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Tillage Method and Sowing Rate Relations for Dryland Spring Wheat, Barley, and Oat

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ABSTRACT

Some farmers in the Inland Pacific Northwest (PNW) have reported lower grain yield of spring cereals with no-till (NT) compared with conservation tillage (CT). A 4-yr field study was conducted in a 300-mm annual precipitation zone to determine tillage method and sowing rate effects on seed-zone water, seed-zone temperature, plant stand, grain yield, grain yield components, and straw production for three spring-sown cereal species. Wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and oat (*Avena sativa* L.) were sown at 120, 200, and 280 seeds m^{-2} in a split plot design with NT and CT as main plots and sowing rate $\times$ cereal species combinations as subplots. Factors other than tillage method (i.e., drill, sowing date, fertilizer rate, sowing depth) were held constant. There were no differences in plant stand between NT and CT, but grain yield was reduced by 5% in NT in part because of less water in the seed zone compared with CT during early plant development. Disruption of capillary continuity with CT appeared to restrict upward movement of water, resulting in greater retention of water in the seed zone underlying the depth of tillage. Grain yield was not affected by sowing rate for any crop species because increased number of heads per unit area (HPU) and kernels per head (KPH) consistently compensated for reduced plant stand density. With precise seed placement, sowing rate of spring cereals can be reduced by 50% or more from rates commonly used.

Farmers in wind erosion-prone areas of the PNW are interested in NT and CT practices to conserve soil and increase economic returns. Winter wheat–summer fallow (WW–SF) with intensive tillage is the prevailing cropping system in areas that receive < 330 mm annual precipitation, most of which occurs during the cool season. Some farmers sow spring cereals (mostly wheat or barley) in lieu of summer fallow when they feel that adequate plant-available water is stored in the soil during the winter. Increased cropping intensity (i.e., less fallow), especially using NT that provides year-round cover, is a best management practice to control wind erosion in the low-precipitation zone (Papendick, 2004). In the U.S. Great Plains, where summer rainfall is dominant, cropping intensification increased annualized grain yields, net economic return, and water use efficiency (WUE) compared with WW–SF (Peterson and Westfall, 2004). Little information of this type is available for climate and soils of the dryland PNW.

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Modern NT drills efficiently place seed and fertilizer in one pass through standing residue of the previous crop, but many farmers suspect that sowing rates of spring-sown cereal crops should be increased with NT because of reduced plant stands compared with CT. With CT, two or more tillage operations are used to prepare the seedbed and most of the residue is mixed in or buried below the soil surface. Additionally, some farmers report that grain yield with NT is slightly but consistently reduced compared with CT even when excellent NT plant stands are achieved (Donald Wellsandt, farmer near Ritzville, WA, personal communication).

Schillinger et al. (1999) sowed spring barley in eastern Washington using several types of NT drills compared with CT sowing method in years of above normal (i.e., 336–490 mm) annual precipitation. Lower plant stand density reduced grain yield and above-ground dry matter production in some NT drill treatments, but NT grain yields equaled or exceeded those of CT where uniform plant stands were achieved.

The most widely recommended sowing rate for dryland spring wheat in the northern Great Plains and the PNW is 200 seeds m^{-2} (Paulsen, 1987), but some farmers sow up to 350 seeds m^{-2}. Considerable variability in optimum sowing rates for cereals often involve interactions with tillage, cultivar, and environmental factors. The common sowing rate for dryland spring cereals in the < 300-mm annual precipitation zone of the PNW is 240 seeds m^{-2}. Sowing rates as high as 800 seeds m^{-2} are reported for oat production in Finland (Peltonensainio and Jarvinen, 1995).

Of the three yield components, HPU and KPH are considered more important than kernel weight (KW) for determining wheat grain yield (Donaldson et al., 2001; Shah et al., 1994). Heads per unit area is generally the most important yield component for wheat (Garcia del Moral et al. (2003), but under conditions of drought, KPH often has the greatest effect on grain yield (Arnon, 1972; Schillinger and Young, 2004). High sowing rates often result in increased HPU (Guberac et al., 2000; Stougaard and Xue, 2004) with corresponding reduction in KPH (Carr et al., 2003b). In response to increasing sowing rates, cereal grain yield will generally rise rapidly, reach a broad plateau, and then decline slowly (Carr et al., 2003a; Paulsen, 1987).

