Tillage Depth and Timing Effects on Soil Water Profiles in Two Semiarid Soils

Stewart B. Wuest*
USDA-ARS
P.O. Box 370
Pendleton, OR 97801

A 2-yr winter wheat (*Triticum aestivum* L.)–fallow rotation continues to be the most common cropping system in much of the U.S. Pacific Northwest. The sustainability of soils in the region depends on our ability to halt or greatly reduce wind and water erosion. An incomplete understanding of how tilled summer fallow preserves seed-zone moisture for timely fall crop establishment has slowed efforts to optimize tillage techniques for creating profitable and erosion-resistant systems. This 2-yr study created a series of soil mulches at two sites representing major soils in the region. It was found that timing and depth of mulch creation had consistent effects at all four site-years. Tillage performed in mid-June to depths of 10 and 15 cm preserved up to 0.01 kg kg^{-1} greater water content than no or 5-cm tillage, an amount of water that can make substantial differences in the germination of winter wheat. The later or shallower tillage treatments produced water contents similar to zero tillage below the 15-cm depth. Temperature profiles at 1-cm resolution demonstrated different shapes under different mulch treatments, which may prove useful in making quick mulch performance comparisons in the field. To optimize the timing and depth of summer fallow tillage, it will be necessary to characterize spring water storage plus the potential for end-of-summer water storage for each soil type.

In some areas of the world, a Mediterranean climate pattern and fertile soils create highly productive environments for rain-fed winter wheat. Mild, wet winters allow growth of cool-season cereals before the onset of warm, dry summers ideal for filling grain on stored soil moisture plus spring rainfall in a relatively pest-free environment (Cantero-Martinez et al. 2007). This is true of the inland U.S. Pacific Northwest, where winter wheat has been the dominant crop in dryland production areas for more than a century (Schillinger and Papendick, 2008). More than half of the region receives <450 mm of precipitation annually, most of which falls during the cool to cold winters.

To produce maximum yields, winter wheat must be planted early enough in the fall to develop an adequate root system before the onset of winter (Russelle and Bolton, 1980). Wheat planted too late in the fall yields up to 30% less than wheat emerging earlier (Donaldson et al., 2001). Spring-planted wheat typically produces yields that are half that of winter wheat because it germinates, develops, and fills grain during a time of rapidly increasing evapotranspiration and temperature.

Because fall rains are often sparse and unpredictable, tilled summer fallow is used to maintain moisture in the seed zone during the hot, dry summer. This seed-zone moisture allows deep planting of winter wheat after 90 or more days with maximum soil surface temperatures above 40°C, relative humidity below 40%, and little or no precipitation (Schillinger and Papendick, 2008). Planting wheat following 14 mo of fallow also provides stored soil moisture for fall and early winter growth. This stored soil moisture is vital for stabilizing yields and reducing risk, and has allowed profitable wheat production in some areas with annual rainfall as low as 150 mm yr^{-1} (Schillinger and Young, 2004).

Soil Sci. Soc. Am. J. 74:1701–1711
Published online 2 Aug. 2010
doi:10.2136/sssaj2010.0046
Received 25 Jan. 2010.
*Corresponding author (Stewart.Wuest@ars.usda.gov).

A major challenge to the sustainability of winter wheat–summer fallow production practices in the Pacific Northwest is soil erosion by wind and water. Both forms of erosion are greatly reduced when crop residues remain on the surface and when surface organic matter is allowed to accumulate, increasing aggregate strength and reducing surface slaking and crusting. A gradual change toward more erosion-resistant practices has occurred on many farms over the decades, but ideas on what types, depths, and timings of tillage are needed for successful winter wheat establishment vary widely even among neighboring farmers. We need a systematic and comprehensive understanding of how tilled soil mulches preserve seed-zone moisture, and prescriptions for erosion-resistant practices for different soil and climate combinations.

Historically, most North American research on tillage and evaporation has been focused on short-term, high moisture conditions common in climates with humid summers or shallow water tables such as the Great Plains of the United States (Black and Power, 1965; Willis and Bond, 1971; Aase and Tanaka, 1987; Peterson et al., 1996; Anderson, 2004). The effects of surface soil condition and residue cover are quite different under dry soil conditions within Mediterranean climates during the summer (Pikul and Allmaras, 1984).

In a laboratory test, Flury et al. (2009) measured the diffusion resistance of crop residue and found that it was most affected by the thickness of the residue layer. In another laboratory test, Hanks and Woodruff (1958) found that 0.5 cm of compact soil was as effective at reducing evaporation as 3 cm of straw. Aase and Tanaka (1987) measured the effect of standing or flat straw in the field. Both slowed evaporation for about 10 d, but in dry years there was little net effect by the end of summer. It appears that in areas with dry summers, surface residues often play a minor role in reducing overall evaporation. These dry locations have low residue production, so thick layers of surface residue are not possible.

Tests of tillage techniques to create erosion-resistant summer fallow in the Pacific Northwest have provided promising results (Schillinger, 2001). Minimizing soil inversion, maintaining a certain amount of surface cloddiness, and residue left standing upright has been achieved while maintaining seed-zone moisture nearly identical to traditional tillage methods. Results such as these, however, are highly dependent on the reaction of a particular soil type to the tools and timing used and can be confounded by weather and other variables. To translate improved methods to other soil types and locations, we need to identify the relevant characteristics of an effective soil mulch.

Papendick et al. (1973) investigated the effect of shallow vs. deep soil mulches with and without surface residue in one of the driest areas of the Pacific Northwest. Their 6-cm-thick soil mulch was not as effective as an 11-cm mulch, and 4000 kg ha^{-1} straw added to the surface made little difference to the soil temperature or moisture below the 11-cm mulch. Similarly, Schillinger and Papendick (1997) showed that a deep tillage mulch best preserves seed-zone moisture following winters of less than average precipitation. Hammel et al. (1981) found differences in temperature between tilled and untilled fallow that correlated with the preservation of seed-zone moisture. The model Hammel et al. (1981) fit to the data indicated that a tilled surface layer provided effective resistance to liquid flow much sooner that an untilled soil surface, reducing the loss of stored water early in the summer. Oveson and Appleby (1971) compared different dates of initial tillage in the spring and concluded that delaying tillage could be a detriment to the resulting seed-zone moisture in dry years, and that the performance of untilled summer fallow also depended on weather conditions in a particular year. These Pacific Northwest studies were conducted at single locations with limited treatments, so they were not capable of contrasting soil types or exploring trends of continuous variables. With the goal of providing information for improving tillage practices across the region, the dynamics of surface soil water needs to be studied under a variety of climate conditions and a range of tillage depths, timings, and soils.

Our study was designed to measure the effects of the timing of soil mulch establishment and mulch depth on soil water content in the seed zone during fallow. We also measured soil temperature profiles to see if they might be useful in detecting density and moisture discontinuities.

