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Minimum tillage and no-tillage winter wheat–summer fallow for low precipitation regions

J.D. Williams and S.B. Wuest

Abstract: Dryland wheat (*Triticum aestivum* L.) is the principal crop grown on 3.35 million ha (8.28 million ac) of the semiarid Inland Pacific Northwest of the United States. In areas with less than 300 mm (12 in) of annual precipitation, challenges for wheat production are similar to those found in the Mediterranean region and Australia. Successful crop production depends on adequate precipitation capture and storage and weed control, which prove problematic under no-tillage (NT), the most effective soil conservation practice. Sweep-tillage (ST) is proposed as an equally effective conservation system, with local conventional wisdom saying that it produces higher yields than NT systems. A study established in 2006 and concluded in 2018 evaluated the performance of NT and ST winter wheat–summer fallow production systems. The null hypothesis for this research assumed no statistically significant differences in any of the soil and plant characteristics measured between NT and ST treatments. Sixteen 0.04 ha (0.10 ac) plots were established in a randomized complete block design, with two rotation entry points for a total of four treatment plots per year replicated in four blocks. Data were analyzed using a generalized linear mixed model. The NT system produced significantly higher crop yields and higher precipitation use efficiencies than the ST system (NT 3.38 ± 0.33, ST 2.66 ± 0.27 Mg ha^{-1} [NT 50 ± 5, ST 40 ± 4 bu ac^{-1}]). Infiltration rates were higher and soil temperatures were lower in the NT system. The higher yields and lower soil temperatures in the NT system were unexpected and contrary to previous research conducted in this region.

Key words: minimum tillage—summer fallow—undercutter—no-tillage—crop residue conservation—winter wheat

Winter wheat (*Triticum aestivum* L.) is among the most productive and profitable crops grown in rainfed agricultural regions of the world. The mild, wet winters and hot, dry summers in the Pacific Northwest (United States) are ideal for rainfed soft white winter wheat production using a two-year winter wheat–14-month fallow system. With crop production of approximately 3.4 Mt ha^{-1} per two-year rotation (48 bu ac^{-1}) (Schillinger and Papendick 2008), this system remains the economic mainstay of the region. Until recently, this level of production was dependent on tillage for weed control and soil water manipulation, in which all residues were buried to create a "black" fallow. This system produces acceptably reliable wheat yields under variable annual weather conditions of temperature and precipitation, but it also results in unsustainable soil and nutrient loss (Gollany et al. 2011; Williams et al. 2014; Zuzel 1994). Conservation tillage systems were developed to reduce or eliminate these problems.

The most effective reduced tillage system, no-tillage (NT), substantially reduces erosion (Sharratt and Feng 2009; Williams et al. 2014). Unfortunately, some early adopters of NT in the late 1970s and early 1980s had spectacular decreases in yield; university- and USDA-led research projects recorded yield losses of up to 50% (Smiley et al. 2013). Nearly all the early adopters were unable to continue their efforts to produce dryland wheat using NT. A second wave of NT adoption in the Pacific Northwest began in the late 1990s and early 2000s with the advent of improved wheat varieties, herbicides, and equipment; research in the intermediate precipitation zone (300 to 450 mm [12 to 16 in] mean annual precipitation) and producer experience provided evidence that NT could meet or exceed tillage-based production in two-year wheat–fallow rotations (Williams and Long 2011). As of 2013, the adoption of NT or other conservation tillage methods were practiced in 70% of the region, including substantial increases in areas with <300 mm (12 in) mean annual precipitation, the low precipitation zone (Bista et al. 2017). This change in practices led to substantially more residue covering the ground and a substantial reduction in soil erosion by wind and water (Sharratt et al. 2017). However, not all impediments to NT adoption have been resolved.

Apparent impediments to successful NT adoption include combinations of the following: insufficient seed-zone water from mid-August to mid-September, insulation by residue reducing the accumulation of heat units resulting in poor crop establishment in late fall plantings, increased bulk density near the soil surface, poor weed control and the development of herbicide resistant weeds, and increased disease loading. Consequently, NT adoption has remained lower in the low precipitation zone of east central Washington and north central Oregon. Sufficient autumn precipitation to replenish soil water for germination and establishment often does not arrive until late October to mid-November (Thorup-Kristensen et al. 2009). In black-fallow or conservation tillage systems, breaking the capillary continuity to the soil subsurface conserves soil water with a tilled soil mulch through the summer, making seeding possible from mid-August and early September (Al-Mulla et al. 2009; Schillinger and Bolton 1993). Winter wheat seeded this early in the crop cycle significantly outpro-

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duces mid- and late-fall seeding by up to 30% (Donaldson et al. 2001), more so in the northern end of the region where growing degrees accumulate slower with substantially less precipitation (unpublished data comparing Echo, Oregon, with Lind, Washington). Thus, some producers continue to look for and evaluate variations on reduced tillage.

One of the most promising reduced tillage operations developed in the last 30 years is the undercutter or sweep-tillage (ST). Like the traditional black-fallow system, special deep-furrow seed drills are used to plant deep into soil moisture. Unlike the traditional system, tillage is limited to once in late spring or early summer with the undercutter. The ST system depends on herbicides for primary weed control throughout the first 10 to 12 months of fallow to reduce fuel, equipment, and time costs needed for tillage. This single, once-per-crop-cycle tillage is intended to reduce the capillary continuity very near the soil surface, while leaving all the crop residue on the soil surface for erosion control and to provide insulation during the hottest days of the year, thus reducing evaporative losses. The desired result is to make seeding possible before the end of the dry summer period (late August through mid-September), allowing wheat to germinate ahead of weeds and providing time for seedling wheat to become winter hardy and establish a deep root system. If successful, this practice will meet the needs of producers faced with growing herbicide resistance by weeds such as cheat grass (*Bromus tectorum* L.) and Russian thistle (*Salsola tragus* L.) or those who have found other intractable problems with the adoption of NT.

An experiment to compare NT to ST was established in 2006. Comparisons of the two systems address issues of tilled soil versus NT, which also involves early versus late seeding, seed-row fertilizer differences, and surface residue differences. The working null hypothesis for this research is that no statistically significant differences exist between treatments for any of the soil and plant characteristics measured with the primary goal of comparing crop yields in the two systems. Local conventional wisdom suggested that the ST with early seeding would produce higher yields than the NT.

