SOIL WATER AND TEMPERATURE IN CHEMICAL VERSUS REDUCED-TILLAGE FALLOW IN A MEDITERRANEAN CLIMATE

Y. A. Al-Mulla, J. Q. Wu, P. Singh, M. Flury,
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ABSTRACT. *A 2-year rotation of winter wheat (*Triticum aestivum *L.)-summer fallow is a dominant cropping system in the dryland region of the Pacific Northwest United States. Traditional, tillage-based summer fallow relies on a soil mulch to disrupt capillary continuity to conserve seed-zone water for early establishment of winter wheat. However, tillage to create the soil mulch and to subsequently fertilize and control weeds often results in unacceptable levels of wind erosion due to the burial of crop residues and the exposure of fine soil particles. Chemical (no-till) fallow (CF) and reduced-tillage fallow (RT) are two alternatives for reducing wind erosion. Our objectives were: (i) to assess the effects of CF and RT on seed- and root-zone temperature and water regimes; and (ii) to test the Simultaneous Heat and Water (SHAW) model for simulating management effects on soil temperature and water. Weather data, soil temperature, and water content were monitored in paired CF and RT treatments during April 2003-March 2004. The RT treatment was observed to retain more seed-zone water over summer compared to CF, consistent with relevant literature for Mediterranean environments and of critical importance to farmers. During the wet winter, CF gained more water than RT because of later planting of winter wheat, and thus less water use. Observed soil temperatures were higher in the CF due to its lower dry soil albedo, higher bulk density and thermal diffusivity than in the RT. SHAW-simulated water contents followed the general trend of the field data, though it slightly under-predicted soil water content for CF and over-predicted for RT. SHAW under-predicted soil temperature during the dry summer and over-predicted for the wet (November-December) period yet the overall trend was properly described with differences between simulations and observations decreasing with soil depth. Overall, SHAW proved adequate in simulating seed-zone and whole-profile soil water and temperature, and therefore may serve as a useful modeling tool for tillage and residue management.*

Keywords. *Winter wheat, Seed-zone water, Chemical fallow, Reduced-tillage fallow, Pacific Northwest, SHAW.*

Tillage-based, winter wheat-summer fallow is the predominant agricultural system on 1.8-million ha of farmland in the low-precipitation (<350 mm annually) dryland cropping region of the Pacific Northwest (PNW). Climate in this region is Mediterranean. The primary goal of summer fallow is to store a portion of winter precipitation during the dry summer period to provide sufficient seed-zone soil water for early winter wheat establishment and high grain yield potential (Leggett et al., 1974; Pannkuk et al. 1997; Schillinger et al., 1998). Traditional-tillage summer fallow involves eight or more tillage operations to establish a soil mulch and to control weeds to conserve seed-zone water by increasing resistance to water and heat flow (Papendick et al., 1973; Hammel et al., 1981). Such intensive tillage often buries surface residue and pulverizes soil particles that leaves the soil highly vulnerable to wind erosion (Papendick, 2004).

Chemical fallow (CF) and reduced-tillage fallow (RT) systems that reduce wind erosion have been developed (Schillinger, 2001; Janosky et al., 2002), but are not yet widely adopted by farmers. Lindstrom et al. (1974) and Hammel et al. (1981) reported increased evaporative loss of seed-zone water in CF compared to tilled fallow and concluded that tillage is required to retain sufficient seed-zone water for early establishment of winter wheat.

In the dryland region, deep planting (up to 20 cm below the soil surface) with deep-furrow grain drills is commonly practiced by farmers to reach adequate soil water for germination and emergence of winter wheat. Early planting, i.e., in late August or early September, is typically preferred. If soil water is insufficient, planting is delayed until mid-October or the onset of fall rainfall. Delayed planting consistently and significantly reduces winter wheat grain and straw yield compared to early planting (Donaldson et al.,

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2001). Therefore, maintaining adequate seed-zone soil water in summer fallow for early planting is critical.

Schillinger and Papendick (1997) and Schillinger (2001) showed that RT adequately conserved seed-zone soil water with a minimum number of non-inversion tillage operations. Cost reductions of non-selective herbicides combined with increased fuel prices have recently renewed interest in the CF and RT practices among both farmers and scientists.

Soil water regimes are impacted by dynamic and interactive water and heat transport processes. Liquid water flow, vapor movement, and heat transfer must be considered simultaneously to understand the effect of tillage management on water dynamics in summer fallow (Papendick et al., 1973). SHAW (Simultaneous Heat and Water) (Flerchinger and Saxton, 1989) was developed to characterize water and heat flow in the root zone as affected by tillage and residue management. The SHAW model simulates coupled heat and water movement, considering both snow accumulation and soil freezing and thawing, within a soil-plant-water continuum (Flerchinger and Pierson, 1997).

The SHAW model has been tested and applied for quantifying soil water and temperature as well as surface energy balances under a variety of conditions. Comparisons with field data showed that SHAW was well suited to account for diverse tillage and residue management practices (Flerchinger and Saxton, 1989), their impact on frost depth (Flerchinger and Hanson, 1989), vegetation effects in semi-arid sagebrush rangeland (Flerchinger and Pierson, 1997), and the impacts of spatially and temporally varying snowmelt on subsurface flow in a mountainous environment (Flerchinger et al., 1994). The SHAW model has also been used to simulate seed-zone soil water and temperature conditions to predict seed germination (Hardegree and Flerchinger, 2003; Flerchinger and Hardegree, 2004; Ekeleme et al., 2005; Masin et al., 2005).

In the PNW, tillage management can be used to optimize seed-zone soil water and temperature conditions for seed germination. The SHAW model can help to develop management strategies that optimize seed- and root-zone water content while minimizing soil disturbance and erosion. Our objectives were: (i) to assess the effects of CF and RT on seed- and root-zone water and temperature regimes; and to (ii) test the SHAW model's ability to simulate management effects on soil water and temperature distribution.