MATERIALS AND METHODS

The experiment was conducted at two sites during the summers of 2007 and 2008. At both sites, precipitation falls mostly as rain during the winter. Air temperatures average 0.6°C in January. Summers are hot and dry, with an average temperature of 21°C in July. The first site was located 15 km northeast of Pendleton, OR (45°43′ N, 118°38′ W, elevation 458 m). Annual precipitation averages 420 mm yr^{-1}. The soil was a Walla Walla silt loam (a coarse-silty, mixed, superactive, mesic Typic Haploxeroll) containing 21% fine to very fine sand, 69% silt, 10% clay, and about 11.1 g kg^{-1} organic C in the top 10 cm. This Walla Walla soil has a water potential of 1.5 MPa at a water content of about 0.096 kg kg^{-1} (Wuest et al., 1999) when measured using a Peltier thermocouple psychrometer (Tru Psi, Decagon Devices, Pullman, WA). In its untilled state, crop residue covered 80 to 90% of the surface to a thickness of 1 to 2 cm. The second site was 17 km northwest of Pendleton, OR (45°44′ N, 119°3′ W, elevation 315 m) where precipitation averages 290 mm yr^{-1} and the soil is a Ritzville silt loam (a coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll) containing 32% fine to very fine sand, 60% silt, 8% clay, and about 7.3 g kg^{-1} organic C in the top 10 cm. The Ritzville soil has a water potential of 1.5 MPa at a water content of about 0.064 kg kg^{-1} (same method as above). In its untilled state, crop residue covered 40 to 50% of the surface to a depth of up to 1 cm. Both sites have weather stations within 300 m of the plots.

The plot area was kept weed free from the previous winter through the completion of the experiment. The four tillage depth treatments (0, 5, 10, and 15 cm) were applied at six dates in 2007 and five dates in 2008. The first-year treatment dates on the Walla Walla soil were 11 June, 25 June, 9 July, 23 July, 6 Aug., and 20 Aug. 2007, and on the Ritzville soil were 15 June, 29 June, 13 July, 27 July, 10 Aug., and 24 Aug. 2007. In the second year, treatment dates on the Walla Walla soil were 12 May, 17 June, 14 July, 14 Aug., and 16 Sept. 2008, and on the Ritzville soil were 14 May, 16 June, 15 July, 15 Aug., and 15 Sept. 2008.

To create the soil mulch treatments, the surface residue was removed and circular areas of soil 1 m in diameter were removed with a shovel to the specified depth; the soil screened through a 2.5- by 5-cm wire mesh to break up clods, returned to the excavated hole, and leveled to a loose, even layer. This resulted in layers of soil mulch thicker than the tillage depth because tilling the soil decreased its bulk density. For the zero tillage depth (untilled) treatment, plots were undisturbed including leaving the surface residue in place. One plot of each tillage depth was created at each treatment date.

To verify that hand tillage of 1-m-diameter plots was a reasonable representation of soil conditions found under normal farming conditions, water content profiles were also measured at the Walla Walla soil site in plots where standard farm equipment was used to create tilled summer fallow. A soil sample was taken from the center of each 4- by 70-m plot in untilled and tilled fallow treatments replicated in four blocks.

A soil sample was taken from untilled soil at each tillage date to provide an initial water content profile. At the end of the summer, samples were taken from every plot. In the first year, final samples were taken on the Walla Walla soil on 4 Sept., 17 Sept., and 1 Oct. 2007, and on the Ritzville soil on 6 Sept., 21 Sept., and 5 Oct. 2007. In the second year, final samples were taken from the Walla Walla soil on 24 Sept. and 22 Oct. 2008, and from the Ritzville soil on 1 and 24 Oct. 2008. These end of summer samples were taken within 20 cm of the center of the treated area, and the holes were filled with soil after sampling to minimize the effect of sampling on evaporation before the next sampling.

The soil samples were divided into increments of 0 to 3 cm, 2-cm increments to 15-cm depth, then 5-cm increments to 30-cm depth. This was a total of 10 depth increments, and the measurements were based on the surface of the soil core after it was removed from the field. Sample compaction was common because of the very loose nature of the dry, tilled soil mulches. Samples were collected using a metal sampling tube with a 44.8-mm-diameter cutting edge. The soil core was maintained intact and protected in the tube while being sliced to provide more accurate estimates of bulk density (Wuest and Schillinger, 2008). The soils were dried for 24 h at 105°C for gravimetric water content determination (Topp and Ferre, 2002).

To measure differences in water content profiles between tilled and untilled soil that were not confounded by differences in bulk density, the depth in the soil profile is expressed in terms of dry soil mass per unit area instead of linear depth (e.g., centimeters) from the soil surface. This was important because a soil that has been tilled often has an elevated soil surface compared with its untilled state, and therefore a sample taken to a specific linear depth reaches less deep and collects less soil than in the untilled state (McGarry and Malafant, 1987; Ellert and Bettany, 1995; VandenBygaart and Angers, 2006; Wuest, 2009). The cross-sectional area of the soil core was used to convert the sample mass to kilograms per square meter.

Exact equivalent mass depths for comparing water content were calculated using linear interpolation between data points above and below the mass depth chosen for comparison. In this study, the uniform mass depths used for comparisons between treatments were 125, 150, 200, and 250 kg m^{-2}, which correspond with linear depths of approximately 10, 12, 16, and 20 cm. These are common seed placement depths using deep furrow drills in Pacific Northwest summer fallow systems.

Temperature measurements were made in the Walla Walla soil in 2008 using thermistors (RL0503–5820–97MS, General Electric, Edison, NJ) at 1-cm intervals vertically in a thin array fixed in glass-reinforced plastic. The arrays included a controlled current that was run through all the thermistors in series as well as a precision resistor for determining the exact amperage (McInnes, 2002). The voltage drop across each thermistor was read by a datalogger (CR1000, Campbell Scientific, Logan, UT) at 1-min intervals. At least 20 cm of wire coming from the array was buried to prevent the conduction of heat toward the array. Data from two arrays were averaged for each plot. Peak-to-peak temperature amplitude was determined as the difference between the highest and lowest temperature in a 24-h period. The period was started at 0400 h so that minimums and maximums at different depths would result from the same daytime insolation event (verified by examination of the data). Only sunny days were chosen. To standardize amplitude profiles for comparison on different days, the amplitude at each depth was expressed as its ratio to the temperature amplitude at the surface.

Statistical Analysis

The objective was to determine the effects of tillage timing and depth on soil water content. The two soils and 2 yr were considered only as samples from the larger recommendation domain and were therefore treated as random effects in a mixed-effects linear statistical model (Littell et al., 1996). Three tillage timings were chosen for analysis: mid-June, mid-July, and mid-August. The response variable was soil water content measured in late September. The mixed model therefore consisted of tillage depth (0, 5, 10, and 15 cm) and timing (mid-June, mid-July, and mid-August) and their interaction as fixed effects, and soil type, year, and their interaction with timing and tillage as random effects. Linear contrasts of the differences between least square means were calculated for the depth and timing factors.

RESULTS

Precipitation, air temperature, relative humidity, and soil water profiles in untilled plots during the course of the summer are shown for each site and each year in Fig. 1 and 2. As is typical, little rain fell between June and October, and that which did fall had little effect on soil moisture below 10 cm (mass-depth of about 125 kg dry soil m^{-2}). Crop-year precipitation from September 2006 to August 2007 was 394 mm at the Walla Walla soil site and 267 mm at the Ritzville site. From September 2007 to August 2008, precipitation was 348 mm at the Walla Walla site and 248 mm at the Ritville site.

The final soil water contents showed a smooth response to timing of tillage. The effects of tillage timing and depth were also consistent between the two soils (no apparent interaction involving site effects). Figure 3 shows the means of the four site-years for the four tillage depths at three tillage timings. At the late September sampling time chosen for the graph, the two deepest tillage treatments had created drier upper soil layers and greater soil water contents at a mass-depth of 250 kg m^{-2} (about 20-cm depth). Lesser amounts of deep water were preserved by 10- and 15-cm-deep tillage at the two later tillage dates. The bottom point on each line indicates the lowest measurement (about 30 cm), and it can be seen that the deepest mid-June tillage maintained almost 0.01 kg kg^{-1} greater soil water at that depth than the other tillage treatments. Statistically significant linear contrasts for data at the chosen equivalent mass-depths are summarized in Table 1 and listed in Table 2.

