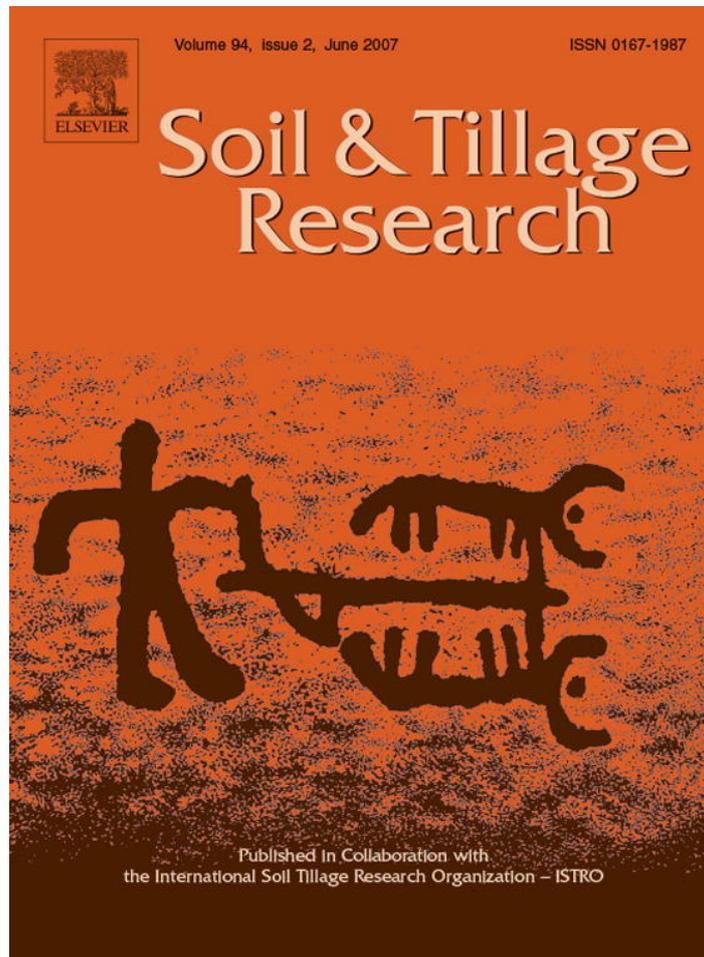


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Long-term continuous cropping in the Pacific Northwest: Tillage and fertilizer effects on winter wheat, spring wheat, and spring barley production

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Abstract

Conventional tillage winter wheat (*Triticum aestivum*) (WW)–summer fallow reduces soil productivity and increases soil erosion. Conservation tillage management, together with intensive cropping may have the potential to reverse these sustainability concerns. The objective of this study was to determine the effects of conventional tillage (CT) and no-tillage (NT) systems on grain yield of long-term annual cropping of monoculture WW, spring wheat (SW), and spring barley (*Hordeum vulgare*) (SB) grown with or without fertilizer, in the Pacific Northwest region of the USA. In unfertilized crops, grain yield of WW, SW, and SB was 15%, 25%, and 50% higher, respectively, in CT than in NT plots, an indication of the involvement of yield limiting factors under the NT cropping system. When fertilized, there were no significant differences in grain yield of WW. Yields of SW and SB, however, remained 21% and 15% higher, respectively, in CT than in NT, an indication that factors other than fertility were involved. These results suggest that in order for NT management to be widely adopted by area growers, the yield-limiting factors need to be addressed.

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1. Introduction

Conventional tillage winter wheat–summer fallow rotation is the predominant cropping system in dryland areas of the Pacific Northwest (PNW), where annual precipitation is less than 400 mm. Fallowing is used primarily to store winter precipitation, allow mineralization of nutrients (N, S), and to control weeds and is economical where rainfall is not adequate to produce a

crop every year (Leggett et al., 1974; Bolton and Glen, 1983). This rotation system, however, depletes soil organic carbon, exacerbates soil erosion and it is not biologically sustainable (Rasmussen et al., 1980, 1998; Rasmussen and Parton, 1994; Reicosky et al., 1995). Trends since the 1950s indicate that the profitability of fallow cropping systems is also declining in the PNW region, because costs are rising while grain prices are remaining static (Duff et al., 1995).