Materials and Methods

This research was conducted 21.5 km (13.4 mi) west-northwest of Pendleton, Oregon (45°43' N, 119°03' W). Elevation at the site is ~320 m (1,050 ft), with 2% slope on a north-northeast aspect. A meteorological station located at the site since 2001 recorded precipitation, wind speed and direction, solar radiation, relative humidity, and air and soil temperature. Mean annual precipitation based on 17 crop years (September to August) was 270.5 ± 22.0 mm (10.65 ± 0.87 in), with 91% falling during the winter wheat growth and grain fill period from October through June, placing this site in the low precipitation zone of the Inland Pacific Northwest (Schillinger and Papendick 2008). Mean annual temperature for the period of record was 11.7°C (53.6°F) with a maximum of 45.6°C (114.1°F) and a minimum of –24.2°C (–11.6°F). Damaging temperatures are infrequent, with crown-damaging cold or hot temperatures affecting grain fill less than 1% of the time (figure 1). Frost-free conditions range from 150 to 170 days between May and September, with transient snow cover resulting from maritime fronts that produce low intensity storms. The soil was a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls in US classification system; Haplic Kastanozems in Food and Agriculture Organization [FAO]) containing <15% sand, 5%~10% clay, and ≥75% silt on 2% to 7% slopes (FAO 1997; Johnson and Makinson 1988).

Two cropping systems were established in 2006 to evaluate the effect of tillage practices on crop production and soil characteristics in a two-year winter wheat–summer fallow (WW-SF) rotation. The ST fallow consisted of one pass of a wide-blade (81 cm [31.9 in]), minimal soil inversion undercutter sweep in the spring or early summer of the fallow year at a depth of 14 cm (5.5 in), resulting in a surface mulch with bulk density of 1.13 g cm^{-3} (0.04 lb in^{-3}). The undercutter sweep operation is intended to kill weeds, break capillary pore connection between soil surface and profile, maintain surface roughness, and not bury residue (Schillinger 2001; Schillinger 2007; Zaiken et al. 2008). Liquid fertilizer was applied through two tubes located under each sweep. Additional weed control was accomplished by herbicide applications. Winter wheat was seeded with a deep-furrow drill in September except for two years when the seed zone was very dry (approximately permanent wilting point). The goal was to put seeds into damp soil (>–0.8 MPa) for immediate germination and stand establishment. Mid-September seeding occurs later than in locations farther north but is common for this location where winters are milder.

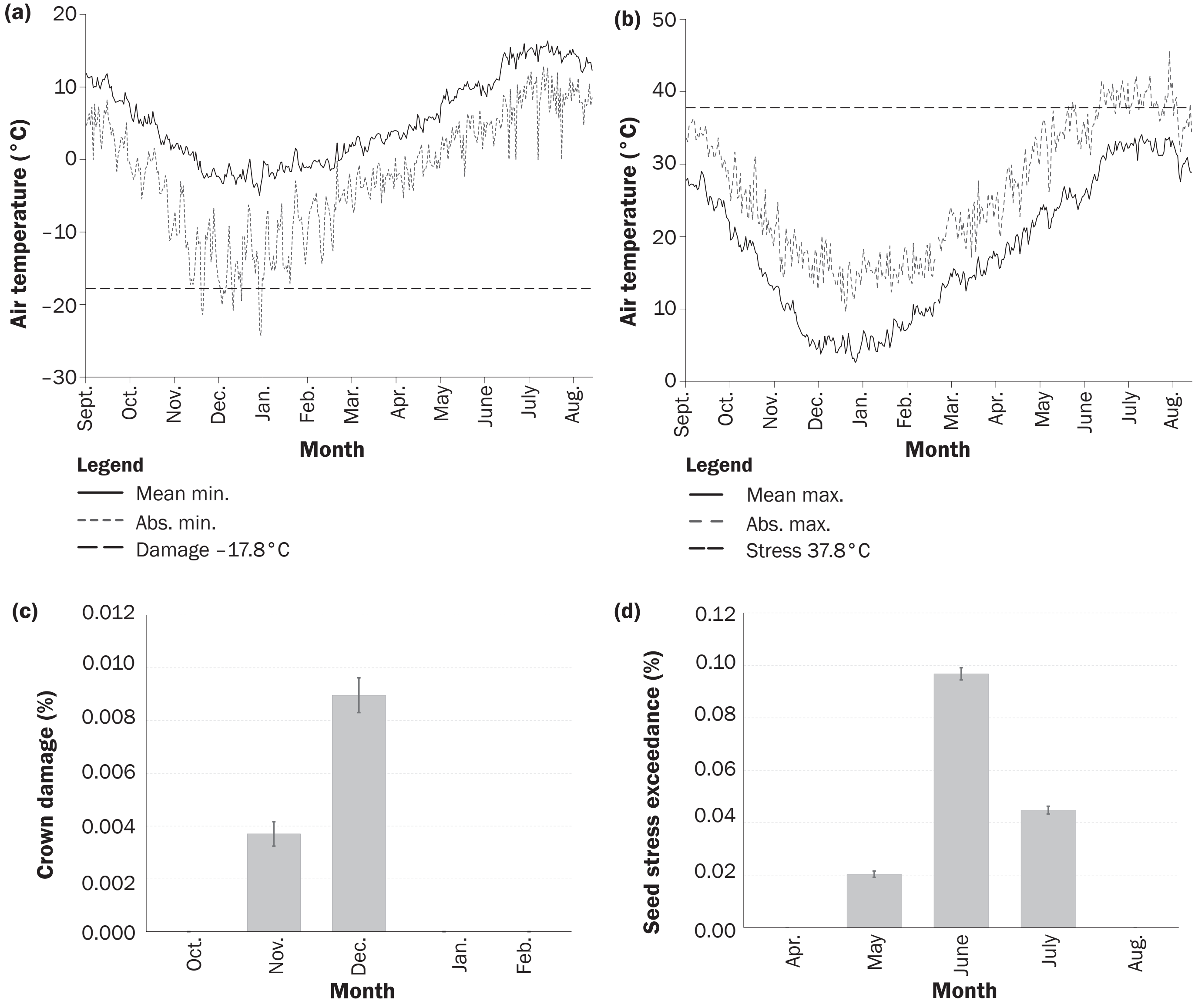
In the NT treatment, weeds were controlled with herbicides throughout the fallow period. Winter wheat was seeded and fertilized in mid-October if soil water was available; with inadequate soil water, planting was postponed until late October in anticipation of November precipitation. NT seeding was completed with a one-pass system using a Conserva-Pak (Indian Head, Saskatchewan, Canada) medium disturbance hoe-opener drill equipped on 305 mm (120 in) spacing. Fertilizer was placed 25 mm (1 in) below and 25 mm (1 in) to the side of the seed.