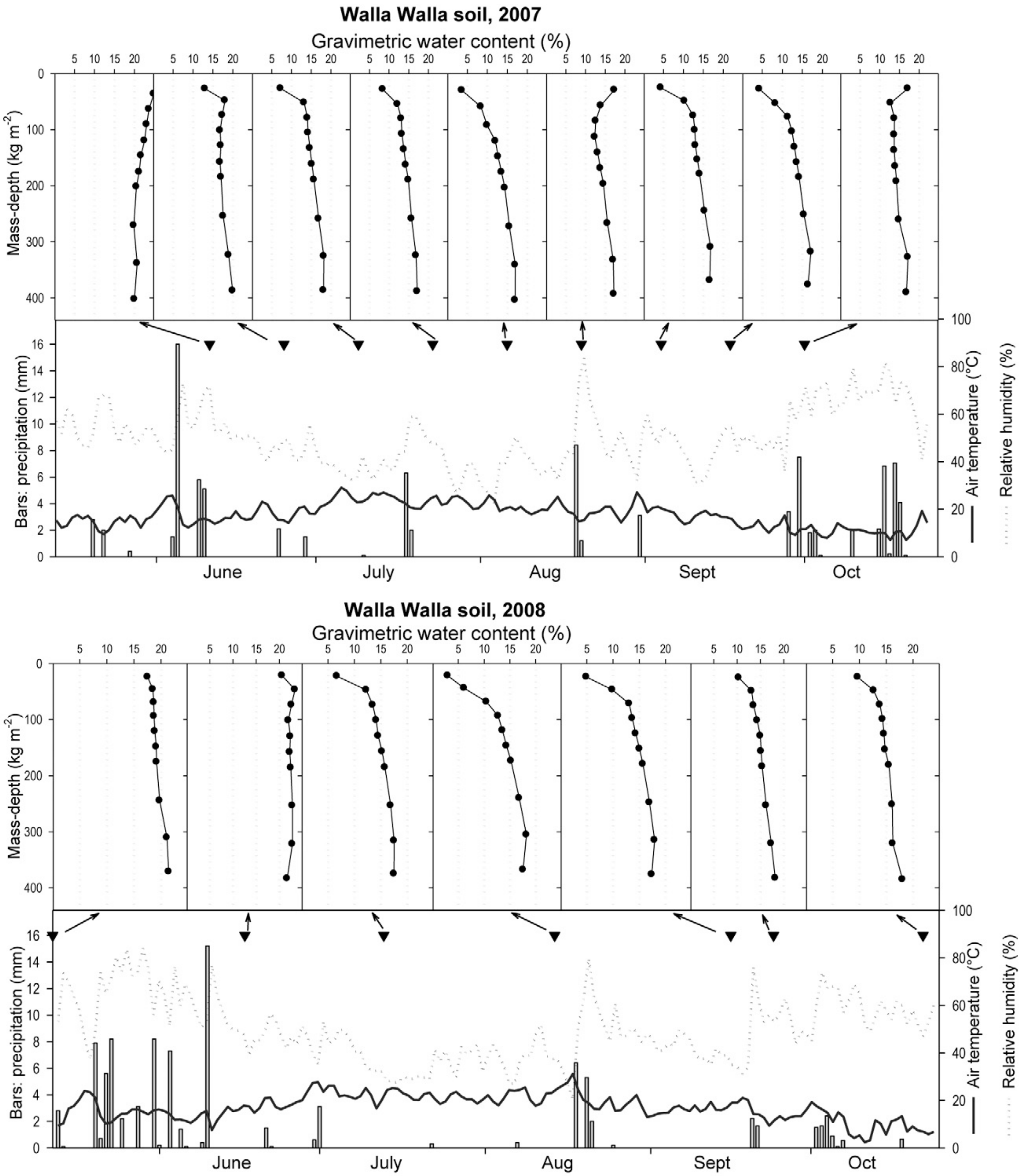

Fig. 1. Precipitation, average air temperature, and relative humidity during the summer fallow period at the Walla Walla soil site. Triangles show when soil water content profiles were measured (the same time as tillage treatments or final sampling) and arrows indicate the corresponding water profile in untilled soil.

The difference between soil textures and water-holding characteristics are evident in Fig. 4, where the mid-June and mid-July tillage timings for both years are averaged for each soil. The Walla Walla soil has a finer texture and held more water at both the air-dry surface and at 30-cm depth. The shapes and relationships of the soil moisture profiles for different tillage depths are similar for the two soils, except that near the surface, the untilled fallow (0-cm tillage) on the Ritzville soil was just as dry as the tilled treatments, whereas the untilled fallow on the Walla Walla soil maintained a moisture level with more than twice the gravimetric water content of the tilled treatments. The difference between soils was partly due to a thicker residue layer on the untilled Walla Walla soil. Figure 4 also shows the depth where soil samples indicated a bulk density change between the tilled soil mulch above and the untilled soil below.

Soil moisture profiles similar to the small-plot treatments were measured in large plots where commercial tillage equipment was used on the Walla Walla soil. In July and September, untilled