Intensive cropping systems, together with conservation tillage management, have the potential to reduce soil erosion and halt or reduce the decline in soil organic carbon (Collins et al., 1992). Although annual cropping reduces the time during which the soil is vulnerable to water and wind erosion, it leaves the soil exposed during

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seeding and early plant growth before full ground cover is achieved when CT management is used. With the introduction of NT practices, there is renewed interest in annual cropping of cereals, a system that was first practiced in the late 1800s (Leggett et al., 1974, McGregor, 1989; Brumfield, 1997). NT systems have many advantages over CT systems. In NT systems, residues remain on the surface and protect the soil from erosion (Allmaras et al., 1973; Ramig and Ekin, 1987). 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). 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) and crop productivity under dryland conditions. Despite these attributes the potential for grain yield fluctuations in annual NT systems is still greater than in a wheat-fallow system because the previous crop dries the soil profile every year. However, given the conservation attributes of NT systems, we think that annual NT cropping systems may, in the long run, be more reliable and profitable than both annual CT cropping systems and fallowing. Furthermore, the success of NT systems will depend on the crop grown. Many growers are interested in annual NT cropping but there is little information on the reliability of these systems.

The objective of this experiment was to determine the long-term effects of CT and NT cropping systems on grain yield of annually cropped WW, SW, and SB. Data to compare CT and NT systems were obtained from long-term continuous annual monoculture experiments initiated in 1931, 1977, 1982, and 1997 at Oregon State University, Columbia Basin Agricultural Research Center (CBARC) near Pendleton, Oregon.

2. Materials and methods

2.1. Description of experiments

The oldest long-term experiments (LTEs) in western USA are located at CBARC (45.7°N, 118.6°W, with elevation of 438 m), near Pendleton, Oregon. The soil at CBARC is a coarse, silty, mixed, superactive mesic Typic Haploxeroll (Walla Walla silt loam), and based on a soil survey conducted in 1931, it is 1.2 m deep to caliche (clay layer) and about 2.4 m to bedrock. CBARC is characterized by 70% of the precipitation occurring during the winter months, with average crop-year (1 September–31 August) precipitation of about 400 mm.

The continuous CT cereal long-term experiment, at CBARC, serves as the cereal monoculture baseline for comparing other long-term crop rotations. The current monoculture plots of WW, SW, and SB were initiated in 1931, 1977, and 1982, respectively. The experiments have undergone a few changes since their inception. The plot layout is shown in Fig. 1. Each crop was grown annually in two strips. Each strip was divided into four sub plots that were harvested separately every year. Fertilizer treatments were applied to these sub-plots at the beginning of the experiments, but beginning in 1993, all plots in the fertilized strip received uniform fertilizer. The plots of WW, SW, and SB received annual applications of 100, 90, and 90 kg N ha⁻¹, respectively. In addition, all fertilized plots received annual applications of 10 kg P ha⁻¹ and 16 kg S ha⁻¹. Four plots in the second strip were not fertilized.

In 1997, a NT companion block with eight plots was added adjacent to the CT plots following the design of the CT experiments. As with the CT plots, four plots received no fertilizer and the other four plots of WW, SW, and SB received annual applications of 112, 100, 100 kg N ha⁻¹, respectively. The fertilized NT plots also received 10 kg P ha⁻¹ and 16 kg S ha⁻¹, annually. The NT plots received 10–12 kg N ha⁻¹ more than CT plots to partially counteract N immobilization. NT plots received urea [CO(NH₂)₂], ammonium nitrate solution (NH₄NO₃), ammonium polyphosphate solution (NH₄PO₃)_n, and ammonium thiosulfate (NH₄)₂S₂O₃ applied in bands located 15 cm deep between the seed rows at seeding. CT plots were fertilized after plowing with a shank applicator using the same fertilizers as in the NT plots; the shanks were spaced 30 cm apart.

2.2. Agronomic practices

The most practical, generally recommended methods and equipment available to growers were used for all other practices. CT plots were moldboard plowed after harvest and cultivated or harrowed as needed to prepare a seedbed. Target seeding rates on CT and NT plots were 237 and 269 seeds m⁻², respectively, for WW; 280 and 312 seeds m⁻², respectively, for SW; and 248 and 280 seeds m⁻², respectively, for SB. Seeding rates were 11–14% higher in NT than CT plots to counteract plant establishment problems normally encountered under NT conditions. A JD (John Deere) 8300[®] double disk drill with a 17 cm row spacing was used to seed CT plots and a JD1560 with a 18.8 cm row spacing or a Conserva Pak[®] drill (Conserva Pak Seeding Systems, Indian Head, SK, Canada) with a 30 cm row spacing was used to seed the NT plots.

