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Predicting seed-zone water content for summer fallow in the Inland Pacific Northwest, USA

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ABSTRACT

The Horse Heaven Hills in south-central Washington contains the world's driest rainfed wheat (*Triticum aestivum L.*) region. The climate is Mediterranean with average annual precipitation as low as 150 mm. The cropping system is winter wheat-summer fallow. Tillage is used in the spring of the 13-month fallow to establish a dry soil mulch to help retain seed-zone water to establish winter wheat planted deep into fallow in late August. However, the Horse Heaven Hills is often so dry that even tillage-based summer fallow (TF) cannot retain adequate seed-zone water, and farmers must then wait until the onset of rains in mid October or later for planting. In such dry years, farmers would be better off practicing no-till fallow (NTF) to protect the soil from wind erosion; but no predictive tools are available to assist in these decisions. The objectives of our study were (1) to predict seed-zone water contents and water potentials in late August or early September based on soil water content measured in early April and (2) to compare seed-zone water in TF and NTF. Experiments were conducted for 5 years at each of two sites. Soil water content was measured in both early April and late August. Soil properties and residue loads were characterized to calibrate the Simultaneous Heat and Water model (SHAW). Seed-zone water was simulated in late August based on measured soil water contents in early April and measured temperature and precipitation from April to August. The SHAW model correctly predicted seed-zone water content 80% of the time. The amount and timing of rainfall occurring in April, May, and June was the most important factor controlling the seed-zone water content in late August, suggesting that farmers should delay their decision on whether to practice TF or NTF until late in the spring.

1. Introduction

Winter wheat is profitably produced with as little as 150 mm annual precipitation in the Inland Pacific Northwest (PNW) of the United States in a 2-year winter wheat-summer fallow rotation (Schillinger and Young, 2004; Schillinger and Papendick, 2008). The majority of precipitation occurs between November and April, and summers are dry. Water evaporates from fallow soil during the summer, so farmers till the soil in the spring of the fallow year to create a loose, dry tillage mulch to preserve a portion of the over-winter precipitation in the seed zone (Papendick et al., 1973; Lindstrom et al., 1974; Hammel et al., 1981). Winter wheat is then planted in late August or early September as deep as 20 cm below the soil surface with deep-furrow drills to reach adequate water for germination and seedling emergence. Deep planting into carryover soil water is desirable because shallow planting after the onset of rains in late October or November reduces grain yield by 30% or more (Donaldson et al., 2001). Therefore, preserving seed-zone water during fallow is critical for profitable wheat production.

Primary spring tillage to create the loose, low bulk density soil mulch is usually conducted in April or early May. The main purpose of the tillage mulch is to reduce liquid and vapor flow by disrupting capillary and pore channels below the soil surface and by increasing thermal insulation (Papendick et al., 1973; Lindstrom et al., 1974; Hammel et al., 1981). However, as these soils are low in organic matter and lack structure, they are easily pulverized with excessive tillage and become vulnerable to wind erosion. The city of Kennewick, WA, northeast of the Horse Heaven Hills, has suffered severe air quality deterioration by wind-blown dust originating from tilled fallow (TF) (Sharratt and Lauer, 2006). Health hazards from wind-blown soil particulates of 10 μm and smaller (i.e., PM10) are well documented (Dockery and Pope, 1994; Saxton, 1995; Koren, 1995; Peden, 2001; USEPA, 2006).

Conservation tillage methods to minimize wind erosion from fallow have been extensively tested and are successfully practiced by many farmers. With conservation tillage, implements operate below the surface to break soil capillary continuity and control weeds without mixing or stirring the soil surface, and thus retain ample residue from the previous wheat crop. Conservation tillage

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fallow is equally effective as intensive tillage fallow for retaining seed-zone soil water and subsequent winter wheat grain yield (Schillinger, 2001; Janosky et al., 2002), but the pace of adaption among farmers is slow because expensive new equipment is required.

The wide-spread practice of no-till (i.e., chemical) fallow (NTF) could essentially eliminate wind erosion (Bond and Willis, 1969; Ramig and Ekin, 1984; Flury et al., 2009; Al-Mulla et al., 2009). However, in the Pacific Northwest, NTF is not as effective in preserving seed-zone soil water as a tillage mulch (Hammel et al., 1981; Wuest, 2010; Wuest and Schillinger, 2011), and this is the reason why NTF is not commonly practiced in this dry region.

The Horse Heaven Hills region is often so dry that adequate seed-zone water cannot be maintained even with TF, forcing farmers to wait until the onset of rains in mid-to-late fall to plant winter wheat. In such dry years, given the problem of wind erosion, farmers would be better off practicing NTF. However, as NTF will not preserve seed-zone water for late August planting (unless the unlikely thunderstorm in mid-to-late August wets the surface with 15 mm or more rainfall), farmers need to know, before they conduct primary tillage in the spring, whether TF will maintain sufficient seed-zone water for deep planting in late August–early September. To help farmers decide whether TF or NTF is preferable, we need to be able to predict the seed-zone soil water content and potential.

In this study, a numerical water and heat flow model was used to predict seed-zone water in late August based on measurements of soil water contents in early April. Physically based hydrological soil models describe relevant processes of water and heat flow, and if calibrated properly, can be used as accurate predictive tools. The SHAW model simulates coupled heat and water movement in the root zone as affected by tillage and residue management within a soil–plant–water continuum (Flerchinger and Saxton, 1989; Flerchinger, 2000). The SHAW model has been tested and applied for quantifying soil water and temperature dynamics for diverse tillage and residue management practices (Flerchinger and Saxton, 1989; Al-Mulla et al., 2009), and to simulate seed-zone soil water and temperature conditions to predict seed germination (Hardegree and Flerchinger, 2003; Flerchinger and Hardegree, 2004).

The objective of our study was to quantify seed-zone soil water dynamics for the dryland winter wheat-summer fallow cropping system in the Horse Heaven Hills of the Pacific Northwest. Specific objectives were to: (1) predict seed-zone water contents and water potentials in late August based on soil water measured in early April, and (2) compare seed-zone water in TF versus NTF.

2. Materials and methods

2.1. Field experiments

A 5-year field experiment was conducted at each of two sites in the Horse Heaven Hills, denoted Eastern and Western sites, respectively (Fig. 1). At each site, TF and NTF treatments were established in individual 61 × 18 m plots. Experimental design was a randomized completed block with four replications. Total experiment area at each site was 3.8 ha. The soil at the Eastern site is a Ritzville coarse silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls) and at the Western site a Warden coarse silt loam (coarse-silty mixed, superactive, mesic Xeric Haplocambids) (Rasmussen, 1971).

In early April and again in late August or early September from 2006 to 2010 at both sites, soil volumetric water content in 30- to 180-cm depth was measured in 15-cm increments by neutron thermalization (Hignett and Evett, 2002). Volumetric soil water content in the 0- to 30-cm depth was determined from two 15-cm core samples using gravimetric procedures (Topp and Ferre, 2002). Seed-zone volumetric water content was determined in late August in 2-cm increments to a depth of 26 cm with an incremental soil sampler.

