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Winter Hydrologic and Erosion Processes in the U.S. Palouse Region: Field Experimentation and WEPP Simulation

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Soil erosion by water is detrimental to soil fertility, crop yield, and the environment. For cold areas, knowledge of winter hydrologic processes is critical to determining land-use and management practices for reducing soil loss and protecting land and water resources. Adequate understanding of winter processes is also essential to developing models as effective predictive tools. This study evaluated the effects of two contrasting tillage practices on winter hydrologic and erosion processes, and the suitability of the Water Erosion Prediction Project (WEPP) model with a newly implemented energy-budget-based winter routine for quantifying these processes. Research plots subject to two tillage treatments—continuous tilled bare fallow (CTBF) and no-till (NT) seeding of winter wheat (*Triticum aestivum* L. cv. Madsen) after spring barley (*Hordeum vulgare* L.)—were established at the USDA-ARS Palouse Conservation Field Station, Pullman, WA. The plots were monitored for runoff, erosion, soil temperature, water content, and depths of snow and freeze–thaw during October to May of 2003–2004 through 2006–2007. The NT plot generated negligible runoff and erosion (0.5 mm, 0.2 Mg ha^{-1}) compared with CTBF (323 mm, 547 Mg ha^{-1}). Frost occurred more frequently and was deeper in CTBF, probably due to its lack of residue and shallower snow depth. The modified WEPP model could reasonably reproduce major winter processes, yet it cannot represent all the complicated winter phenomena observed in the field. Continued efforts are needed to further improve the ability of WEPP to properly account for soil freeze–thaw and thus transient soil hydraulic properties and hydrologic and erosion processes.

Abbreviations: CTBF, continuous tilled bare fallow; NT, no-till; WEPP, Water Erosion Prediction Project.

Detachment and removal of the topsoil by runoff is detrimental to soil fertility and crop yield (Busacca et al., 1985; Schertz et al., 1985; Young et al., 1985; McCool and Busacca, 1999) as well as the environment (Lal, 1998). For cold areas, knowledge of winter hydrologic processes is crucial to developing land-use and management plans for reducing soil loss and protecting land and water resources. In the U.S. Pacific Northwest, where the majority of the precipitation falls in winter (McCool and Roe, 2005; Western Regional Climate Center, 2008), understanding winter phenomena, including snow accumulation and melt as well as soil freeze–thaw, is a prerequisite for predicting surface runoff and water erosion (Lin and McCool, 2006).

On average, in water years 1941 through 2007, the NOAA weather station of Pullman 2NW, located near Pullman, in eastern Washington, received 59% of the annual precipitation during the winter season of November through March (Western Regional Climate Center, 2008). McCool (1990) reported observations of numerous freeze–thaw cycles and up to 85% of average yearly soil loss during the winter season in the Palouse region of the Pacific Northwest. Davis and Molnau (1973), based on a study conducted at the eastern edge of the Palouse region, found that between 20 and 25% of incident precipitation was lost to runoff. Water erosion has led to an average soil loss of 35 Mg ha^{-1} yr^{-1}, with maximum soil loss rates reaching 225 to 450 Mg ha^{-1} yr^{-1} in the Palouse region (USDA, 1978), which was among the highest in the United States and greatly exceeded the recommended tolerable rates of 5.0 to 12.0 Mg ha^{-1} yr^{-1} (Soil Conservation Service, 1982).

The high soil erosion rate in the Palouse region has resulted from a combination of winter precipitation, intermittent freezing and thawing of soils, steep slopes, and conventional management practices that often leave the soil pulverized and unprotected during the wet season (Papendick et al., 1983). Results from past studies have shown that substantial water erosion in the region is related to rain on frozen or thawing soils and is often exacerbated by the warm, moist Pacific air masses that cause precipitation combined with rapid thaw (Yoo and Molnau, 1982; Zuzel et al., 1982). McCool and Roe (2005) found an annual average of 103 diurnal freeze–thaw cycles for water years 1940 through 1982 for Pullman, WA, which agrees with the nearly 100 freeze–thaw cycles reported by Hershfield (1974) for the Palouse region.

