 kg N ha^{-1} Solution 32 (32-0-0, NPK: 35% Urea -45% ammonium nitrate (NH_4NO_3). Wheat was harvested at the end of July or the beginning of August.

Winter Wheat-Winter Pea Rotation (WW-WP) (Modified Fallow)

Winter Pea (WP): Winter pea was grown mostly as a cover crop and occasionally allowed to set seed when soil moisture was adequate. Following winter wheat harvest, the plots were sprayed with glyphosate at rates ranging from 0.84-1.26 kg a.e. ha^{-1} for control of summer weeds in late September to early November. The plots were then seeded with winter pea at a rate of 78 seeds m^{-2} in October or November using a Fabro® drill with rows 30 cm apart. Cultivars used included 'Austrian winter pea' in 2004 and 2009, an experimental line (PS9430706) in 2005, 'Spector' from 2005 to 2007, 'Universal' in 2008 and 2010. N-Dure™ inoculant (INTX Microbials, LLC, Kentland, IL) was applied at the rate of 71 g per 23 kg of seed based on the manufacturer's recommendation. About 9 kg N ha^{-1} was applied in the form of starter fertilizer at a depth of 7.5 cm. Winter pea was sprayed with 92.4 g a.i. ha^{-1} Assure II® (Quizalofop: P-Ethyl: Ethyl(R)-2-[4-6-chloroquinoxalin-2-yl oxy)-phenoxy]propionate) with 1% v/v crop oil concentrate for grassy weed control in April**.** In May winter pea was sprayed for broadleaf weeds with 0.21 kg a.i.ha^{-1} Sencor® and 280g a.i.ha^{-1} MCPA. No surfactant was used. Pea was undercut at flowering when moistures was not adequate based on the percentage of crop-year precipitation received at that time. The pea crop was harvested in late July or early August if the crop was allowed set seed. Glyphosate, at a rate of 0.84-1.26 kg a.e. ha^{-1} was then applied to kill weeds before seeding winter wheat.

Winter Wheat (WW) Winter wheat was seeded in late October or early November at 240 seeds m^{-2} using a Fabro® drill with rows 30 cm apart. Cultivars used include 'Tubbs' in 2004, 'Stephens' in 2005, and 'ORCF-101' (Clearfield^{TM}) in 2006, 2007, and 2008, "Tubbs 06" in 2009, and ORCF-102 in 2010. Fertilizer, in the form of urea was banded 2.5 cm below the seed during planting. Ammonium sulfate was applied as a starter with the seed. The rates ranged from 43 to 52 kg N ha^{-1} and 7 kg S ha^{-1}. In March of the following spring, winter wheat plots were sprayed with 0.18 g a.i.ha^{-1} Harmony Extra® and 0.7 kg ha^{-1} Bronate Advanced with 0.25% v/v NIS for broadleaf weed control. In March of 2007 Clearfield^{TM} wheat was sprayed with 0.5 kg a.e. ha^{-1} Clearmax® herbicide for cheatgrass control. Included was 0.5 % v/v nis and 2 kg N ha^{-1} Solution.

Three-year Rotation

No-Till Winter Wheat-Spring Barley-Chemical Fallow (WW-SB-CF)

The experiment had only one three-year rotation, winter wheat, spring barley and chemical fallow (WW-SB-CF). Practices for winter wheat following chemical fallow and spring barley following winter wheat were identical to those described previously. No Clearmax was used on WW-SB-CF in the years 2004-2010. Weeds were controlled during fallow and before planting SB using glyphosate.

Flex Cropping

This experiment had two flex crop treatments where crops grown and rotation dependent on soil available moisture at planting and projected market price. In these rotations, crops grown included WW, SW, SB, spring pea (*Pisum sativum* L.) spring mustard (*Brassica* spp.), and spring canola (*Brassica* spp.). Only residue cover and soil organic carbon results from this rotation were included in this paper.

Grassland

Three plots, each representing a replication and measuring 7.3 m by 53.6 m were demarcated in grassland adjacent to the plots in 2006. The grassland plots, which had been under a WW-SF system from 1911 to 1991 and undisturbed since then (approximately 23 years), served as a baseline for comparisons with cultivated areas. Plant species that include Sherman Big Blue (*Poa-secunda* Sherman), intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey], pubescent wheat grass (*T. intermedium ssp. barbulatum*), covar sheep fescue (*Festuca ovina* L.) and ladak alfalfa (*Medicago sativa* L.) were seeded in 1991 when cultivation was terminated. At present sheep fescue is, by far, the most dominant species. A rough estimate shows that current biomass composition is 90% sheep fescue, 9% wheatgrass and 1% yarrow (*Achillea millefolium* L. *var.occidentalis* DC.). The grassland plots received no external fertilizer or biomass inputs. Biomass was not harvested. Soil organic matter data from these plots was compared with other rotations in this experiment.