Both the TF and NTF were established on standing and undisturbed stubble of the previous winter wheat crop. The TF treatment consisted of an application of glyphosate herbicide (0.84 kg acid equivalent/ha) in March, a primary spring tillage with a tandem disk to a depth of 13 cm in early April, liquid aqua NH_3-N injected with shanks spaced 30 cm apart in May, followed by one or two rodweeding operations at a depth 10 cm to control weeds as needed in June and July. In the NTF treatment, stubble from the

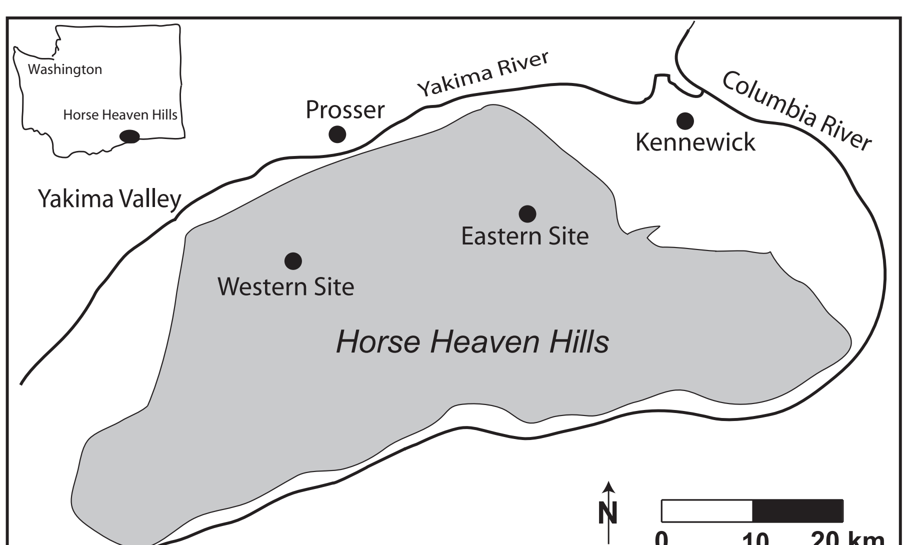

Fig. 1. Location of the experimental sites in the Horse Heaven Hills, Washington.

previous winter wheat was left standing throughout the entire 13-month fallow period and weeds were controlled with glyphosate herbicide (0.84 kg acid equivalent/ha) in mid March and with other selected herbicides as needed thereafter until late August. Winter wheat was planted deep (as deep as 18 cm below the soil surface) in TF in late August with deep-furrow drills when sufficient seed-zone water was present, or otherwise planted shallow (2 cm below the soil surface) in mid October or later. The NTF treatment at both locations were planted to at a depth of 2 cm in middle of October or later after the onset of fall rains. Nitrogen fertilizer was applied at the time of planting with a no-till drill in the NTF treatment.

2.2. Weather data

Weather data during the study period for the two sites were obtained from two meteorological stations of the Washington State University Agricultural Weather Network (AgWeatherNet, 2010). Station Carlson (453 m above mean sea level) is located 0.7 km northeast of the Eastern site and Station McKinley Spring (324 m above mean sea level) is located 1.0 km north of the Western site. Data used were hourly precipitation, air temperature, wind speed, relative humidity, and solar radiation. Average annual precipitation from 2006 to 2010 at the Eastern site was 228 mm and at the Western site 174 mm.

2.3. Characterization of soil properties and residue cover

In August 2009, soil and residue samples were collected from plots at both sites to determine soil properties, residue mass, and percent residue cover. Undisturbed soil samples were collected at three depths (0–15 cm, 15–30 cm, and 30–40 cm) using a 5.7-cm inner diameter sampler (Soil core sampler-model 0200, Soilmoisture Equipment Corp., Santa Barbara, CA). As the TF treatment had a loose, low bulk density surface soil mulch of ≈15 cm depth, the sampler core was inserted by hand in order not to compact the soil. For the deeper layers of TF and for sampling in the NTF treatment, soil above the layer of interest was first excavated and a constant weight was then dropped on the sampler to obtain soil cores. Soil samples were also taken for determination of organic matter and particle size distribution at four depths (0–15 cm, 15–30 cm, 30–40 cm, and 50–70 cm).

Surface residue data were obtained by clipping at the ground level and gathering from a representative 1 m^2 area. Dry weight of residue was determined after oven drying at 60 °C for 72 h. Digital photographs were taken prior to residue sampling to assess the percent residue cover. The photographs were divided into grids and percent residue cover was assessed for each grid (USDA, 1992).

Organic matter was determined using a TruSpec CN Analyzer (Model TruSpec CN, LECO Inc., MI). Soil pH was measured in a 1:1 w/v soil–water extract. For particle size analysis, soil samples were pretreated with H_2O_2 to remove organic matter and with Na-acetate to remove carbonates (Gee and Or, 2002). After pretreatment, the soil was passed through a series of sieves, the smallest being 850 μm. All soil material from both sites passed through the smallest sieve. The particle size distribution was then determined by static light scattering (MasterSizer S, Malvern, England). The water retention characteristic (i.e., primary drainage curve) was determined from the undisturbed cores. The hanging water column method was used for potentials >−100 hPa, followed by the pressure plate method for potentials between −100 and −5000 hPa, and dew point measurements for potentials <−5000 hPa (Bittelli and Flury, 2009). Saturated hydraulic conductivity was measured using the constant-head method (Reynolds et al., 2002).

On May 25, 2010, in situ measurements of field saturated hydraulic conductivity were conducted. The field saturated hydraulic conductivity was measured with a Guelph permeameter (Model 2800, Soilmoisture Equipment Corp., Santa Barbara, CA) at a depth of 25 cm and 40 cm at each farm site. Soil property and residue measurements were replicated three times.

2.4. SHAW modeling

The SHAW model was used to simulate soil water for each site and treatment for the 5 years. SHAW is a one-dimensional, finite difference model that includes a detailed mechanistic description of water, vapor, and heat flow through soil and residue layers, and is specifically designed to cope with differences in tillage management (Flerchinger and Saxton, 1989; Flerchinger, 2000). Water flow in the soil is considered in both liquid and vapor form:

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

where the terms represent, respectively, rate of change in volumetric liquid content; net vertical liquid flux; net vapor flux; and a source/sink term. The symbol θ_l is liquid volumetric water content, t is time, z is depth from the surface, K is unsaturated hydraulic conductivity, ψ is soil matric potential, ρ_l is density of liquid water, q_v is water vapor flux, and U is a source/sink term. Corresponding units are given in Appendix A. The liquid flux is computed using matric potential gradient and hydraulic conductivity. The soil water characteristics in SHAW is represented as (Brooks and Corey, 1966):

$$\psi = \begin{cases} \psi_e\left(\dfrac{\theta}{\theta_s}\right)^{-b} & \text{if } \psi < \psi_e \\ \psi_e & \text{if } \psi \geq \psi_e \end{cases} \tag{2}$$

where ψ_e is air-entry potential, θ is volumetric water content, θ_s is saturated water content, and b is a pore size distribution index. The unsaturated hydraulic conductivity K is computed using (Campbell, 1974):

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

where K_s is saturated hydraulic conductivity.