Freeze–thaw reduces the soil cohesive strength (Formanek et al., 1984; Kok and McCool, 1990) and consequently increases

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soil erodibility (Van Klaveren and McCool, 1998). Frost heave and expansion of soil pores occur frequently during freezing due to the density difference of ice and water, weakening soil structure and aggravating soil loss (Formanek et al., 1984). Froese and Cruse (1997) found that frozen layers beneath the thawed surface may impede infiltration, cause water to perch above this layer leading to a soil water matric potential of zero, and result in low soil shear strength and high detachment rates. Rills may form on a recently thawed soil even under low-intensity rainfall (Van Klaveren, 1987), which can substantially increase soil loss on hillslopes (Meyer et al., 1975; Mutchler and Young, 1975; Morgan, 1977). Bullock et al. (1988) submitted that freezing can be more damaging to soil aggregates than a single pass of most tillage equipment.

Management practices also play an important role in winter runoff and erosion. Tillage operations pulverize and compact the soil and bury crop residue (Kenny, 1990). Greer et al. (2006) and McCool et al. (2006) concluded that crop management had a major effect on infiltration, runoff, and erosion in the Palouse region, and the effect was greater for precipitation events under unfrozen than frozen soil conditions. When a frost layer is present and the soil infiltration capacity is reduced, crop management has a greater relative effect on erosion than on runoff.

The WEPP model is a physically based model developed in the late 1980s for predicting runoff and erosion from field to watershed scales (Flanagan et al., 1995; Laflen et al., 1997). It has proved useful for predicting water balance and soil erosion as affected by cropping systems and management practices (Greer et al., 2006; Pieri et al., 2007). The original winter routine of WEPP, however, was found inadequate for the Pacific Northwest (McCool et al., 1998; Greer et al., 2006). A new energy-budget-based winter routine was developed and tested using historical field data collected at two experimental sites near Pullman, WA, and Morris, MN (Lin and McCool, 2006). The new winter routine was programmed to operate as a stand-alone version for testing and was incorporated in WEPP as an alternative approach to its internal winter routine as part of this study.

Long-term erosion research plots have been established and monitored at the USDA Palouse Conservation Field Station, 3 km northwest of Pullman, WA, since early 1970. As part of a recent erosion study supported by the USDA National Research Initiative program, these plots were further instrumented and monitored for winter processes during October to May of 2003–2004 through 2006–2007. Winter phenomena, including snow accumulation and melt, soil freeze–thaw, surface runoff, and erosion under two contrasting tillage treatments, namely, continuous tilled bare fallow (CTBF) and continuous no-till (NT) with direct-seeded annual winter wheat following no-till spring barley (Gledhill, 2002), were evaluated. The comprehensive data allow an improved understanding of water movement and heat transfer in the soil profile and a better testing of WEPP performance with the newly developed winter routine by Lin and McCool (2006). Therefore, the objectives of this study were to: (i) evaluate winter hydrologic and erosion processes as affected by CTBF and NT in the U.S. Pacific Northwest; and (ii) assess the suitability of WEPP with a newly implemented energy-budget approach for quantifying field-observed winter processes.

Materials and Methods

Experimental Site and Field Monitoring

The experimental site comprised three pairs of CTBF and NT plots on a south-facing field at the Palouse Conservation Field Station (46°44′ N, 117°8′ W, 762 m above mean sea level). Each pair of plots was established on a different slope gradient (17, 23, and 24%) and each plot was 24 m long and 3.7 m wide. The soil is Palouse silt loam (a fine-silty, mixed, superactive, mesic Pachic Ultic Haploxeroll). Average annual precipitation (1940–2007) is 531 mm (Western Regional Climate Center, 2008). Two tillage treatments, CTBF and NT, were applied. A rotovator, with a depth of 15 of 18 cm, was used three times in early September each year for the CTBF plots, and the USDA cross-slot drill (Baker et al., 1996) was used for planting winter wheat in the NT plots. In August of 2003 and September of 2005, the CTBF plots were irrigated with 30 mm of water before tillage to create tilled surfaces without large clods.

One pair of CTBF and NT plots (80 m apart and on a slope gradient 23%) was chosen to measure residue and soil properties and was extensively instrumented for monitoring soil water and temperature, in addition to other hydrologic and erosion processes, in the winter seasons of 2003–2004 through 2006–2007.

Surface residue properties, including the amount of dry biomass, cover percentage, and the height of standing stubble, were measured for the NT treatment each year after harvest. Three measurements were made on each NT plot (top, middle, and bottom). Standing and flat residue was collected from a 1-m^2 area (with a 1-m^2 frame) at each measurement location. Digital images were taken before residue collection and were later analyzed to determine the residue cover percentage using regular grid counting following McCool et al. (1989). The amount of dry biomass was obtained by weighing the residue samples after oven drying. All NT plots had 100% residue cover and the CTBF plots had no residue.