Wheat cultivars, planting dates, and seed and fertilizer rates differed from year to year (table 1). Producers traditionally sow early seeded wheat at lower rates to reduce costs and control excessive vegetative growth because the long early growing period promotes tillering and production of an adequate number of heads. Late seeding uses greater seed rates than early seeding to make up for reduced heat units needed for tillering before winter. Late seeding with NT drills are also most commonly supplied with starter fertilizer, including phosphorus (P) as it apparently aids in stand establishment and often produces a small but measurable yield increase (Lutcher et al. 2010). Yields of early seeded winter wheat into tilled soil at this location rarely respond to P fertilizer. For both of our early and late seeding treatments, the nitrogen (N) application was based on a soil test for each treatment and a recommended 0.04 kg N kg^{-1} wheat (0.04 lb of N bu^{-1}) of expected yield. In-crop herbicides were applied as needed for weed control. A complete list of pesticides, active ingredients, and manufactures is given in supplemental table S1.

Sixteen 7.3 m × 54.9 m (24 ft × 180 ft) plots were established in a randomized complete block design, with two rotation entry points for a total of four treatment plots per year replicated in four blocks. Soil water was measured between harvest time and autumn precipitation in 2009, 2010, 2011, 2013, and 2015 to evaluate soil water accumulation and crop-soil-water use. To compare treatments with different surface soil bulk densities (Wuest 2009), depths were compared at equivalent mass depths (50, 100, 125, 225, and 550 kg m^{-2} [10.24, 20.48, 25.60, 46.08,

Figure 1

(a) Minimum and (b) maximum air temperatures from 2001 to 2017 at the research site, and the percentage of days when temperatures were (c) cold enough to cause wheat crown damage or (d) hot enough to cause damaging heat stress (45°43' N, 119°03' W).



and 112.65 lb ft^{-2}]) corresponding approximately to 5, 9, 10, 15, and 40 cm (2, 3.5, 4, 6, and 16 in) depths below the soil surface. Soil water at individual depths and accumulated in the profile were tested for differences between treatments. Soil temperature profiles in fallow plots were measured at the soil surface, below the soil surface at 1 cm (0.4 in) increments up to 25 cm (10 in), and at depths of 30, 35, 40, and 45 cm (12, 14, 16, and 18 in) (Wuest 2010) at one-hour time steps from June 6, 2003, through September 25, 2013, and June 5, 2004, through October 16, 2014. Single-ring ponded infiltrometer measurements were conducted in the final year of fallowed plots during the spring of 2018. These measurements were made by driving 30 cm (12 in) diameter sharpened metal cylinders 20 cm (8 in) deep into the soil, always including one crop row inside the sample area. The inside circumference was tamped to seal any gaps between the cylinder and the soil. Water was maintained at a constant depth of 2 to 3 cm (0.8 to 1.2 in) with float valves for 2 hours. Readings from calibrated reservoirs provided periodic measurements of the water infiltration rate. Two hours is sufficient to achieve near steady-state infiltration in this environment (Wuest 2005; Wuest et al. 2006). Crops were harvested with a 2 m (6.6 ft) header on a plot combine with a straw chopper and spreader. Grain from each plot was weighed in a weigh wagon with ±4.5 kg (±9.92 lb) resolution. Representative samples were collected from each plot for protein analysis.

Data were examined to determine if transformation was needed (Gbur et al. 2012). Data were analyzed to evaluate the effect of tillage on grain yield, precipitation use efficiency, infiltration, soil water storage, and soil profile temperature. Data were analyzed using a generalized linear mixed model (GLIMMIX) in SAS 9.4 (Littell et al. 2006; SAS 2012). Soil temperature data, collected on a one-hour time step, were analyzed using

Table 1

Winter wheat varieties and rates of seeding and fertilizer applications for crop years 2007 to 2017 in crop systems research in the 200 to 300 mm dryland cropping region of northeastern Oregon.

Crop year	Treatment*	Wheat variety	Sweep date	Rod-weed date	Seeding date	Seeding rate (kg ha^{-1})	46-0-0 Drill applied (kg ha^{-1})	16-20 Drill applied fertilizer (kg ha^{-1})	32-0-0 Sweep applied (kg N ha^{-1})
2007	ST	Stephens	June 28, 2006	—	Sept. 5, 2006	67	—	—	56
2008	ST	Stephens	Mar. 6, 2007	Aug. 6, 2007	Sept. 6, 2007	76	—	—	0
2009	ST	Tubbs06: Stephens†	May 1, 2008	—	Aug. 29, 2008	76	—	—	29
2010	ST	CF102	May 27, 2009	July 14, 2009	Sept. 8, 2009	94	—	—	49
2011	ST	CF102	June 16, 2010	—	Sept. 21, 2010	56	—	—	0
2012	ST	CF102	June 20, 2011	—	Sept. 29, 2011	56	—	—	85
2013	ST	CF102	May 30, 2012	—	Oct. 25, 2012	114	—	—	123
2014	ST	CF102	June 7, 2013	—	Oct. 24, 2013	136	—	—	132
2015	ST	Bobtail	May 28, 2014	—	Sept. 24, 2014	101	—	—	18
2016	ST	Ovation	June 17, 2015	—	Sept. 20, 2015	132	—	—	80
2017	ST	Bobtail	July 3, 2016	—	Sept. 13, 2016	96	—	—	8
2018	ST	Bobtail	July 12, 2017	—	Sept. 28, 2017	68	—	—	59
2007	NT	Stephens	—	—	Sept. 6, 2006	67	56	81	—
2008	NT	Stephens	—	—	Oct. 15, 2007	99	0	100	—
2009	NT	Tubbs06	—	—	Oct 2, 2008	118	0	100	—
2010	NT	CF102	—	—	Oct. 15, 2009	115	16	107	—
2011	NT	CF102	—	—	Nov. 3, 2010	120	52	100	—
2012	NT	CF102	—	—	Oct. 14, 2011	120	18	104	—
2013	NT	CF102	—	—	Oct. 25, 2012	114	23	102	—
2014	NT	CF102	—	—	Oct. 24, 2013	136	16	103	—
2015	NT	Bobtail	—	—	Oct. 17, 2014	114	16	0	—
2016	NT	Ovation	—	—	Oct. 16, 2015	130	0	103	—
2017	NT	Bobtail	—	—	Oct. 11, 2016	118	0	100	—
2018	NT	Bobtail	—	—	Oct. 12, 2017	97	38	112	—

