Dryland Cropping Systems

Tillage Effects on Water Use and Grain Yield of Winter Wheat and Green Pea in Rotation

Stephen Machado,* Steve Petrie, Karl Rhinhart, and Robert E. Ramig

ABSTRACT

Under water-limited conditions, increasing water use efficiency (WUE) is essential for successful crop production. A 7-yr study (1977–1982, and 1985) to evaluate tillage and tillage timing effects on soil water storage, crop water use, and grain yield of winter wheat (*Triticum aestivum* L.) and spring green pea (*Pisum sativum* L.) in rotation, was conducted near Pendleton, OR. Treatments included (i) fall plow (FP)–fall moldboard plow after wheat and after pea, (ii) maximum tillage (MT)–fall roto-till after wheat and fall sweep after pea, (iii) spring plow (SP)–spring moldboard plow after wheat and fall moldboard plow after pea, and (iv) minimum tillage (MinT)–no-till (NT) after wheat and fall sweep after pea. During the wheat phase, water storage efficiency was 44, 40, 38, and 34%, for FP, MT, SP, and MinT, respectively. Corresponding values during the pea phase were 50, 53, 59, and 57%, for FP, MT, SP, and MinT, respectively. Wheat used all of the stored water and an additional 31, 41, 43, and 61% more water than water stored under FP, MT, SP and MinT, respectively. Pea used 71, 67, 67, and 60% of stored water under FP, MT, SP and MinT, respectively. Wheat and pea yields under MT, FP, and SP were not different. Lowest yield was obtained under MinT during both wheat and pea phases. WUE was highly correlated with yield and was lowest under MinT. Improving weed control, retaining stubble for soil erosion control, and reducing sweep operations in MinT should improve yields in this treatment.

Under dryland conditions, where crop yields are water-limited, cropping systems that increase water storage and WUE, and prevent soil erosion are imperative for successful crop production. In eastern Oregon, winter wheat is commonly grown in rotation with green pea under dryland conditions in the foothills of the Blue Mountains, where annual precipitation ranges from 380 to 500 mm. This inland Pacific Northwest (PNW) region has a Mediterranean-type climate with mild, wet winters and warm dry summers. About 70% of precipitation falls between September and February; therefore crops mature under increasing drought and heat stresses. Under these conditions, cropping practices that increase WUE are necessary to avoid crop failures. The standard tillage regime in eastern Oregon for winter wheat–green pea rotation is FP, which leaves little or no surface residue to prevent soil erosion or curb evaporation. Conservation tillage, where minimum tillage or NT is practiced, leaving about one-third of the soil covered with residues after planting, is being adopted worldwide. Crop residues left on the surface reduce soil water evaporation (Schillinger and Bolton, 1993; Hatfield et al., 2001), increase water infiltration (Logsdon et al., 1990; Hatfield et al., 2001; Franzluebbers, 2004), increase soil water storage (Ramig et al., 1983; Bolton and Glen, 1983; Bonfil et al., 1999; Halvorson et al., 1999) and reduce soil erosion (Allmaras et al., 1973; Ramig and Ekin, 1987).

Conservation tillage can include NT, strip-till, ridge-till, and mulch-till. Even under conventional tillage, delaying cultivation until spring may be considered a temporary conservation measure; standing stubble protects the soil from erosion during winter. Furthermore, standing residue has been shown to trap snow, enhance water infiltration, and increase soil water storage (Aase and Siddoway, 1990). Clearly, PNW wheat–pea cropping rotations can benefit from conservation tillage systems. To evaluate the potential success of these practices, an understanding of how conservation tillage practices influence water storage, crop water use, pests, and yield of wheat and pea is required. Pikul et al. (1993) and Payne et al. (2000, 2001) have reported on different aspects of a wheat–pea experiment specific to inland PNW which is the subject of this paper. Pikul et al. (1993) reported on tillage effects on soil properties and found that there were no significant differences in saturated hydraulic conductivity between tilled and non-tilled layers but the paper does not report on water storage and crop water use. Payne et al. (2000) predicted yield response to precipitation and heat stress but also did not report on measured soil moisture and crop water use. In related work, Payne et al. (2001) modeled yield response using crop evapotranspiration (ET) as one of the variables in the model. The paper, however, does not attempt to explain the differences in ET among tillage treatments. In Canada, Lafond et al. (2006) reported an increase in yield for field pea (7%), flax (12.5%), and spring wheat (7.4%) grown under conservation tillage on cereal stubble compared to conven-

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Published in Agron. J. 100:154–162 (2008).
doi:10.2134/agronj2006.0218

Abbreviations: ET, evapotranspiration; FP, fall plow; MinT, minimum tillage; MT, maximum tillage; NT, no-till; SP, spring plow; WUE, water use efficiency.

tional tillage in a summer rainfall region. The increase was due to an increase in soil water in the 0 to 30 cm soil layer. Cutforth et al. (2002) also reported an increase in the WUE of field pea when seeded in stubble in the Canadian prairies. There is little information on tillage effects on water storage, crop water use, and WUE in wheat–pea rotations in the inland PNW, a winter rainfall region. This information is crucial to understanding the underlying processes and formulating sound agronomic decisions. The objective of this study was to quantify the effects of different tillage methods and timing of tillage operations on soil water storage, WUE, and grain yield of winter wheat and green pea in rotation.