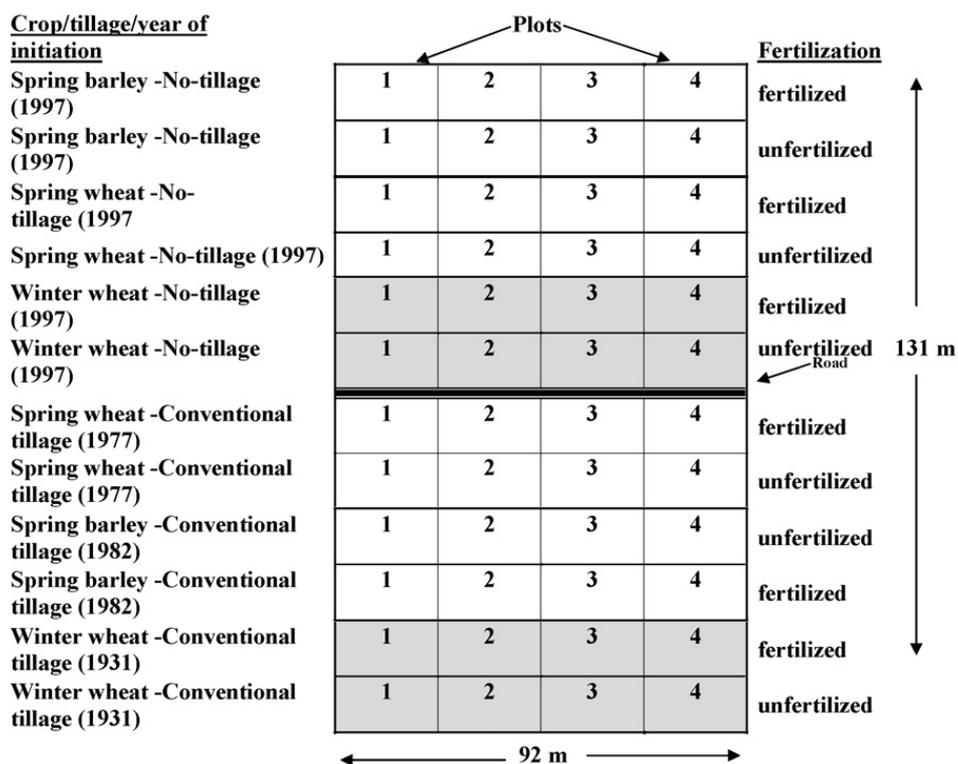


Fig. 1. Plot layout of the long-term continuous winter wheat, spring wheat, and spring barley monoculture and tillage experiment, at CBARC, Pendleton, OR.

Varieties of WW, SW, and SB seeded in this experiment were ‘Stephens’, ‘Alpowa’ or ‘Zak’, and ‘Baronesse’, respectively. Weeds were controlled by herbicides; which during the last 6 years included: glyphosate (*N*-(phosphonomethyl)glycine) for pre-plant and post harvest weed control, glyphosphate + 2,4-D (2,4-dichlorophenoxyacetic acid) for post harvest weed control, bromoxynil (3,5-dibromo-4-hydroxybenzoni-trile isooctyl ester of 2-methyl-chlorophenoxyacetic acid) for post-harvest weed control; diclofop methyl (methyl 2-[4-(2,4-dichlorophenoxy) phenoxy] propano-ate for grassy weed control, metribuzin (4-amino-6-(1,1-dimethylethyl)-3-methylthio)-1,2,4-triazin-5 (4*H*)-one for pre-emergence and in-crop grassy weed control, sulfosulfuron (*N*-[[4,6-dimethyloxy-2-pyrimidinyl) amino] carbonyl]-2-(ethylsulfonyl) imidazo [1,2-*a*] puridine-3-sulfonamide) for broadleaf and grassy weed control, and triallate (*S*-(2, 3, 3-trichloro-2-propenyl) bis(1-methylethyl)carbamothioate) for pre-plant grassy weed control. In the 2002–2003 crop-year, we resorted to Clearfield TechnologyTM (Colquhoun et al., 2003) to control grassy weeds in WW grown with NT management. Clearfield WW variety of “Stephens” (ORCF101) was seeded and BeyondTM herbicide, an ammonium salt of imazamox (3-pyridinecarboxylic acid, 2-(4,5-dihydro-4-methyl-4-(1-methylethyl)-5-

oxo-1*H*-imidazol-2-yl)-5-(methoxymethyl)-monamm-onium) was used to control downy brome (*Bromus tectorum*) in the NT plots, but not in the CT plots where we seeded the original “Stephens” variety.