The objective of this study was to determine tillage method $\times$ sowing rate effects on stand establishment, grain yield, grain yield components, and straw production of recrop (i.e., no summer fallow) spring wheat,

Abbreviations: C, crop species; CT, conservation tillage; DWP, days without precipitation; HPU, heads per unit area; KPH, kernels per head; KW, kernel weight; NT, no-till; PNW, Pacific Northwest; R, sowing rate; T, tillage method; WUE, water use efficiency; WW–SF, winter wheat–summer fallow; Y, year.

barley, and oat. In addition, seed-zone water content and seed-zone temperature were periodically compared between NT and CT (in wheat only) during the first 6 wk after sowing.

MATERIALS AND METHODS

Field Layout

A 4-yr field experiment was conducted at four sites from 1999 to 2002 on the Donald Wellsandt farm near Ritzville, WA. Annual precipitation averages 300 mm with 70% occurring between 1 September and 31 March. The soil is a Walla Walla silt loam (Coarse-silty, mixed, superactive, mesic Typic Haploxerolls) derived from loess overlying basalt bedrock. Soil depth is greater than 180 cm and there are no restrictive layers or rocks. Slope at the experimental sites is less than 2%.

Treatments consisted of three cereal species sown in the spring at three sowing rates into both NT and CT. Cereals were 'Alpowa' soft white wheat, 'Baronesse' 2-row barley, and 'Monida' oat, sown at 120, 200, and 280 seeds m^{-2}. All seed was certified by the Washington State Crop Improvement Association and treated with a broad-spectrum fungicide–insecticide formulation of tebuconazole {α-[2-(4-chlorophenyl) ethyl]-α-(1,1-dimethylethyl)-1*H*-1,2,4-triazole-1-ethanol} thiram [bis(dimethylthiocarbamoyl)disulfide] and lindane [1,2,3,4,5, 6-hexachlorohexane]. The 4-yr average 1000-kernel weight (after seed treatment) of wheat, barley, and oat seed was 41, 45, and 31 g, respectively. Tests conducted in Petri dishes before sowing showed that all seed had 97% or greater germination. The experimental design was a split plot in a randomized complete block arrangement with four replications. Main plots were tillage (NT and CT) and subplots were cereal species × sowing rate combinations. There were 72 plots (i.e., 9 subplots in each whole plot) with a total area of 0.53 ha. Individual plots were 30 m long by 2.45 m wide.

The previous crop in all years was spring wheat with the stubble left standing and undisturbed after grain harvest in August. No-till sowing had not been practiced at any of the sites before the experiment. In early March, 0.32 kg a.e. (acid equivalent) ha^{-1} glyphosate herbicide [*N*-(phosphonomethyl) glycine] was applied to all plots to control winter-annual grass weeds and volunteer from the previous crop. In late March, 3 to 4 d before sowing, the CT whole plots were prepared by making two passes with a field cultivator operated 7 cm deep with overlapping 18-cm-wide V-blades and an attached short-tine five-bar harrow. During the 4-yr period, all plots were sown in a single day between 29 March and 4 April with a 2.4-m-wide custom-built no-till drill equipped with Cross-slot (Baker Manufacturing, Christchurch, New Zealand) notched-coulter openers on 20-cm-wide row spacing. Seed was placed with 4 cm of soil cover in both NT and CT. Though depth of cultivation was 7 cm in CT, seed in CT was placed 1 cm below the depth of tillage with only 4 cm of soil cover because of compression of the tilled soil layer by the packer wheels of the Cross-slot drill. Fertilizer and seed were delivered simultaneously in the same row with fertilizer placed 2 cm below and 3 cm to the side of the seed. Thus, both seed and fertilizer were always delivered below the depth of tillage in the CT treatment. The quantity of available soil water and residual N, P, and S was measured in March to determine fertilizer needs on the basis of a yield goal that ranged from 1.6 Mg ha^{-1} in 2001 to 3.4 Mg ha^{-1} in 2000. Fertilizer rate was held constant for all treatments each year. Ammonium nitrate + urea provided the liquid base to supply a 4-yr average of 43 kg N, 15 kg P (aqueous solution of $NH_4H_2PO_4$), and 12 kg S [aqueous solution of $(NH_4)_2S_2O_3$] ha^{-1} yr^{-1}. Broadleaf weeds were effectively controlled during the growing season with 0.56 kg ai (active ingredient) ha^{-1} bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) applied at the tillering stage of growth. Neither grass nor broadleaf weeds were a problem in this experiment.