The net vapor flux through soil is driven by potential and temperature gradients. Vapor flux through soil is expressed as:

$$q_v = q_{vp} + q_vT = -D_v\rho'_v\frac{dh}{dz} - \varsigma D_v hs\frac{dT}{dz} \tag{4}$$

where q_{vp} is vapor flux due to water potential gradient, q_{vT} is vapor flux due to temperature gradient, D_v is vapor diffusivity in the soil, ρ'_v is saturated vapor density, h is relative humidity within the soil, s is change in saturated vapor density with respect to temperature, and T is temperature.

The flux of water vapor in the air voids of a residue layer is estimated by:

$$\frac{\partial\rho_v}{\partial t} = \frac{\partial}{\partial z}\left(K_v\frac{\partial\rho_v}{\partial z}\right) + E_r \tag{5}$$

where the terms represent, respectively, the rate of change in vapor density; net vapor flux into a residue layer; and evaporation rate from residue elements. The symbol ρ_v is vapor density within the residue or soil, K_v is convective vapor diffusion coefficient, and E_r is rate of evaporation from a residue element to the void space within the residue. The evaporation rate (E_r) from a residue layer with a thickness of Δz is expressed as:

$$E_r\Delta z = K_r(h_a\rho'_v - \rho_v) \tag{6}$$

where K_r is vapor conductance between residue elements and air voids. Evaporation is estimated using vapor fluxes from soil and residue to air.

For the numerical simulations, the soil was discretized into 22 nodes: 2.5-cm increments were used from the soil surface to 25 cm depth, 5-cm increments from 25 to 50 cm depth, and 30-cm increments from 50 to 200 cm depth. The initial condition was set as the measured soil water contents and temperatures in spring. The lower boundary condition for water flow was set as unit gradient and the upper boundary condition was the observed precipitation. The lower boundary condition for heat flow was set as the mean annual air temperature and the upper boundary condition was the observed weather condition, i.e., air temperature, wind speed, relative humidity, and solar radiation. We used an hourly time step for the simulations. Following the morphological description of the soils in the field, for the numerical simulation we considered the soil to have four layers (a tillage mulch or an upper A_p-horizon, a lower A-horizon, a B1- and a B2-horizon). A residue layer of 2 cm thickness was present in NTF.

Parameters needed for the SHAW model were obtained from the laboratory measurements and are shown in Table 1. Measured soil water characteristic data were analyzed with the RETC code (van Genuchten et al., 1991) to fit the Brooks and Corey model (Eq. 2).

The dynamics of water flow was simulated for each site and treatment from March to September for the years 2006–2010. This allowed us to test the hypothesis that SHAW simulations can accurately predict late August water contents based on measured early April water contents. Simulations were run in forward mode, using the initial and boundary conditions as specified above. The simulated water contents for the planting dates were then compared with the field measurements.

Statistical analysis was conducted to determine the differences in soil water content in TF and NTF and between model simulations and experimental data. Specifically, paired t-tests, with a significance level of 5%, were conducted using SAS (SAS Institute Inc., 2004). To assess the model performance we used the root mean square error (RMSE):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\theta_o^i - \theta_m^i)^2}{n}} \quad (7)$$

where θ_o is observed water content and θ_m is simulated water content.

3. Results and discussion

3.1. Soil properties and residue cover

The soil properties of the TF and NTF treatments were similar (Table 1) except for bulk density and hydraulic properties in the top 15 cm. The soil texture is typical for a sandy loam (USDA soil classification). The 50- to 70-cm depths at the Western site had less clay than soils at the Eastern site, but the texture was still classified as a sandy loam. Organic matter in the A-horizon was greater at the Eastern site compared with the Western site, which can be attributed to greater residue biomass production due to higher precipitation. The range of 0.4–2% wt/wt organic matter is typical for agricultural soils in the semi-arid central part of the Pacific Northwest (Boling et al., 1998). Surface residue cover for NTF was about 70% and dry biomass was 4000 kg ha^{-1} at the Eastern site, compared to 50% and 2000 kg ha^{-1} at the Western site, respectively. The TF had essentially no surface residue.

3.2. Weather data

Annual precipitation during the 5-year study period in relation to the longer-term annual average precipitation is shown in Fig. 2. Mean annual temperature was 10.0 °C and mean annual average precipitation was 228 mm (2006–2010) at the Eastern site, compared to 11.3 °C and 174 mm (2006–2010) at the Western site, respectively. Annual precipitation in 2007, 2008, and 2009 was less than average, and in 2006 and 2010 was greater than

Table 1
Measured soil properties under tillage fallow and no-till fallow at the two experimental sites. Values shown are means (n = 3). A description for all symbols is provided in Appendix A.

Treatment	Horizon	Depth (cm)	Sand (%wt.)	Silt (%wt.)	Clay (%wt.)	OM (%wt.)	pH	ρ_b (g/cm^3)	θ_s (m^3/m^3)[a]	b	ψ_e (m)	K_s (cm/d)[b]	K_{fs} (cm/d)[c]
							Eastern site						
Tillage fallow	A_p[d]	0–15	56	31	13	1.10	6.0	1.08	0.54	2.30	−0.5	94	123
	A	15–30	55	31	14	0.75	5.3	1.26	0.49	2.87	−0.48	na	8
	B1	30–40	58	28	14	0.57	6.2	1.28	0.49	3.04	−0.47	na	44
	B2	50–70	57	30	13	0.64	7.2	na	na	na	na	na	na
No-till fallow	A1	0–15	57	29	14	1.48	6.3	1.26	0.44	3.00	−0.7	77	29
	A2	15–30	54	31	15	0.57	5.8	1.30	0.48	2.98	−0.48	na	na
	B1	30–40	56	30	14	0.54	6.9	1.24	0.50	3.00	−0.46	92	44
	B2	50–70	54	33	13	0.56	7.1	na	na	na	na	na	na
							Western site						
Tillage fallow	A_p	0–15	51	32	18	0.63	7.0	1.26	0.47	3.00	−0.48	57	21
	A	15–30	47	35	18	0.39	6.8	1.38	0.44	3.08	−0.48	37	15
	B1	30–40	51	33	16	0.47	7.5	1.44	0.43	2.85	−0.59	38	30
	B2	50–70	56	32	12	0.81	7.8	na	na	na	na	na	na
No-till fallow	A1	0–15	51	30	19	1.21	6.8	1.31	0.45	3.00	−0.7	57	7
	A2	15–30	50	32	18	0.49	6.9	1.38	0.45	2.75	−0.54	30	84
	B1	30–40	53	32	15	0.52	7.7	1.42	0.44	3.01	−0.58	27	43
	B2	50–70	65	25	10	2.43[e]	8.2	na	na	na	na	na	na

na: data not available.
[a] Saturated water content.
[b] Constant-head saturated hydraulic conductivity.
[c] Field-saturated hydraulic conductivity.
[d] Tillage mulch layer, A_p stands for the tillage pan subhorizon in the A-horizon.
[e] Includes inorganic carbonate.