Data Collection

Phenology, Plant Population, Plant Height, Grain Yield and Yield Components

All measurements, except grain yield, were made in the outer 3.6 m of the 15 x 105 m plots. Grain yield was determined by harvesting the 7.8 m strip in the center of each plot. Data on phenology that were collected included dates of seeding, plant emergence, flowering, and physiological maturity. Crops were considered to have reached these stages when 50% of the plants in a plots had emerged, flowered, and matured. Plant populations were determined two to three weeks after plant emergence. Plants were counted in four 1 x 1 m quadrats in the outer 3.6-m wide by 105-m long strips of each plot and the mean number of plants m^{-2} calculated. Plant height of wheat and barley, from the tip of the main shoot ear to the crown at ground level, was measured using a meter ruler at physiological maturity. At about two to three weeks after physiological maturity wheat bundles were collected from four one-meter quadrats in the outer 3.6-m wide by 105-m long strips of each plot. Wheat and barley in each quadrat was cut at the crown level and weighed to determine total plant weight. Ears from each bundle were cut off from all plants at the peduncle using scissors and counted to determine the number of ears m^{-2}. Spikelets per ear were then counted from 10% of the total number of ears m^{-2}. These ears were then threshed and the total grains per ear counted. Grains per spikelet were then calculated by dividing grains per ear by spikelets per ear. The rest of the ears from the bundle were then threshed and the grain weight added to grain weight from 10% of the ears to obtain total grain weight per bundle (one-meter quadrat). Harvest index (HI) was calculated by diving total grain weight by total bundle weight. Straw residue weight was calculated by subtracting total grain weight from total bundle weight. Four batches of 1000 grains each were counted from grain from each bundle, weighed, and averaged to determine 1000 grain weight. Crops were harvested in late July or early August. A strip following the centerline of each 15-m wide plot was harvested using a commercial combine with a 5.5-m header. Grain yield was measured using a GYC-150 Yield Cart (Unverferth Manufacturing Co., Shell Rock, IA) to obtain grain yield per treatment. To compare grain yields of rotations involving fallow and grain yields of annual crops, grain yields of two-year fallow rotations (WW-SF and WW-CF) were annualized by dividing grain yield of wheat by two. Grain yields of the three-year rotation (WW-SB-CF) were annualized by dividing the sum of the winter wheat and spring barley grain yields by three. Grain protein was measured using the Inframatic 9200 (Perten Instruments, Hägersten, Sweden). Plant population, phenology, plant height, and HI were determined in all six years. Ears m^{-2} were measured in 4 of 6 years. Spikelets per ear, grains per ear, grains per spikelets, and 1000 grain weight were measured in 3 of 6 years, and protein in 2 of 6 years.

Crop Residue Cover and Soil Organic Carbon

Crop residue cover was measured from four one-meter quadrats in the fall and the spring of the sixth crop-year (2009-10). A digital image of the residue in the quadrat was taken and percent residue cover estimated using the dot grid method (Dickey et al., 1989). Residue in a quarter of the quadrats was collected and weighed. The relationship between residue cover and weight was fitted using quadratic regression with residue weight as the independent variable and cover as the dependent.

Soil samples for soil organic carbon determination were taken at depths of 0-10, 10-20, 20-30, and 30-60 cm using a hand probe, 2.5 cm in diameter (Spectrum Technologies, Inc., Aurora, IL.). Four samples per plot were taken and samples at the same depth were mixed and analyzed. The soil samples were oven dried at 40° C for 48 hours and ground with a rolling pin. The ground soil was then passed through a 2-mm sieve and then through a 1-mm sieve. Any visible organic matter not collected in the sieves was removed using tweezers. The resulting material was placed into a 60-mL capped round bottle containing two steel rods and placed on a vial rotator for four hours to pulverize the soil. A subsample (25 to 28 mg) was then weighed out into a 5x9 mm tin capsule (C. E. Elantech, Inc., Lakewood, NJ) for analysis. Soil samples were analyzed for total carbon using a Flash 1112 elemental analyzer (Thermo-Finnigan, Milan, Italy). If pH of the samples was below 6.5 then TC was assumed to be entirely soil organic carbon (SOC). If pH was more than 6.5 SOC soil samples were analyzed for inorganic carbon using a CA-100 TOC analyzer (Skalar Analytical B.V., Breda, The Netherlands). Soil organic matter was then determined by subtracting inorganic carbon from total carbon.

Precipitation, Soil Moisture, and Water Use Efficiency

Daily precipitation was measured at an official weather station located 0.5 km from the experimental site. Measurements of soil water content were taken throughout the crop-year using a PR2 probe (Delta-T Devices Ltd., Cambridge, England). The probe senses soil moisture content (% volume) at 10-, 20-, 40-, 60-, and 100-cm depths by responding to dielectric properties of soil with minimal influence from either salinity or temperature. Measurements were taken from two access tubes in each plot at or close to seeding and every two to four weeks thereafter until crop maturity. At each soil depth profile, three measurements were taken, each time with the probe rotated to a different direction. The WUE was calculated by dividing grain yield by total water use in the 100 cm soil depth profile or growing season evapotranspiration. Total water use or growing season evapotranspiration, defined here as evapotranspiration from seeding to maturity, was the sum of growing season precipitation and soil water depleted (Deibert et al., 1986; Norwood, 1999; Chen et al., 2003). Soil water depletion was the difference between soil water content measured at or near seeding and the soil water content measured after maturity. Growing season precipitation was precipitation received from the seeding to maturity for all crops in the rotations. For all treatments soil moisture at seeding was assumed to be the culmination of precipitation received and soil moisture loss or depleted between the previous harvest and seeding. Based on estimated internal soil drainage values for the long-term experiments at CBARC (Payne, 1998, 2001), soil drainage below the crop rooting depth was assumed to be negligible. Although some runoff and erosion occurred in the 2005-06 crop-year when the site received the most precipitation, it was negligible. The WUE was estimated using the following equation:

$$WUE = \frac{GY}{[(W_{SD} - W_{MAT}) + P_{SDMAT}]} \ldots\ldots\ldots\ldots..(1)$$

where GY is grain yield (Mg ha^{-1}), W_{SD} is soil water content at seeding, W_{MAT} is soil water content at maturity, and P_{SDMAT} is precipitation from seeding to maturity. For the three-year rotation involving winter wheat, spring barley, and chemical fallow WUE was calculated as total grain yield for one cycle of the rotation divided by the sum of the soil water depletion and the growing season precipitation for each crop (Peterson et al., 1996) as follows:

$$WUE = \frac{GY_{WW}+GY_{SB}}{[(W_{SDWW}-W_{MATWW})+P_{GSWW}]+[(W_{SDSB}-W_{MATSB})+P_{GSSB}]} \ldots..(2)$$

where GY_{ww} is winter wheat grain yield, GY_{SB} is spring barley grain yield, W_{SDWW} is soil water at seeding for winter wheat, W_{MATWW} is soil water at maturity for winter wheat, P_{GSWW} is growing season precipitation for winter wheat, W_{SDSB} is soil water at seeding for spring barley, W_{MATSB} is soil water at maturity for spring barley, and P_{GSSB} is growing season precipitation for spring barley.