Materials and Methods

Treatments

The field study was initiated in 2002 at the Washington State University Dryland Research Station at Lind, Washington (47°00′12″N, 118°33′46″W, 500 m a.s.l.). Long-term (1917-2002) mean annual precipitation was 244 mm. The experiment site was level with zero slope. The soil at the site is a Shano silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids), deep, well-drained and formed on loess. Prior to 1998, the site was in a traditional tillage-based winter wheat-summer fallow cropping system. From 1998 to 2001, no-till spring wheat was produced annually followed by no-till winter wheat harvested in July 2002.

A treatment each of the CF and RT (70 × 8 m) was established following winter wheat harvest in 2002 (fig. 1). The RT treatment consisted of an application of glyphosate herbicide [N-(phosphonometheyl) glycine] in early March 2003, at a rate of 0.32-kg acid equivalent ha^{-1} to control weeds; a primary spring tillage plus liquid aqua NH_3-N injection at a depth of 13 cm in early April 2003 with a non-inversion, undercutter sweep equipped with overlapping 80-cm wide blades; and rod-weeding (a 2-cm^2 rotating rod) at a depth of 10 cm in June and July 2003 to control Russian thistle (*Salsola iberica)* and other broadleaf weeds. Unlike traditional summer fallow tillage methods, where the soil surface is mixed and stirred, the undercutter sweep method causes minimal surface disturbance while breaking capillary continuity from the subsoil to the surface. In the CF treatment, the soil-residual herbicide (Spartan (sulfentrazone), 0.28 kg active ingredient/ha) was applied to standing wheat stubble in mid-December 2002. Stubble was left standing and undisturbed throughout the fallow period. Winter wheat was planted on 28 August 2003 with a deep-furrow drill in the RT treatment whereas winter wheat was planted and fertilized in one pass with a Cross-slot™ no-till drill on 28 October 2003 in the CF treatment (fig. 1).

Instrumentation and Monitoring

The two treatments were monitored from 11 April 2003 until 14 March 2004 using meteorological and soil sensors connected to a data logger (CR10X, Campbell Scientific Inc., Logan, Utah). The weather data, such as wind speed and direction, solar radiation, relative humidity, air temperature,

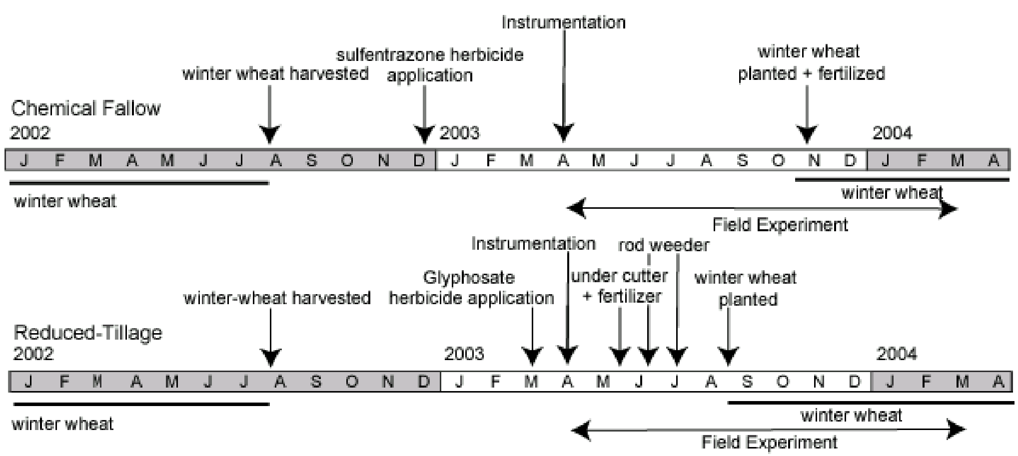

Figure 1. Management operations for the chemical fallow (CF) and reduced-tillage fallow (RT).

and precipitation, were monitored every 30 minutes. The soil data, including water content and temperature, were recorded every hour.

Water potential and soil temperature were monitored with a total of 10 heat dissipation sensors (Model 229, Campbell Scientific Inc., Logan, Utah) installed from 2.5- to 47.5-cm depths in 5-cm increments. The heat dissipation sensors were calibrated following Flint et al. (2002). Water content was monitored at the depth of 15-90 cm in 15-cm increments with six horizontally installed soil water probes (Echo Probe, Decagon Devices Inc., Pullman, Wash.). The water probes were calibrated in the laboratory by placing them into containers of soil taken from the field site, adjusting the soil water content incrementally, and fitting linear calibration equations to the data. In addition, we determined gravimetric water contents at the depths of 0-15 cm and 15-30 cm in every two weeks from 18 April to 8 September 2003. Gravimetric measurements were used to verify water content readings from the soil water probes. Additionally, gravimetric water content was determined from soil cores (four replicates) in 2-cm increments to a depth of 22 cm and 15-cm increments to a depth of 180 cm on 27 August 2003, immediately before the planting of winter wheat in the RT treatment. During tillage and planting operations, sensors in the top 20 cm of soil were removed and then reinstalled immediately thereafter.

The SHAW Model

The SHAW model uses information on vegetation canopy, snow, and surface residues to describe one-dimensional, coupled water and heat flow in soils (Flerchinger and Saxton, 1989; Flerchinger, 2000a). Water flow is modeled in both liquid and vapor forms using the Richards equation:

$$\frac{\partial \theta_l}{\partial t} + \frac{\rho_i}{\rho_l}\frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial \psi}{\partial z}+1\right)\right] + \frac{1}{\rho_l}\frac{\partial q_v}{\partial z} \quad (1)$$

where θ_l and θ_i are the volumetric liquid water and ice contents, respectively, ρ_l and ρ_i are the liquid and ice densities, respectively, K is the unsaturated hydraulic conductivity, ψ is the matric potential, and q_v is the vapor flux. The soil water characteristic in SHAW is represented by (Brooks and Corey, 1966):

$$\psi = \psi_e \left(\frac{\theta_l}{\theta_s}\right)^{-b} \quad (2)$$

where ψ_e is the air entry potential, b is a pore size distribution parameter, and θ_s is the saturated volumetric water content. The unsaturated hydraulic conductivity K is computed from (Campbell and Norman, 1998):

$$K = K_s \left(\frac{\theta_l}{\theta_s}\right)^{(2b+3)} \quad (3)$$

where K_s is the saturated hydraulic conductivity. The Clausius-Clapeyron equation is used to calculate water potentials under frozen conditions.