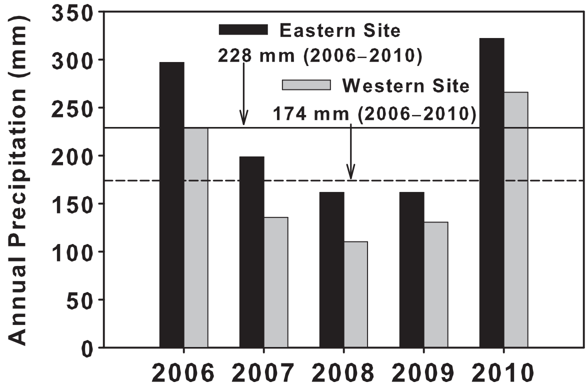

Fig. 2. Annual precipitation for 2006–2010 and longer-term average annual precipitation (horizontal lines) at the Eastern and Western sites.

average (Fig. 2). For more detailed discussion of the experimental results, we chose a relatively dry year (2009) and a relatively wet year (2010). Fig. 3 shows the daily temperature and precipitation for 2009 and 2010. There was considerably more rainfall during the spring in 2010 as compared to 2009, with substantial rains in April and May 2010. In 2009, cumulative rainfall from April through August was 36 mm for the Eastern site and 29 mm for the Western site. In 2010, cumulative rainfall from April through August was 120 mm for the Eastern site and 92 mm for the Western site. As discussed later, this difference in spring rainfall will prove to be relevant for seed-zone water contents in late August.

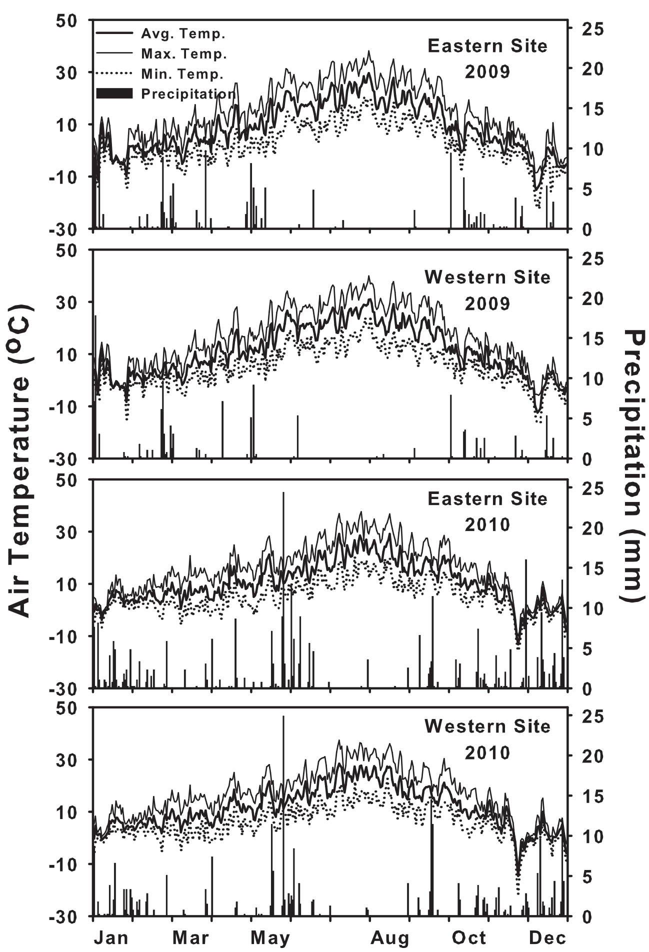

Fig. 3. Daily mean air temperature and precipitation at the Eastern and Western sites in 2009 and 2010.

3.3. Measured water contents

Fig. 4 shows the depth distribution of the water contents for the Eastern and Western sites in early April and late August in 2009 and early September in 2010. The water contents in early April reflect the over-winter storage of precipitation. The Eastern site received 130 mm of precipitation from October 2008 to April 2009, and this precipitation wetted the soil to a depth of 60–80 cm (Fig. 4). During spring and summer, water was lost by evaporation, and seed-zone water content decreased drastically, resulting in a steep gradient of the water content in the top 30 cm of the soil. The increase in water content in the deeper soil layers (below 100 cm depth) from spring to late summer suggests that water was draining from the topsoil into the subsoil, driven by the gradient in water potential. The Western site received 103 mm of precipitation from October 2008 to April 2009, and this comparatively smaller quantity of precipitation did not wet the soil as much as at the Eastern site (Fig. 4). The water contents in the top 30 cm at the Western site were only about half of those at the Eastern site (0.1 m^3/m^3 compared to 0.2 m^3/m^3). From October 2009 to March 2010, the Eastern and Western sites received 111 mm and 89 mm of precipitation, respectively. The trends of the soil water dynamics in 2010 were similar to 2009; however, because of the greater amount of rainfall during the spring of 2010, water contents at planting were considerably higher (Fig. 4).

The total quantities of water stored in the top 30 cm of the soil are summarized in Table 2. The comparatively lower temperature and higher precipitation at the Eastern site resulted in a greater amount of water stored over winter at the Eastern site than at the Western site (Table 2). During the summer, a considerable amount of water was lost from the seed zone. Averaged over the 5 years, soil water loss from early April to late August was 49% in TF and 64% in NTF at the Eastern site, and 40% in TF and 52% in NTF at the Western site.

At the Eastern site in 2009, the TF contained 59 mm of water in the top 30 cm in early April and 26 mm in late August, representing a 56% loss of seed-zone water (Table 2). The corresponding loss in NTF was 74%. At the Eastern site in 2010, the TF contained 59 mm

Table 2
Total water measured in the top 30 cm of the soil under tillage fallow and no-till fallow at the Eastern and Western sites. Water contents in spring are the same for tillage and no-till fallow plots as water contents were measured just before establishment of the tillage treatments.

Date	Tillage fallow	No-till fallow	Tillage fallow	No-till fallow
	Eastern site		Western site	
	mm			
March 29, 2006	46	46	40	40
August 25, 2006	27^{a*}	23^{a}	28^{a}	21^{b}
March 22, 2007	48	48	43	43
August 29, 2007	24^{a}	13^{b}	30^{a}	24^{b}
March 28, 2008	50	50	43	43
September 3, 2008	28^{a}	20^{b}	24^{a}	21^{a}
April 1, 2009	59	59	39	39
August 20, 2009	26^{a}	16^{b}	20^{a}	12^{b}
March 10, 2010	59	59	43	43
September 8, 2010	26^{a}	25^{a}	24^{a}	22^{a}

[*] Statistical tests were done to check for significant differences between tillage fallow and no-till fallow for each year and site separately (only August/September data were tested, as spring data are identical). Significant differences at the 5% confidence level between tillage fallow and no-till fallow are denoted with superscripts: if letters between the two tillage treatments are different, then the difference is significant.