Experimental Design and Statistical Analyses

The experimental consisted of 8 cropping systems involving annual cropping of winter wheat (WW-WW), spring wheat (SW-SW), and spring barley (SB-SB), two-year rotations involving winter wheat-summer fallow (WW-SF), winter wheat-chemical fallow (WW-CF), and winter wheat-winter pea (WW-WP), a three-year winter wheat-spring barley-chemical fallow (WW-SB-CF) rotation, and a flexible cropping system (Flex) where the crop to be planted each season depended on moisture predictions and market prices. Each phase of the WW-SF, WW-CF, WW-WP, and WW-SB-CF rotations was represented every year to ensure that data were collected every season. The rotations and their phases, totaling 14 treatments, were mapped into 42 plots of 15 × 105 m arranged in a randomized block design within three blocks. Data were analyzed by PROC GLIMMIX SAS procedure for a randomized complete block design (Gbur, et al., 2012). Treatment means differing in F test were separated using Tukey’s test at the 0.05 level of probability. It must be noted that this study was not a factorial experiment but a comparison of cropping systems. Therefore the model used in this analysis resembled a simple one-way

ANOVA ($Y_{ik} = \mu_i + R_k + \varepsilon_{ik}^{R}$ where μ_i is the mean for the *i*th treatment, R_k is the *k*th block effect, and ε if the error) with fixed replications or blocks, where treatment represented data (yield, ears, or soil water) from each rotation.

RESULTS AND DISCUSSION

Precipitation

Total crop-year precipitation (September-August) varied from 200 mm to 430 mm with an average of 285 mm during the study (Table 1). The average precipitation during the study period (2004-5 to 2009-10 crop years) was 3 mm below the 94-year (1909-10 to 2003-4 crop years) average precipitation at Moro (288 mm). Winter precipitation (August to February) ranged from 93 mm to 283 mm and spring precipitation (March to July) from 51 mm to 148 mm, during the experiment (Table 1). Spring precipitation was higher than winter precipitation only in the 2004-05 crop-year. Compared with the 94-year average precipitation, winter precipitation (187 mm) was 13 mm lower and spring precipitation (98 mm) was 10 mm higher during the study period. A 10 mm increase in spring precipitation can increase grain yield by 150 to 174 kg ha^{-1} in the IPNW (Schillinger et al., 2008). On average winter and spring precipitation accounted for 66% and 34% of total precipitation, respectively, during the study period. Corresponding values for 94 years before this study were 69 and 31% respectively (Table 1) showing that winter precipitation decreased while spring precipitation increased during the last 6 years of the study period. The wide year to year variations in total (CV=0.28), winter (CV=0.32), and spring precipitation (CV=0.37) at Moro makes annual cropping risky and prediction of crop performance challenging. However, the increase in spring precipitation observed during the study period creates conditions suitable for annual cropping. If the changes in winter and spring precipitation continue, the potential for cropping intensification, increased residue production, and SOC accretion will be improved (Wood et al., 1991; Halvorson et al., 2002).

Seeding Date, Plant Population and Phenology

Table 2 shows results on seeding date and phenology. Statistics on some of the variables displayed on this table are not very useful as these variables were influenced by crop type (winter or spring). However, these variables show important phenological differences between fall and spring seeded crops that can be valuable in degree-days computations and crop management. Seeding dates of fall seeded crops were dictated by seed zone moisture availability and the ability of the drill to place seed in the moisture zone. Winter wheat in the WW-SF rotation was seeded first during the first week of October. Using a deep furrow HZ drill, seeds were placed in the moisture zone 10 to 15 cm below the soil mulch created by rod weeding during fallow preparation. Spring cultivation and rod weeding creates a dust much that disrupts soil capillarity thereby impeding evaporation of stored soil moisture (McCall, 1925). Winter wheat in the WW-CF and WW-SB-CF rotations was seeded next about 11 to 14 days later compared to WW-SF. Seed zone moisture in these NT summer fallow rotations wasn’t significantly different from that of WW-SF at 10 to 15 cm depth close to the time of planting in the fall of 2006, 2007, 2008, and 2009 (Fig. 1). However, the Fabro® drill, using hoe openers, was not able to place seed deep enough in the moisture zone and therefore seeding was usually delayed until after the top 10 cm was sufficiently wet from fall rains. In crop-years where fall precipitation was delayed wheat was “dusted in”, meaning wheat was seeded into dry soil at a depth of about 5 to 10 cm. Eventually fall precipitation replenished soil moisture allowing seed to germinate. Winter wheat in WW-WW and WW-WP rotations was seeded last in the last week of October or first week of November. Winter wheat germinated after about 16 days in the WW-SF and after 20 to 21 days in the WW-CF and WW-SB-CF rotations. Wheat emerged after 44 and 46 days in the WW-WW and WW-WP rotations, respectively. On average, plant population for NT wheat in WW-CF was significantly lower than plant populations for WW, SW and SB in other rotations (Table 3). The reason for low plant populations under WW-CF are not clear. However, plant population was not correlated with grain yield (Table 4). Similar results showing the lack of correlation between plant population and grain yields have been reported by Lithourgidis et al (2006).