MATERIALS AND METHODS

Data discussed in this paper were obtained from a long-term experiment with a winter wheat–spring green pea 2-yr rotation at the Columbia Basin Agricultural Research Center (CBARC), Pendleton, OR (45.7° N, 118.6° W, elevation 438 m). The soil at CBARC is a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll). The CBARC receives 70% of its precipitation during the winter months (September–February). Average crop-year (1 September–31 August) precipitation is about 406 mm. The ongoing wheat–pea rotation experiment was established in the spring of 1962. Each plot was 7.3 m wide and 37 m long. All plots were spring-plowed in 1962 and tillage regimes first applied in the 1963–64 crop-year. The tillage treatments have been modified over time. This study reports on and discusses data for seven crop-years from 1976–1977 to 1981–1982 and in 1984–85, when soil moisture was monitored and treatments did not change. Results on tillage effects on soil water storage, crop water use, and WUE during this period were not published and are still relevant to the current winter wheat and green pea growers. Green pea refers to immature spring pea harvested for freezing and canning. The treatments for that period were (i) fall plow (FP)–moldboard plow after wheat and after pea (control), (ii) maximum tillage (MT)–fall roto-till after wheat and fall sweep after pea, (iii) spring plow (SP)–spring moldboard plow after wheat and fall moldboard plow after pea, and (4) minimum tillage (MinT)–NT after wheat and fall sweep after pea. Details of the treatments follow.

Treatment 1: Fall Plow

After harvesting wheat, plots were moldboard-plowed in the fall to a depth of 15 to 18 cm. This treatment was designed to explore the effect of increased surface roughness during winter on water storage. In early spring, plots were sprayed with glyphosate (N-(phosphonomethyl)glycine) at rates ranging from 314 to 628 g acid equivalent (a.e.) ha^{-1}. Before seeding pea, plots were cultivated one to three times to a depth of approximatley 10 cm with a spring-tooth cultivator (John Deere CC, John Deere, Moline, IL). The plots were roller-packed using a Dunham Culti-packer (Dunham Co., Dunham, OH) after planting pea. Before seeding wheat, plots were moldboard-plowed in the summer after pea harvest followed by secondary tillage using a spring-tooth cultivator to a depth of approximately 10 cm. Glyphosate was applied as needed to control weeds. This is the standard tillage regime in eastern Oregon for winter wheat–green pea rotation and the control for this experiment.

Treatment 2: Maximum Tillage

Following wheat harvest, plots were roto-tilled in the fall to a depth of 12 to15 cm to break up wheat stubble. In the spring, plots were sprayed with glyphosate, or glyphosphate + 2,4-D (2,4-dichlorophenoxyacetic acid), cultivated with a 2.4 m V-shaped Noble (Noble Farms Ltd., Nobleford, AB, Canada) sweep to a depth of 8 cm and rod-weeded to a depth of about 4 cm when necessary before pea was sown in March or early April. The 2,4-D rates ranged from 426 to 750 g a.e. ha^{-1}. Plots were roller-packed after sowing pea. Soon after pea harvest in July, plots were cultivated with a sweep to stop pea vine growth and water use and to stop weed growth and weed seed production. In the fall, before seeding wheat, plots were chisel plowed (or deep ripped) to a depth of 30 to 38 cm to break the soil pan created by roto-tilling, and then rod-weeded. The purpose of this treatment was to explore the effect of increased surface roughness during the winter period on water storage

Treatment 3: Spring Plow

This treatment was identical to FP before sowing wheat and will be abbreviated as SP(FP) when discussing the wheat phase. After wheat harvest, stubble was left standing and weeds were controlled during winter and early spring with herbicides that included paraquat dichloride (1,1′-dimethyl-4,4′-bipyridinium dichloride) and glyphosate. Paraquat dichloride rates ranged from 560 to 1120 g a.e. ha^{-1}. Immediately before seeding pea in the spring, the plots were moldboard plowed to a depth of 15 to 18 cm and roller-harrowed. Plots were roller-packed after seeding pea. This treatment was introduced to maintain crop residue surface cover over winter during the pea phase to minimize or stop soil erosion.

Treatment 4: Minimum Tillage

The MinT was an attempt to increase surface residue levels. Only surface tillage was used in this system to manage residue to facilitate sowing. Before sowing pea, wheat stubble was finely mowed to a short height and the plot cultivated repeatedly with a Dunham skewtreader (Dunham Co., Dunham, OH) to a depth of about 3 to 4 cm in the fall. A skewtreader is an implement with tined wheels on two ganged shafts angled like a section of a tandem disk. This cultivation was done to break and uniformly distribute wheat residue to improve drill performance during pea seeding. Herbicides (paraquat dichloride or glyphosate) were used to control weeds during winter. No mowing or skewtreading occurred before sowing wheat into pea stubble; herbicides (paraquat dichloride or glyphosate) were used to control weeds. A sweep at a depth of 8 cm was used soon after pea harvest to control post-harvest weeds, stop pea vine growth and water use, and to loosen surface soil compacted by repeated skew-treading in preparation for the pea phase.

Table 1. Analysis of variance (ANOVA) table for change in soil water storage, soil water depletion, grain yields, and water use efficiency under the wheat and pea phases of a wheat–pea rotation, 1977 to 1982 and 1985, Columbia Basin Agricultural Research Center (CBARC), Pendleton, OR.

	P < *F*	
Treatment	**Winter wheat**	**Green pea**
	Water storage	
Tillage	**	**
Year	†	†
Year × tillage	ns‡	*
	Water depletion	
Tillage	ns	ns
Year	†	†
Year × tillage	ns	ns
	Grain yield	
Treatment		
Tillage	**	ns
Year	†	†
Year × tillage	ns	***
	Water use efficiency	
Tillage	ns	ns
Year	†	†
Year × tillage	ns	*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Significant at the 0.0001 probability level.
‡ ns = nonsignificant.