Measurements

Volumetric water content in the 1.8-m soil profile was measured in six locations within the experiment area each spring just before soil preparation and sowing by gravimetric (Top and Ferre, 2002) and neutron thermalization (Hignett and Evett, 2002) methods. The neutron probe was specifically calibrated for Ritzville silt loam soil. As spring cereals in the PNW generally deplete volumetric soil water to 4.5% by time of grain harvest, plant available soil water was calculated as average volumetric soil water content (%) in the 1.8-m soil profile at time of planting minus 4.5%. Precipitation was measured on site each year with a computerized weather station. Before sowing, surface residue remaining from the previous crop was measured in both NT and CT (after tillage in CT) main plots by clipping and gathering all aboveground dry matter within a 1-m-diam. hoop. The wheat straw was placed in paper bags and allowed to air dry for 10 d before weighing.

Mass water content in the 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths in the seed row was measured on several sampling dates within 6 wk after sowing on three soil cores per plot in the medium sowing rate (i.e., 200 seeds m^{-2}) wheat treatment in NT and CT plots by procedures described by Top and Ferre (2002). Soil temperature at depth of seed placement was determined on the same plots and dates as the mass soil water content measurements (i.e., in the 200 seeds m^{-2} wheat treatment several times within 6 wk after sowing) with eight soil thermometers placed 4 cm below the soil surface in the seed row and allowed to equilibrate 4 min before recording readings.

Table 1. Plant available soil water in the 1.8-m soil profile at time of sowing in late March or early April, August-through-March precipitation, growing season precipitation, and 12-mo total precipitation during the 4-yr experiment as well as the 30-yr average near Ritzville, WA.

Year	Available soil water†	Precipitation					
		August–March	April	May	June	July	12-mo total
	mm						
1999	193	251	8	15	28	3	305
2000	175	255	14	27	27	18	341
2001	96	121	36	11	16	5	189
2002	137	216	11	7	14	2	250
4-yr average	150	211	17	15	21	7	271
‡30-yr average		222	23	26	18	11	300

† Available soil water for cereals was calculated as total volumetric soil water (%) in the 1.8-m soil profile at time of planting minus 4.5%.
‡ The 30-yr (1974–2004) average precipitation is for the city of Ritzville located 5 km west of the experiment sites.

Table 2. Analysis of variance for plant stand, grain yield, grain yield components, and straw production for spring wheat, barley, and oat sown either no-till or after conservation tillage at three sowing rates during 4 yr near Ritzville, WA.†

Source	df	Straw wt.	Heads m^{-2}	Kernels $head^{-1}$	Kernel wt.	Grain yield	Plant stand
Year (Y)	3	***	***	***	***	***	***
Tillage (T)	1	**	*	**	ns	***	ns
Crop (C)	2	***	***	***	***	ns	***
Sowing rate (R)	2	ns	***	***	ns	ns	***
Y × T	3	ns	ns	ns	ns	ns	***
Y × C	6	ns	***	***	***	***	***
Y × R	6	ns	ns	ns	ns	ns	***
T × C	2	ns	ns	ns	ns	ns	ns
T × R	2	ns	ns	ns	ns	ns	ns
C × R	4	ns	ns	***	ns	ns	ns

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
ns = no significant difference.
† There were no three- or four-way interactions.

Plant stand establishment was measured by counting individual plants in three 1-m-long row segments in each plot 25 d after sowing. Grain yield was determined by harvesting the grain from plants in the middle 8 of 12 rows in a swath through each 30-m-long plot with a Hege 140 plot combine (Hege Maschinen GmbH, Waldenburg, Germany) with 1.5-m-wide cutting platform, collecting grain in a cloth bag, and weighing grain on a digital scale accurate to 0.1 g. Head density and total above-ground dry biomass production were measured by hand-cutting the above-ground portion of plants from 1-m-long row segments in three locations in each plot just before harvest in early August. Plants were placed in a low-humidity greenhouse for 7 d then weighed. Kernels per head was calculated on the basis of heads per square meter and 1000-kernel