Heat flow is described by Fourier's law and by considering the advection of heat due to liquid water and vapor flow as well as latent heat due to evaporation and freezing (Flerchinger and Saxton, 1989). Thermal conductivity of the soil, k, is calculated by (DeVries, 1963):

$$k = \frac{\sum_j m_j \upsilon_j k_j}{\sum_j m_j \upsilon_j} \quad (4)$$

where the subscript j indicates the different phases, i.e., soil minerals, organic matter, water, ice, and air, m_j is a weighting factor, υ_j is the volume fraction of the different phases, and k_j is the thermal conductivity. Heat input is determined from the net amount of absorbed solar radiation, with both land slope and reflection and backscattering due to plant canopy or surface residues taken into consideration (Flerchinger et al., 2003). Sensible and latent heat transfer at the soil surface is calculated following a bulk aerodynamic approach (Flerchinger et al., 2003).

SHAW Model Parameters and Simulations

Inputs for SHAW simulations were determined primarily based on laboratory and field measurements while other parameters were obtained from the literature (tables 1 and 2). The fraction of soil surface covered by crop residues was estimated using a grid-based method (USDA Soil Conservation Service, 1992; Leiting, 2003). Two top-view digital images of the soil surface were taken in May 2003, four weeks after the sweep-tillage operation in the RT plot. A regular grid (25 × 20 cm in size with 6×4 grids) was superimposed over the images and the percentages of residue coverage for six selected grid points were estimated and averaged. Percent crop residue cover was converted to a biomass load in kg/ha(USDA Soil Conservation Service, 1992). Values for albedo of surface residues and dry soil under CF and RT were derived from previous studies (Campbell and Norman, 1998; Fernhout and Kurtz, 1999).

Soil samples representing the soil surface and major soil horizons (Ap, Bw, C) were taken at the depths of 2.5, 10, 30, and 60 cm in each treatment. Bulk density was determined using the core method (Blake and Hartge, 1986); organic matter by loss on ignition (Sheldrick, 1984); particle size distribution by sieving and static light scattering following removal of carbonates and organic matter (Kunze and Dixon, 1986); and saturated hydraulic conductivity on undisturbed samples with the constant head method (Klute and Dirksen, 1986). Soil water characteristics of undisturbed samples

Table 1. Input parameters for SHAW modeling.

Parameter	Chemical Fallow	Reduced-Tillage Fallow
Fraction of surface covered by residue	0.37	0.24
Dry weight of residue on surface (kg/ha)	800	520
Albedo of dry soil	0.13[a]	0.18[a]
Albedo of residue	0.23[b]	0.23[b]
Wind-profile surface-roughness		
Parameter for momentum transfer (cm)	0.6[c]	0.4[a]
Wind-profile roughness parameter for momentum transfer with snow cover (cm)	0.15[d]	0.15[d]
Exponents for calculating albedo of moist soil	0[d]	0[d]

[a] For tilled soil (Campbell and Norman, 1998).
[b] From Fernhout and Kurtz (1999).
[c] For no-till plot (Flerchinger, 2000b).
[d] From Flerchinger (2000b).

were obtained using hanging water columns (0 to -0.01 MPa), a pressure plate apparatus (-0.01 to -0.5 MPa, Soil Moisture Equipment, Santa Barbara, Calif.), and a dew point psychrometer for water potentials less than -0.5 MPa, (WP-4, Decagon Devices Inc., Pullman, Wash.). Equation 2 was fitted to the soil water characteristic data to determine hydraulic properties (air-entry potential ψ_e, and the pore size distribution parameter *b*). A nonlinear parameter optimization procedure was used to estimate optimal parameter values from the experimental data.

The SHAW model was used to simulate soil temperature and water content over the entire field experiment period. The Shano silt loam soil is typically more than 1.8 m deep (USDA Soil Conservation Service, 1967), and the soil domain for the modeling was assumed as 200 cm deep. The domain was discretized into a total of 22 nodes, conforming to three morphological layers of 0 to 25 cm, 25 to 50 cm, and 50 to 200 cm and corresponding to the positions of the soil water and temperature sensors. For water flow, a unit-gradient boundary condition was used for the lower boundary and a specified flux (observed precipitation) for the upper boundary. For heat flow, a constant temperature, i.e.,the annual mean air temperature was assumed for the lower boundary and atmospheric weather conditions (field-observed air temperature, wind speed, and humidity) were used for the upper boundary condition. The initial conditions for water and heat flow consisted of observed soil water and temperature profiles on 11 April 2003.

The field-observed solar radiation data appeared erroneous possibly due to malfunctioning of the measurement device. Consequently, daily solar radiation data was estimated from daily maximum and minimum temperatures using ClimGen, an embedded program of the CropSyst model (Stöckle et al., 2003). Daily solar radiation was then converted into hourly data using latitude and day of the year following Campbell and Norman (1998).

Statistical Analysis

Nonparametric statistical analyses were conducted to determine differences in water contents and soil temperatures between CF and RT. Correlation analyses of time series of (1) daily soil water content and (2) daily soil temperature under each treatment indicated a lack of independence within the individual samples, i.e., there was a serial correlation over time within each sample. Normality tests of the paired differences of daily soil water content and daily soil temperature under the two treatments further suggested the non-normality of the samples. Hence, nonparametric tests were performed.