2.3. Data collection

Data on yield and yield components were collected from each sub-plot and crop. Four bundles, of above ground plant material corresponding to each sub-plot treatment, were collected at full maturity before the plots were harvested. Each bundle area was four drill rows wide and 1 m long. Heads per bundle area were counted and straw and grain weights determined. Grain from each of the four plots in each treatment was harvested separately using a small plot combine. Grain was weighed and then sampled for the determination of kernel weight. To compare grain yield of CT and NT wheat, only data from 1997–1998 (when the NT plots were initiated) to 2002–2003 crop-year are presented. Unfortunately some of the yield component data from bundle samples were not recorded every year due to budgetary constraints. Bundle straw and grain weight (to calculate harvest index, $HI = \text{total bundle grain weight} / \text{total bundle plant weight}$) measurements were initiated in the 2001–2000 crop-year, and plants m^{-2}

and head m^{-2} measurements were initiated in the 2001–2002 crop-year.

2.4. Statistical analyses

The experimental design of the oldest of the experiments (CTWW), which was established in 1931, did not conform to currently accepted designs used in agricultural research. The fertilized and unfertilized treatment under each tillage treatment had four sub-plots, but the treatments were not replicated (Fig. 1). Although the treatment variables were not replicated in space, they were replicated in time as data are collected from each sub-plot every year. Consequently, we analyzed the experiments using PROC MIXED procedures (Littell et al., 1996) with repeated measures for year in conjunction with autoregressive time series modeling procedures, all standard techniques for analyzing data taken over time.

Since the experiments were conducted at each site (or plot) for the 1997–1998 to 2002–2003 crop-years, the outcome measurements (e.g. yields) were correlated over time. Thus, we applied a mixed effects model to incorporate temporal correlation and assumed temporal correlation had a first-order autoregressive (AR-1) structure (Lindsey, 1999). More specifically, suppose there were n years of measurements, then the correlated errors between the j th and k th years is ρ^u where ρ is a correlation and $u = |j - k|$, the absolute difference of j and k . This AR-1 correlated model implies that the correlation becomes weaker as the difference between times gets larger. This is a reasonable assumption for our case, as the outcomes of crop yields might be more highly correlated when 2 years are closer together rather

than when 2 years are far apart. We used the PROC MIXED procedure in SAS (Littell et al., 1996) to implement the AR-1 correlated model. Suppose there were a total of K subjects, the estimating equation for our model was:

$$\sum_{i=1}^K \dot{\mu}_i V_i^{-1} (y_i - \mu_i) = 0,$$

where, $y_i = (y_{i1}, \dots, y_{in})$ is a response variable (yields) measured from year 1 to year n for subject i , and $\mu_i = \beta_0 + \beta_1 \times \text{tillage}_i + \beta_2 \times \text{year}_i + \beta_3 \times \text{crop}_i + \beta_4 \times \text{fertilizer}_i$. V_i is a covariance matrix with the AR-1 correlation structure mentioned above, and $\dot{\mu}_i$ is the derivative of μ_i with respect to parameter $\beta = (\beta_0, \dots)$. Coefficient β_0 is the intercept, and the rest of the coefficients measure effects on tillage, year, crop, and fertilizer, respectively.

The ANOVA results for crop, nitrogen (N), year, and tillage treatments, and the interaction among these factors are shown in Table 1. Our analysis shows that all above factors were highly significant with P -value less than 0.001.