Crop Management

When discussing crop-year, the year the crop was harvested will be quoted from this point forward. For instance, crop-year 1977 refers to the cropping season that started in the fall of 1976 and ended in the summer of 1977. For crop-year 1977 through 1985, all wheat plots were seeded in the fall (September or October) using a JD (John Deere) HZ split packer hoe drill (John Deere, Moline, IL) on 36-cm spacing and harvested between June and July. For crop-years 1977 through 1981, 1983, and 1984 all pea plots were seeded using a JD LZA hoe type drill on 18-cm spacing and harvested in June. In 1985 all pea plots were seeded with a JD 8300 double disc type drill on 17-cm spacing. In 1982 tilled pea treatments were seeded with a JD LZA hoe type drill on 18-cm spacing and MinT pea treatments were seeded with a JD VB double disc type drill on 18-cm spacing. Pea was seeded in March or early April.

Target sowing rates were 200 seeds m^{-2} for winter wheat and 75 seeds m^{-2} for pea cultivars. 'Hyslop' winter wheat was sown in crop-years 1977 and 1978. 'Stephens' winter wheat was sown in crop-years 1979 through 1985. 'Dark Skin Perfection' pea was seeded in all crop years except 1982 and 1983 when 'Perfected Freezer' pea was sown. The pea was not inoculated with Rhizobium.

Ammonium nitrate (NH_4NO_3), 34–0–0 (N–P–K), was broadcast on winter wheat plots before final tillage or seeding at a rate ranging from 45 to 93 kg N ha^{-1} based on soil tests. Pea was not fertilized in 1980 and 1982. In the other 5 yr, ammonium sulfate ($(NH_4)_2SO_4$), 21–0–0–24 (N–P–K–S) was broadcast at a rate of 22 to 25 kg N ha^{-1} before final tillage or seeding.

Soil Water Measurements

One access tube was installed in each plot and soil volumetric water content measurements, at 30.5 cm intervals to a depth of 2.44 m, were obtained using neutron attenuation. Details of the process were described by Payne et al. (2001). For wheat, soil moisture was measured at the start of wheat growth in early March following winter dormancy and at wheat harvest in July. For pea, soil moisture was measured at pea planting in early April and at pea harvest in late June. For both crops, the change in soil water storage over the winter was the difference in soil water amount, expressed as water depth, in the 0 to 2.44 m layer, measured between harvest and the first spring reading in the following year. Storage efficiency is change in soil water storage from harvest to the first spring soil water reading expressed as a percentage of precipitation for the same period. For both crops, soil water depletion is the difference between the first spring soil water content measurement and the soil water content measured after harvest. Growing season precipitation is precipitation received from the start of active growth to harvest for wheat and from seeding to harvest for peas. In the PNW, significant plant growth and transpiration occur from March to July for wheat and early April to June for pea. Growing season evapotranspiration, defined here as evapotranspiration during the period of active growth, is the sum of growing season precipitation and soil water depleted (Deibert et al., 1986; Norwood, 1999; Chen et al., 2003). Based on estimated internal soil drainage values for the long-term experiments at CBARC (Payne, 1998; Payne et al., 2001), soil drainage below the crop rooting depth was assumed to be negligible. Runoff and erosion were also assumed to be negligible because the experiment is located on fairly level ground (<2% slope). The WUE was determined using the following equation:

$$\mathrm{WUE} = \frac{\mathrm{GY}}{\mathrm{GSET}} \qquad [1]$$

where GY is grain yield (kg ha^{-1}) and GSET (mm) is growing season evapotranspiration.

Grain Yield

Wheat was harvested with plot combines. Harvested widths ranged from 1.5 to 2.5 m (depending on combine used); the length of the harvested area was 37 m. Grain was cleaned using a screen air cleaner, weighed, and reported on a dry weight basis. Green pea, at a tendrometer reading of about 98, was swathed using a locally designed draper swather with a 3.7-m wide platform. During the study period (1977–1985), vines from each plot were hauled to a central stationary thresher where green peas were removed from vines, cleaned of debris, weighed, and reported on a fresh weight basis. The vines were not returned to plots.

Data Analysis

The experimental design was a split plot in a randomized complete block arrangement with four replications. Crops (winter wheat or green pea) were assigned to main plots and tillage treatments were assigned to subplots. Each replication contained eight plots (four tillage treatments for each of the two crops in rotation). Each phase of the rotation was present every year to ensure yearly data collection for both wheat and pea. Since experiments were conducted for each plot from 1977 to 1982, and 1985, the data from each plot can be correlated over time. To that end we analyzed data using PROC MIXED procedures with repeated measures for year in conjunction with Auto-Regressive time series modeling procedures (Littell et al., 1996; Lindsey, 1999). Data on water storage, water depletion, WUE, and yield were analyzed separately for each crop. Results obtained in 1983 and 1984 were omitted because of incomplete soil water data.

RESULTS

Tillage Effects on Over-Winter Soil Water Storage

The change in stored water in the 0 to 2.44 m soil profile during the pea phase for FP, MT, SP, and MinT averaged 15, 29, 47, and 61%, respectively, more than the same treatments during the wheat phase (Fig. 1a, 1b).