*Sweep-tillage (ST) row space 36 cm (14 in), no-tillage (NT) row space 30 cm (12 in).

†Mix ratio 50:50.

this same generalized linear mixed model comparing individual means of selected, relatively consistent time periods. Satterthwaite approximation was used to estimate standard error. All data were analyzed using spatial replication as the random effect.

Results and Discussion

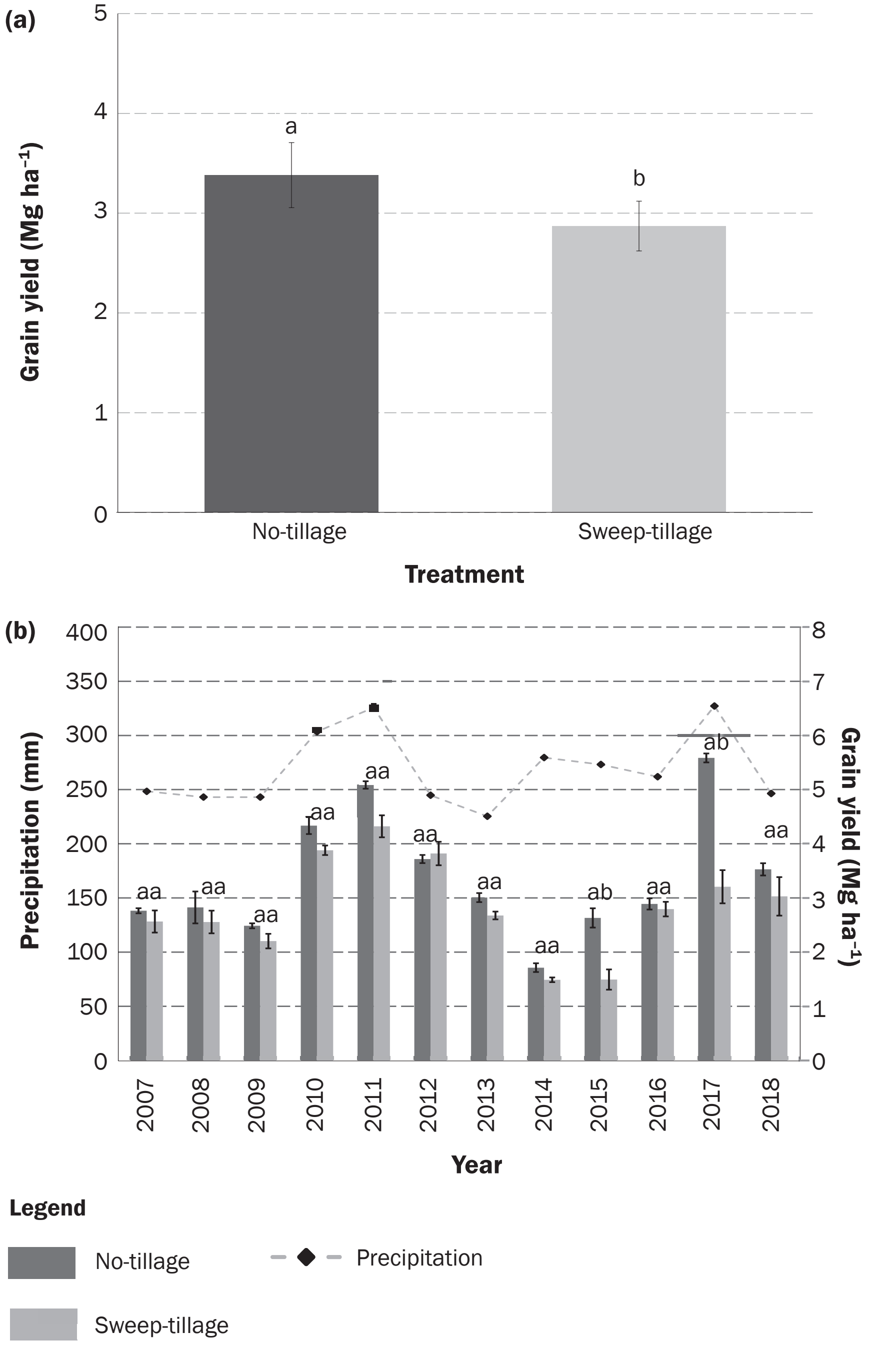
The NT treatment produced significantly more winter wheat (NT 3.38 ± 0.33, ST 2.96 ± 0.27 Mg ha^{-1} [NT 50 ± 5, ST 40 ± 4 bu ac^{-1}]) (figure 2a) and had higher precipitation use efficiencies (figure 3a) from 2007 through 2018, during which two years stood out with exceptionally high differences of $p \leq 0.05$ (2015 and 2017) (figures 2b and 3b). Grain protein measured only in 2012, 2015, and 2017 was significantly lower in the NT (13.37% ± 0.09%) than in the ST (14.30% ± 0.29%). These are high protein levels for soft white wheat, and there was never any indication that either treatment suffered from inadequate N supply. Volumetric soil water was not significantly different between the treatments at any depth after 14 months of fallow and immediately before seeding (figure 4). Ponded water infiltration rates measured following 12 years of treatment were significantly faster in the NT than the ST treatment ($p \leq 0.05$) (figure 5).