3. Results and discussion

3.1. Precipitation

Precipitation for the 1997–1998 to 2002–2003 crop years is shown in Table 2. The 73-year average crop year precipitation at CBARC, Pendleton, was 406 mm. The average crop-year precipitation during the study period was 398 mm. During the study period, precipitation was greater than the 73-year average in 1998–

Table 1

Tillage and fertilizer effects on grain yield of continuous winter wheat, spring wheat, and spring barley (1997–1998 to 2002–2003 crop-years) at CBARC, Pendleton, OR

Source of variation	d.f. (Num)	d.f. (Den)	F value	Pr > F
Crop	2	36	112.39	<0.0001
Nitrogen (N)	1	36	676.90	<0.0001
Tillage (tlg)	1	36	185.29	<0.0001
Year (Yr)	5	180	165.71	<0.0001
Crop × N	2	36	10.71	0.0002
Crop × tlg	2	36	36.03	<0.0001
Crop × Yr	10	180	19.65	<0.0001
N × tlg	1	36	19.89	<0.0001
N × Yr	5	180	124.17	<0.0001
Tlg × Yr	5	180	32.75	<0.0001
Crop × N × tlg	2	36	11.33	0.0002
Crop × N × Yr	10	180	13.19	<0.0001
N × Tlg × Yr	5	180	6.15	<0.0001
Crop × N × Tlg × Yr	20	180	26.21	<0.0001

Table 2
Grain yield of winter wheat, spring wheat, and spring barley under fertilized and unfertilized conventional tillage (CT) and no-tillage (NT) cropping systems and precipitation (1997–1998 to 2002–2003 crop-years) at CBARC, Pendleton, OR

Crop-year	Winter wheat (Mg ha ⁻¹) ^a				Spring wheat (Mg ha ⁻¹) ^a				Spring barley (Mg ha ⁻¹) ^a				Precipitation (mm) ^b		
	Unfertilized		Fertilized		Unfertilized		Fertilized		Unfertilized		Fertilized		Crop-Yr (09–06)	Winter (09–02)	Spring (03–06)
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT			
1997–1998	3.70c	2.37d	5.24a	4.22b	2.99b	2.78b	4.07a	4.03a	3.43b	2.91c	5.11a	5.31a	382	223	159
1998–1999	2.78b	3.85a	2.81b	4.00a	2.82b	1.87c	3.60a	2.91b	3.96b	1.23d	4.37a	3.34c	428	316	112
1999–2000	2.51b	1.52c	4.19a	4.55a	2.31c	1.05d	4.65a	2.88b	3.70c	0.81d	5.89a	4.37b	474	289	185
2000–2001	2.58c	3.03b	3.90a	3.73a	1.68c	1.31d	2.90a	2.41b	3.65b	2.02c	4.64a	3.99b	400	256	144
2001–2002	1.63b	0.90c	2.53a	2.24a	1.32c	1.13c	2.23a	1.78b	2.78b	1.97c	3.38a	2.33c	320	197	124
2002–2003	2.19b	1.40c	2.51ab	2.74a	2.11a	1.69b	2.28a	1.54b	2.67b	1.30c	3.14a	3.16a	386	261	125
Average	2.56b	2.18c	3.53a	3.58a	2.20c	1.64d	3.29a	2.59b	3.36c	1.70d	4.42a	3.75b	398	257	142

^a Letters compare means across rows. Means with similar letters are not significantly different from each other at $P < 0.05$.

^b Crop year precipitation (September–June) distribution from the 1997–1998 to 2002–2003 crop-years at CBARC, Pendleton, OR. Winter precipitation is precipitation received from September to February and spring precipitation is precipitation received from March to June.

1999 and 1999–2000 crop-years. Precipitation was lowest in 2001–2002 crop-year. Winter precipitation (September to February) was highest in 1998–1999 and lowest in 2001–2002 crop-years, while spring precipitation (March–June) was highest in the 1999–2000 and lowest in 1998–1999 crop-years.

3.2. Grain yield response to tillage and fertilizer

3.2.1. Unfertilized treatments

On average, yield of unfertilized WW, SW, and SB was 15%, 25%, and 50%, higher, respectively, under CT than under NT plots (Table 2), indicating the involvement of yield limiting factors in the NT cropping system. The difference in yield was greater in spring crops than in WW; the greatest difference in yield between fertilized and unfertilized plots was observed in SB. Our results are in agreement with Albrecht et al. (2005) who reported CT yield that was 32% greater than NT yield in unfertilized summer fallow cropping systems. In our study, higher grain yields in unfertilized CT compared to NT plots was attributed to higher harvest index ($r = 0.63$; $P < 0.01$) and heavier kernels ($r = 0.43$; $P < 0.01$) in WW, heavier kernels in SW ($r = 0.30$; $P < 0.10$), and to higher numbers of heads m^{-2} ($r = 0.84$; $P < 0.01$) and heavier grains in SB ($r = 0.75$; $P < 0.01$) (Table 3).