During the wheat phase, there were no significant tillage by year interactions on change in water storage. However, there were significant year and tillage main effects on water storage (Table 1). Water storage was influenced by the amount of winter precipitation and was generally higher in years that had high winter precipitation ($r = 0.77$, $P < 0.0001$). On average, all fall-cultivated treatments [FP, MT, and SP(FP)] stored significantly more winter precipitation than the MinT treatment (Table 2). The water storage efficiency was 44, 40, 38, and 34%, for FP, MT, SP(FP), and MinT, respectively. Soil water profile data indicated that on average MinT stored the most water in the 0 to 30 cm zone and this was significantly so when compared to MT (Fig. 1a). Below this zone, MinT stored the least amount of water and this was significantly so in the 30 to150 cm zone. The FP stored less water than SP(FP) and MinT in the 0 to 30 cm zone but stored the highest in the 30 to 150 cm zone. The SP(FP) stored slightly more water than MT in the 0 to 30 cm zone but stored similar amounts of water to MT below this zone.

During the pea phase, there was a significant interaction between tillage and year on the amount of water stored in the 0 to 2.44 m profile (Table 1). In 1977, the driest year of the period under study, SP and MinT treatments, with wheat stubble during winter, on average stored about 100 and 42% more water than FP and MT, respectively (Table 3). In that year, SP and MinT achieved storage efficiencies of 50 and 47% compared with 34 and 24% under MT and FP, respectively. In years when winter precipitation was high, differences in water stored and storage efficiency were minimized or eliminated. During the pea phase, water storage efficiency was 50, 53, 59, and 57%, for FP, MT, SP(FP), and MinT, respectively. The total amount of water stored in the whole profile (0–2.44 m zone) was significantly higher under MinT and SP than under MT and FP (Table 3). However, the change in stored water at each depth under MinT and SP, although consistently larger than other treatments, was not significant (Fig. 1b).

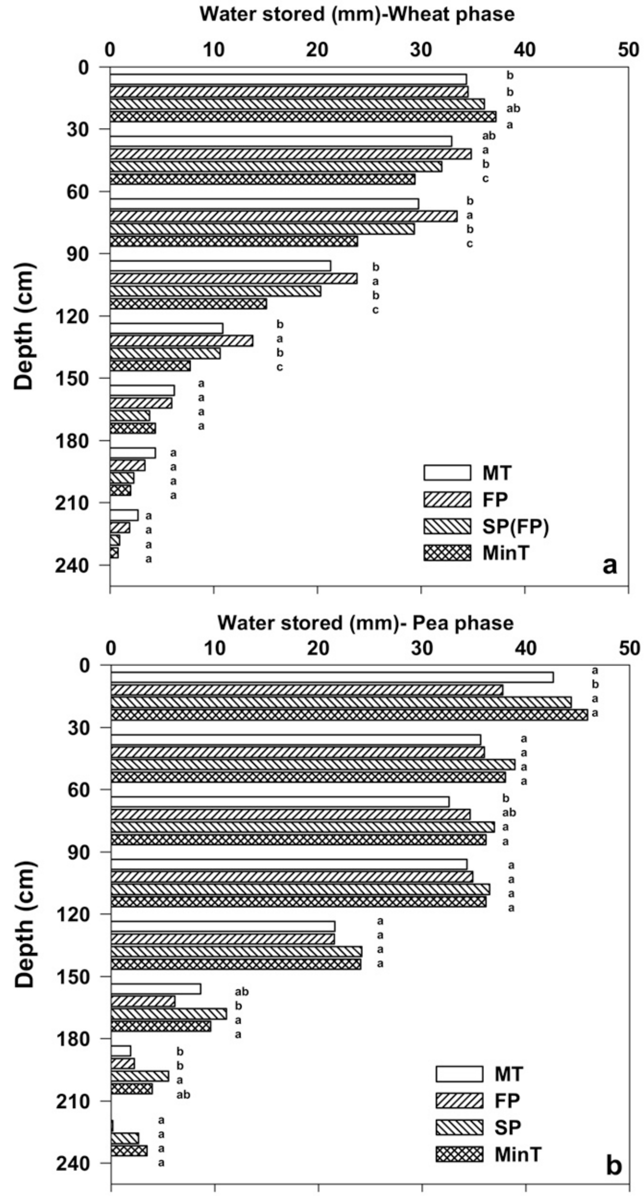

Fig. 1. Maximum tillage (MT), fall plow (FP), spring plow (SP), and minimum tillage (MinT) effects on soil profile water storage distribution (mm 305 mm^{-1}) during (a) winter wheat phase (pea harvest to first spring moisture reading) and (b) green pea phase (wheat harvest to first spring moisture reading) at Columbia Basin Agricultural Research Center (CBARC), Pendleton, OR. Means (at each depth zone) with the same letter are not significantly different at the 0.05 probability level.

Tillage Effects on Water Depletion

There were no significant tillage by year interactions on the amount of water depleted during both wheat and pea phases (Table 1). Overall tillage had no significant effect on soil water depletion during both wheat and pea phases except in 1977 (Tables 2 and 3). In that year, water depletion during both the wheat and pea phases was lowest under FP treatments (Tables 2 and 3). There were, however, significant year effects on water depleted. In general, there was more water depleted in years where crop-year precipitation was high; 1980 and 1985 were exceptions for wheat and pea, respectively. The reason

Table 2. Tillage effects on change in soil water storage [harvest (June or July) to March], soil water depletion [March to harvest (June or July)], and water use efficiency under winter wheat in rotation with green pea, 1977–1982 and 1985, Columbia Basin Agricultural Research Center (CBARC), Pendleton, OR.