Specifically, signed-rank tests, the nonparametric analogue of paired *t*-tests, with a significance level of 5%, were conducted using the univariate procedure of the SAS program (SAS Institute Inc., 2004) on (i) daily mean water content and soil temperature monitored with sensors for each individual depth between April 2003 and March 2004 in the CF and RT plots, (ii) water contents determined from the core samples taken for 0 to 15 cm and 15 to 30 cm between April and September 2003, and (iii) mean water contents determined from the replicated core samples taken at 12 to 22 cm (typical layer for winter wheat seed placement) on 27 August 2003.

Additionally, root mean square deviations ($RMSD = \sqrt{\sum_{i=1}^{n}(x_{s,i} - x_{o,i})^2/n}$, $x_{s,i}$ and $x_{o,i}$ are simulated and observed values, respectively) between the SHAW-simulated and field-observed soil water and temperature at various depths under the CF and RT were also determined.

Results and Discussion

Soil Water Contents and Potentials

Soil physical properties of the CF and RT plots were similar, except for the top 10 cm, where RT had considerably lower bulk density and a less negative air entry potential (table 2). Temporal variations of precipitation and soil water in the two treatments are shown in figure 2. In CF, the top 30 cm of soil dried during the summer months to about 0.10 m^3/m^3, but the subsoil below 30 cm retained water near 0.15 m^3/m^3. The effect of the precipitation on soil water was not evident until December (fig. 2b and c). When sensors were replaced after planting in the CF plot, the replaced sensors malfunctioned at the beginning, leading to a period of missing data (fig. 2b). In the RT plot, the top 30-cm sensors started to malfunction in December 2003, and data were thereafter discarded (fig. 2c).

The top 15 cm of soil was wetter in the CF than in the RT, in particular in late summer (fig. 2d). The soil water content below the 15-cm depth was generally higher than that in the top 15 cm for both CF and RT plots reaching 0.15 m^3/m^3 at 90 cm (fig. 2c). For the CF plot, soil water contents at 15 cm and 30 cm were similar and decreased from 0.13 m^3/m^3 in April to 0.11 m^3/m^3 in September. For the same period, soil water content at the top 15 cm in the RT plot decreased from 0.13 to 0.08 m^3/m^3 while soil water content at 30 cm varied between 0.11 and 0.14 m^3/m^3. Soil water content at 90 cm in both plots was above 0.15 m^3/m^3 most of the time.

The nonparametric signed-rank tests showed that, over the entire monitoring period of April 2003 to March 2004, the water contents measured with the Echo probes at each depth were significantly different between the two treatments (fig. 3a). At most depths water contents in CF were higher than in RT, but at the 30-cm depth, the opposite was found (fig. 3a). The water potentials indicated that the differences in water contents at 30-cm depth were due to differences in the soil water characteristic at this depth.

The average soil temperatures at the various depths were consistently higher in the CF plot than in the RT plot (fig. 3b). Temperature measurements at the 47.5-cm depth in the RT plot were erroneous for the entire study period, and therefore no comparison was made for this depth.

On 11 April 2003, the CF contained 139 mm of water in the 0- to 90-cm depth, and the RT contained 123 mm of water. By 28 August 2003 the CF contained 148 mm and the RT contained 128 mm of water. This increase in water storage was likely due to the rainfall occurring in April and May 2003; and the slightly greater increase in the CF was possibly because the rainfall more effectively infiltrated into the undisturbed CF surface compared to the RT soil mulch. After 28 August 2003 the water storage continuously decreased until the onset of the fall rainfall. By 14 March 2004, the CF and RT contained 167 and 152 mm of water, respectively. Observed data for the top 30 cm of soil for RT was missing

Table 2. Measured soil properties under chemical fallow and reduced-tillage fallow.[a]

Parameter	Depth (cm)	Chemical Fallow	Reduced-Tillage Fallow
K_s (cm/min)	2.5	0.072 ±0.042	0.084 ±0.012
	10	0.072 ±0.042	0.084 ±0.012
	30	0.066 ±0.03	0.102 ±0.06
	60	0.078 ±0.018	0.072 ±0.042
ρ_b (g/cm^3)	2.5	1.17 ±0.04	0.80 ±0.04
	10	1.17 ±0.04	1.15 ±0.04
	30	1.14 ±0.05	1.16 ±0.09
	60	1.33 ±0.06	1.27 ±0.07
θ_s (m^3/m^3)	2.5	0.54 ±0.01	0.60 ±0.03
	10	0.54 ±0.01	0.60 ±0.03
	30	0.58 ±0.01	0.59 ±0.03
	60	0.51 ±0.02	0.56 ±0.02
Sand (% wt.)	2.5	46.9	45.6
	10	46.9	45.6
	30	46.6[b]	42.4
	60	46.3	44.0
Silt (%wt.)	2.5	47.0	48.3
	10	47.0	48.3
	30	47.7[b]	51.8
	60	48.4	50.2
Clay (%wt.)	2.5	6.1	6.1
	10	6.1	6.1
	30	5.8[b]	5.8
	60	5.4	5.9
OM (%wt.)	2.5	1.3	1.8
	10	1.3	1.8
	30	1.2	1.3
	60	1.0	1.3
B	2.5	2.77 ±0.01	2.61 ±0.02
	10	2.77 ±0.01	2.61 ±0.02
	30	2.76 ±0.01	3.02 ±0.03
	60	3.41 ±0.07	2.9 ±0.1
ψ_e (kPa)	2.5	-3.1 ±0.1	-2.5 ±0.4
	10	-3.1 ±0.1	-2.5 ±0.4
	30	-2.7 ±0.2	-2.0 ±0.2
	60	-2.4 ±0.5	-2.5 ±0.3

[a] Errors denote one standard deviation of three replicates.
[b] The original lab measurements of soil texture for the 30-cm depth in chemical fallow were 29%, 64%, and 7% for sand, silt, and clay, respectively. These results were regarded erroneous and averages of sand, silt and clay contents for the 10- and 60-cm depths, as shown in the table, were used instead in SHAW modeling.

during 10 December 2003–14 March 2004 (fig. 2c); hence, observed data for the 45-cm depth was used to replace the missing data. The greater net gain in soil water in the CF plot was due to the late planting of winter wheat, and thus less water use by the growing crop compared to the early-planted RT.