Grain yield of unfertilized CTWW was significantly higher than the yield of unfertilized NTWW in 4 of 6 years and NTWW yielded more the other 2 years (Table 2). Grain yield of unfertilized CTWW was weakly correlated to spring precipitation ($r = 0.32$, $P < 0.05$), while unfertilized NTWW grain yield was correlated to winter precipitation ($r = 0.59$, $P < 0.01$).

Unfertilized CTSW produced significantly higher grain yield than unfertilized NTSW in 4 of 6 years. Grain yield of unfertilized SW declined from 1997–1998 to 2001–2002 crop-year before increasing in 2002–2003 crop-year (Table 2). The decline was more gradual under CT than under NT. The decline in unfertilized CTSW yield could be attributed to the effect of winter precipitation that also decreased from 1998–1999 to 2001–2002 crop-years; the yield increased in 2002–2003 crop-year when the winter and total crop-year precipitation increased ($r = 0.47$, $P < 0.001$). The sharp decline in grain yield of unfertilized NTSW from 1997–1998 to 1999–2000 crop-years, despite the increase in crop year precipitation in the same period, suggests that factors other than water were involved.

In unfertilized plots of SB, grain yield was significantly higher under CT than under NT in all 6 study years (Table 2). Unfertilized CTSB grain yield

Table 3

Tillage and fertilizer effects on grain yield and yield components of continuous annual winter wheat, spring wheat, and spring barley at CBARC, Pendleton, OR (1997–1998 to 2002–2003 crop-years)

Crop	Tillage	Fertilizer, N, P, S (kg ha ⁻¹)	Plants m ⁻² (02–03)	Plants m ⁻² (% target)	Heads m ⁻² (02–03)	Heads plant ⁻¹	1000 kernel weight (g) ^a	Harvest index (00–03) ^a	Grain yield (Mg ha ⁻¹) ^a
W. wheat	CT	0, 0, 0	140	59	217a	1.6	46.90a	0.47a	2.56a
W. wheat	NT	0, 0, 0	237	88	205a	0.9	39.44b	0.39b	2.18b
S. wheat	CT	0, 0, 0	214a	77	256b	1.2	36.77a	0.46a	2.20a
S. wheat	NT	0, 0, 0	224a	72	281a	1.3	33.27b	0.44a	1.64b
S. barley	CT	0, 0, 0	204b	82	444a	2.2	39.84a	0.51a	3.36a
S. barley	NT	0, 0, 0	225a	80	312b	1.4	36.61b	0.43b	1.70b
W. wheat	CT	100, 10, 16	118	50	312b	2.6	43.32a	0.41a	3.53a
W. wheat	NT	112, 10, 16	205	76	345a	1.7	37.88b	0.39a	3.58a
S. wheat	CT	90, 10, 16	229b	81	415a	1.8	30.74a	0.39a	3.29a
S. wheat	NT	100, 10, 16	272a	86	312b	1.1	30.27a	0.39a	2.59b
S. barley	CT	90, 10, 16	205b	83	641a	3.1	34.82b	0.42b	4.42a
S. barley	NT	100, 10, 16	292a	104	512b	1.8	36.90a	0.48a	3.75b
		se	4.09 ^b	–	11.16		0.59	0.01	0.08

^a Means with similar letters are not significantly different from each other at $P < 0.05$.

^b se applies to spring wheat and spring barley.

closely followed trends in winter precipitation ($r = 0.59$, $P < 0.01$), while yield of unfertilized NTSB decreased drastically in the first 3 years of the experiment when winter precipitation was increasing ($r = -0.56$, $P < 0.01$) (Table 2), suggesting that factors other than water were involved.