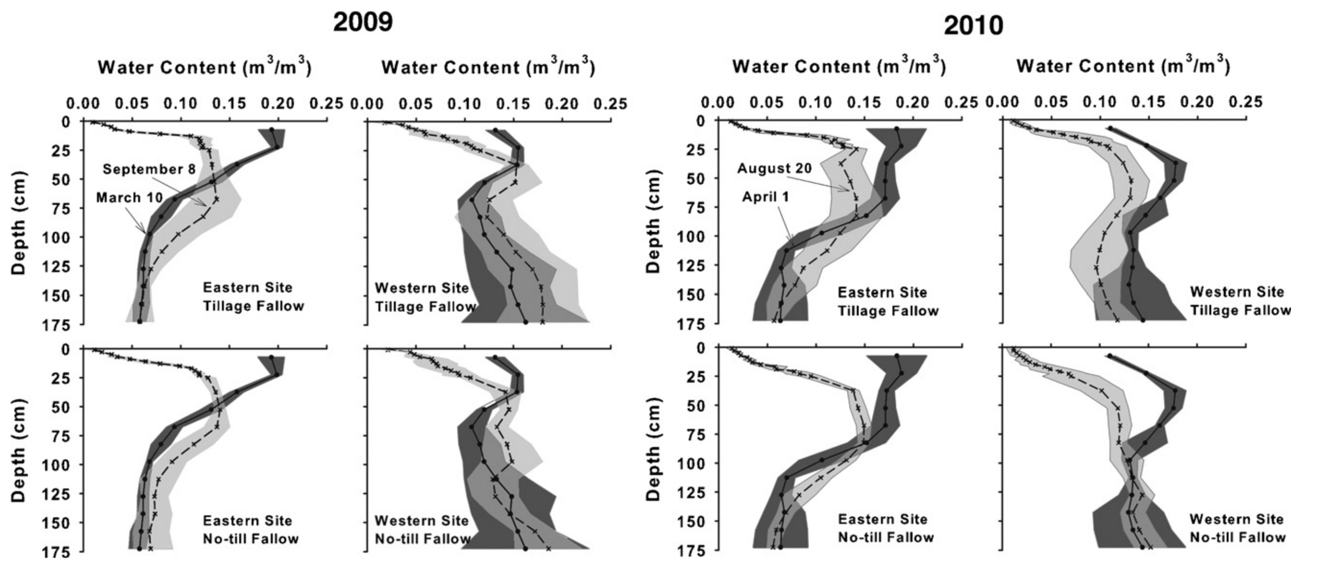

Fig. 4. Soil water profile just before tillage in spring and at planting for tillage fallow and no-till fallow treatments at the Eastern and Western sites. Symbols indicate means and shaded area standard deviations of measurements.

of water in early March and 26 mm in early September, representing a 56% loss of seed-zone water. The corresponding loss in NTF was 58%, about the same as in TF. The reason for the similar water loss in 2010 is due to rainfall in spring 2010, which helped to elevate the water content in the soil compared to 2009 (Table 2). Little water will be gained after primary spring tillage of TF because water does not readily flow through the loose tillage mulch layer. In contrast, additional soil water accumulation will occur in NTF whenever substantial precipitation occurs because capillary pores and channels from the surface to the subsoil remain open. Schillinger (2001) and Wuest (2010) reported that delayed primary spring tillage will benefit water storage when substantial rainfall occurs in May and early June (i.e., after the typical April date for primary spring tillage) and before temperatures become too hot. However, primary tillage needs to be conducted before the onset of hot, dry summer weather because accelerated soil drying occurs in NTF compared to TF under such conditions (Wuest, 2010; Wuest and Schillinger, 2011).

For both the Eastern and Western sites, the TF consistently contained greater seed-zone water in late August–early September than NTF (Table 2). The drying front in the seed zone penetrated deeper into the soil under NTF than with TF (Fig. 4). The near surface (0–10 cm) at all sites and treatments was very dry, with water contents less than 0.06 m^3/m^3. Considering a depth of 18 cm as the deepest practical planting depth, we compared the water contents of TF versus NTF at this depth. At the Eastern site in 2009, the TF at 18-cm depth had a water content of 0.12 m^3/m^3 compared to 0.06 m^3/m^3 for NTF. At the Western site, the TF at 18-cm depth had a water content of 0.09 m^3/m^3 compared to 0.04 m^3/m^3 for NTF. In 2010, water content at 18-cm depth was 0.12 and 0.11 m^3/m^3 at the Eastern site and 0.09 and 0.08 m^3/m^3 at the Western site for TF and NTF, respectively.

The lower limit of the volumetric water content for winter wheat seed germination and emergence for a Ritzville silt loam soil in the Pacific Northwest is considered to be 0.11 m^3/m^3 (Schillinger and Papendick, 1997). At the Eastern site, the water contents with TF at 18-cm depth were greater than this threshold for germination and seedling emergence at planting time in all 5 years of our study. In NTF, however, the water contents were always less than this threshold except in 2010. At the Western site, the water contents in TF at 18-cm depth were greater than the threshold for seed germination at planting time only in 2006 and 2007, and the water contents were less than this threshold for NTF in all 5 years. In such dry environments, early planting into NTF is generally only feasible when thunderstorms in mid-to-late August deliver 15 mm or more of rain and the water penetrates 15 cm or more into the soil profile (Wuest and Schillinger, 2011). Such storm events occur approximately once every 10 years. Substantial rain events that occur in July and up to mid August are of little benefit for either TF or NTF as the water is mostly evaporated by the time of late August planting.

3.4. Model simulation results

The simulated dynamics of the water content and water potentials from March to October of 2009 in the top 30 cm of soil reflect the drying of the soil profile during the summer (Fig. 5). The soil starts to dry from the top and the drying front moves downward as the hot, dry summer progresses. Rainfall in May caused the water content to increase again, but then the water content continuously declined. Even a substantial rainfall of 4–5 mm in June did not elevate the soil water content noticeably. Most of this mid-summer rainfall penetrated less than 10 cm into the soil and was evaporated back into the atmosphere. Both, the TF and NTF treatments show considerable drying at 10 cm depth. At the Eastern site, water potentials decreased drastically in late August in both TF and NTF. At the Western site, this decrease occurred much earlier, i.e., already in the beginning of August. The physics of accelerated late-summer soil water evaporative loss in the Pacific Northwest has been summarized in detail by Flury et al. (2009).

Fig. 6 shows the water dynamics for 2010. Substantial rainfall in May and June penetrated and elevated the soil water content to a depth of 30 cm. However, rainfall ceased in July and August and the soil surface dried out.