The Palouse soil was sampled at locations on the paired CTBF and NT plots. Soil coring to 1 m was performed with a Giddings probe (Giddings Machine Co., Windsor, CO). Undisturbed samples were collected in the 0- to 0.1-, 0.1- to 0.2-, 0.2- to 0.4-, 0.4- to 0.6-, 0.6- to 0.8-, and 0.8- to 1-m depth intervals, and measurements were made of saturated hydraulic conductivity (K) by the constant-head method (Reynolds et al., 2002), dry bulk density by the core method (Grossman and Reinsch, 2002), and organic matter by dry combustion (Sheldrick, 1984). Particle-size analysis was done by sieving and static light scattering after removing carbonates and organic matter (Gee and Or, 2002). These lab-measured values were reported in Greer et al. (2006) and used in the subsequent WEPP modeling in this study.

Field monitoring at the paired CTBF and NT plots typically started in October, shortly before the onset of the winter season, and extended to May. This period is hereafter referred to as the *monitored period*. Measurements of surface runoff, water erosion, snow depth, and frost and thaw were made on all six plots, but only the paired CTBF and NT plots on the 23% slope were instrumented with soil liquid-water content and temperature sensors at various depths. Each year soil water and temperature sensors within the top 16-cm depth at the paired CTBF and NT plots were removed before, and reinstalled after, tillage and planting operations. The depths of snow and soil frost and thaw were recorded manually and daily at three locations (top, middle, and bottom slope positions along the east edge of each plot) when snow was present on the ground and during each freeze–thaw event, beginning in December 2003. Frost tubes containing methylene blue dye solution, in which dye migrates from the freezing point and concentrates in the unfrozen portion of the tube during freezing, provided information about freeze and thaw depths (McCool and Molnau, 1984). Surface runoff and sediment loss were measured the day after each precipitation event. Runoff and sediment yield were sampled (starting from November 2003) from a calibrated sediment collection tank with a volume of 2.27 m^3 (600 gallon) at the bottom of each plot. Sediment in the tank was resuspended with a recirculating pump; a tee acted as a splitter, diverting part of the outflow to a smaller auxiliary tank. The auxiliary tank was agitated and two 1-L runoff samples were collected for analysis. These samples were oven dried to determine the sediment concentration and thus yield.

Soil water and temperature sensors were installed in late January 2004 on the west edge of the CTBF plot and on the east edge of the NT plot. Volumetric liquid soil water was monitored using individually calibrated ECHO probes (Decagon Devices, Pullman, WA) at the depths of 2, 4, 8, 16, 32, 64, and 100 cm, and soil temperature was monitored at the same depths and at the soil surface using thermocouples (Decagon Devices). The thermocouples at the surface were lightly covered with soil under CTBF and residue under NT. The electronic data were collected on a datalogger (Model CR-10X, Campbell Scientific, Logan, UT) at 15-min intervals. The soil temperature profile allowed the separation of runoff events into occurrences with frozen, thawing, or unfrozen conditions and verification of the frost-tube measurements.

An automatic weather station was installed between the paired CTBF and NT plots with 23% slope, measuring precipitation with a tipping-bucket rain gauge (Campbell Scientific) and wind speed and direction using an anemometer. Net radiation was measured using net radiometers (Model Q7.6.1-L, Radiation and Energy Balance Systems, Bellevue, WA); temperature and relative humidity were measured using a Vaisala temperature and relative humidity probe (CS500-L, Campbell Scientific). All weather measurements were made at 15-min intervals. During late summer each year, the automatic weather station was temporarily removed for several weeks for tillage and planting operations. Therefore, data from the automatic weather station are missing for these periods. A Belfort rain gauge (Alter shielded, weighing type) was also installed 20 m from the south border of the CTBF plot for independent precipitation measurement. Additionally, the NOAA weather station, Pullman 2NW, located 0.4 km to the east of the experimental site, monitored daily precipitation and maximum and minimum air temperatures.

WEPP Model Application

WEPP Model Overview

The WEPP model is a process-oriented model based on the fundamentals of hydrology, erosion mechanics, plant growth, and open channel hydraulics (Flanagan et al., 1995). It can be used to simulate spatial and temporal distributions of net soil loss and sediment deposition along a hillslope or across a watershed during an event or on a continuous basis (Flanagan and Nearing, 1995).