Tillage†	1977	1978	1979	1980	1981	1982	1985	Mean
	mm 305 mm^{-1} soil depth							
Water storage								
MT	41.47a‡	183.13a	150.43a	134.11a	191.71a	141.22b	125.22a	138.19ab
FP	59.06a	186.82a	161.29a	128.84a	171.56ab	199.52a	140.40a	149.50a
SP(FP)	36.32a	169.54a	137.73a	131.44a	188.92a	154.50b	108.84a	132.47b
MinT	36.41a	160.02a	128.02a	117.86a	143.70b	158.24b	93.54a	119.68c
Water depletion‡								
MT	174.63a	151.77a	218.32a	193.29a	228.03a	210.00a	193.55a	195.65a
FP	129.22b	159.89a	225.17a	170.56a	219.96a	242.38a	219.90a	195.30a
SP(FP)	130.30b	164.40a	215.90a	189.50a	216.41a	211.71a	197.87a	189.48a
MinT	169.74ab	148.91a	192.47a	190.38a	210.88a	239.33a	200.72a	193.20a
	kg ha^{-1} mm^{-1} soil depth							
Water use efficiency‡								
MT	8.06b	17.86a	8.02a	15.91a	18.48a	15.47a	11.28a	13.58a
FP	9.95ab	18.25ab	7.71a	15.43a	18.39a	13.71a	10.25a	13.38ab
SP(FP)	10.44a	16.87a	7.35a	15.85a	18.29a	14.13a	11.39a	13.52a
MinT	9.30ab	15.40b	7.16a	14.40a	18.23a	12.88b	10.78a	12.59b

† MT, maximum tillage; FP, fall plow; SP, spring plow during pea phase; SP(FP), fall plow during wheat phase; MinT, minimum tillage.

‡ Means within column groupings with similar letters are not significantly different from each other at the 0.05 probability level.

Table 3. Tillage effects on change in soil water storage [harvest (June or July) to March], soil water depletion [March to harvest (June or July)], and water use efficiency under green pea in rotation with winter wheat, 1977 to 1982 and 1985, Columbia Basin Agricultural Research Center (CBARC), Pendleton, OR. Water storage and extraction data are shown as mm per 305 mm soil depth.

Tillage†	1977	1978	1979	1980	1981	1982	1985	Mean
	mm							
Water storage								
MT	67.48ab‡	214.44a	182.82a	209.81b	187.07ab	225.93a	162.75a	178.61b
FP	47.67b	190.82a	209.99a	224.22ab	162.18b	193.29b	175.13a	171.90b
SP	98.89a	211.14a	207.39a	245.75a	214.76a	211.20ab	170.18a	194.19a
MinT	93.39a	197.04a	209.87a	211.77b	207.20a	241.24a	185.61a	192.30a
Water depletion								
MT	91.38ab	107.76a	130.62a	144.78a	132.33a	119.95a	111.69a	119.79a
FP	83.76b	104.71a	154.37a	121.22a	154.24a	124.02a	114.62a	122.42a
SP	139.38a	118.04a	139.13a	141.79a	151.38a	111.44a	105.86a	129.58a
MinT	86.93ab	92.71a	145.29a	133.29a	150.11a	129.67a	108.71a	120.96a
	kg ha^{-1} mm^{-1}							
Water use efficiency								
MT	5.88a	16.80a	16.10a	13.52b	16.83a	9.87a	12.32ab	13.04a
FP	5.63a	18.22a	14.77ab	18.85a	14.52a	11.05a	11.28ab	13.47a
SP	7.00a	15.07a	13.99ab	15.48ab	15.85a	7.86ab	13.67a	12.70a
MinT	8.32a	15.09a	11.74b	16.43ab	17.16a	6.49b	10.09b	12.19a

† MT, maximum tillage; FP, fall plow; SP, spring plow during pea phase; SP(FP), fall plow during wheat phase; MinT, minimum tillage.

‡ Means within column groupings with similar letters are not significantly different from each other at the 0.05 probability level.

why water depletion was low in these years was not apparent. In 1980, wheat had excellent stands but there was heavy downy brome (*Bromus tectorum* L.) infestation in MinT plots. In 1985, frost damaged the fifth to seventh nodes in pea and prevented the spraying of weeds. On average, wheat under FP, MT, SP(FP), and MinT used 60, 63, 46, and 60%, respectively, more water than pea under the same treatments. Wheat used all of the stored water and an additional 31, 41, 43, and 61% more water than stored water under FP, MT, SP(FP) and MinT, respectively. On the other hand, pea used about 71, 67, 67, and 60% of stored water under FP, MT, SP(FP), and MinT, respectively.

Tillage Effects on Grain Yield

Tillage and year significantly influenced wheat grain yield but there were no significant tillage and year interactions (Table 1). On average, wheat grain yields were significantly higher in all the fall tillage treatments [MT, FP, and SP(FP)] than in MinT (Fig. 2). However there were no significant differences in grain yield among the fall tillage treatments. The MinT yields were 94% of the average yield for other treatments and were lowest in 6 of 7 yr. In three of the study years, there was heavy downy brome infestation in MinT plots compared with other treatments. Grain yield of wheat generally followed trends in precipitation and was high when crop-year precipitation was high (Fig. 2). Wheat grain yields were highly correlated to both winter precipitation (r = 0.77, $P < 0.0001$) and growing season precipitation (r = 0.85, $P < 0.0001$). Wheat grain yields were lowest in 1977, the driest year, and highest in 1981, the wettest year (Fig. 2). There were some stand establishment problems in 1979 that resulted in heavy downy brome infestation and low yields when compared with 1985, which had comparable precipitation.