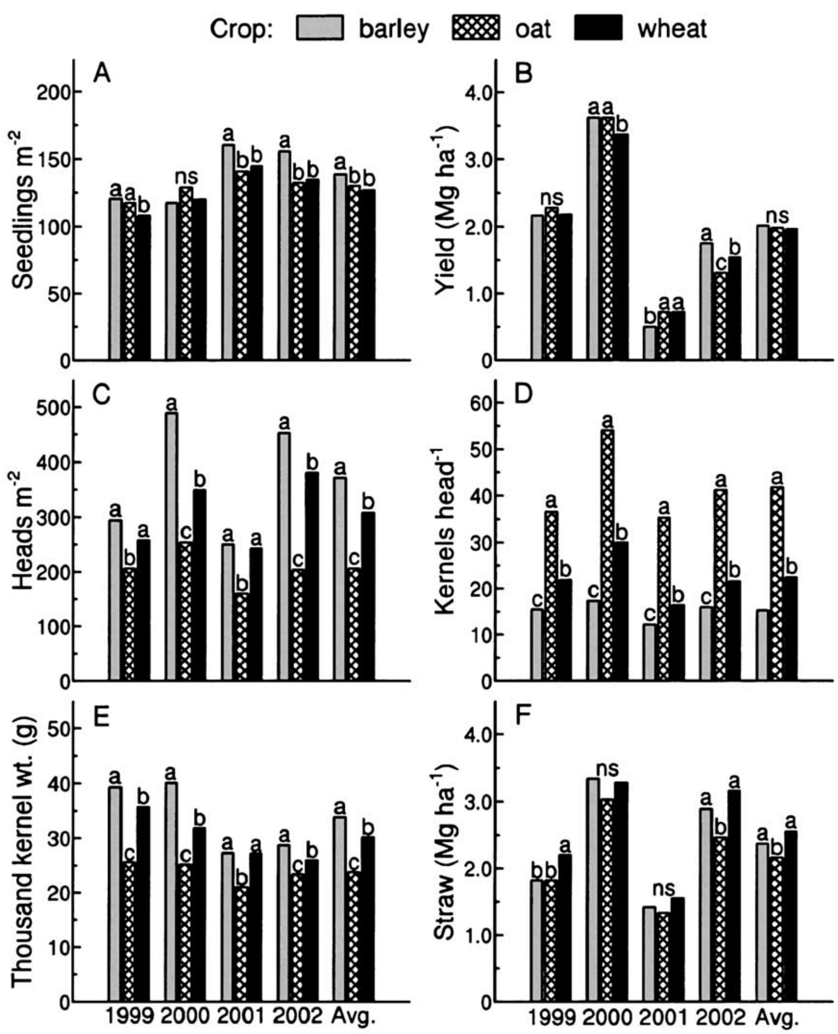

Fig. 1. Yearly and 4-yr average plant stand, grain yield, yield components, and straw production for spring-sown wheat, barley, and oat. Data are combined across two tillage methods (conservation-till and no-till) and three sowing rates (120, 200, and 280 seed m^{-2}). Within-year and 4-yr-average means followed by the same letter are not significantly different at the 0.05 probability level.

weight after passing heads though a hand-fed thresher. Straw production was determined by subtracting the weight of the grain from the whole aboveground plant weight.

An analysis of variance for all data was conducted by the PROC GLM procedure of SAS (SAS Inst., 1999). Treatment means were considered significantly different at $P < 0.05$. The Bonferroni method was used to control the experimentwise error rate for multiple comparisons.

RESULTS AND DISCUSSION

Precipitation and Soil Water

Annual crop year (1 August to 31 July) precipitation during the 4-yr study ranged 189 to 341 mm and averaged 271 mm (Table 1). The 30-yr average annual precipitation for the site is 300 mm. Plant available water in the 1.8-m soil profile at time of sowing ranged from 96 to 193 mm during the 4-yr period (Table 1). A minimum of 125 mm plant available soil water at time of sowing is recommended for spring cereal production in the inland PNW (Leggett, 1959; Schillinger et al., 1999); below this level farmers are encouraged to make conservation-tillage summer fallow in lieu of sowing spring cereals. Growing-season (April–July) precipitation ranged from 34 to 86 mm compared with the long-term average of 78 mm (Table 1). Over-winter soil water storage and annual precipitation were considered average in 1999 and 2002 and above average in 2000. The 2001 crop year was one of severe drought.