Difference in grain yield between unfertilized CT and NT plots could have been caused by a number of factors that include reduced nutrient availability. A number of studies have shown that CT aerates the soil and accelerates breakdown of buried crop residues (Rasmussen et al., 1980; Rasmussen and Parton, 1994, 1998; Reicosky et al., 1995) and in doing so releases N and other nutrients for the subsequent crop. NT crops were more likely to be N deficient due to N immobilization (Allmaras et al., 1973; Ramig et al., 1983; Rice and Smith, 1983; Rasmussen and Douglas, 1992; Franzluebbbers, 2004). This lack of N may have resulted in reduced HI and kernel weights under NT. Other studies have indicated that seed germination and seedling growth were slower under NT due to cooler and wetter soils compared to CT soils (Allmaras et al., 1973; Ramig et al., 1983; Schillinger and Bolton, 1993; Rasmussen, 1993; Reicosky et al., 1995). Tiller number was also reduced under NT conditions (Rasmussen, 1993). Furthermore, increased disease and weed pressure have also been reported in NT cropping systems (Allmaras et al., 1973; Ramig et al., 1983; Reicosky et al., 1995; Smiley, 1996). Although diseases were not monitored in our study, diseases such as

Pythium root rot (*Pythium ultimum* var. *sporangiferum* and *P. irregulare*), Rhizotonia root rot (*Rhizoctonia solani* AG-8 and *R. oryzae*), and take all (*Gaeumannomyces graminis* var. *tritici*) were shown to be more damaging under NT than under CT conditions in experiments conducted in adjacent fields at CBARC (Smiley, 1996). Observations made in our study indicated that NT plots were usually heavily infested with weeds, particularly downy brome and this was particularly so in the early years of the NT experiments. High downy brome infestations prompted us to use Clearfield technology to reduce weed populations in the 2002–2003 crop-year. Populations of downy brome fell in the later years of the study. Low grain yield under NT in our study could be attributed to some or all of the above mentioned stresses.

3.2.2. Fertilized treatments

Fertilization generally increased grain yield of all crops under both CT and NT cropping systems (Table 2). When fertilized, there was no difference in grain yield between CTWW and NTWW; however, in spring crops, differences remained. The grain yield of SW and SB remained 21% and 15% higher, respectively, in CT than in NT. Although CT grain yield remained higher than NT grain yield, relative differences were reduced by fertilization. This was particularly so in SB where the difference between CT and NT narrowed by 35%. Albrecht et al. (2005) also reported a smaller (7%) difference in winter wheat yield between

CT and NT summer-fallow cropping systems fertilized at 134 kg N ha^{-1} . Our results suggest that fertilization influenced the yield of SB more than yield of SW. Our observations during the growing season indicated that crops grown under NT management grew slower in the early spring and lagged at most growth stages compared to CT crops probably due to cold and wet soil conditions in early spring. When fertilized, NTWW was able to make up for the lost time. But, because spring crops have a shorter growing season, crops under NT could not make up for the slow start even when fertilized.

Applying N, P, and S increased CTWW grain yields in 4 of 6 years and increased NTWW grain yields in 5 of 6 years (Table 2). Grain yield of fertilized CTWW was significantly influenced by spring precipitation ($r = 0.76$, $P < 0.01$), while grain yield of fertilized NTWW was influenced by both winter ($r = 0.55$, $P < 0.01$) and spring ($r = 0.62$, $P < 0.01$) precipitation. There was no yield advantage from fertilization for either CT or NT cropping systems in the 1998–1999 crop-year because of the soil moisture shortage during the spring of this crop-year (Table 2). High CTWW grain yield in fertilized plots was obtained in the 1997–1998, 1999–2000, and 2000–2001 crop-years when both winter and spring precipitation were above normal (Table 2). High grain yield in fertilized NTWW was obtained in the first 4 crop-years (Table 2) when either winter or spring precipitation or both were high. Grain yield of fertilized CTWW and NTWW was not significantly different in 4 of 6 years (Table 2). On average, there was no significant difference in grain yield between fertilized plots of CTWW and NTWW indicating that fertilization overcame lower yield of NT observed in unfertilized plots. Although there were significantly more heads m^{-2} in fertilized NTWW than in fertilized CTWW, the reduction in kernel weight and HI (Table 3) under NT resulted in comparable grain yield between CTWW and NTWW. Grain yield was significantly correlated with kernel weight ($r = 0.78$; $P < 0.01$) and HI ($r = 0.72$; $P < 0.01$) in fertilized winter wheat plots.