Soil temperatures during summer fallow throughout the measured soil profile and all times of the day pooled from mid-June through mid-October averaged 0.16°C ± 0.01°C (0.29°F ± 0.02°F) cooler in the NT than in the ST ($p \leq 0.05$). This relationship was not constant throughout this time frame, changing monthly and exhibiting a diurnal pattern of heat distribution and differences vertically in the soil profile. These findings will be discussed further in the following section. The most dynamic treatment differences occurred in the top 6 to 10 cm of the soil profile, where the NT was significantly cooler in the late afternoon during June, August, September, and October (June, August, and October are depicted in figure 6). Deeper in the soil profile and below this cooler zone, the soil temperature was significantly warmer during the summer in the NT than the ST ($p \leq 0.05$).

Our expectations were for the ST to produce higher yields than the NT given the conventional wisdom that earlier seeding improves yield potential. Instead the NT outyielded the ST in all but 1 year (2012) and performed significantly better in 2015 and 2017 and for the average of 12 years (figures 2a and 2b). Precipitation in 2011 (the fallow year of the 2012 crop, 325.7 mm [12.82 in]) and 2017 (327.2 mm [12.88 in]) were unusually high, outside the 95% upper

Figure 2

(a) Twelve-year mean and (b) annual winter wheat yield produced from 2007 through 2008 with no-tillage (NT) and sweep-tillage (ST) in the low precipitation zone of the Inland Pacific Northwest. Columns with different letters are significantly different ($p \leq 0.05$).



confidence level of 292.3 mm (11.51 in) (figure 7).

The annual precipitation for crop year 2015 was within 3 mm (0.12 in) of the mean value recorded since 2001 and within the range of precipitation where treatment yields were not significantly or substantially different. The ST crop was seeded a full month before the NT (September 24 versus October 24). Precipitation was below normal until December of that year, but the NT was seeded immediately after the first precipitation of the crop year at or above normal growing degree days (heat units). Unfortunately, soil water measurements were not taken from within the plots in the autumn of 2014. Analysis of soil water measurements in an adjacent reduced tillage research project that year did not show significant differences in soil water taken at 30 cm (12 in), 60 cm (24 in), 120 cm (48 in), or throughout the entire profile in the autumn of 2014 compared to 2015, 2016, or 2017. Those results suggest that the soil water was not exceptionally low, and lack of it should not have been responsible for later germination or poor stand establishment. Although precipitation in 2015 was below or at a normal level until May (figure 7), significantly more precipitation fell than normal in May and June. The additional rain possibly infiltrated more readily into the NT and contributed to a greater yield than in the ST.

Dryland crop research in the low and intermediate precipitation zones of the Inland Pacific Northwest has largely focused on precipitation captured during the fallow year and the subsequent soil water storage through the hot and dry months of June, July, and August (Al-Mulla et al. 2009; Schillinger 2001; Schillinger and Bolton 1993; Williams et al. 2014; Wuest 2010). Soil water dynamics are controlled by soil texture, soil structure, differential vapor pressure, temperature, and interactive water and heat transport processes (Al-Mulla et al. 2009). In soil where tillage destroyed structure, precipitation can be trapped at or near the surface and evaporate. Once precipitation has infiltrated into the soil profile, it can biologically transpire, percolate deeper, or evaporate. Typically, most precipitation that falls in this region after March through mid-June will not runoff due the small drop size and low intensity (Williams 2008; Williams et al. 1998). This will contribute to increased yields during crop years (Machado et al. 2015; Schillinger et al. 2008) and stored water in fallow years if it does not evaporate before percolating into the root zone. Recent research (Williams et al. 2018) shows more intensive tillage/disturbance of these soils can lead to an increase in the small and subaggregate size classes that contribute to surface sealing, reduced infiltration rates, and increased precipitation retention at the soil surface where it will more likely evaporate.

Seed-zone moisture in autumn following a dry summer is largely dependent on the capillary rise of soil water (see Castillo et al. [2015] for application in distributed hydro-

Figure 3

(a) Twelve-year mean precipitation use efficiency (PUE) and (b) annual mean precipitation use efficiency values under no-tillage (NT) and sweep-tillage (ST) winter wheat production in the low precipitation zone of the Inland Pacific Northwest. Columns or annual values with different letters or asterisks are significantly different ($p \leq 0.05$).