Crop Species Effects on Plant Stand, Grain Yield, and Yield Components

Highly significant year (Y) × crop species (C) interactions occurred for grain yield, yield components, and plant stand (Table 2). Plant stand, grain yield, yield components, and straw production for wheat, barley, and oat are shown for each year in Fig. 1. Some of the Y × C interactions are subtle. For example, plant stand of barley was not different from that of oat in 1999 and 2000 or from that of wheat in 2000 (Fig. 1A). The Y × C interaction for the fluctuating order of grain yields among crops is apparent (Fig. 1B), but the 4-yr average grain yield among crops was about the same at 2.1 Mg ha^{-1}. Average long-term grain yield for WW–SF (i.e., one crop every other year) on the farm where this study

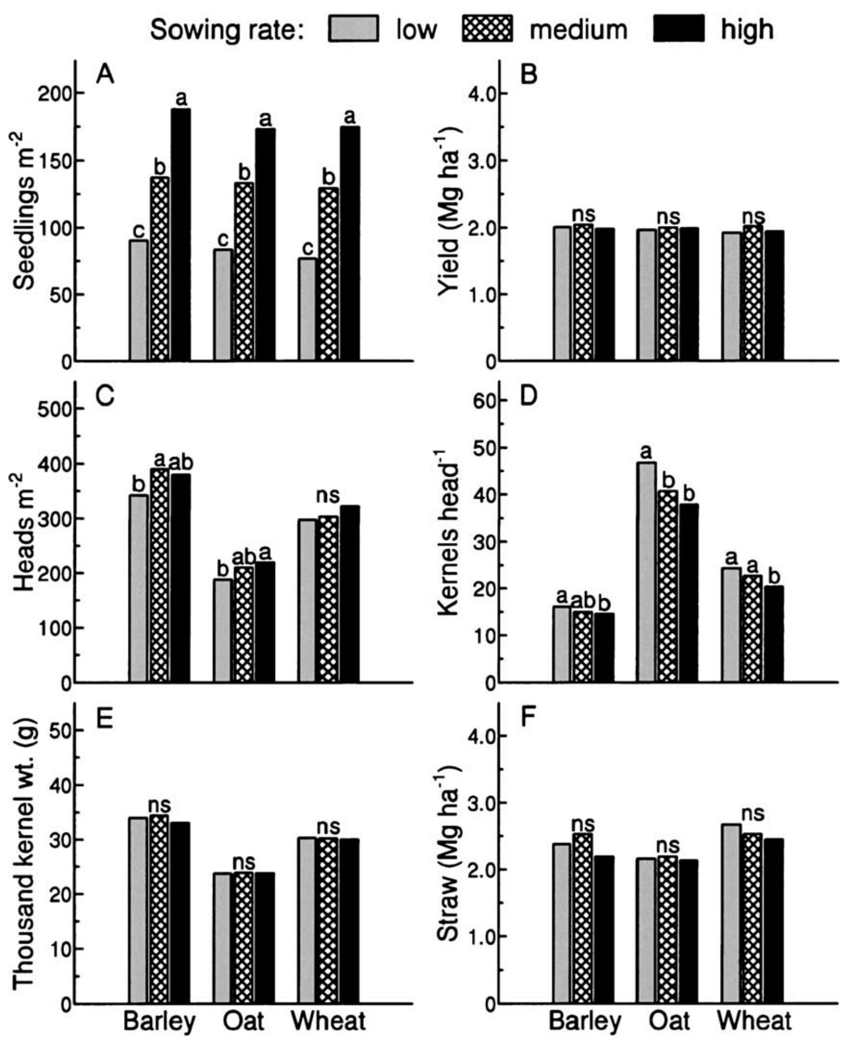

Fig. 2. Plant stand, grain yield, yield components, and straw production for spring-sown wheat, barley, and oat as affected by three sowing rates (120, 200, and 280 seeds m^{-2}) combined across tillage method (conservation-till and no-till) and averaged over 4 yr. Within-crop species means followed by a different letter are not significantly different at the 0.05 probability level.

was conducted is 3.7 Mg ha^{-1}. Thus, the 4-yr average grain yield for recrop spring cereals in this study was 58% of the long-term average grain yield for WW–SF. On the basis of grain yields, production costs, and crop prices, Juergens et al. (2004) reported that recrop spring wheat must produce 65% of the grain yield of WW–SF to be economically competitive.