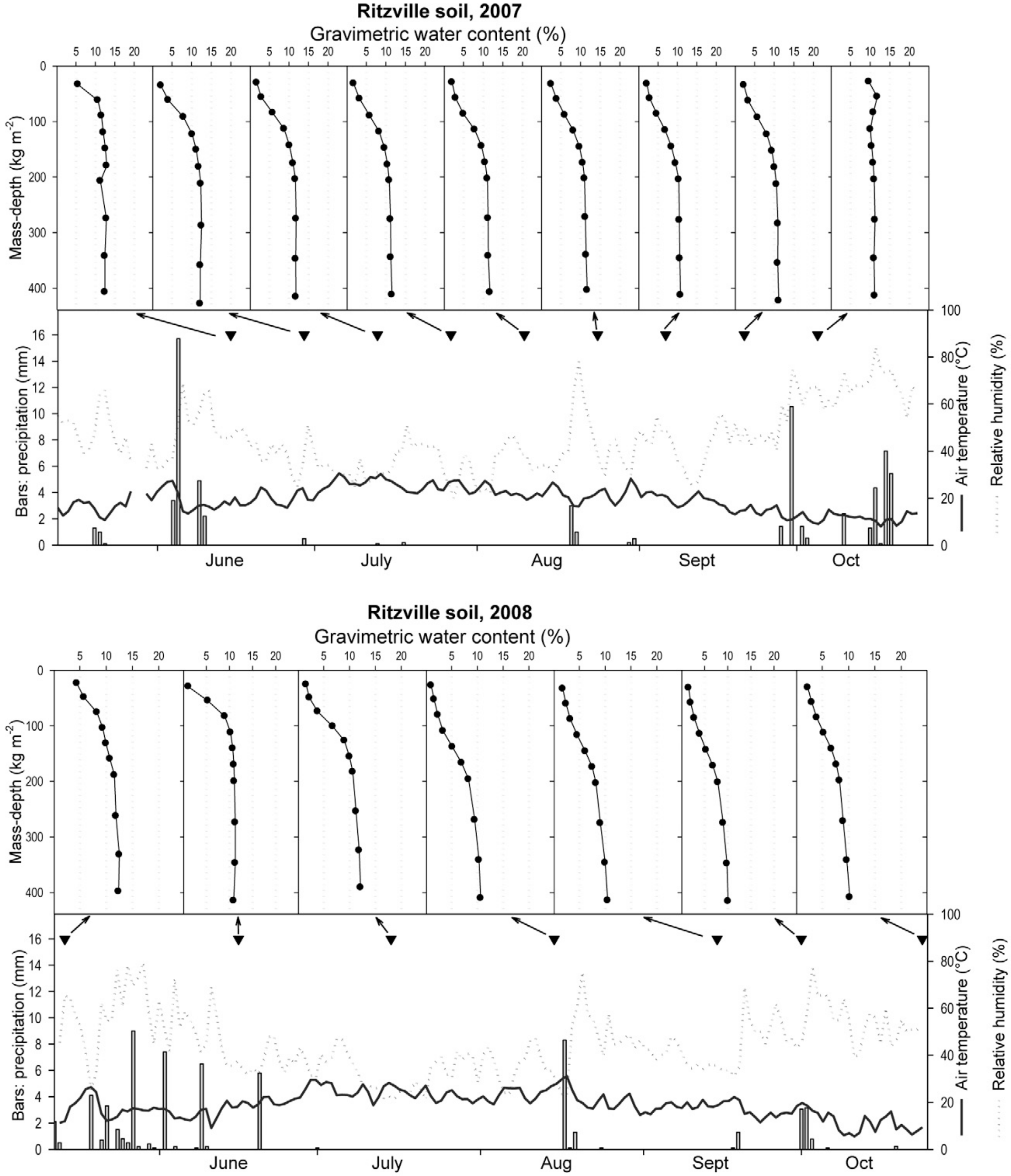

Fig. 2. Precipitation, average air temperature, and relative humidity during the summer fallow period at the Ritzville soil site. Triangles show when soil water content profiles were measured (the same time as tillage treatments or final sampling) and arrows indicate the corresponding water profile in untilled soil.

fallow had more soil water at the surface and less at deeper depths than tilled fallow (Fig. 5). The tillage was performed in May 2008, and the soil was retilled with a rod-weeder to control weeds in mid-June and early August. Data are included in the September graph from plots that were not fallow but instead had recently undergone wheat harvest, showing the increase in water available for fall planting due to summer fallow. The October data (Fig. 5) show a loss of soil water in the tilled fallow after the planting of wheat.

Soil temperature profiles were measured in the Walla Walla soil in the mid-July 2008 tillage treatments. Figure 6 shows the depth profile of diurnal temperature amplitude, expressed as the ratio at a specific depth to that at the surface. The 16 July measurement date is 2 d after the tillage treatments were performed. The zero tillage depth treatment has a distinct change in trend at the 4-cm depth that is consistent at all three temperature measurement dates. This depth corresponds with the depth of a natural increase in bulk density in non-tilled plots, from about 1.0 g cm^{-3} above

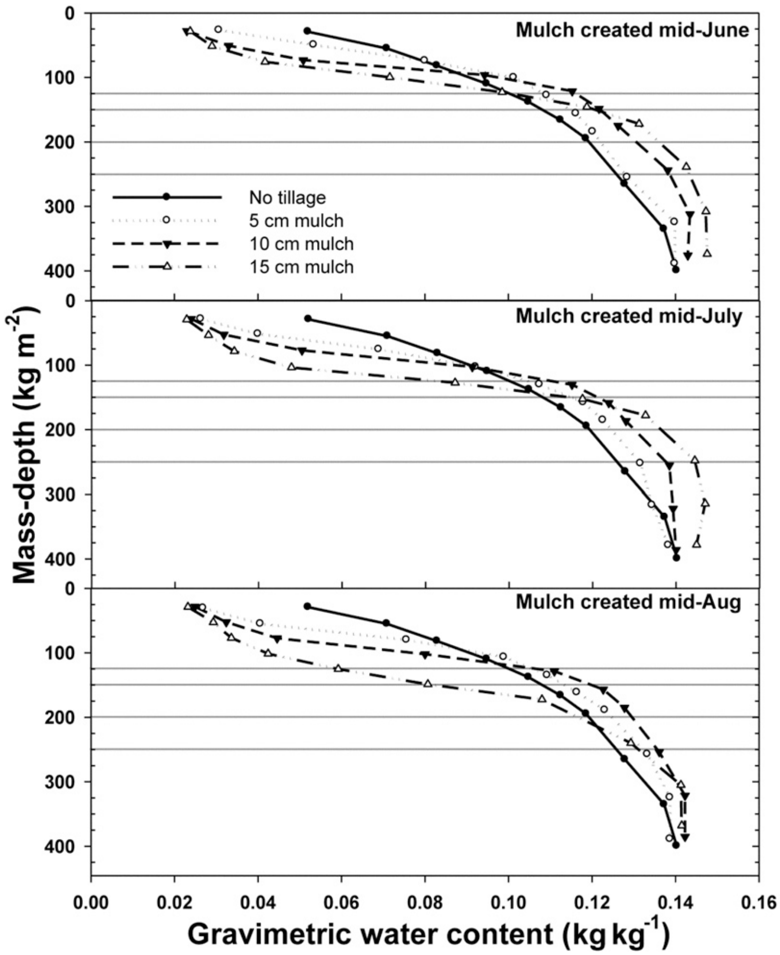

Fig. 3. Effect of timing and depth of soil mulch on soil water content in late September. Mean of all four site-years. Zero-tillage data are identical in all three graphs. Depth in the soil profile was measured as the cumulative mass of dry soil, which allows comparison of treatments independent of soil bulk density differences. Linear distance from the soil surface for each point, starting at the top, is 3, 5, 7, 9, 11, 13, 15, 20, 25, and 30 cm. Horizontal gridlines are placed at 125, 150, 200, and 250 kg m^{-2}, which are the depths for which equivalent mass-depth values were interpolated and analyzed using linear contrasts (see Tables 1 and 2).

5 cm to about 1.2 g cm^{-3} below 5 cm (data not shown). The 5-cm tillage treatment has a less distinct bend at the same 4-cm depth for all three measurement dates. The 10- and 15-cm tillage treatments also have a bend at 4 cm in July. In August and September the 10-cm tillage treatment has a bend at a soil depth of 10 cm, and the 15-cm tillage treatment has bends at 10 cm and 18 cm.

Figure 7 shows minimum and maximum temperatures for the Walla Walla soil in late September 2008. All four tillage depth treatments parallel each other, but it can be seen that the simple average of maximum and minimum for the no-tillage treatment at 30 cm is lower than the other treatments.

Table 1. Summary of significant (*P* < 0.05) contrasts for the data in Fig. 3. Values for each curve at the four equivalent mass-depths were calculated by linear interpolation. Tillage depths were 0 (no tillage), 5, 10, or 15 cm deep. Tillage dates were June, July, or August.

Depth in soil profile	Significant (*P* < 0.05) linear contrasts
kg m^{-2} mass-depth	
125	July and Aug.: 15-cm treatment vs. all other treatments and tillage dates 15-cm treatment differs between tillage dates
150	Aug.: 15-cm treatment vs. all other treatments and tillage dates
200	June: 0 and 5 vs. 10 and 15 cm July: 0 vs. 10 and 15, 5 vs. 15 cm Aug.: 0 vs. 10, 10 vs. 15 cm
250	June: 0 and 5 vs. 10 and 15 cm July: 0 vs. 10 and 15, 5 vs. 15 cm Aug.: 0 vs. 5, 10, and 15 cm 15-cm treatment differs between tillage dates

DISCUSSION

The effects of rainfall apparent in the moisture profiles of the untilled soil (Fig. 1 and 2) were much greater than would be seen in tilled soil because water falling on tilled soil tends to be held in a thin crust suspended at the top of the loose soil and quickly evaporates. Without tillage, surface water is transported deeper, and surface residue provides some short-term protection from evaporation. During the summer, however, the small amounts of rain normally received make little difference in seed-zone soil moisture unless substantial amounts fall late in the summer close to seeding time and after temperatures start dropping.