The energy-budget-based winter routine by Lin and McCool (2006) was incorporated into WEPP (Version 2008.7) in this study. The energy-budget approach essentially estimates the energy balance across the air–earth interface. This routine is based on the governing equation

$$\downarrow G = \downarrow R_n - \uparrow H - \uparrow \mathrm{LE} \qquad [1]$$

where G is energy flow into the soil surface, R_n is net radiation, H is sensible heat, and LE is the latent heat of vaporization. Energy flow is considered positive in the direction of the arrows and the components are expressed in units of energy flux density (J m^{-2} h^{-1}). A major assumption of this approach is that the components of energy balance are in equilibrium during a daily cycle. Snow depth is estimated using the equivalent water volume of precipitation and snow density (with a default initial value of 100 kg m^{-3} and maximum of 500 kg m^{-3} for snow density) that changes in response to climatic conditions (air temperature, new snowfall, and net radiation). Frost and thaw depths are determined by considering the net energy flux into the soil, the total soil water content (liquid plus ice), and the latent heat of fusion. A detailed description of the approach to, and governing equations for, individual energy-budget components can be found in Lin and McCool (2006).

Soil frost hinders water infiltration into the soil profile due to the presence of ice. McCauley et al. (2002), based on laboratory tests, reported that saturated hydraulic conductivity could be reduced by up to five orders of magnitude in frozen soils. In this study, the saturated hydraulic conductivity of frozen soil was modeled as a harmonic mean of the hydraulic conductivity values of frozen and unfrozen fractions within a soil layer, with a reduction factor applied to the saturated hydraulic conductivity of the frozen fraction as given by

$$K_e = \frac{1}{\mathrm{ff}/(K_u \mathrm{rf}) + (1-\mathrm{ff})/K_u} \qquad [2]$$

where K_e is the equivalent saturated hydraulic conductivity of a soil layer, ff is the frozen fraction (ratio of frozen depth vs. total depth of the layer), K_u is the saturated hydraulic conductivity of unfrozen soil, and rf is a reduction factor.

In addition to frost, soil surface crusting resulting from raindrop impacts can also reduce the soil hydraulic conductivity (Rawls et al., 1990; Philip, 1998; Ruan et al., 2001). In this study, adjustment of the saturated hydraulic conductivity for the CTBF treatment was made by applying the adjustment factor of 0.01 if the daily rainfall amount exceeded a threshold value of 10 mm and 0.5 otherwise. Such adjustments were not made for the NT treatment because we assumed that the residue cover reduced the impact of raindrops and helped retain the soil infiltration capacity.

WEPP Inputs and Simulation

The WEPP model was executed to simulate the winter hydrologic and erosion processes for 2003–2004 through 2006–2007 under the CTBF and NT conditions. The WEPP model requires four sets of input data: climate, slope, soil, and management. The WEPP climate inputs include daily precipitation (in breakpoint form, with data pairs indicating time and daily cumulative precipitation), air temperature (daily maximum and minimum), solar radiation, wind speed and direction, and dew-point temperature.

Daily maximum and minimum air temperature data were taken from the automatic weather station, with missing data for late summers supplemented by those from the NOAA Pullman 2NW station. Data from the Belfort rain gauge was used as precipitation input. Periods of erroneous or missing solar radiation and wind data were generated using a stochastic climate generator (CLIGEN; Nicks et al., 1995).

Slope inputs describe the aspect (azimuthal angle from due north), width, length, and shape of the hillslope. The shape of the hillslope was represented by paired data of relative distance and slope steepness from the top of the plot. The elevations along the slope were measured using a laser level, and steepness was subsequently calculated.

The soil profile from the surface to a 1-m depth was discretized into six layers with a 0.1-m increment for the first two layers (corresponding to the depths of primary and secondary tillage) and a 0.2-m increment for the remaining four layers. Soil inputs included the laboratory-measured textural and hydraulic properties for each of the six soil layers from Greer et al. (2006). Other crucial soil inputs were erodibility parameters, i.e., critical shear stress and rill and interrill erodibility. Table 1 summarizes the soil inputs for the WEPP simulation.

Information on the initial field conditions, yearly management operations, and plant growth (including field-measured residue data) was contained in the management input file. The crop-specific (winter wheat) inputs were primarily from the WEPP user summary (Flanagan and Livingston, 1995). Preliminary WEPP runs indicated that field-observed residue conditions under the CTBF and NT treatments were consistent with WEPP-simulated results. Hence, the crop and residue parameters from the WEPP user summary were used without adjustment. Management inputs are presented in Table 2.