There were dramatic differences in how crops partitioned grain yield in HPU (Fig. 1C) and KPH (Fig. 1D) and, to a lesser extent, in KW (Fig. 1E). Order of magnitude differences appear to have caused the Y $\times$ C interaction for HPU and KPH, whereas the interaction for KW is more obvious.

Over the 4-yr period, barley and wheat produced more straw than oat (Fig. 1F). There was no Y $\times$ C interaction for straw production (Table 2).

Sowing Rate Effects on Plant Stand, Grain Yield, and Yield Components

Sowing rate had a highly significant effect on plant stand density for all crops (Table 2). About 60% of seeds that were sown became established plants regardless of sowing rate and crop species (Fig. 2A). Sowing rate did not affect grain yield in any crop species (Fig. 2B). The only C $\times$ sowing rate (R) interaction was for KPH (Table 2). There were no differences in grain yield because the low sowing rate produced 85% or more HPU (Fig. 2C) and slightly higher KPH (Fig. 2D) compared with the medium and high sowing rate in all crops. Sowing rate did not affect KW (Fig. 2E) or straw production (Fig. 2F) in any crop species.

Tillage

Surface residue measured just before sowing averaged over the 4-yr period was 3640 (87% cover) and 1070 (46% cover) kg ha^{-1} for NT and CT, respectively. The only tillage-related interaction was Y $\times$ tillage (T) for plant stand (Table 1), but overall there were no differences in plant stand between NT and CT (Fig. 3A). However, averaged over the 4-yr period, CT produced slightly greater grain yield compared with NT (Fig. 3b) because of higher number of HPU (Fig. 3C) and KPH