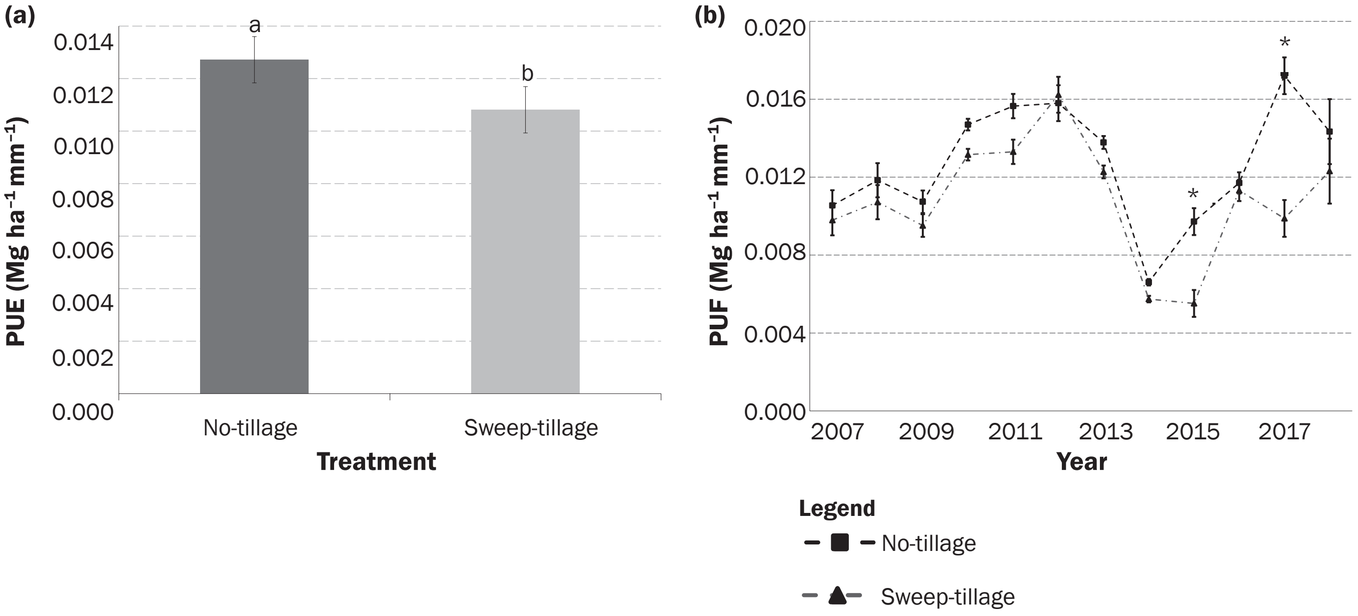
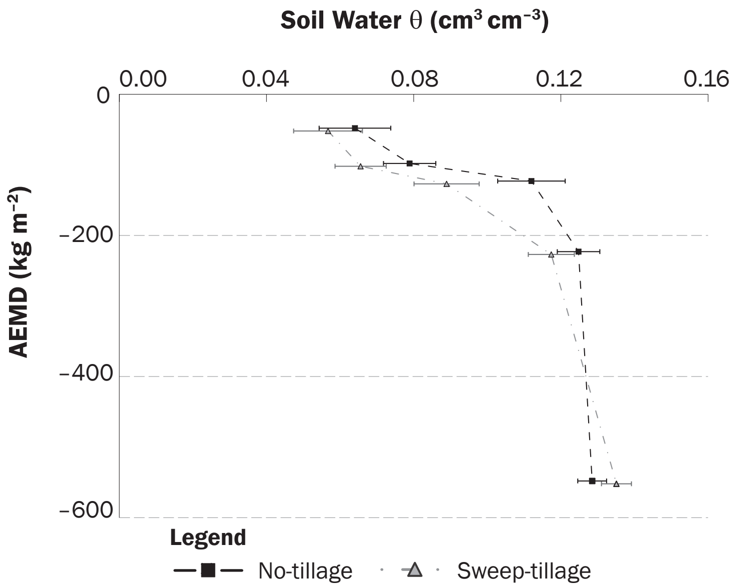


Figure 4

Soil water in no-tillage (NT) and sweep-tillage (ST) winter wheat production in the low precipitation zone of the Inland Pacific Northwest after 14 months of fallow and before seeding. Depths were compared at soil accumulated equivalent mass depths: 50, 100, 125, 225, and 550 kg m^{-2} are approximately equal to 5, 9, 10, 15, and 40 cm below the soil surface.

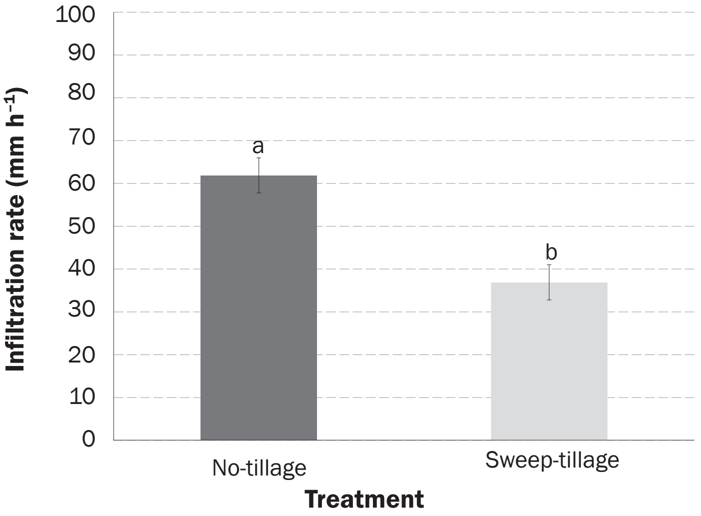


logic models). Although our soil water data at planting were not statistically significantly different between the NT and ST treatments, greater yield would indicate greater water availability in the NT system. Examination of total soil water deeper than 10 cm (4 in) in the soil profile reveals marginally more (but not statistically significant) soil water in the ST profile following fallow and immediately before seeding (figure 8). These data indicate chemically fallowed soil water conductivity is continuous with no interruption to the soil surface, creating a gradient in soil water content without a substantial difference in the total evaporation found in ST. These results also suggest that the ST treatment should have produced as much or more grain based on the relationship of water stored after summer fallow: 0.008 Mg ha^{-1} mm^{-1} (7.3 bu ac^{-1} in^{-1}) (Schillinger et al. 2008). With a 2.46 mm (0.10 in) greater mean water storage (not statistically significant), the ST should have outproduced the NT by 0.003 Mg ha^{-1} (0.73 bu ac^{-1}), but instead the NT had significantly higher production (figures 2a and 2b).

There has been limited research published in the Pacific Northwest concerning soil temperatures. Al-Mulla et al. (2009) reported higher soil temperatures in NT fallow than in reduced tillage fallow at Lind, Washington, from May through March. Recorded at 2.5 cm (1 in), 12.5 cm (5 in), and 17.5 cm (7 in), NT was 1.3°C (2.34°F), 1.1°C (1.98°F), and 1.0°C (1.80°F) warmer at their site, whereas NT at our site was cooler in the shallower depth during daylight hours into the evening except during July's peak air and soil temperatures (figure 6): June (0.08°C ± 0.02°C [0.14°F ± 0.04°F]), August (0.76°C ± 0.08°C [1.37°F ± 0.14°F]), September

Figure 5

Ponded water infiltration rates in no-tillage (NT) and sweep-tillage (ST) winter wheat crops produced in the low precipitation zone of the Inland Pacific Northwest. Columns with different letters are significantly different ($p \leq 0.05$).



(0.25°C ± 0.02°C [0.45°F ± 0.04°F]), and October (0.59°C ± 0.05°C [1.06°F ± 0.09°F]). At the 20 cm (8 in) and 45 cm (18 in) depths, mean temperatures were statistically higher in the NT through much of the day during August but not October. Temperatures in both treatments at 45 cm (18 in) fully merged in October.