Fall-planted wheat reached flowering and maturity earlier than spring planted crops (Table 2). However, differences in maturity dates were less pronounced as the differences in flowering dates resulting in longer grain filling durations (flowering to maturity) for fall-planted crops (Table 2). Late flowering and maturity dates were negatively associated with grain yield (-0.64 and -0.42, respectively) while longer grain filling duration was positively correlated with grain yield (Table 4).

Yield Components, Plant Height, Protein, Harvest Index, and Straw Residues

Winter wheat in WW-SF and annual SB produced significantly more ears m^{-2} than crops in other rotations (Table 3). Annual WW produced the lowest numbers of ears m^{-2}. In this treatment the number of ears m^{-2} was also lower than the number of plants m^{-2} indicating that either not all shoots produced an ear or some plants died before producing ears. Annual WW had high infestation of root-lesion nematodes which were found to reduce the ability of roots to absorb water and consequently reduced grain yield (Smiley and Machado, 2009). Ears m^{-2} were significantly correlated with grain yield (r=0.55, $P<0.0001$). Donaldson et al. (2001) found a similar relationship between ears m^{-2} and grain yield in south central Washington just north of the Moro LTE. Spring barley in SB-SB and WW-SB-CF produced the highest spikelets per ear and spring wheat produced the lowest. Grains per spikelet and grains per ear were generally higher in wheat than in spring barley. This was expected given that the two-row spring barley grown for this study had only one fertile spikelet at each node of the rachis resulting in a single grain per spikelet. In wheat, grains per spikelet and grains per ear are dependent on both cultivar and growing conditions. However, spikelets per ear, grains per spikelet, and grains per ear were all not correlated with grain yield (Table 4). Donaldson et al. (2001) found a positive and significant correlation between grains per ear and grain yield in winter wheat in their planting date experiment. This is probably because the difference between the first (mid-August) and last (October) seeding dates was large enough to cause differences in grains per ear in their experiment. In this experiment a clear relationship between grain yield and grains per ear could not be obtained because we evaluated different crops (WW, SW, SB) with differing grain yield and grains per ear relationships. For example spring barley that produced the lowest grains per ear produced the highest grain yield through high numbers of ears m^{-2} (Table 3). As expected, both grain weight and plant height were higher in winter than in spring crops and positively correlated with grain yield (Table 4). Winter crops had a longer growing season than spring crops that favored high productivity. Harvest index was highest in spring barley, lowest in winter wheat in WW-CF, and not correlated with grain yield. Harvest index is usually correlated with grain yield (Hay, 1995) but the comparisons of winter vs. spring crops and wheat vs. barley masked the correlation between HI and grain yield in this experiment. Straw biomass was lowest in WW in WW-WP and WW-WW and highest in winter wheat in WW-SF and WW-SB-CF. Spring wheat and spring barley had comparable straw residue weights as winter wheat in WW-

CF. Straw biomass was positively correlated with grain yield (r=0.67; $P<0.0001$) (Table 4). Grain protein in winter and spring wheat ranged from 8.5 to 11.3%, which was typical of soft white wheat (8.5-10.5%). There were no significant differences in grain protein in the other rotations. Grain protein was not correlated with grain yield.

Grain yield and Water Use Efficiency

Table 5 shows grain yields of all rotations from 2004-05 to 2009-10 crop years. Annual monocropping of WW, SW, and SB and annual rotation of WW and WP produced grain yields that varied substantially from year to year with timing and amounts of precipitation. Grain yield from annual SW, SB, and SB following WW in the three-year rotation (WW-SB-CF) was significantly and positively correlated with total precipitation and in particular winter precipitation and with April and June precipitation (Table 6.). Similar results were obtained in the Pacific Northwest (Camara et al., 2003). Grain yield of annual WW was not significantly correlated with precipitation due to confounding effects of diseases and weed infestation (Smiley and Machado, 2009). In general wheat yield in all fallow rotations was not correlated to precipitation (Table 6). Wheat grown after fallow rely on moisture stored in the fallow period and precipitation during the crop year and therefore may not be as dependent on the amount of crop-year or growing season precipitation as annual crops (Leggett et al., 1974; Bolton and Glen, 1983).

Under annual cropping, WW in rotation with WP produced the highest grain yields in five of six years and on average (2004-5 to 2009-10 crop-years) produced higher average grain yields (2.16 Mg ha^{-1}) than WW-WW, SW-SW, and SB-SB. Winter wheat in the WW-WP rotation had a longer growing season and grain filling duration (Table 2) that favored high grain yields. In most years WP was undercut and killed before flowering and that probably conserved soil moisture and provided N for the subsequent wheat crop. Although wheat in WW-WW had similar phenology to wheat in WW-WP, it produced the lowest ears m^{-2} (Table 3) and grain yields (Table 5) among all cropping systems due to root-lesion nematode infestation (Smiley and Machado, 2009), weed control, and moisture problems. Growing winter wheat year after year did not allow enough time for ridding the seedbed of weeds and the use of Osprey and Olympus herbicides to control cheatgrass did not always work well due to spray timing problems. The Moro location is usually windy during early spring making timely weed control by spraying difficult. In other years Clearfield technology was used successfully for grassy weed control in WW-WW. Low grain yield in WW-WW in the 2005-06 crop-year, when precipitation was highest, was attributed to reduced moisture uptake due to root damage caused by root-lesion nematodes (Smiley and Machado, 2009; Smiley, et al., 2013a).