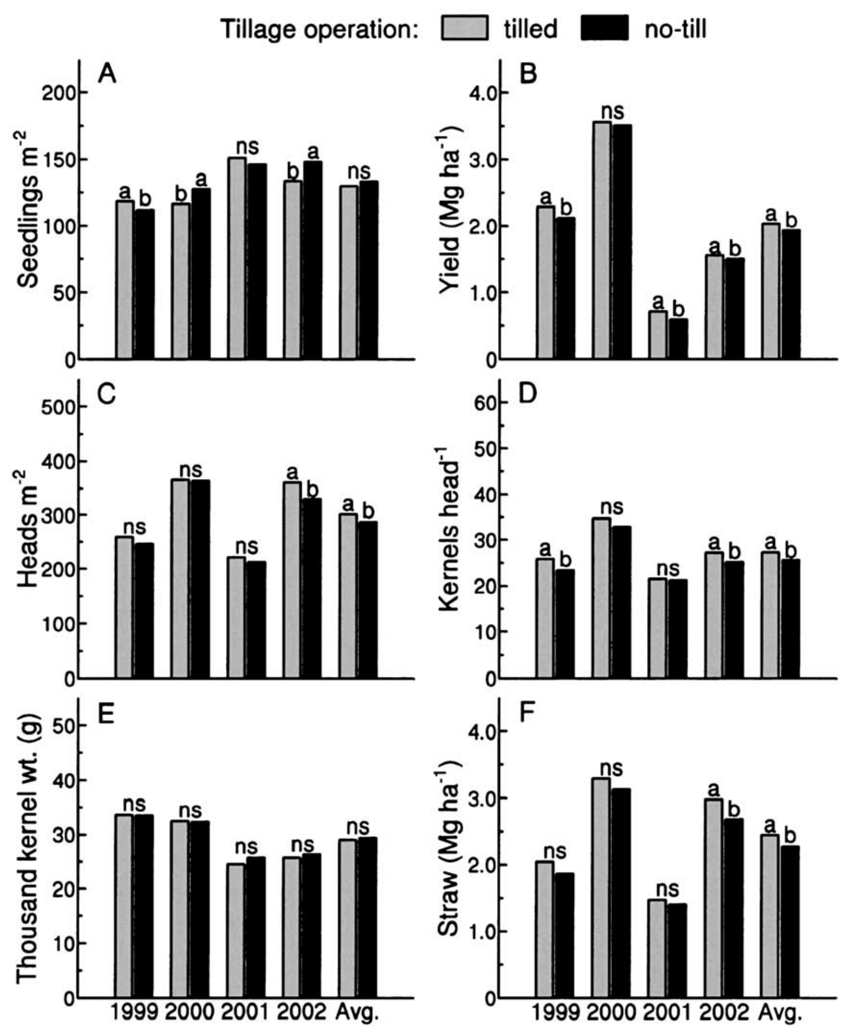

Fig. 3. Yearly and 4-yr average plant stand, grain yield, yield components, and straw production with conservation-till vs. no-till sowing method. Data are combined across three spring-sown crop species (wheat, barley, and oat) and three sowing rates (120, 200, and 280 seeds m^{-2}). Within-year and 4-yr-average means followed by the same letter are not significantly different at the 0.05 probability level.

(Fig. 3D). The KW of NT and CT averaged across crop species was never different (Fig. 3E); therefore, KW was not a factor in the grain yield differences between the two tillage systems. In addition to grain yield, overall straw production was also greater in CT compared with NT (Fig. 3F).

Why did the grain yield differences between NT and CT occur? Fertilizer amount and method of injection into undisturbed soil (i.e., below the depth of tillage in CT) was the same for the two systems. It is well known that immobilization of N will occur when N is broadcast on the surface or mixed with straw in the soil, and this may reduce grain yield (Malhi et al., 2001). But immobilization is not a problem when fertilizer N is placed in a band below the residue and/or tillage layer (Rasmussen et al., 1997). If there were differences in N availability between NT and CT, or insufficient supply of N, this would have likely become apparent during the wet 2000 crop year when yield potential was high. Yet 2000 was the only year when there were no differences in grain yield (Fig. 3B) or grain yield components (Fig. 3C, 3D, and 3E) between tillage treatments. Therefore, N availability is unlikely to be a factor in the grain yield differences measured between NT and CT in this study.

Soil temperature at depth of seed placement 4 cm below the soil surface tended to be lower in NT during the first 6 wk after sowing during all years (Fig. 4), most likely because the surface residue mass in NT was more than three times greater than in CT. Soils in the 0- to 5-cm depth tended to be drier more times during the 6-wk sampling period in the CT than in NT with some indication that this was more likely true with time after precipitation (Fig. 4). On the other hand, water content