The difference between our findings and those of Al-Mulla et al. (2009) might well be the difference between our data collected over the course of two summers and their data collected for one spring, summer, autumn, winter, and early spring cycle. However, our results differed in other substantial points. Al-Mulla et al. (2009) propose that two conditions could have led to higher temperatures in NT: soil bulk density and soil surface albedo. Lower bulk density could increase heat loading, resulting from lower thermal diffusivity in the conventional fallow (Al-Mulla et al. 2009). We found no differences in soil bulk density down to a depth of 40 cm (16 in) for NT (1.37 ± 0.01 g cm^{-3} [0.05 ± 0.00 lb in^{-3}]) and ST (1.30 ± 0.01 g cm^{-3} [0.05 ± 0.00 lb in^{-3}]). The lower bulk density in the reduced tillage recorded by Al-Mulla et al. (2009) was likely the result of the June or July pass by a rod weeder they performed that we did not. This additional tillage is one possible explanation for lower temperatures in their reduced tillage treatment than was found in ours. We did not measure albedo or ground covered by crop residue; visually nearly 100% cover was attained in both treatments by straw from the previous crop and fallow cycle. Therefore, both treatments were equally capable of insulating the soil surface and reflecting much of the solar energy. Finally, data collected by Al-Mulla et al. (2009) were collected and analyzed on a daily time step and thus not able to capture the diurnal nuance. Our results are more similar to those found by Shen et al. (2018) who took measurements at a 10 cm (4 in) depth in maize (*Zea mays* L.) and soybeans (*Glycine max* L.) in northeast China with annual temperatures of 4.4°C (7.92°F) and found temperatures were 0°C to 1.5°C (0°C to 2.70°F) cooler following seeding in NT compared to moldboard plow tillage. These measurements were also analyzed on a daily time step, but they found different results from year to year and biweekly time periods within years when the tillage treatment temperatures relative to each other switched.

We do not believe that soil temperature alone can explain the differences in the crop production of these two systems. The soil profile temperature difference from June through October of –0.07°C (–0.13°F) in the NT probably makes only a small physiological difference to the production of wheat. Although the soil profile was cooler in the NT treatment, that difference was concentrated in the soil surface and during the sunlit hours of the day; otherwise, there was no difference in soil temperature at or near the surface, and the temperatures deeper in the soil profile were significantly warmer in the NT than in the ST. More than two years of data collected throughout the entire two-year crop–fallow cycle would have provided a more revealing view of the role of soil temperature in this system. We also note that the temperature data were not collected during the years in this study when NT significantly outproduced ST.

Early seeding in low rainfall zones is subject to several hazards, including excessive water use, soil crusting before emergence, and insufficient seed-zone water for uniform emergence. At our site, the early seeded ST treatment attracted noticeably more rodent activity, which likely contributed to lower yields. Even well-established best management practices will not perform as reliably on the margins of the climate zone where they have proven adequate. In contrast, at this site the NT seeding was consistently uniform in emergence and development.

Research from similar climates and cropping systems produced comparable results, including areas surrounding the Mediterranean (Amato et al. 2013; Bassu et al. 2009; Moret et al. 2007; Sommer et al. 2012) and in Australia (Hunt et al. 2013; Ward et al. 2012). In general, these research projects demonstrated that tillage or NT were not the primary factor in crop yield and that, specifically, crop residue on the soil surface has a relatively minor effect on yield (Hunt et al. 2013; Sommer et al. 2012). It does appear that NT can outyield tilled systems under high water stress (Amato et al. 2013) but only with adequate weed control during fallow to conserve stored water (Bassu et al. 2009; Hunt et al. 2013). Worldwide NT could prove to be the most resource efficient and economic system in the driest winter wheat growing regions.

Summary and Conclusions

The purpose of this research was to evaluate the productivity of NT and minimum tillage winter wheat–fallow systems. Each system was applied with standard practices used by producers in the low precipitation zone of the US Pacific Northwest. The NT system produced significantly higher crop yields and higher precipitation use efficiencies than the ST system. The later NT seeding dates did not adversely affect grain yields relative to the ST grain yields. There were significant differences between the tillage systems' physical characteristics: infiltration rates were higher and soil temperatures were lower in the NT system. The higher yields and lower soil tem-

Figure 6

Soil temperatures late in (a) June, (b) July, and (c) August before seeding and in (d) October shortly before or after seeding crops in no-tillage (NT) and sweep-tillage (ST) winter wheat production located in the low precipitation zone of the Inland Pacific Northwest. Treatment difference is significant where * occurs above standard error bars ($p \leq 0.05$).