Winter wheat grain yields from rotations involving fallow (WW-SF, WW-CF, and WW-SB-CF) were not significantly different from each other in each of the six years of the study and when averaged over the six years (Table 5). Although wheat in the NT rotations (WW-SB-CF and WW-CF) was seeded 11 to 14 d later, emerged 4 to 5 days later, and matured with 12 to 23 fewer days than wheat in WW-SF, it appeared to have compensated for delays in seeding and emergence and fewer days to maturity. The grain filling duration of wheat in these rotations, which ranged from 36 to 37 days, was not significantly different and was correlated with grain yield ($r = 0.52$, $P<0.0001$)(Table 4). Wheat grain yield from WW-SF, although slightly higher, was not significantly different from WW-CF grain yield. These results indicated that the traditional WW-SF could be replaced by either WW-CF or WW-SB-CF rotations without yield penalty in north-central Oregon. Spring barley grain yield in the WW-SB-CF rotation, although lower, was not significantly different from annual spring barley yield (SB-SB).

When grain yields from all rotations were compared on an annual basis, annual SB produced the highest grain yield (2.03 Mg ha^{-1}) (Table 5). The higher grain yield in annual SB compared to annual SW was attributed to the production of higher numbers of ears m^{-2} and spikelets per ear (Table 3). Grain yield of barley has been shown to be highly correlated with the number of ears m^{-2} (del Moral and del Moral, 1995). Barley also produces more ear bearing tillers than wheat (Alzueta et al., 2012). Furthermore, root lesion nematode infestation was lowest in annual SB in this experiment (Smiley and Machado, 2009). Spring barley's ability to suppress root lesion nematodes populations created growing conditions conducive for producing high yield. Wheat from WW-SB-CF rotation produced the second highest yield followed by WW-SF. Grain yields from these rotations were, however, not significantly different from each other. Annualized grain yields of the WW-CF and SW-SW rotations, although lower, were not significantly different from annualized grain yields of WW-SB-CF and WW-SF rotations. Annualized grain yields of WW-WW and WW-WP were the lowest. The results indicated that annual cropping of SB and SW was possible in this 282 mm precipitation zone. However, annual cropping remains risky due to high variation in growing season precipitation (CV= 0.28). Growing WW in rotation with WP was also possible provided moisture was adequate and the pea cover crop supplied enough nitrogen to make the rotation economical.

Water use efficiency was positively associated with grain yield ($r = 0.49$, $P<0.0001$) and ranged from about 6.7 kg ha^{-1}mm^{-1} in annual WW to 12.0 kg ha^{-1}mm^{-1} in annual SB (Table 5). Rotations that produced high grain yield generally had high WUE. However, WUE of annual SB was not significantly different from WUE of WW-SB-CF, WW-CF, WW-SF, and SW-SW cropping systems. The WUE of WW-WW and WW-WP was significantly lower than WUE of the other cropping systems, reflecting low yield potential on annual basis in these rotations. Bolton and Glenn (1983) reported WUEs of 5.56 and 5.74 kg $ha^{-1}mm^{-1}$ at Lind, WA and Pendleton, OR, respectively, under WW-SF. Aase and Pikul (2000) reported WUEs of 4 kg $ha^{-1}mm^{-1}$ for annual WW and about 8.58 to 9.0 kg $ha^{-1}mm^{-1}$ for SW-Fallow in semiarid northern Great Plains. The higher WUE reported for this study compared to values reported by Bolton and Glenn (1983) and Aase and Pikul (2000) could be attributed mostly to calculations based on a 100 cm soil depth profile and to some extend improvements in yield of new cultivars and improved management practices. The WUE of winter wheat in rotations under no-till (WW-CF and WW-SB-CF), although higher, was not significant different from WUE of winter wheat in WW-SF (Table 5). Chemical fallow, therefore, did not lead to improved WUE, but also did not reduce WUE during this study.

Crop Residue Cover and Weight and Soil Organic Carbon

Results on plant residue cover measured soon after seeding fall (2009) and spring (2010) crops are shown in Fig 2 and 3, respectively. Percent residue cover was highest under NT annual WW and the lowest after WW-SF in fall-seeded crops (Fig. 2). Annual cropping has been shown to increase crop biomass and residue cover (Shaver et al., 2003). In the WW-SP rotation (Flex) residue cover was lower after SP phase than the WW phase. In spring-seeded crops annual SW produced the highest residue cover followed by annual SB and SW in a flex crop rotation with SP (Fig. 3). Overall, plant residue cover was higher in annual cereal cropping systems than after fallow and pea systems. Residue cover was highly correlated with residue weight (Fig. 4). The correlation between cover and weight was stronger at low residue weights and weaker as residue weight increased. Based on these results estimating residue weight from weight or vice-versa was more accurate when residue weight was below 300 g m^{-2} (3.0 Mg ha^{-1}) or below 40% cover. Above 40% cover, residues accumulated without corresponding increase in percent cover as crop residues pile on. The Natural Resources Conservation Service (NRCS) and Conservation Technology Information Center (CTIC) defines conservation tillage as any tillage and planting system that covers 30 percent or more of the soil surface with crop residue, after planting, to reduce soil erosion by water (USDA-NRCS, 1999).

Annual cropping systems sequestered more SOC than fallow cropping systems (Fig 5). Soil organic carbon values in the 0-10 cm depth profile were highest under annual SW, annual SB but these values were not significantly different from SOC values obtained from the grassland plots. There were no significant differences in SOC in the 0-10 cm soil depth profile among other rotations. Below 10 cm, there were no significant differences in SOC among all rotations including the grassland plots. However, the result that SOC levels under these cropping systems in the top 10 cm are at par with grassland values may indicate that the grassland in this region is inherently low in biomass production and SOC accrual compared with other grasslands in agro-climatic zones of the IPNW. Brown and Huggins (2012) showed that SOC has been decreasing in native lands that have been converted to cropping in the IPNW. Increases in SOC in annual cropping systems was largely attributed to higher residue production compared with fallow cropping systems where one crop was grown in two years (Table 3, Fig 2. and 3.). For example SW-SW produced 2.54 Mg ha^{-1} of straw while WW-SF produced 1.48 Mg ha^{-1} of straw on an annual basis (Table 3). The WW-SF cropping systems have been shown to produce about half the amount of residue inputs required to maintain SOC (Machado, 2011). Rotations producing and retaining more crop residues will eventually increase SOC accretion and associated ecosystem services such as increased water infiltration, water holding capacity, cation exchange capacity, soil aggregation and reduced soil erosion that favor increased agricultural productivity (Johnson, et al., 2009). Increased carbon sequestration is a prerequisite to developing agricultural production systems that are resilient to climate change (Lal, 2004a; Lal, 2004b).