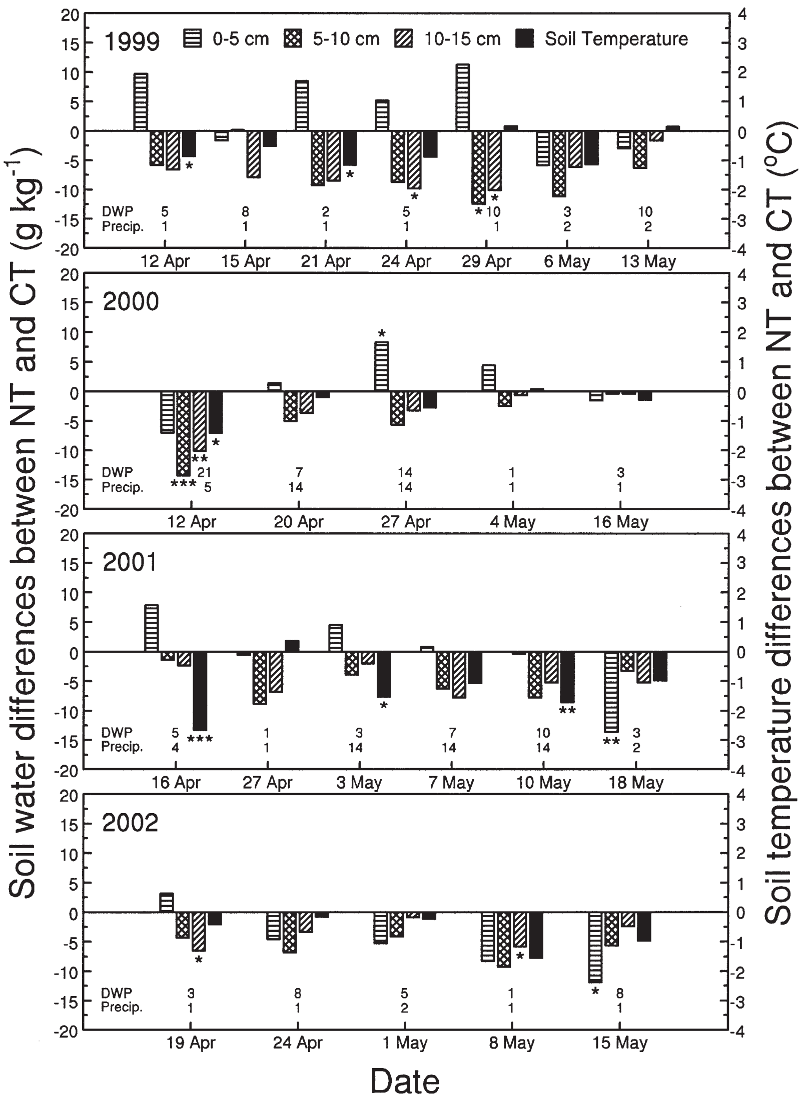

Fig. 4. Early-season soil water variation at 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths, and soil temperature in the seed row 4 cm below the soil surface at depth of seed placement, in no-till (NT) vs. conservation-till (CT) (zero line) spring wheat (200 seeds m^{-2} sowing rate) during 4 yr. The first number below bars indicates days without precipitation (DWP) preceding soil water and soil temperature measurements. The second number below bars is the amount of precipitation (mm) that occurred during the last precipitation event. Bars below the zero line indicate less water or lower temperature with NT compared with CT. Bars above the zero line indicate more water or higher temperature with NT compared with CT. *,,*** = significant differences at the 0.05, 0.01, and 0.001 probability level, respectively.**

at the 5- to 10-cm and 10- to 15-cm depths trended higher, in some cases significantly so, in CT than in NT (Fig. 4). These data for newly sown spring wheat in NT vs. CT are consistent with findings by Schillinger et al. (1999). Cultivation reduces the soil bulk density of the tillage layer and effectively breaks its capillary continuity with the subsoil. The restriction to upward water flow accelerates drying of the upper layers between rains that slows water loss from below even more, following the principles described by Papendick et al. (1973) and Hammel et al. (1981) for tilled summer-fallow soils. This may at least partially explain why more water was retained in the 5- to 15-cm depth in CT than in NT. With no disturbance by tillage, liquid water is more free to move up or down across the seed-zone region. This along with 46% residue cover with CT compared with 87% with NT may help explain the trend for higher moisture contents in the 0- to 5-cm depth and less in the 5- to 15-cm depths with NT compared with CT, especially with increasing time after rains.

The overall increase in seed-zone water content with CT shown in Fig. 4 had a significant effect on grain yield. A simple linear regression coefficient of determination for the relationship of water content and grain yield showed ($P < 0.001$) that 34% of the difference in wheat grain yield between NT and CT at the medium sowing rate over the 4-yr period was due to differences in soil water content at the 5- to 15-cm depth during the first 6 wk after sowing.

SUMMARY AND CONCLUSIONS

Water content in the 5- to 15-cm soil depth was generally greater in CT compared with NT during the first 6 wk after sowing. No-till is widely acknowledged throughout the world for being more efficient than tillage-based farming for both soil water storage and WUE by crops (Bradford and Peterson, 2000); but such advantage for NT appears to not hold true for spring-sown crops in the low-precipitation region of inland PNW in either relatively dry years (this paper) or wet years (Schillinger et al., 1999). Soil water above the tillage depth is subject to loss by evaporation but, by breaking soil capillary continuity, tillage increased soil water retention in the seed zone and accounted for 34% of the difference in grain yield between CT and NT.

Tillage method did not affect stand establishment, but grain yield was 5% greater in CT compared with NT. The higher grain yield in CT was due to a greater number of HPU and KPH than in NT. Kernel weight was not a factor in grain yield.

Although plant stands always increased proportionate to sowing rate in all crops, grain yield was not affected by sowing rate in any crop. With low sowing rate, HPU was reduced in barley and oat but not in wheat. All crops compensated for low sowing rate and associated low plant stand density (and low HPU in barley in oat) with high KPH. Sowing rate had no effect on KW or straw production in any crop. Results suggest that, with precise placement of seed, farmers in the dryland inland PNW could reduce sowing rates of recrop spring wheat, barley, and oat to 120 seeds m^{-2} with no adverse affect on grain yield compared with higher sowing rates.

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