There was a significant tillage and year interaction for green pea yield (Table 1). Green pea yield was influenced by precipitation, particularly growing season precipitation (r = 0.87, $P < 0.0001$). Compared to wheat, winter precipitation

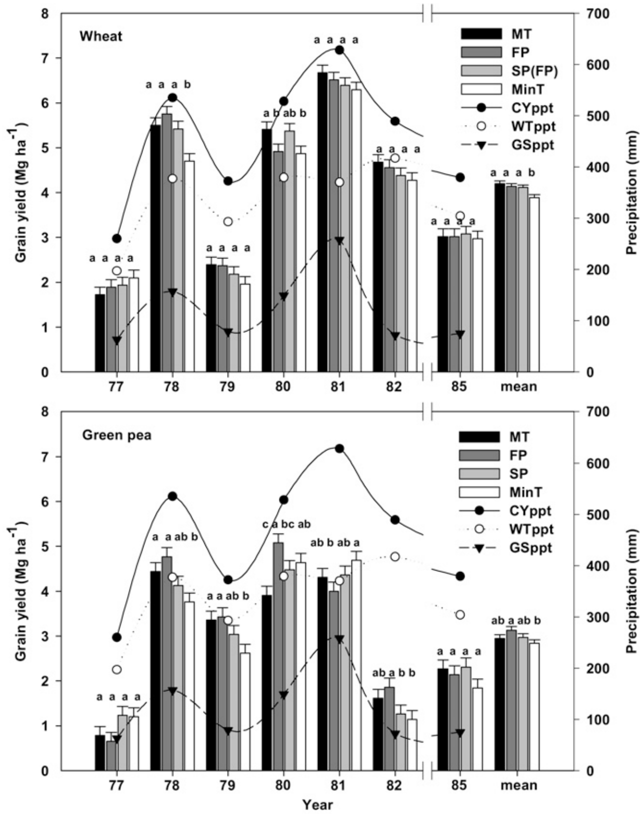

Fig. 2. Maximum tillage (MT), fall plow (FP), spring plow (SP) (FP for wheat), and minimum tillage (MinT) effects on grain yield of winter wheat and green pea in rotation at Columbia Basin Agricultural Research Center (CBARC), Pendleton, OR from 1977 to 1982 and 1985. The graphs also show crop-year precipitation (CYppt) (1 September–31 August), winter precipitation (WTppt) (1 September–28 February), and growing season precipitation (GSppt) (1 March–31 August). Means (within each year) with the same letter are not significantly different at the 0.05 probability level.

had less influence on pea yields (r = 0.53, P < 0.0001). Pea yields in all treatments were low in 1977, 1982, and 1985 (Fig. 2). Both winter and growing season precipitation were lowest in 1977. Low pea yields in 1982 were partly attributed to pea leaf weevil (*Sitona lineate*) infestation and partly to low growing season precipitation (Fig. 2). In this year, both SP and MinT treatments produced the lowest pea yields. In 1985, pea yields were low due both to low winter and growing season precipitation and to frost that damaged the fifth, sixth, and seventh nodes. The frost damage prevented weed spraying, resulting in heavy lambsquarters (*Chenopodium berlandieri* Moq.) infestation. High pea yields were recorded from 1978 to 1981. Pea yields were slightly lower in 1979 due both to low winter and growing season precipitation and to heavy Russian thistle (*Salsola iberica* Sennen) and lambsquarters infestation. The FP and the MT treatments produced significantly higher yield than the SP and MinT in 1978 and 1979. The lowest and highest yield was obtained under MT and FP, respectively, in 1980. In 1981, when the highest precipitation was received, the highest and lowest yield was obtained under MinT and FP, respectively. On average, the highest yield was obtained under FP although the yield was not significantly different from yields obtained under MT and SP treatments. MinT produced the lowest average yield

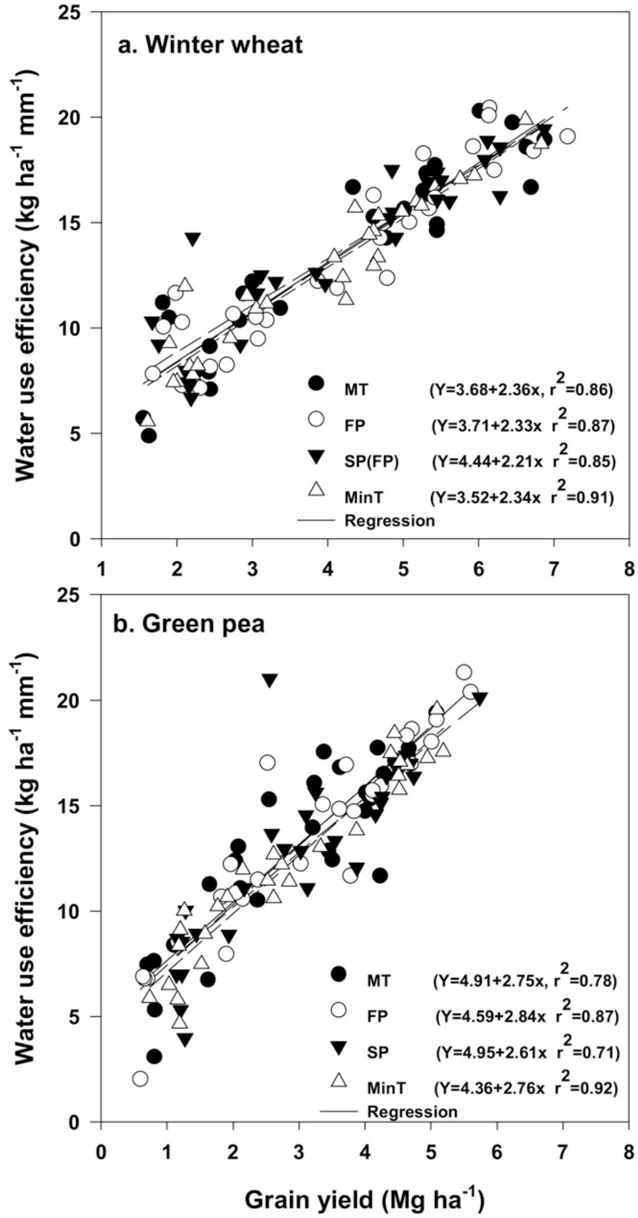

Fig. 3. Maximum tillage (MT), fall plow (FP), spring plow (SP), and minimum tillage (MinT) effects on grain yield and water use efficiency of (a) winter wheat and (b) green pea in rotation at Columbia Basin Agricultural Research Center (CBARC), Pendleton, OR. Data shown are 7-yr means (1977–1982 and 1985).

although this was not significantly different from the yield of MT and the SP treatments.