The measured water contents at the time of planting are depicted by the symbols in Figs. 5 and 6. For the Eastern site in 2009, the measured water contents at 10 cm depth were drier than simulated by the model. For TF, water contents were 0.06 m^3/m^3 measured and 0.07 m^3/m^3 simulated, and for NTF 0.03 m^3/m^3 measured and 0.06 m^3/m^3 simulated. Water contents at the 20 cm and 30 cm depths were under predicted by the model simulations for TF, and over predicted for NTF. For the Eastern site in 2010,

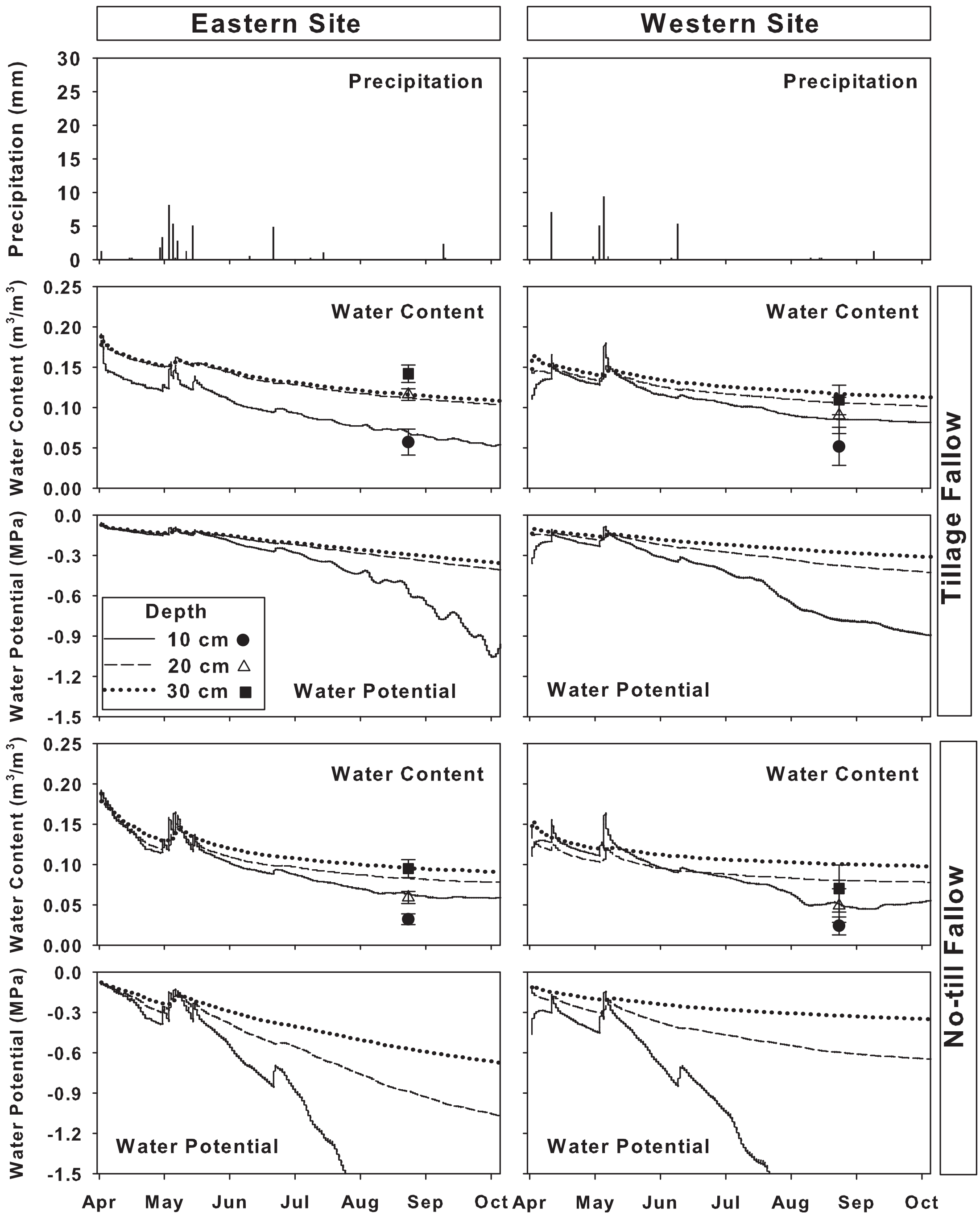

Fig. 5. Temporal dynamics of simulated water content and water potential in 2009 for tillage fallow and no-till fallow at the Eastern and Western sites. Symbols are observed water contents at three corresponding depths on August 20, 2009.

water content at 10 cm depth was well predicted by the model. For the Western site the model accurately predicted water content for NTF, but over predicted for TF.

Depth profiles of observed and simulated water contents at the time of planting show that the simulated water contents followed the general trend of the observed data (Fig. 7). The simulations well represented seed zone drying in TF, but had too steep a gradient in water content for NTF, i.e., the soil did not dry as deep compared to the measured water contents. Overall, the model simulated the seed-zone water (0–30 cm depth) more accurately for TF than for NTF.

In general, the simulated total quantities of water in the top 30 cm of the soil in late August–early September matched the measured amounts well (within a few millimeters of water storage) for all years of the experiment (Table 3) except on a few occasions. As expected, simulations showed that TF retained more seed-zone water compared to NTF. The comparison of simulated and measured depth profiles of soil water contents followed a similar pattern for all years, indicating that the model was able to capture the dynamics of the soil water flow for different weather conditions. Root mean squared errors were between 0.016 and 0.025 m^3/m^3.

3.5. Using the SHAW model as a decision tool to predict seed-zone water content

The steep gradient in the water content profile in late-summer makes exact numerical predictions challenging. An increment of