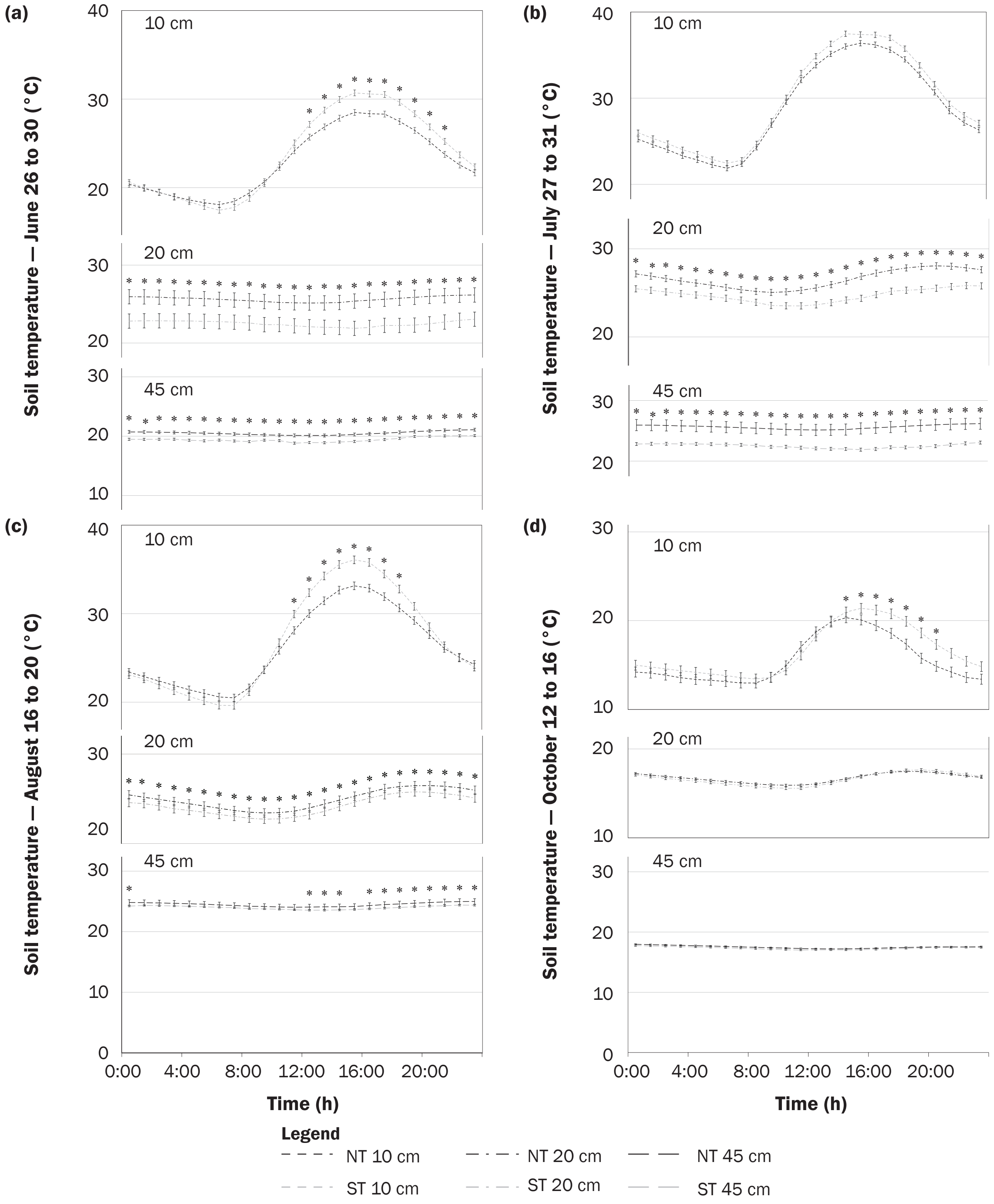


Figure 7

Mean and standard deviation monthly precipitation (2001 to 2018) in relation to high productivity years in the no-tillage (NT) treatment (2011, 2015, and 2017) from data collected at the research site in the low precipitation zone of the Inland Pacific Northwest.

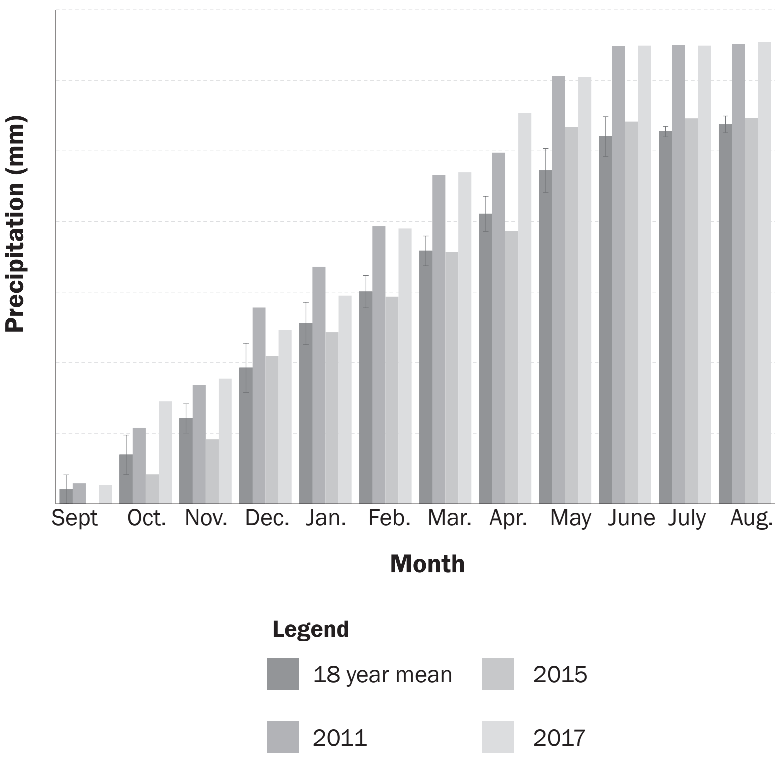
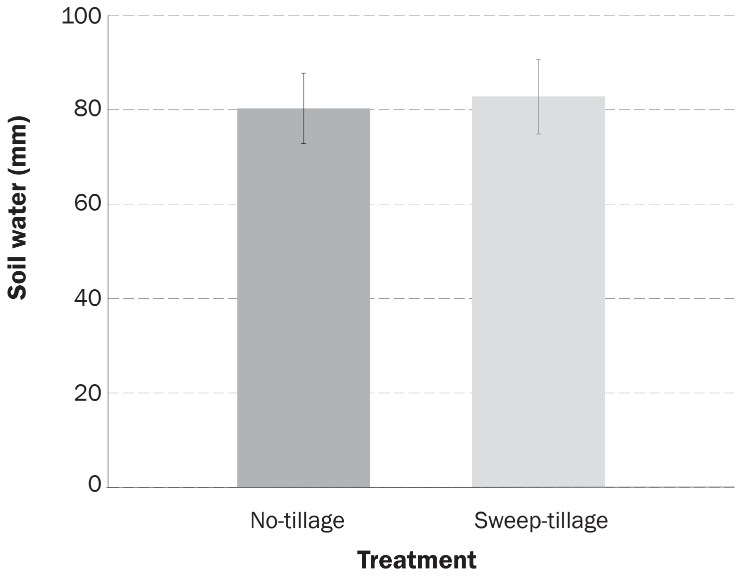


Figure 8

Soil water in the 10 to 100 cm depth at seeding in no-tillage (NT) and sweep-tillage (ST) winter wheat production located in the low precipitation zone of the Inland Pacific Northwest.



peratures in the NT system were unexpected and contrary to previous research conducted in this region. Understanding what factors caused the differences in yield would aid in developing improvements for both tilled and NT systems.

Supplemental Material

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2021.00062.

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