Tillage Effects on Water Use Efficiency

Overall there were no significant tillage effects and tillage by year interactions on WUE during the wheat phase (P = 0.09). However, a closer examination of the means indicated that WUE in MT and SP(FP) was higher (P < 0.05) than WUE in MinT (Table 2). There were significant year effects on WUE. The WUE was highest in 1981 when grain yield was highest and lowest in 1979 when yield was low (Table 2). The WUE was highly correlated with wheat grain yield under all tillage treatments (Fig. 3a). The correlation was highest under MinT.

There were significant tillage by year interactions on WUE during the pea phase (Table 1). Tillage had no significant effect on WUE in either 1977, the driest year of the study period or in 1978, a year with twice as much precipitation as 1977 (Table 3). In other years with high precipitation, tillage effects were not consistent. On average, there were no significant differences in WUE among tillage treatments (Table 3). The WUE was highly correlated with green pea yield (Fig. 3b). As during the wheat phase, the correlation was highest under MinT during the green pea phase.

The WUE of wheat and pea was remarkably similar (Fig. 4). The WUE was highly correlated with overall wheat and green pea yields (Fig. 4). Payne et al. (2001) found similar results. The regression line for green pea is above the regression line of wheat indicating that green pea had a higher WUE than wheat. This was probably so because the pea was harvested in an immature state (fresh or green) and used less water than wheat. On average, however, WUE of wheat and green pea was 13.27 and 12.85 kg ha^{-1} mm^{-1}, respectively. The average WUE of pea was lower than that of wheat because of the wide spread of pea WUE values that included the lowest and highest values (Fig. 4).

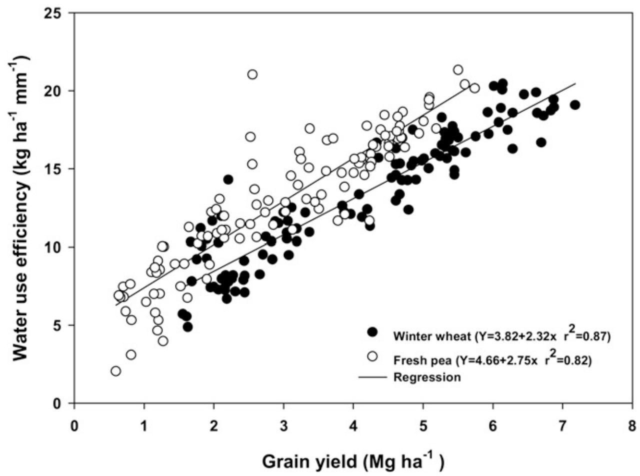

Fig. 4. Grain yield and water use efficiency of winter wheat and green pea in rotation at Columbia Basin Agricultural Research Center (CBARC), Pendleton, OR. Data shown are 7-yr means (1977–1982 and 1985).

DISCUSSION

Under dryland conditions, the primary challenge is to develop cropping systems that increase WUE and grain yield and protect the soil resource from degradation. Grain yield of both wheat and pea was highly and positively correlated with WUE (Fig. 3, 4) signifying that improvements in grain yield will increase WUE. The WUE values obtained in this study were similar to values determined by Rasmussen (1988) at a nearby location and by Payne et al. (2001). In our study, WUE was influenced by grain yield, soil water depletion, and growing season precipitation (Eq. [1]). Agronomic practices that can change the value of these variables can change the value of WUE. Among these variables, growing season precipitation cannot be manipulated but its storage and use can. Soil water depletion, a component of growing season evapotranspiration, was not different among tillage treatments except in 1977. This implied that evapotranspiration was more or less similar among the tillage treatments for both wheat and pea during all other study years. It is, however, not possible to estimate how much of the water depleted was lost through soil evaporation and through the plant (transpiration) using our data. Consequently, we were unable to determine how different tillage treatments influenced soil water evaporation and transpiration. However, tillage treatments that reduce soil evaporation and increase transpiration will likely increase grain yield and WUE. De Wit (1958) showed that there was a strong and positive correlation between transpiration and crop productivity. Furthermore, growing conditions that are favorable for plant growth will likely increase grain yield and, therefore, WUE.