CONCLUSIONS

Results from the 6-year study showed that wheat and barley can be successfully produced under NT systems in north-central Oregon regions receiving annual precipitation of about 280 mm. There was no yield penalty for growing wheat under WW-CF and WW-SB-CF systems using NT compared with WW-SF. Given the conservation attributes of NT systems brought about by surface residues and ecosystem services provided by SOC accretion, the authors recommend the adoption of NT chemical fallow (WW-CF) or the more intensified 3-yr rotation (WW-SB-CF) that allows the production of two crops in three years in place of the traditional WW-SF. Annual cropping of spring wheat and spring barley under NT is also recommended if deemed profitable. Soil under annual cropping systems would be better protected from wind and water erosion and has the potential to accumulate more SOC than soil under fallow systems. Annual WW that had the lowest grain yields would be uneconomical and is not recommended at this juncture. However, if trends in the increase in spring precipitation continue, annual cropping of winter wheat may be possible in this region. Furthermore, annual cropping was observed to increase soil surface residues and SOC accretion, services essential for enhancing grain yields, agricultural sustainability, and developing climate resilient cropping systems.

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Figure Captions

Fig 1. Seed zone moisture at 10-cm, 20-cm, 30-cm, and 40-cm soil depth profiles in annual winter wheat (WW-WW), winter wheat-winter pea (WW-WP), winter wheat-summer fallow (WW-SF), winter wheat-chemical fallow (WW-CF), and winter wheat-spring barley-chemical fallow rotations at or close to seeding in the fall of 2006, 2007, 2008, and 2009 at the in long-term experiment at the Columbia Basin Agricultural Research Center, Moro, OR.

Fig. 2. Post-plant crop residue cover in the Fall of 2009 after summer fallow in the winter wheat-summer fallow rotation (SF-WW), after chemical fallow in the winter wheat-chemical fallow rotation (CF-WW), after winter wheat in annual winter wheat (WW-WW), after chemical fallow in the winter wheat-spring barley-chemical fallow rotation (CF-WW-SB), after winter wheat in the winter wheat-spring pea flex rotation (WW-SP), and after spring pea in the winter wheat-spring pea flex rotation (SP-WW) in the long-term experiment at the Columbia Basin Agricultural Research Center, Moro, OR .

Fig. 3. Post-plant crop residue cover in the Spring of 2010 after spring wheat in annual spring wheat (SW-SW), after spring barley in annual spring barley (SB-SB), after winter wheat in the winter wheat-spring barley-chemical fallow rotation (WW-CF-SB), after spring pea in the spring pea-spring wheat flex rotation (SP-SW), and after spring wheat in the spring wheat-spring pea flex rotation (SW-SW) in long-term experiment at the Columbia Basin Agricultural Research Center, Moro, OR.

Fig. 4. Relationship between residue cover and weight during the 2009-10 crop-year in long-term experiment at the Columbia Basin Agricultural Research Center, Moro, OR,

Fig. 5. Soil organic carbon content in the 0-10, 10-20, 20-30, and 30-60 cm soil depth profiles of grassland, annual winter wheat (WW-WW), annual spring wheat (SW-SW), annual spring barley (SB-SB), winter wheat-winter pea (WW-WP), winter wheat-summer fallow (WW-SF), winter wheat-chemical fallow (WW-CF), winter wheat-spring barley-chemical fallow rotation (WW-SB-CF), and Flex rotation in long-term experiment at the Columbia Basin Agricultural Research Center, Moro, OR in the 2009-10 crop year.

Table 1. Total, winter (August to February), and spring (March to July) precipitation from 2004-05 to 2009-10 crop-year at Moro Long Term Experiment, Moro, Oregon.

Crop-Year	Total (mm)	Winter (mm)	Spring (mm)	Winter %	Spring %
2004-05	200	93	107	47	53
2005-06	430	283	148	66	34
2006-07	281	217	64	77	23
2007-08	222	171	51	77	23
2008-09	230	148	82	64	36
2009-10	349	211	137	61	39
6-yr mean	285	187	98	66	34
100-yr mean	288	200	88	69	31
Difference	-3	-13	10	-4	4

Table 2. Seeding date, Flowering date, maturity date, and intervals between seeding, emergence, flowering, and maturity of winter wheat, spring wheat, spring barley, and winter peas grown under different cropping systems at CBARC, Moro, OR, 2004-05 to 2009-10 crop years.