Water contents determined from the gravimetric sampling between April and September 2003, indicated that at the 0- to15-cm depth RT was wetter than CF (mean daily difference 0.0145 m^3/m^3, n = 9, signed-rank S-value = -17.5, P = 0.04). For the 15- to 30-cm depth, the water content was also higher in RT than in CF, though not statistically significant at α = 0.05 (mean daily difference 0.0098 m^3/m^3, n = 9, S-value = 13.5, P = 0.13). The disagreement between the gravimetric sampling and sensor measurement for the 0- to15-cm depth, where matric potential gradient tends to be large and soil water content varies substantially, may be attributed to the vertical position difference between the core sampling and the sensor placement.

A detailed depth-distribution of water content and water potential for 27 August 2003, one day before planting in the RT plot, is shown in figure 4. The soil close to the soil surface in August is typically very dry (water content of 0.01 to 0.04 m^3/m^3 in the top 0 to 10 cm), and the water potentials were more negative than -1.2 MPa. Both water contents and water potentials show a steep gradient close to the soil surface, with dry soil overlaying moist soil (water content > 0.10 m^3/m^3).

The lower limit of the water content in the zone of seed placement for winter wheat emergence on silt loam soils in the Inland PNW is considered to be 0.11 m^3/m^3 [reported by Schillinger and Papendick (1997) for a Ritzville silt loam, very similar in texture to the Shano silt loam at the study site]. For our soil, this corresponds to a water potential of -0.21 to -0.25 MPa based on the soil water characteristics. On 27 August 2003, at a depth of 16 cm, typical of seed placement, the water content was 0.10 m^3/m^3 in the CF and 0.11 m^3/m^3 in the RT (fig. 4), the former just below and the latter right at the threshold for successful seedling emergence. The signed-rank test of soil water contents for 12–22 cm revealed wetter condition under RT, but not statistically significant (n = 6, S-value = -7.5, P-value = 0.16). Because water content in CF was below the threshold for seedling emergence, planting in CF was delayed until the rain season started in October. The drying of the seed zone in CF during the hot summer months has been widely observed in the study region, which is a reason why CF is generally not practiced by farmers.

The SHAW-simulated water contents followed the general trend of the experimental data (fig. 5a and b). For the CF, SHAW under-estimated soil water for the 15- and 45-cm depths during summer; however, the differences between the modeled results and observations were small (fig. 5c). Absolute differences in soil water between simulated and observed data were in most cases less than 0.03 m^3/m^3 (fig. 5c and d). Larger deviations between simulations and measured values were observed, mainly for the 15-cm depth, during winter. Interpolation of temperature measurements at the 12.5- and 17.5-cm depths shows that soil temperature at the 15-cm depth never fell below 0°C, hence the deviations between simulated and measured water contents may not be attributed to soil freezing at this depth. Partition between rain and snow, which is site-specific and is difficult to be accurately represented by the model, may have contributed to the discrepancy between the model predictions and field observations.

For the planting date of 28 August 2003, SHAW underestimated the water content in the seed zone, but overestimated the water content in the root zone (fig. 4b). SHAW-simulated soil water for the 16-cm depth was 0.09 m^3/m^3 for both the CF and RT, a soil water content insufficient for winter wheat planting (fig. 4b). SHAW simulations could not resolve the small, but important differences in seed-zone water content for successful seedling emergence.