It is important to note that the tillage mulches created in this experiment could be described as moderately fine, with no clods greater than about 2-cm diameter and a flat surface with no large voids or tool grooves remaining. This is more uniform and has fewer large voids than most one-pass tillage implements would create but not as fine as is common when summer fallow is worked several times under dry conditions using a rod-weeder.

Our discussion concentrates on the highest water contents found in the measured profile. The no-tillage (0-cm) treatment sometimes produced the greatest water contents in the top 100 kg m^{-2} (Fig. 3 and 4), but these moisture levels are not sufficient for establishing stands of winter wheat during hot weather at the end of summer. The goal of farmers is to provide the greatest water content possible as close to the surface as possible so that the wheat will emerge quickly and grow during the early fall when the weather is still warm. Deep-furrow drills are used to move soil into ridges between crop rows and place the seed 7 to 15 cm below the furrow bottom. The water content levels needed to germinate wheat under field conditions in all the soil types in the Inland Pacific Northwest have not been determined. In sealed vessels under laboratory conditions, a water content of about 0.10 kg kg^{-1} (1.1 MPa) was necessary for rapid germination of wheat in the Walla Walla soil (Wuest et al., 1999).

In both soil types, a 15-cm soil mulch created soon enough in the spring resulted in greater seed-zone water content than later or shallower tillage (Fig. 3;

Table 2. Differences (Diff.) of least square means and standard errors (SE) of the difference for gravimetric water content for contrasts where $P > |t|$ was <0.05. Analyses were made at four equivalent masses, 125, 150, 200, and 250 kg m^{-2}.

Contrast				125 kg m^{-2}		150 kg m^{-2}		200 kg m^{-2}		250 kg m^{-2}	
Depth	Date	Depth	Date	Diff.	SE	Diff.	SE	Diff.	SE	Diff.	SE
cm		cm		kg kg^{-1}							
0	June	10	June					–0.0113	0.0039	–0.0105	0.0034
			July					–0.0096	0.0041	–0.0088	0.0035
			Aug.					–0.0098	0.0041	–0.0079	0.0035
		15	June					–0.0156	0.0039	–0.0153	0.0034
			July	0.0180	0.0084			–0.0165	0.0041	–0.0153	0.0035
			Aug.	0.0407	0.0084	0.0237	0.0065				
	July	10	June					–0.0103	0.0041	–0.0105	0.0035
			July					–0.0086	0.0039	–0.0088	0.0034
			Aug.					–0.0088	0.0041	–0.0079	0.0035
		15	June					–0.0146	0.0041	–0.0154	0.0035
			July					–0.0155	0.0039	–0.0153	0.0034
			Aug.	0.0396	0.0084	0.0245	0.0065				
	Aug.	5	Aug.							–0.0109	0.0043
		10	June					–0.0142	0.0054	–0.0168	0.0044
			July					–0.0125	0.0054	–0.0151	0.0044
			Aug.					–0.0127	0.0052	–0.0142	0.0043
		15	June					–0.0185	0.0054	–0.0216	0.0044
			July					–0.0194	0.0054	–0.0216	0.0044
			Aug.	0.0328	0.0115	0.0179	0.0088			–0.0111	0.0043
5	June	10	June					–0.0097	0.0042	–0.0106	0.0036
			July							–0.0089	0.0037
			Aug.							–0.0080	0.0037
		15	June					–0.0140	0.0042	–0.0155	0.0036
			July	0.0231	0.0092			–0.0149	0.0044	–0.0154	0.0037
			Aug.	0.0458	0.0092	0.0289	0.0071				
	July	10	June							–0.0085	0.0037
		15	June					–0.0118	0.0044	–0.0134	0.0037
			July					–0.0127	0.0042	–0.0134	0.0036
			Aug.	0.0414	0.0092	0.0282	0.0071				
	Aug.	15	June					–0.0106	0.0044	–0.0107	0.0037
			July	0.0197	0.0092			–0.0115	0.0044	–0.0107	0.0037
			Aug.	0.0425	0.0092	0.0265	0.0071				
10	June	15	July	0.0256	0.0092						
			Aug.	0.0483	0.0092	0.0353	0.0071	0.0137	0.0044		
	July	15	July	0.0260	0.0092						
			Aug.	0.0488	0.0092	0.0355	0.0071	0.0119	0.0044		
	Aug.	15	July	0.0213	0.0092						
			Aug.	0.0441	0.0092	0.0335	0.0071	0.0122	0.0042		
15	June	15	Aug.	0.0376	0.0092	0.0318	0.0071	0.0179	0.0041	0.0106	0.0032
	July	15	Aug.	0.0228	0.0092	0.0299	0.0071	0.0189	0.0041	0.0105	0.0032

Table 2). If mulch creation was delayed until mid-July or mid-August, or if the mulch was too shallow, the deep soil water content was reduced to levels similar to no soil mulch at all. These results support the conclusions of prior research, where under dry springtime conditions, earlier or deeper tillage produced greater seed-zone water (Oveson and Appleby, 1971; Papendick et al., 1973; Schillinger and Papendick, 1997). In fact, under dry spring conditions, June can be too late for a 15-cm mulch to maintain maximum soil moisture. In the same location and soil as our study, Oveson and Appleby (1971) had the best results with tillage in April. In our 2007 and 2008 study, May and June rainfall delayed the start of net soil drying.

Using water content measured at the deepest depth as an indication, significant amounts of stored soil water were lost without

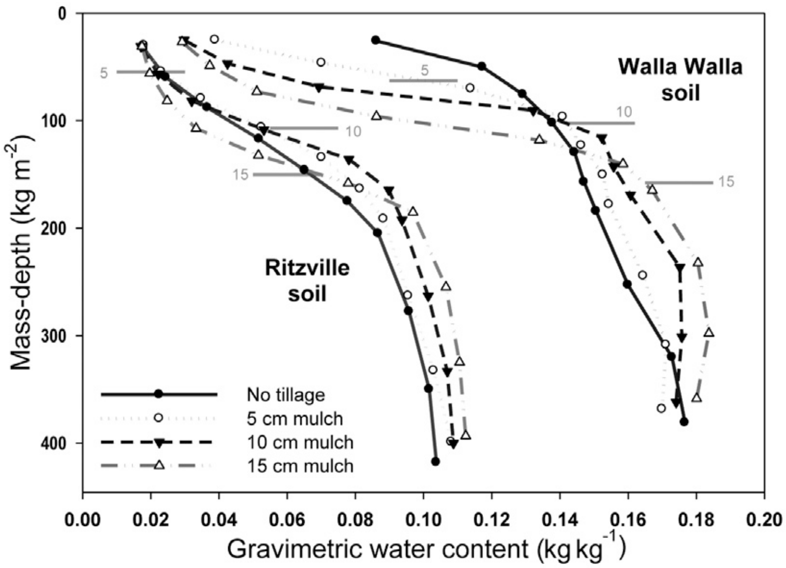

Fig. 4. Comparison of Ritzville and Walla Walla soil water profiles measured in late September, mean of mid-June and mid-July tillage treatments for both years. Short horizontal bars show the depth where bulk density change indicates the bottom of the tilled layer for each treatment.