	Phenology								
Rotation†	Seeding date‡	Flowering date‡	Maturity date‡	Seeding-Emergence	Seeding-Flowering	Seeding-Maturity	Emergence-Flowering	Emergence-Maturity	Flowering-Maturity
Annual cropping									
Annual winter wheat (WW-WW)	304 b	166 c	201 b	44 b	228 d	263 d	183 d	212 d	35 a
Annual spring wheat (SW-SW)	90 g	178 ab	207 a	18 e	88 f	117 f	70 f	100 e	29 b
Annual spring barley (SB-SB)	90 g	177 b	207 a	17 ef	87 f	117 f	70 f	100 e	30 b
Winter wheat-winter pea (WW-WP)‡‡	305 a	163 cd	198 bc	46 a	224 e	259 e	177 e	213 e	35 a
Two-year rotations									
Winter wheat-summer fallow (WW-SF)	276 e	159 e	196 c	16 fg	249 a	286 a	232 a	269 a	37 a
Winter wheat-chemical fallow (WW-CF)	287 d	162 de	198 b	20 d	241 b	277 b	221 b	257 b	36 a
Three-year rotations									
WW-SB-CF (Winter wheat)	290 c	162 de	198 bc	21 c	237 c	274 c	216 c	246 c	37 a
WW-SB-CF (Spring barley)	93 f	180 a	207 a	15 g	88 f	114 g	72 f	99 e	27 b
s. e.	0.2	0.7	0.7	0.3	0.6	0.6	0.7	0.7	0.7

†All plots are direct seeded except the conventional winter wheat - summer fallow treatment.

Means with same letter are not significantly different at the 0.05 probability level (Tukey's Test)

CF, chemical fallow; SB, spring barley; SW, spring wheat; SF, summer fallow; WW, winter wheat.

‡ Days from January 1.

‡‡ Results shown pertain to WW.

Table 3. Plant population, yield components and crop residue of winter wheat, spring wheat, spring barley, and winter peas under different cropping systems at CBARC, Moro, 2004-05 to 2009-10 crop years.

Rotation†	Plant population	Ear number	Spikelets per ear	Grains per spikelet	Grains per ear	1000 grain wt	Height	Harvest index	Straw residues	Grain Protein
	Plants m^{-2}	Ears m^2				g	cm		Mg ha^{-1}	%
Annual cropping										
Annual winter wheat (WW-WW)	186 ab	164 d	15 bc	1.9 a	30 bc	39 a	65 b	0.42 bc	1.93 c	8.5 b
Annual spring wheat (SW-SW)	187 ab	225 c	13 c	2.1 ab	26 c	34 b	68 b	0.41 c	2.52 b	11.3 a
Annual spring barley (SB-SB)	185 ab	324 a	20 a	1.0 c	19 d	35 b	50 c	0.45 a	2.54 ab	10.9 a
Winter wheat-winter pea (WW-WP)‡	197 a	206 c	16 b	1.9 ab	29 bc	38 a	70 b	0.42 bc	1.45 d	10.8 ab
Two-year rotations										
Winter wheat-summer fallow (WW-SF)	178 bc	335 a	17 b	1.8 b	28 bc	40 a	79 a	0.37 d	2.95 a	10.4 ab
Winter wheat-chemical fallow (WW-CF)	165 c	256 b	17 b	2.1 a	34 a	38 a	80 a	0.42 bc	2.29 b	11.3 a
Three-year rotation										
WW-SB-CF (Winter wheat components)	182 abc	275 b	18 ab	1.9 ab	32 ab	39 a	78 a	0.40 bcd	2.62 ab‡	11.0 a
WW-SB-CF (Spring barley components)	196 ab	275 b	20 a	1.0 c	19 d	39 a	52 c	0.44 ab		11.2 a
s.e.	4.2	8.1	0.5	0.06	0.95	0.72	1.4	0.008	0.10	0.5

†All plots are direct seeded except the conventional winter wheat - summer fallow treatment
Means with same letter are not significantly different at the 0.05 probability level (Tukey Test)
CF, chemical fallow; SB, spring barley; SW, spring wheat; SF, summer fallow; WW, winter wheat.
‡ Results shown pertain to WW

Table 4. Correlation of yield with phenological stages, yield components, protein, height, harvest index, and water use efficiency

	Yield	Flowering date	Maturity date	Flowering-Maturity	Plant population	Ears m^{-2}	Spikelets per ear	Grains per spikelet	Grains per ear	1000 grain weight	Protein	Height	Harvest Index	Straw residues
FlowD	-0.64****													
MatD	-0.42****	0.57****												
FlowMat	0.52****	-0.88****	-0.11^{ns}											
Pop	-0.14^{ns}	0.56****	0.30**	-0.51****										
Ears m^{-2}	0.55****	-0.26**	-0.15^{ns}	0.23*	-0.05^{ns}									
Spikelets per ear	0.12^{ns}	0.28^{ns}	0.28^{ns}	-0.06^{ns}	0.00^{ns}	0.25*								
Grains per spikelet	0.00^{ns}	-0.32*	-0.28^{ns}	0.20^{ns}	-0.13^{ns}	-0.22^{ns}	-0.79****							
Grains per ear	0.09^{ns}	-0.54****	-0.31*	0.28*	-0.33*	-0.18^{ns}	-0.51****	0.92****						
1000 grain weight	0.44****	-0.55****	-0.05^{ns}	0.62****	-0.47***	0.35**	0.48****	-0.60****	-0.54****					
Protein	-0.17^{ns}	0.38**	-0.04^{ns}	-0.44****	0.19^{ns}	-0.04^{ns}	0.00^{ns}	0.10^{ns}	0.13^{ns}	-0.45****				
Height	0.52****	-0.38****	-0.51****	0.16*	-0.07^{ns}	0.05^{ns}	-0.39***	0.52****	0.45****	0.00^{ns}	-0.06^{ns}			
HI	-0.15****	0.05^{ns}	0.38****	0.16^{ns}	-0.27^{ns}	-0.08^{ns}	0.02^{ns}	0.10^{ns}	0.17^{ns}	-0.15^{ns}	-0.10^{ns}	-0.43****		
Crop residues	0.67****	-0.59****	-0.55****	0.39****	0.02^{ns}	0.52****	0.13^{ns}	-0.07^{ns}	-0.02^{ns}	0.45****	-0.09^{ns}	0.28*	-0.48****	
WUE	0.49****	-0.09^{ns}	0.13^{ns}	0.18^{ns}	0.04^{ns}	0.55****	0.19^{ns}	-0.28^{ns}	-0.17^{ns}	0.29*	0.01^{ns}	0.04^{ns}	0.21*	0.13^{ns}

^{ns}, *, **, ***, ****, not significant, significant at the 0.05, 0.01, 0.001 and 0.0001 level of probability, respectively.