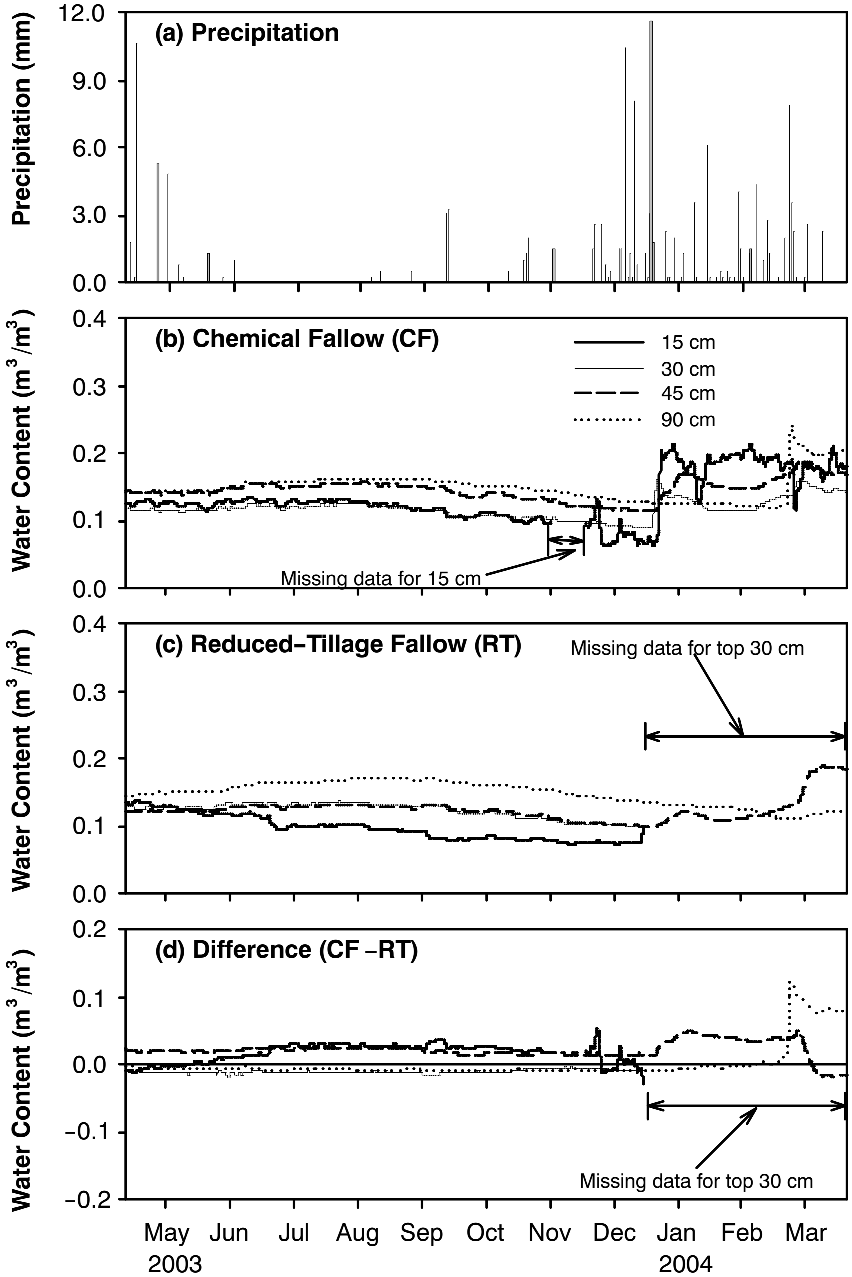

Figure 2. (a) Observed daily precipitation; observed water contents at different depths using Echo probe data under (b) chemical fallow (CF) and (c) reduced-tillage fallow (RT); and (d) difference in water contents between CF and RT.

The *RMSD* values for volumetric soil water content for all depths were in the range of 0.02 to 0.03 m^3/m^3 and 0.01 to 0.03 m^3/m^3 for CF and RT, respectively (table 3). The low values of the *RMSD* confirm good agreement between SHAW-simulated and field-observed soil water contents.

In the SHAW model, effects of tillage are reflected by modified soil properties, such as decreased soil bulk density and a water release characteristics for coarser-textured soil, as done in this study. The undercutter sweep and rodweeder operations in RT created a surface mulch layer with different soil properties that halted the upward movement of liquid water. In applying the SHAW model, we represented these surface properties by different bulk densities (table 2), which, nonetheless, did not suffice to cause significant differences in the model simulation.

Soil Temperatures

Observed and simulated soil temperatures are shown in figure 6. Generally, observed soil temperatures were higher in CF than in RT: on average the differences between CF and RT were 1.3°C at 2.5 cm, 1.1°C at 12.5 cm, and 1.0°C at 17.5 cm. Two factors may have led to the higher temperatures in CF: first, the higher bulk density (table 2) and more compact soil structure in CF can result in a larger thermal

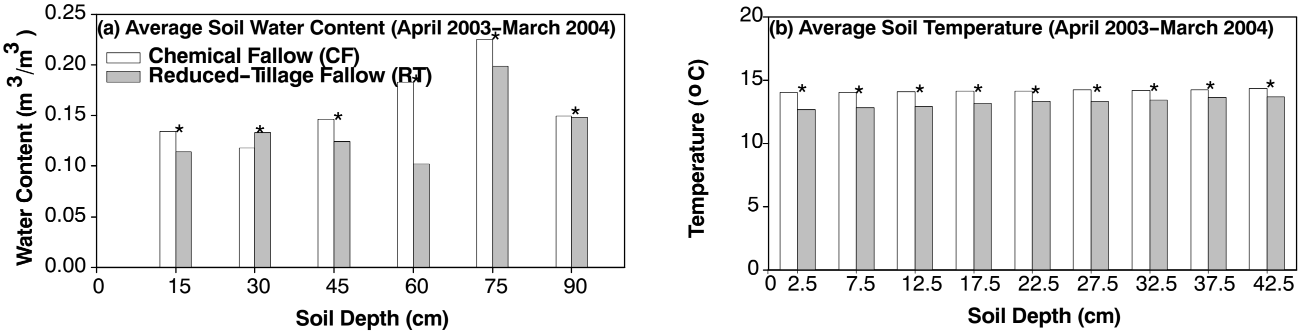

Figure 3. Averaged (a) water contents and (b) soil temperatures for chemical fallow (CF) and reduced-tillage fallow (RT) for 11 April 2003 to 14 March 2004 at different measurement depths. Asterisks denote significant difference at 5% level.

diffusivity; and second, the dry soil albedo of the CF was less than that of the RT (table 1), causing an overall greater heat flow in the CF as compared to the RT plot.

The general trend of the soil temperature was well simulated by SHAW, although a few discrepancies between SHAW predictions and field observations were up to 10°C. SHAW tended to under-predict soil temperature during the drying period (June-July) and over-predict during the wetting (November-December) period. The discrepancies between observed and simulated soil temperature were most