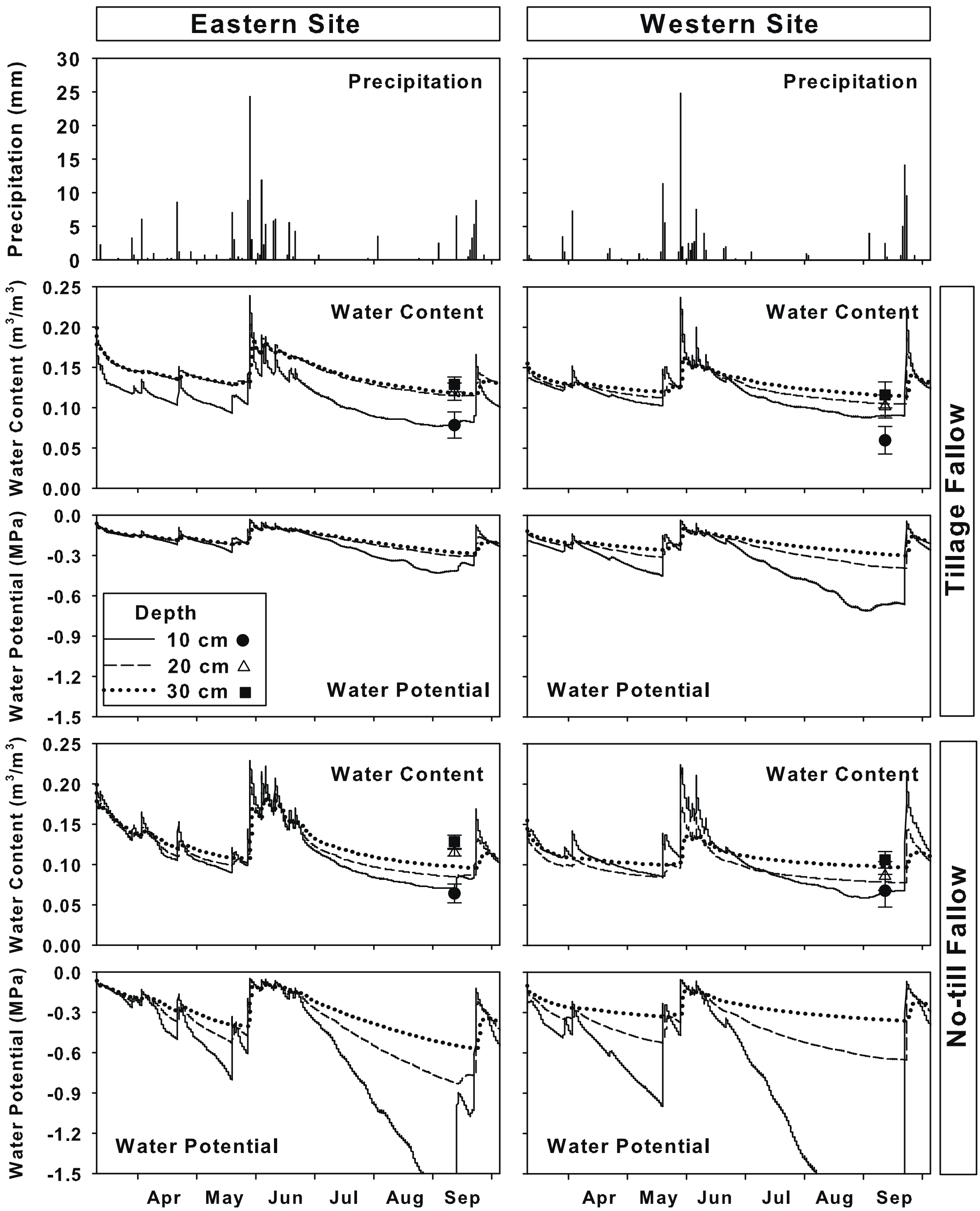

Fig. 6. Temporal dynamics of simulated water content and water potential in 2010 for tillage fallow and no-till fallow at the Eastern and Western sites. Symbols are observed water contents at three corresponding depths on September 8, 2010.

1 cm in depth can drastically change the water content. The top 10 cm of the soil is too dry for planting. Water content increases with depth, but there is a limit on how deep wheat seed can be placed and the depth of soil cover through which seedlings must emerge. For the wheat-fallow region in the Pacific Northwest, we consider 18 cm as the maximum planting depth. Seed can be placed at this depth with existing deep-furrow drill technology. For the use of SHAW as a decision tool to predict water contents in fall, we therefore consider the interval from 15- to 18-cm depth.

We compared the SHAW-simulated seed-zone water contents (using initial conditions of measured water contents in spring and the measured meteorological conditions as boundary conditions) with the measured water contents in late August–early September. If the water contents between 15 and 18 cm exceeded the critical value of 0.11 m^3/m^3 (Schillinger and Papendick, 1997), planting was considered feasible. Table 4 shows both measured and model-predicted water contents in early April and late August–early September. If the water contents in late summer exceeded 0.11 m^3/m^3, the planting decision is depicted as “yes”. The model produced the correct decision except in 2008.

Our results show that it was not always possible to accurately predict the seed-zone water content in late summer based only on water contents in early April. What must also be considered is the amount of rainfall likely to occur in April, May and early June. For

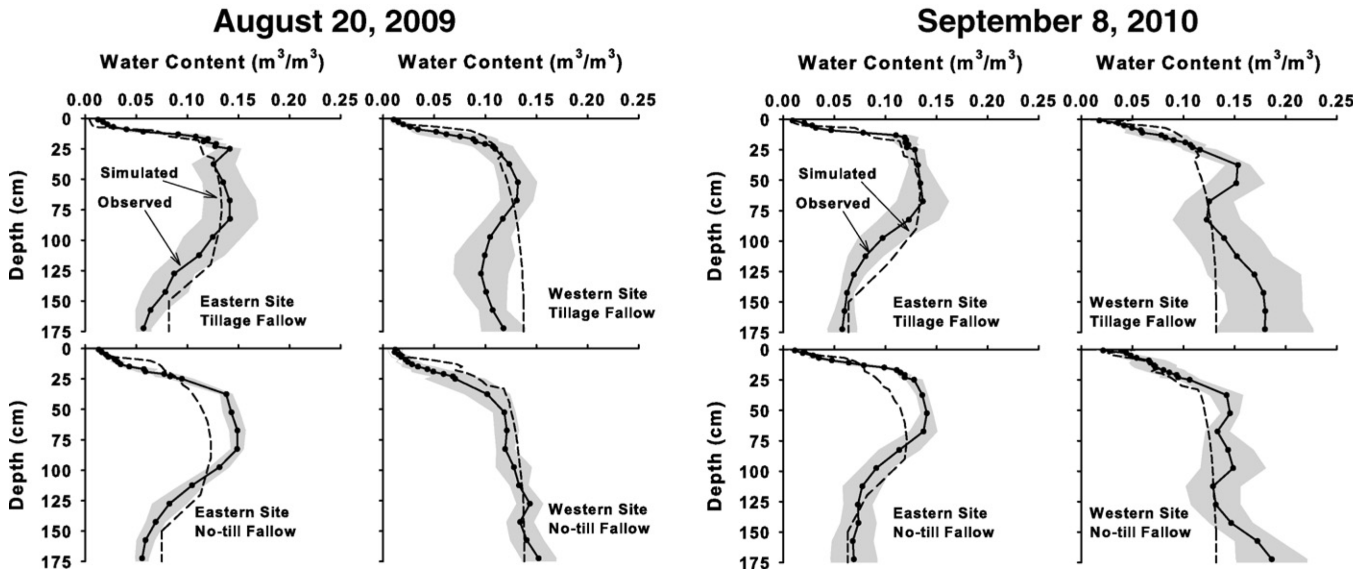

Fig. 7. Observed and simulated soil water profiles at planting for tillage fallow and no-till fallow treatments at the Eastern and Western sites. Observed data are means (circles) and standard deviations (shaded area) of measurements.

Table 3
Measured and simulated total water in the top 30 cm of the soil in late August–early September under tillage fallow and no-till fallow at the Eastern and Western sites. Measured values represent means and standard deviations.