Table 5. Grain yield and water use efficiency (WUE) of winter wheat, spring wheat, spring barley, and winter peas under different cropping systems at CBARC, Moro, OR, 2004-05 to 2009-10 crop years.

Rotation†	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2005-10 mean	Annual Yields‡	2005-10	
	---			Grain yield (Mg ha^{-1})	---				WUE (kg ha^{-1} mm^{-1})	
Annual cropping										
Annual winter wheat (WW-WW)	0.67 b	1.27 b	2.03 b	1.28 a	1.75 a	0.95 c	1.33 d	1.33 c	6.66 b	
Annual spring wheat (SW-SW)	0.62 b	2.56 ab	2.10 b	0.93 ab	1.13 a	2.58 b	1.65 cd	1.65 b	10.39 a	
Annual spring barley (SB-SB)	0.64 b	3.75 a	2.28 b	1.25 a	1.76 a	2.48 b	2.03 bc	2.03 a	12.02 a	
Winter wheat-winter pea (WW-WP)‡‡	2.66 a	2.26 b	2.38 b	0.83 b	2.16 a	2.67 b	2.16 b	1.08 c	8.16 b	
Fallow rotations										
Winter wheat-summer fallow (WW-SF)	3.81 a	4.06 a	4.38 a	2.46 a	2.29 a	4.47 a	3.58 a	1.79 ab	10.47 a	
Winter wheat-chemical fallow (WW-CF)	3.51 a	3.17 a	4.03 a	2.61 a	2.66 a	4.47 a	3.41 a	1.70 b	10.95 a	
Winter wheat-SB-CF (WW phase)	4.08 a	3.91 a	4.34 a	2.69 a	2.53 a	4.93 a	3.75 a	1.86 ab	11.81 a	11.71a
WW-Spring barley-CF (SB phase)	0.72 b	3.32 a	2.08 b	0.50 b	1.67 a	2.69 b	1.83 bc		11.52 a	

†All plots are direct seeded except the conventional winter wheat - summer fallow treatment

Means with same letter are not significantly different at the 0.05 probability level (Tukey’s Test)

WW – winter wheat, SW-spring wheat, SB-spring barley, SF-summer fallow, CF-chemical fallow

‡ Annualized yields for the 2-yr rotations were derived by dividing the yield obtained every other year by 2. For the 3-yr rotation annualized yield was derived from adding winter wheat and spring barley yields of the 3-yr rotation and dividing by 3

‡‡ Results shown pertain to WW

Table 6. Correlation of yield from eight rotations with total, winter, and spring precipitation, Moro Long-term Experiment, Moro, OR (2004-2010)

	Total	Winter	Spring	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
WW-WW	-0.03^{ns}	0.28^{ns}	-0.52^{ns}	0.61^{ns}	-0.76*	-0.34^{ns}	0.74^{*s}	0.25^{ns}	-0.09^{ns}	0.29^{ns}	-0.49^{ns}	-0.07^{ns}	-0.75*	-0.18^{ns}	-0.45^{ns}
SW-SW	0.90**	0.90**	0.60^{ns}	-0.01^{ns}	-0.75*	0.31^{ns}	0.47^{ns}	0.58^{ns}	0.73*	0.77*	0.22^{ns}	0.81**	-0.21^{ns}	0.89**	-0.25^{ns}
SB-SB	0.95***	0.97***	0.59^{ns}	-0.09^{ns}	-0.81**	0.34^{ns}	0.46^{ns}	0.76*	0.74*	0.72*	-0.10^{ns}	0.88**	-0.11^{ns}	0.78*	-0.20^{ns}
WW-SF	0.56^{ns}	0.44^{ns}	0.56^{ns}	0.02^{ns}	-0.21^{ns}	0.07^{ns}	0.28^{ns}	0.51^{ns}	0.19^{ns}	0.22^{ns}	0.36^{ns}	0.64^{ns}	0.10^{ns}	0.58^{ns}	0.38^{ns}
WW-CF	0.31^{ns}	0.20^{ns}	0.38^{ns}	0.04^{ns}	-0.11^{ns}	-0.09^{ns}	0.16^{ns}	0.10^{ns}	0.17^{ns}	0.31^{ns}	0.66^{ns}	0.34^{ns}	-0.06^{ns}	0.53^{ns}	0.12^{ns}
WW-WP	0.30^{ns}	0.05^{ns}	0.62^{ns}	-0.46^{ns}	0.03^{ns}	-0.53^{ns}	-0.22^{ns}	0.37^{ns}	0.14^{ns}	0.31^{ns}	0.54^{ns}	0.53^{ns}	0.47^{ns}	0.37^{ns}	0.46^{ns}
WW-SB-CF	0.47^{ns}	0.31^{ns}	0.57^{ns}	-0.06^{ns}	-0.08^{ns}	0.05^{ns}	0.13^{ns}	0.31^{ns}	0.21^{ns}	0.23^{ns}	0.55^{ns}	0.54^{ns}	0.14^{ns}	0.59^{ns}	0.32^{ns}
SB-CF-WW	0.94***	0.87**	0.72^{ns}	-0.25^{ns}	-0.71^{ns}	0.15^{ns}	0.31^{ns}	0.71^{ns}	0.77*	0.80*	0.16^{ns}	0.93**	0.02^{ns}	0.85**	-0.13^{ns}

^{ns}, *, **, ***, ****, not significant, significant at the 0.10, 0.05, 0.01, 0.001 and 0.0001 level of probability, respectively