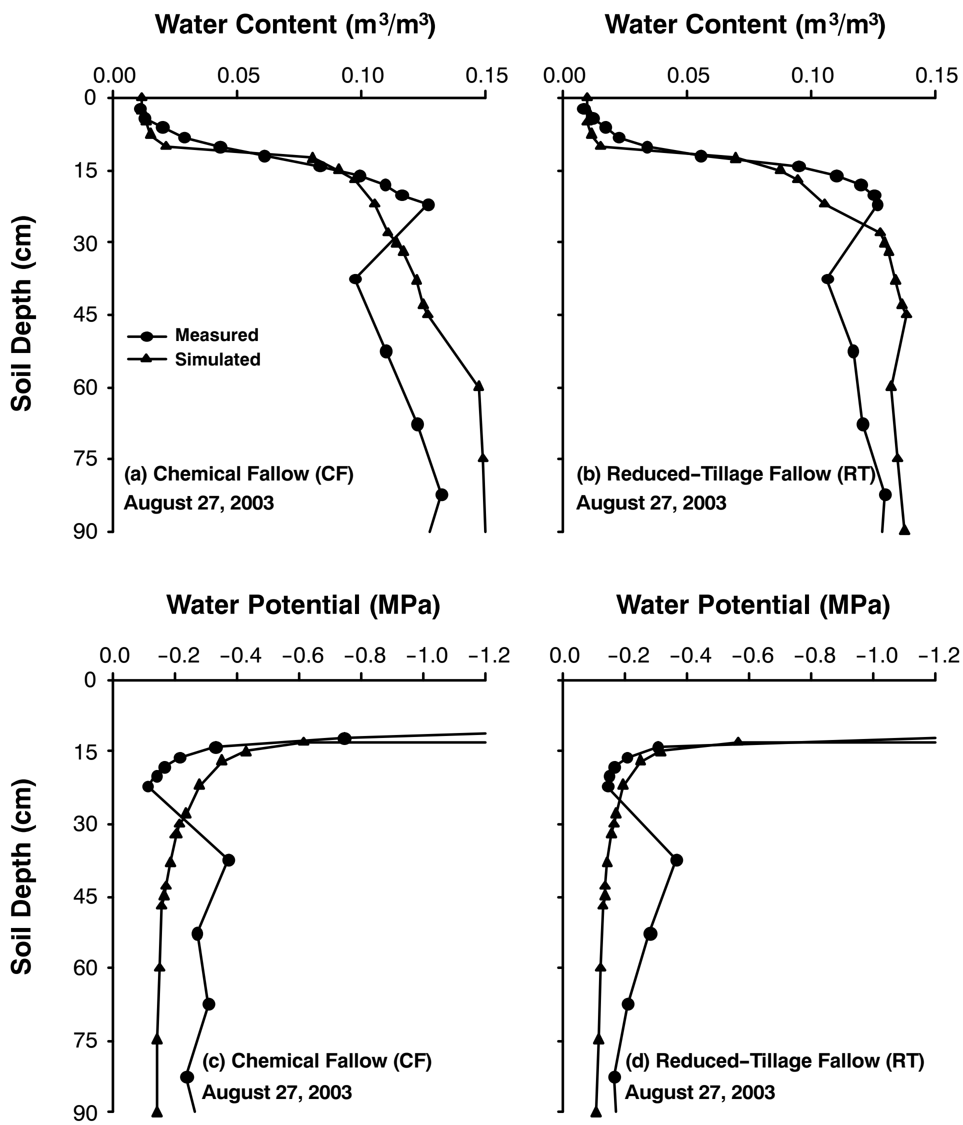

Figure 4. (a and b) Observed (gravimetric sampling) vs. simulated water contents and (c and d) observed vs. simulated water potentials for chemical fallow (CF) and reduced-tillage fallow (RT) on 27 August 2003.

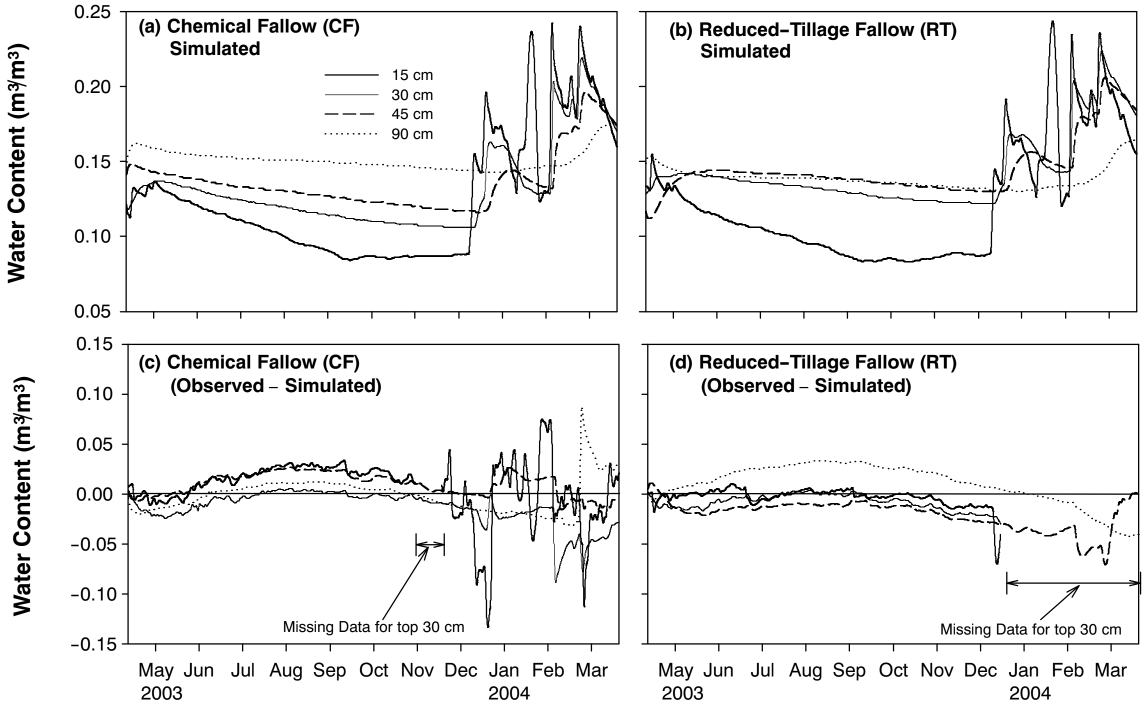

Figure 5. (a and b) Simulated water contents for chemical fallow (CF) and reduced-tillage fallow (RT) and (c and d) differences between observed and simulated data.

Table 3. Root mean square deviations (RMSD) between SHAW-simulated and field-observed soil water and temperature.