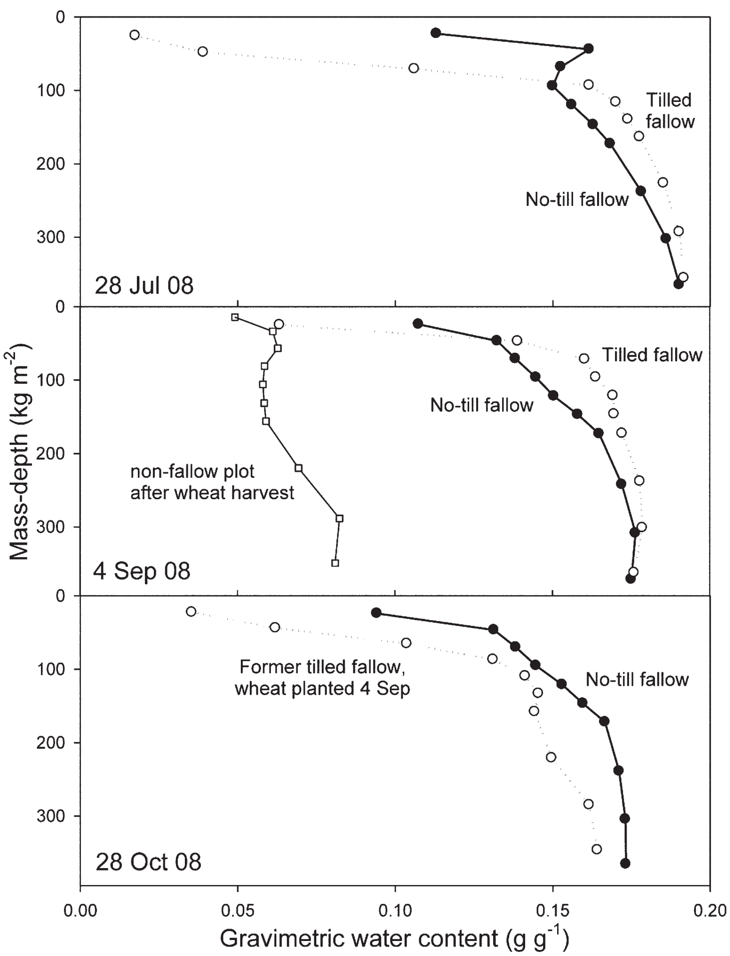

Fig. 5. Example of soil moisture profiles in plots without tillage and those tilled using commercial equipment on the Walla Walla soil. Three sample dates are shown. The plots were tilled with an undercutter-sweep on 7 May 2008 and then rod-weeded on 19 June 2008 at 10-cm depth, and rod-weeded again on 4 Aug. 2008 at 4-cm depth. Winter wheat was planted into the tilled plots after the measurement on 4 September. The 4 September sample date includes a moisture profile from recently harvested winter wheat plots to show the difference summer fallow makes in available soil water.

an early, deep mulch. The data also suggest that there may be a water content toward which a particular soil tends if evaporation is not reduced below the self-mulching tendency of the soil in its untilled state. Evidence for this can be seen in Fig. 3, the mid-August treatment date, where all the mulch treatments resulted in very similar water contents at the lowest depth. This water content probably corresponds to soil texture characteristics that govern the matric potential, in addition to the balance between the water supply and evaporative demand.

In examining Fig. 3, note that all three graphs show water contents measured in late September. The differences between treatments imposed at 1-mo intervals is due to changes in the pretreatment (untilled) water loss before a particular tillage treatment, plus differences in performance of the mulch between the treatment date and the late-September sample date. The differences in pretreatment conditions can be seen in Fig. 1 and 2.

A 5-cm mulch created in mid-June made little difference in deep water content compared with no tillage (Fig. 3). It allowed the soil above 7 cm to become drier, similar to the deeper tillages, but had little if any effect on deep moisture levels. It could be that water flux is dominated by vapor flow in the top 7 cm and that differences in bulk density and residue cover have little overall effect. On the other hand, the shape of the 5-cm mulch curve is similar to the deeper mulches (Fig. 3 and 4), indicating that it has changed the evaporation dynamics in a lesser but similar way. Papendick et al. (1973) found that there was a substantial difference in the performance of a 6-cm mulch depth compared with 11 cm, similar to what we found in 5- and 10-cm mulches.

Progressively deeper tillage resulted in a consistent progression of soil water profile curves (Fig. 3). Deeper tillage increased the depth to which the soil was close to surface dryness. Because the three tilled mulches were structurally identical above 5 cm, it is reasonable to think that the curves differ because of water transport differences near the bottom of each tillage depth. The most horizontal section of each curve indicates where the greatest soil water gradients occurred. Moving down the curve, the profile change from horizontal to vertical indicates higher resistance above that point and lower resistance below. In the Walla Walla soil (Fig. 4), the change in bulk density in both the 10- and 15-cm tillage treatments is close to that transition, at a mass-depth of about 125 to 150 kg m^{-2}.

Although the bend points of the moisture profiles appear to have some relation to the points where bulk density changes were measured, the exact relationships are not obvious. This is partly due to insufficient precision in the bulk density measurements. Changes that occur within a 2-cm increment will only partially influence that sample, and the full change will become evident in the neighboring samples. It is clear that progressively deeper tillage treatments caused corresponding trends in the soil moisture profiles, and the point above which water gradients increased (water profiles become more horizontal) is near to where bulk density changes were measured. To understand the relationships between bulk density, heat flux, and water flux and how tillage influences them, it will be necessary to measure these breakpoints with more precision.

The depth of the soil mulch was also measured at the end of the experiment by inserting a measuring stick until firm soil was felt (data not shown). This mulch depth measurement gave similar results to the bulk density change data but generally indicated deeper mulch depths. The measuring stick method would probably be most useful if measurements were made throughout the experiment to determine if the mulches settled with time. To make accurate comparisons between water content data and a distance measurement such as measuring-stick-based mulch depth or data on temperature from 1-cm-spaced temperature sensors, it will be necessary to accurately index core sample increment depths to the original surface. In firm soils, this is not difficult, but under loose mulches the soil tends to compact in the sample tube as a core is taken, and it is not possible to know at what depths the compaction has taken place.

Many reports comparing tilled and untilled summer fallow have concluded that there were no differences in total root-zone water between the two systems (Oveson and Appleby, 1971; Hammel et al., 1981), but some have measured differences (Schillinger and Bolton, 1993). Research and farmer focus has been on differences in seed-zone moisture, but differences found there will be limited if there are truly no differences in the deeper water supply. It is possible that significant differences would have been found in earlier research if methods with greater precision were used for the zone immediately below the seed zone. In this study, we used mass-depth to eliminate variation due to bulk density differences. This allowed comparison of soil water at depths that do not vary depending on how tillage has changed the elevation of the soil surface. In Fig. 3 and 4, it can be seen that 30-cm samples collected more soil mass from untilled plots than from tilled plots; in effect, the untilled plots were sampled deeper. In a net evaporation environment, deeper samples have greater water content. If water profile comparisons are made using linear depth, as is traditionally done, the difference in effective depth of sampling would have created a bias that gives the appearance of greater than actual water content in soils with greater overall bulk density. The mass-depth method is not influenced by bulk density, so bulk density changes that occurred during the course of the experiment did not change the amount of soil collected from the different treatments. It also reduced sample variance (Wuest, 2009), which should improve statistical power.