Date	Tillage fallow	No-till fallow	Tillage fallow	No-till fallow
	Eastern site		Western site	
	mm			
August 25, 2006	27±2	23±4	28±4	21±3
Simulated	35	29	34	27
August 29, 2007	24±2	13±2	30±3	24±2
Simulated	23	21	28	22
September 3, 2008	28±2	20±2	24±3	21±3
Simulated	22	20	30	24
August 20, 2009	26±2	16±2	20±5	12±5
Simulated	24	21	26	20
September 8, 2010	26±2	25±1	24±4	22±4
Simulated	26	23	29	23

Table 4
Decisions to practice tillage fallow during the spring and summer months. If the SHAW model predicted late-August water content (at 15–18 cm depth) exceeding the threshold of 0.11 m^3/m^3, planting is considered possible and tillage fallow would conserve sufficient seed-zone water for planting. The decision would then be "yes", otherwise the decision would be "no".

Year	MWC[a]-early April (m^3/m^3)	Rain (mm)[b]	Last day of 90% of rainfall	PWC[c] on June 20 (m^3/m^3)	AST[d] (°C)	MWC-late August (m^3/m^3)	Decision[e]	PWC-Late August (m^3/m^3)	Decision[f]
				Eastern site					
2006	0.150	104	June 4	0.144–0.170	21.9	0.121–0.129	Yes	0.111–0.138	Yes
2007	0.174	78	June 9	0.116–0.142	21.1	0.108–0.109	No	0.082–0.109	No
2008	0.173	41	June 21	0.103–0.129	20.7	0.115–0.122	Yes	0.077–0.105	No
2009	0.188	36	June 19	0.102–0.129	20.2	0.108–0.120	Yes	0.083–0.111	Yes
2010	0.199	126	June 16	0.139–0.163	20.0	0.119–0.120	Yes	0.087–0.114	Yes
				Western site					
2006	0.140	81	June 13	0.147–0.151	22.7	0.120–0.124	Yes	0.120–0.120	Yes
2007	0.161	43	June 29	0.123–0.125	22.3	0.132–0.137	No	0.102–0.103	No
2008	0.166	20	June 21	0.125–0.126	21.6	0.103–0.108	No	0.110–0.111	Yes
2009	0.148	29	June 7	0.117–0.117	22.9	0.076–0.088	No	0.100–0.102	No
2010	0.155	101	June 19	0.135–0.139	21.1	0.083–0.091	No	0.100–0.102	No

[a] MWC: Measured water content.
[b] Spring and summer rainfall.
[c] PWC: Predicted water content.
[d] AST: Average summer temperature in June, July, and August (arithmetic mean).
[e] Decision based on measured water contents.
[f] Decision based on predicted water contents.

instance, in 2006, early April water contents were the lowest among all years, but because of the high rainfall during spring, planting was still possible in late August (Table 4).

More relevant than the early April water content is the amount and timing of rain during the mid-to-late spring. In Table 4 we list the amount of rain that occurred during mid-to-late spring as well as the date when 90% of fallow-year precipitation had occurred. The data indicate that when substantial rain occurs in mid-to-late spring, there is a greater likelihood of having sufficient water for planting. Based on the rainfall data, we conclude that a water content measurement in the first few weeks of June would be most indicative for a planting decision: if the water content at 15- to 18-cm depth exceeds 0.15 m^3/m^3 in early June, then late August planting appears to be feasible.

4. Conclusions

Tillage fallow practices were effective in conserving water in the top 30 cm of soil during summer. However, under very dry conditions, such as in the Western portion of the Horse Heaven Hills, even TF was not able to conserve sufficient water for late-August planting in 4 out of 5 years. While the SHAW model was able to correctly predict the seed-zone water content in late summer based on measured water contents in early April, actual meteorological input data were required for a successful prediction. The model predictions were correct 80% of the time. The SHAW model allowed us to determine the factors controlling seed-zone water content in summer fallow. The amount of rain occurring in mid-to-late spring was identified as a major factor for determining the quantity of seed-zone water content in late August–early September.

Our data suggest that farmers should consider delaying their decision on whether to practice TF or NTF until as late as mid June. If at that time, their measured soil water at the 15- to 18-cm depth exceeds 0.15 m^3/m^3, farmers should practice TF and if water content is less than this amount they should practice NTF. There are, however, some practical limitations to our recommendations. Average farm size in the Horse Heaven Hills is approximately 3000 ha, with half in winter wheat and half in summer fallow. Given that a farmer can cover about 50 ha per day, it takes approximately 30 days to complete primary spring tillage. If the farmer waits until mid June to begin primary spring tillage, substantial evaporative soil loss may occur on non-tilled ground by mid July.

Data from our study also suggest that farmers in the extreme dry western region of the Horse Heaven Hills should practice NTF in all but very wet years as they rarely have adequate seed-zone water for late-August planting, even with TF. The widespread practice of NTF would dramatically reduce wind erosion and likely save on operating costs compared to TF. In addition, farmers committed to practicing NTF in the long term could receive monetary payments from federal farm programs that reward environmental stewardship.

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Appendix A

- b pore size distribution index
- D_v vapor diffusivity in the soil (m^2/s)
- E_r rate of evaporation from residue elements to the void space within the residue ($kg/(m^3\ s)$)
- h relative humidity within the soil
- h_a relative humidity of air in equilibrium with the residue elements
- k_r combined thermal conductance/convection term for residue (W/(mC))
- K unsaturated hydraulic conductivity (m/s)
- K_{fs} field saturated hydraulic conductivity (m/s)
- K_r vapor conductance between residue elements and air voids (m/s)
- K_s saturated hydraulic conductivity (m/s)
- K_v convective vapor diffusion coefficient (m^2/s)
- q_l liquid water flux (m/s)
- q_v water vapor flux ($kg/(m^2\ s)$)
- q_{vp} vapor flux due to water potential gradient ($kg/(m^2\ s)$)
- q_{vT} vapor flux due to temperature gradient ($kg/(m^2\ s)$)
- r count ratio (i.e., the ratio of count in soil to the standard count in the water shield)
- s change in saturated vapor density with respect to temperature ($kg/(m^3\ K)$)
- t time (s)
- T temperature (°C)
- U source/sink term in water flux equation ($m^3/(m^3\ s)$)
- z depth from surface (m)
- $\boldsymbol{\zeta}$ enhancement factor for temperature gradient vapor flux
- $\boldsymbol{\theta}$ volumetric water content (m^3/m^3)
- $\boldsymbol{\theta}_l$ liquid water content (m^3/m^3)
- $\boldsymbol{\theta}_m$ simulated water content (m^3/m^3)
- $\boldsymbol{\theta}_o$ observed water content (m^3/m^3)
- $\boldsymbol{\theta}_s$ saturated water content (m^3/m^3)
- $\boldsymbol{\rho}_b$ bulk density of soil (kg/m^3)
- $\boldsymbol{\rho}_l$ density of liquid water (1000 kg/m^3)
- ρ_v vapor density within the residue or soil (kg/m^3)
- ρ'_v saturated vapor density (kg/m^3)
- $\boldsymbol{\psi}$ soil matric potential (m)
- $\boldsymbol{\psi}_e$ air-entry potential (m)

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