In spring wheat, fertilization with N, P, and S significantly increased grain yield of both CT and NT crops in 5 of 6 years (Table 2). Under CT, fertilization increased grain yield in all years except the 2002–2003 crop-year when spring precipitation was very low (Table 2). Yield of fertilized CTSW followed a similar trend as in spring precipitation (Table 2) and was more closely correlated with spring precipitation ($r = 0.73$; $P < 0.01$) than with winter precipitation ($r = 0.45$; $P < 0.01$) (Table 2). Yield of fertilized NTSW declined gradually from the 1997–1998 to 2002–2003 crop-year

(Table 2). The decline in grain yield in fertilized plots was not as pronounced as in unfertilized plots. The CTSW yields were higher than NTSW yields in 5 of 6 years (Table 3). Higher grain yields in CT than in NT plots were attributed to significantly higher numbers of heads m^{-2} ($r = 0.62$; $P < 0.01$) (Table 3).

In spring barley, applying N, P, and S significantly increased the grain yield in all years under CT and in 5 of 6 years under NT. Both fertilized CTSB and NTSB yields were related to spring precipitation ($r = 0.81$; $P < 0.01$ and $r = 0.67$; $P < 0.01$, respectively) (Table 2). Fertilized CTSB produced significantly higher grain yield than fertilized NTSB in 4 of 6 years (Table 2) indicating that there were other factors besides precipitation that were affecting NT yield. On average, grain yield of CTSB was significantly higher than grain yield of NTSB with or without fertilizer (Table 2). Higher grain yield in CT plots was attributed to significantly higher numbers of heads m^{-2} ($r = 0.55$; $P < 0.05$) than under NT (Table 3).

3.3. Crop comparisons

Overall, SB produced the highest grain yield under unfertilized CT and WW produced the highest grain yield under unfertilized NT (Fig. 2). When fertilized, SB produced the highest grain yield under both CT and NT conditions followed by WW and then SW (Fig. 2). Spring barley produced high grain yield through high numbers of heads m^{-2} ($r = 0.75$; $P < 0.01$) (Table 3) and probably earliness to maturity. Our observations indicated that barley grew more rapidly in the spring and covered the soil surface much earlier than SW.

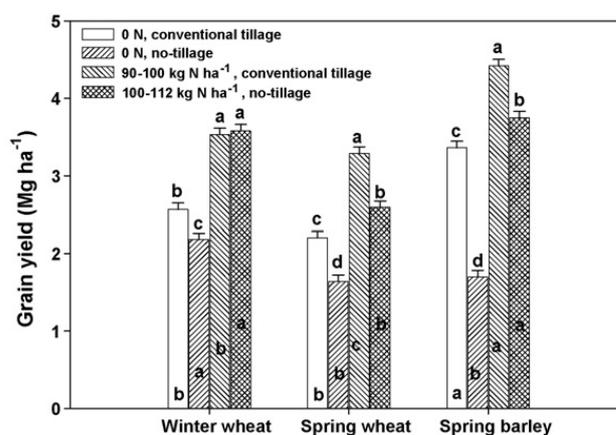


Fig. 2. Tillage and fertilizer effects on grain yield of continuous winter wheat, spring wheat, and barley at CBARC, Pendleton, OR. Yields are 6-year means (1997–1998 to 2002–2003 crop-years). Means with same letters are not significantly different at $P < 0.05$. Letters at the top of bars compare yields within each crop and letters within bars compare yields of the same fertilizer treatment between crops.

In all years, SB matured at about the same time as WW and in doing so escaped terminal drought and high temperature stresses that occurred towards the end of each growing season. In contrast, SW matured last and its grain filling period coincided with drought and high temperature stresses. This was probably why SW did not respond as well as SB to fertilization and had the lowest kernel weight and grain yield under all tillage and fertilizer treatment combinations (Table 2).

4. Summary and conclusions

Grain yield was influenced by crop, tillage and fertilization. For all crops, grain yield when unfertilized was significantly higher with CT than NT management, indicating the presence of yield limiting factors under NT. When fertilized, these differences disappeared for WW, but persisted for SW and SB. These results suggest that in order for NT management to be widely adopted by area growers, the yield-limiting factors need to be addressed. These factors may include slow initial growth due to cooler soil temperature, nutrient deficiency, residue toxicity, and pest pressure. Most research on NT cropping systems has focused on seed and fertilizer placement to ensure maximum seed germination and emergence at the expense of biotic and abiotic factors that may also have an influence on plant growth and grain yield. A greater understanding of these biotic and abiotic factors that affect NT cropping systems is needed to improve plant growth and grain yield.

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