Monitoring soil water at 30 cm or deeper during the spring may be a way to determine the optimum tillage timing. The data might seem to indicate that earlier tillage is better, but tilling earlier than necessary reduces the infiltration of late spring rains. It is also possible that evaporative loss is minor early in the spring when soil temperatures are cooler at lower depths and solar radiation on the soil surface tends to drive water flux downward (Pikul et al., 1985). The timing and importance of these relationships will depend on local soil and weather conditions, so a

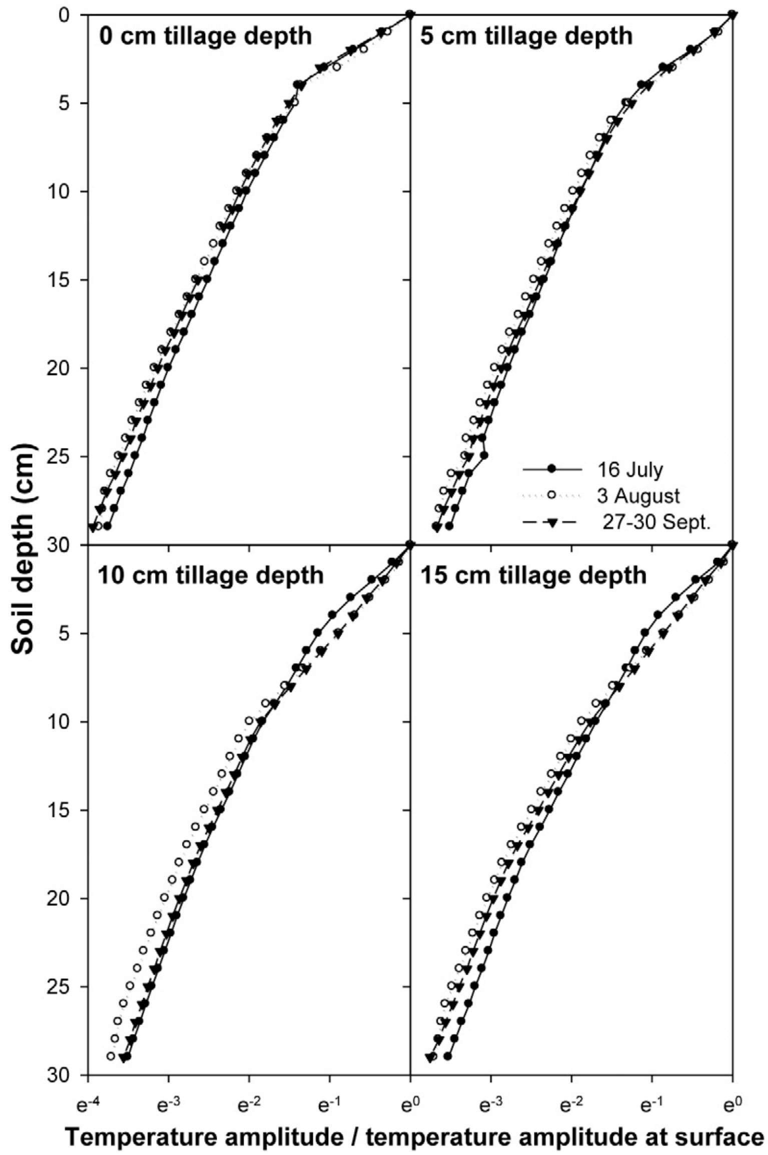

Fig. 6. Soil temperature amplitude profiles for the mid-July treatment date on the Walla Walla soil in 2008. Diurnal temperature amplitude (i.e., range for 24-h period starting at 0400 h) for each depth, as the ratio with the surface temperature amplitude, plotted on a natural-log scale. The first date (16 July) was 2 d after the tillage treatment. The September measurement is the average of three consecutive days. All data represent the average of two independent thermistor arrays placed in each treatment.

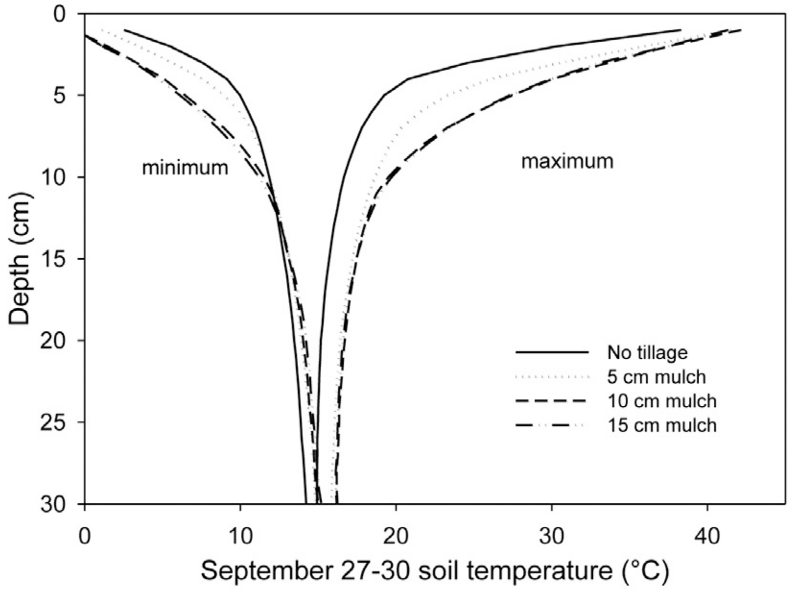

Fig. 7. Minimum and maximum temperatures vs. depth in the mid-July tillage treatment on the Walla Walla soil. Temperatures are the average of three consecutive days, 27 to 30 Sept. 2008.

method for monitoring the direction of water flux might become an important tool for determining when to till.

The bend in temperature amplitude at about 4 cm (Fig. 6) was similar for all treatments 2 d after tillage when the tilled soil was still uniformly moist. The deeper tillage treatments demonstrated differences from the shallow tillage at the later two measurement dates. These temperature profiles follow the same pattern described for heat flux by Ochsner et al. (2007). Greater slope of the amplitude ratio curve occurs with depth and also with increasing diffusivity. On 16 July, the soil moisture would have been relatively low at the soil surface in the untilled treatment (Fig. 1). In the 5-cm tillage depth, the dry surface soil would have been loosened and homogenized to 5-cm depth. The 10- and 15-cm tillage depth treatments loosened and homogenized the soil to 10- and 15-cm depths, and small bends can be seen in relation to these depths in the 16 July data. The straightening of the upper curves at the second two measurement dates may indicate drying of the surface soil, resulting in a reduction in heat capacity, which reduces the decay in amplitude with depth. Bend points in the latter two measurements appear to reflect diffusivity or heat capacity changes due to soil bulk density. Detailed measurements of soil bulk density and water content would make better interpretation of the curves possible, but these data serve to demonstrate that temperature profiles at 1-cm resolution can detect discontinuities in heat flux related to soil physical changes.

The minimum and maximum soil temperature profiles (Fig. 7) appear to give three distinct responses to the four treatments. The two deepest mulch treatments are almost identical. The shape of the 5-cm mulch temperature profile is more like the untilled treatment than those of the deeper tillage mulches but has the same average as the deeper mulches. The untilled treatment has a narrower difference between minimum and maximum and is shifted left, having a lower average temperature. Part of the difference is probably due to the untilled treatment having surface residue cover, where the other treatments had none. In addition, the treatments had different water content profiles (Fig. 4). On a linear depth basis, they also had different dry soil mass profiles. For the treatments in Fig. 7, the untilled treatment had 383 kg m^{-2} dry soil mass and 60 kg m^{-2} water in the top 30 cm, whereas the 15-cm soil mulch treatment had only 355 kg m^{-2} dry soil and 52 kg m^{-2} water. Unfortunately, our procedures did not allow accurate indexing of linear, surface-based measurements and mass-based measurements because of the compaction of the soil mulch samples during the sampling procedure. This means that in this data set, we cannot assign a certain soil and water mass to each temperature depth. It is clear, however, that the temperature profiles in the top third of the untilled treatment were measured in a greater mass of soil and water and therefore greater heat capacity.