One way to increase transpiration and reduce soil water evaporation is to increase soil surface cover. Crop residues, left on the surface, not only reduce evaporation but also increase water infiltration and storage (Unger et al., 1988; Schillinger and Bolton, 1993; Hatfield et al., 2001; Nielsen et al., 2005). In our study, MinT stored the least amount of water during the wheat phase. Soil water loss through evaporation, reduced infiltration, and water depletion by downy brome probably reduced the amount of water stored under MinT. Removal of pea vines during harvest left about 1% surface residue cover under MinT (Payne et al., 2001) that was not sufficient to curb soil water evaporation, particularly in July and August when evaporative demand was highest. Furthermore, sweeping of MinT plots after pea harvest may have created a pan at the 8-cm depth zone that reduced water infiltration. Data on soil profile water storage distribution (Fig. 2) supports this conclusion. Higher water storage in the 0 to 30 cm zone under MinT could not be attributed to mulching effect because of very low residue cover after pea harvest. Reduced water infiltration probably resulted in the accumulation of water in the top soil and less water in the 30 to 210-cm zone. Water in the 0 to 30 cm zone was probably prone to evaporation because of lack of surface residue cover under MinT. The MT treatment was also cultivated with a sweep after harvesting green pea but was chisel plowed or ripped in the fall before seeding wheat, possibly fracturing the pan created by sweeping and increasing water infiltration and storage under this treatment. Similar studies have shown that sweeping created a pan (Rasmussen and Smiley, 1994; Pikul and Aase, 2003; Gollany et al., 2005) that reduced water infiltration (Rasmussen and Smiley, 1994). Higher wheat yields were obtained under FP which stored the most water. Rasmussen and Smiley (1994) also showed that the moldboard plow treatment had higher infiltration rates than the sweep and disc treatments in a nearby long-term tillage experiment conducted on a Walla Walla silt loam. During the wheat growing season, heavy downy brome infestations under MinT presumably increased competition for water thereby decreasing the amount of water available for wheat transpiration and productivity under this treatment. Deibert et al. (1986) also showed that no-till grain yields were reduced in some years by weed competition. A combination of low residue cover, reduced water infiltration caused by sweeping after green pea harvest, and weed competition led to reduced grain yield and WUE under MinT during the wheat phase.

In contrast to the wheat phase, plots under SP and MinT stored more water than other tillage treatments during the pea phase. Wheat stubble in plots under MinT was mowed down to provide between 80 and 100% soil cover (Payne et al., 2001; Karl Rhinhart, unpublished data, 2005). Large amounts of surface residues form mulch that has been shown to increase water infiltration and reduce evaporation, resulting in increased soil water storage (Greb, 1966; Ramig et al., 1983; Schillinger and Bolton, 1993; Bonfil et al., 1999; Halvorson et al., 1999; Hatfield et al., 2001, Lafond et al., 2006). The mulching effect was clearly manifested in 1977, the driest year. In this year, nearly double the amount of soil water was stored under SP and MinT treatments compared to MT and FP treatments. However, yield was not significantly higher than other treatments during this year or during wet years and on average, MinT produced the lowest yield. Low WUE under MinT during the pea phase was attributable to low yields. Compared to dry pea, green pea is harvested in an immature state and requires less water. Therefore, during wet years, the additional water stored under MinT made little or no difference in yield. In wet years other factors, such as weed infestation and growing conditions associated with heavy surface residue cover, strongly influenced yield. Broadleaf weeds were problematic in all treatments and likely reduced yields uniformly across all treatments. Wet soils coupled with thick residue cover under conservation tillage conditions that include MinT have been shown to lower soil temperatures. Cold and wet soils particularly in early spring have been shown to slow down plant growth and development under no-tillage (Allmaras et al., 1973; Ramig et al., 1983; Schillinger and Bolton, 1993; Reicosky et al., 1995; Vyn et al., 1998). Early slow growth may result in smaller plants that may not compete well for light and water under increased weed pressure in years with normal and above-normal precipitation. Although lowest, MinT yield was not significantly different from MT and SP yields. The FP produced the highest yield because moldboard plowing and secondary cultivations prepared a clean (<5% residue cover) seedbed with good tilth that was favorable for rapid pea emergence and growth.

During the wheat phase, WUE in MT and SP(FP) was significantly higher than WUE in MinT largely because of lower yields under MinT. High correlation between grain yield and WUE under MinT indicates that practices or conditions that can improve yield in MinT will increase WUE. Results showed that MinT (after pea harvest during the wheat phase) had low surface residues and stored less water than other treatments. The role of sweeping soil immediately after pea harvest should be re-examined to determine whether weed control effects outweigh the reduction in the amount of water stored. Sweeping in the absence of surface residues appeared to reduce the amount of water stored in the soil profile and should be abandoned. Better weed control using herbicides is needed to reduce the weed problem under MinT during both the wheat and pea phases of the rotation. This would certainly improve yield and WUE under this treatment. Furthermore, the use of crop cultivars that are adapted to high residue conditions under MinT should be evaluated.

CONCLUSIONS

Our results showed that tillage practices and timing of tillage operations affected water storage, water use, and yield of winter wheat and green pea in rotation. However, in absolute terms, differences for grain yield and soil water among tillage practices were small. The choice of tillage practice for a wheat–pea rotation should therefore be based on the interaction of factors that increase WUE and yield. In this study, many factors influenced water use. For example, crop residues increased water storage under MinT during the pea phase. Removal of green pea vines for threshing left the soil exposed and prone to water evaporation. Pea vines should be left on the soil surface to increase surface cover. Sweeping the soil under low residue conditions hindered water storage under MinT probably by reducing the rate of water infiltration and increasing evaporation. Leaving wheat stubble over-winter, as in SP and MinT treatments during the pea phase, increased soil water storage. However, storing the most water without adequate weed control did not guarantee high yields as was the case with MinT during the pea phase. Adequate weed control under MinT should improve yields in this treatment. Conservation attributes of MinT makes this treatment attractive. Under limited water conditions, as in eastern Oregon, any improvement in agronomic practices that increase yield will ultimately increase WUE.

ACKNOWLEDGMENTS

The authors acknowledge Susan Sisson for compiling the soil water data and Robert Ramig and Les Ekin for their stewardship of this trial for many years.

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