	Depth (cm)	RMSD CF	RMSD RT
Water Content (m^3/m^3)	15	0.03	0.01
	30	0.02	0.01
	45	0.02	0.03
	90	0.02	0.02
Temperature (°C)	2.5	2.6	2.8
	12.5	2.5	2.1
	17.5	2.4	2.0
	37.5	2.2	1.9

distinct in the surface layers, and diminished with increasing soil depth. Likely causes of the discrepancies between simulated and observed soil temperature may be the use of estimated solar radiation and errors in the parameterization of the water and heat flow equations. The input parameters for SHAW were very similar for the CF and the RT, except for the surface bulk density and the albedo. Despite different bulk density and albedo, simulated temperature differences between CF and RT were minor: from April 2003 to March 2004, the difference between CF and RT was -0.1°C for 2.5 cm, and -0.3°C for both 12.5 cm and 17.5 cm. The *RMSD* values for soil temperature for different depths (table 3) were in the range of 2.2 to 2.6°C and 1.9 to 2.8°C for the CF and RT, respectively, with the largest discrepancy occurring at the top-most depth of 2.5 cm.

Conclusions

This study showed that tillage management may significantly affect soil water and temperature in summer fallow in the PNW. Detailed measurements on 27 August 2003 suggested that the seed-zone water contents were lower in the CF than in the RT. Considering a threshold water content of 0.11 m^3/m^3 as the lower baseline for successful winter wheat seedling emergence in the silt loam soil at our experimental site, the RT treatment showed an advantage compared to the CF. The overall advantage of RT over CF for obtaining stands of early-planted winter wheat is commonly understood by farmers in the low-precipitation winter wheat-summer fallow cropping region and has been documented in previous studies (Oveson and Appleby, 1971; Hammel et al., 1981; Schillinger and Bolton, 1993). Yet future studies at different locations involving multiple replicates and longer duration are needed in order to further improve the current understanding of seed- and root-zone soil water as impacted by the CF and RT.

SHAW simulations of soil water content follow the general trend of the experimental data. For the CF, SHAW under-predicted soil water content, but for the RT, SHAW over-predicted the water content. However, absolute differences in soil water between observed and simulated data were mostly less than 0.03 m^3/m^3. SHAW over-predicted for the CF and under-predicted for the RT by up to 1°C on average over the entire experimental period. Maximal deviations between measurements and simulations were up to 10°C at the 2.5-cm soil depth. The trend of soil temperatures, nonetheless, was well described by the SHAW model.

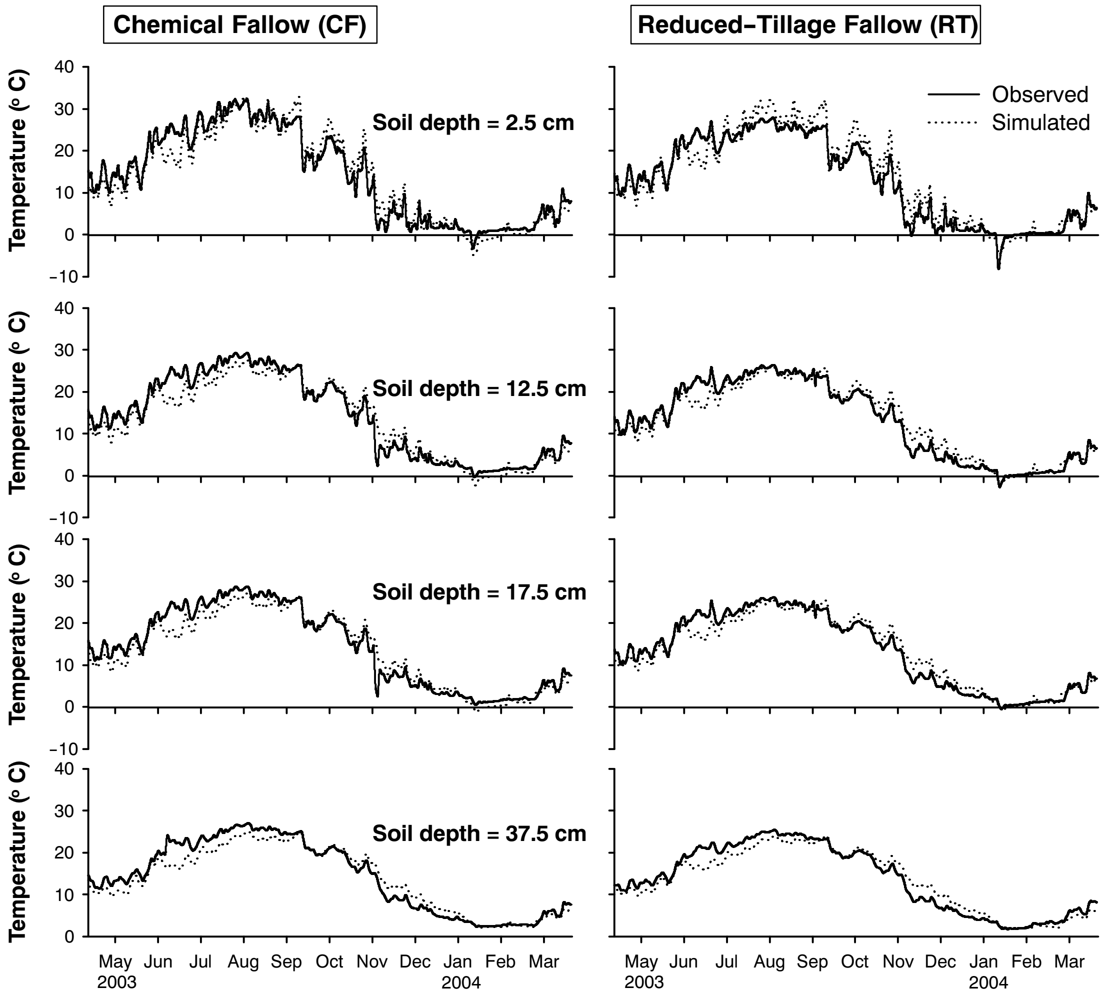

Figure 6. Observed and simulated soil temperatures (daily averages) at different depths for chemical fallow (CF) and reduced-tillage fallow (RT).

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