Both Hammel et al. (1981) and Papendick et al. (1973) found shallow mulch or untilled soil profile temperatures to be a degree or more warmer than under a deep soil mulch. In contrast, Fig. 7 shows lower temperatures in the untilled plots than all three tilled mulches. Our untilled soil had residue cover, which might help explain the lower temperature, but the data of Hammel et al. (1981) also had residue on the untilled soil. An important consideration in the comparison of soil temperature is whether the soil is under a warming trend or a cooling trend during the measurement period. If the tillage systems create different response times (a layer of residue slowing soil warming and cooling, for example), then the temperature differences may be temporary. From Fig. 1 it appears that the last days of September 2008 were under a warming trend, so the lower mean temperatures measured in the untilled vs. the tilled treatments might be because the untilled soil took longer to warm up during warming trends. The relationship might have been reversed if the measurement had been made during a cooling trend. Data from longer periods will be necessary to sort out these issues.

Past research has shown crop residue to have only short-term effects on soil moisture profiles in this climate (Papendick et al., 1973), but its effect on albedo and temperature profiles should be measured to complement other measurements. The effects of surface roughness can also have an effect on the absorption of solar radiation. In any case, our temperature data suggest that detailed comparisons of soil temperature profiles with consideration of surface albedo, surface residue, and the mass and moisture content of the soil above the measurement point might be useful in characterizing the effectiveness of different mulch conditions. In addition, different nighttime temperature minima (Fig. 7) may help to explain the differences between untilled and tilled treatments because water loss during soil cooling cycles that begin in August under Inland Pacific Northwest conditions can be a major component of evaporation (Pikul et al., 1985).

CONCLUSIONS

Depletion of the water supply below the seed zone by a delay of tillage or tillage of insufficient depth appears to limit the maintenance of high moisture levels in the seed zone at the end of summer. These relationships were similar on two soils of different water-holding characteristics. Linear measurements such as tillage depth, mulch thickness, and temperature profiles should be indexed to mass-depth measurement of the soil water and bulk density changes. This will make it possible to accurately identify soil characteristics affecting moisture profiles without the confounding effect of different bulk densities in different treatments. And finally, temperature profiles showed substantial differences between mulch treatments. Because detailed profile measurements can be easily made, it is worthwhile to characterize temperature profiles in an attempt to develop a tool for predicting mulch performance.

REFERENCES

Aase, J.K., and D.L. Tanaka. 1987. Soil water evaporation comparisons among tillage practices in the northern Great Plains. Soil Sci. Soc. Am. J. 51:436–440.

Anderson, R.L. 2004. Impact of subsurface tillage on weed dynamics in the central Great Plains. Weed Technol. 18:186–192.

Black, A.L., and J.G. Power. 1965. Effect of chemical and mechanical fallow methods on moisture storage, wheat yields, and soil erodibility. Soil Sci. Soc. Am. Proc. 29:465–468.

Cantero-Martinez, C., P. Angas, and J. Lampurianes. 2007. Long-term yield and water use efficiency under various tillage systems in Mediterranean rainfed conditions. Ann. Appl. Biol. 150:293–305.

Donaldson, E., W.F. Schillinger, and S.M. Dofing. 2001. Straw production and grain yield relationships in winter wheat. Crop Sci. 41:100–106.

Ellert, B.H., and J.R. Bettany. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529–538.

Flury, M., J.B. Mathison, J.Q. Wu, W.F. Schillinger, and C.O. Stockle. 2009. Water vapor diffusion through wheat straw residue. Soil Sci. Soc. Am. J. 73:37–45.

Hammel, J.E., R.I. Papendick, and G.S. Campbell. 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. Soil Sci. Soc. Am. J. 45:1016–1022.

Hanks, R.J., and N.P. Woodruff. 1958. Influence of wind on water vapor transfer through soil, gravel, and straw mulches. Soil Sci. 86:160–164.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS system for mixed models. SAS Inst., Cary, NC.

McGarry, D., and K.W.J. Malafant. 1987. A cumulative mass coordinate to determine water profile changes in variable volume soil. Soil Sci. Soc. Am. J. 51:850–854.

McInnes, K.J. 2002. Soil heat. p. 1183–1199. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Ochsner, T.E., T.J. Sauer, and R. Horton. 2007. Soil heat storage measurements in energy balance studies. Agron. J. 99:311–319.

Oveson, M.M., and A.P. Appleby. 1971. Influence of tillage management in a stubble mulch fallow–winter wheat rotation with herbicide weed control. Agron. J. 63:19–20.

Papendick, R.I., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in eastern Washington. Soil Sci. Soc. Am. Proc. 37:307–314.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180–186.

Pikul, J.L., Jr., and R.R. Allmaras. 1984. A field comparison of null-aligned and mechanistic soil heat flux. Soil Sci. Soc. Am. J. 48:1207–1214.

Pikul, J.L., Jr., R.R. Allmaras, and S.E. Waldman. 1985. Late season heat flux and water distribution in summer-fallowed Haploxerolls. Soil Sci. Soc. Am. J. 49:1517–1522.

Russelle, M.P., and F.E. Bolton. 1980. Soil temperature effects on winter wheat and winter barley emergence in the field. Agron. J. 72:823–827.

Schillinger, W.F. 2001. Minimum and delayed conservation tillage for wheat–fallow farming. Soil Sci. Soc. Am. J. 65:1203–1209.

Schillinger, W.F., and F.E. Bolton. 1993. Fallow water storage in tilled vs. untilled soils in the Pacific Northwest. J. Prod. Agric. 6:267–269.

Schillinger, W.F., and R.I. Papendick. 1997. Tillage mulch depth effects during fallow on wheat production and wind erosion control factors. Soil Sci. Soc. Am. J. 61:871–876.

Schillinger, W.F., and R.I. Papendick. 2008. Then and now: 125 years of dryland wheat farming in the Inland Pacific Northwest. Agron. J. 100:S166–S182.

Schillinger, W.F., and D.L. Young. 2004. Cropping systems research in the world's driest rainfed wheat region. Agron. J. 96:1182–1187.

Topp, G.C., and P.A. Ferre. 2002. Water content. p. 417–545. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

VandenBygaart, A.J., and D.A. Angers. 2006. Towards accurate measurements of soil organic carbon stock change in agroecosystems. Can. J. Soil Sci. 86:465–471.

Willis, W.O., and J.J. Bond. 1971. Soil water evaporation: Reduction by simulated tillage. Soil Sci. Soc. Am. Proc. 35:526–529.

Wuest, S.B. 2009. Correction of bulk density and sampling method biases using soil mass per unit area. Soil Sci. Soc. Am. J. 73:312–316.

Wuest, S.B., S.L. Albrecht, and K.W. Skirvin. 1999. Vapor transport vs. seed–soil contact in wheat germination. Agron. J. 91:783–787.

Wuest, S.B., and W.F. Schillinger. 2008. Small-increment electric soil sampler. Soil Sci. Soc. Am. J. 72:1554–1556.