Statistical Analysis

Nonparametric Wilcoxon rank-sum tests were conducted using SAS (SAS Institute, 2004) to determine the differences in mean field-measured daily soil liquid-water content between the CTBF and NT treatments for each monitored period. These tests (at a significance level of 0.05) were performed for each sensor-monitored depth and repeated for daily soil temperature. The Wilcoxon rank-sum tests (nonparametric alternative to the two-sample *t*-tests) were chosen due to the consideration of the nonnormality and lack of independence typically associated with daily soil water and temperature data.

Results and Discussion

Field-Observed Winter Processes

During the monitored periods of 2003–2004 through 2006–2007, 75 runoff and erosion events were observed in the CTBF plot (Fig. 1), compared with three in the NT plot. In total, the CTBF plot generated 323 mm of runoff and 547 Mg ha^{-1} of eroded sediment for the entire study period, whereas both runoff and erosion were negligible (0.5 mm and 0.2 Mg ha^{-1}) from the NT plot (Table 3). The amount of runoff and the erosion rate differed for each monitored season and varied substantially among individual events. The standing and flat residue cover, including a duff layer beneath the stubble that has built up due to continuous no-till management since 1998 at the study site, helped to substantially reduce the amount of runoff and erosion in the NT plot. The effect of NT on reducing surface runoff and soil loss was also observed by Cruse et al. (2001) and Greer et al. (2006).

A large runoff and erosion event occurred on 2–3 Jan. 2007. The continuous rainfall event (35 mm in total) caused thawing of the surface soil and produced 27.7 mm of runoff and 224.4 Mg ha^{-1} of erosion from the CTBF plot, accounting for 29% of the total runoff and 71% of the total erosion for the monitored period of 2006–2007. Results were similar for the other two CTBF plots, with slope gradients of 24% (26.0 mm of runoff, 148 Mg ha^{-1} of erosion) and 17% (25.8 mm of runoff, 124 Mg ha^{-1} of erosion). The NT plot, on the other hand, generated negligible runoff (0.13 mm) and no erosion. The NT plots with slope gradients of 24 and 17% also generated neither runoff nor erosion.

Daily soil temperatures at different depths in the CTBF and the NT plots, averaged from the 15-min records, are shown in Fig. 2. Damping of soil temperature fluctuations with depth was observed (Fig. 2). Wilcoxon rank-sum test results indicated that soil temperatures at different depths under CTBF and NT did not differ for each monitored period (*P* value 0.08–0.49), with the difference between mean daily soil temperatures of the CTBF and NT plots always <0.5°C. Crop residue (both standing stubble and flat residue) possibly acted to impede soil heat flux; the NT plot was generally warmer during winter and cooler after March than the CTBF plot.

Field-observed depths of snow, frost, and thaw for the CTBF and NT plots are shown in Fig. 3 and 4, respectively. Snow depths were deeper in the NT plot than in the CTBF plot (Table 4) as a consequence of the greater snow capture and holding capacities of wheat residue (standing stubble in particular) than bare soil

Table 1. Soil inputs for the WEPP simulation.

Parameter	Value
Texture	Silt loam
Number of soil layers	6
Albedo	0.23
Initial saturation of soil porosity, m^3 m^{-3}	0.9
Baseline interrill erodibility, kg s m^{-4}	4.95 × 10^6†
Baseline rill erodibility, s m^{-1}	8.0 × 10^{-3}
Baseline critical shear, N m^{-2}	0.74

† Soil erodibility parameters, including interrill and rill erodibility and critical shear, are from Elliot et al. (1989).

Table 2. Management inputs used in the WEPP simulations for the continuous tilled bare fallow (CTBF) and no-till (NT) treatments.

Parameter	CTBF	NT
Ridge height value after tillage, m	0.02	–
Ridge interval, m	0.2	–
Random roughness value after tillage, m	0.012	–
Fraction of surface area disturbed	1.0	0
Bulk density after last tillage, Mg m^{-3}	1.1	1.1
Initial frost depth, m	0	0
Cumulative rainfall since last tillage, m	0.375	0.375
Initial ridge height after last tillage, m	0.01	0.01
Initial ridge roughness after last tillage, m	0.01	0.01
Initial snow depth, m	0	0
Depth of tillage layer, m	0.2	0 NT
Initial total submerged residue mass, kg m^{-2}	–	0.17
Initial total dead root mass, kg m^{-2}	–	0.33
Stubble height, m	–	0.15

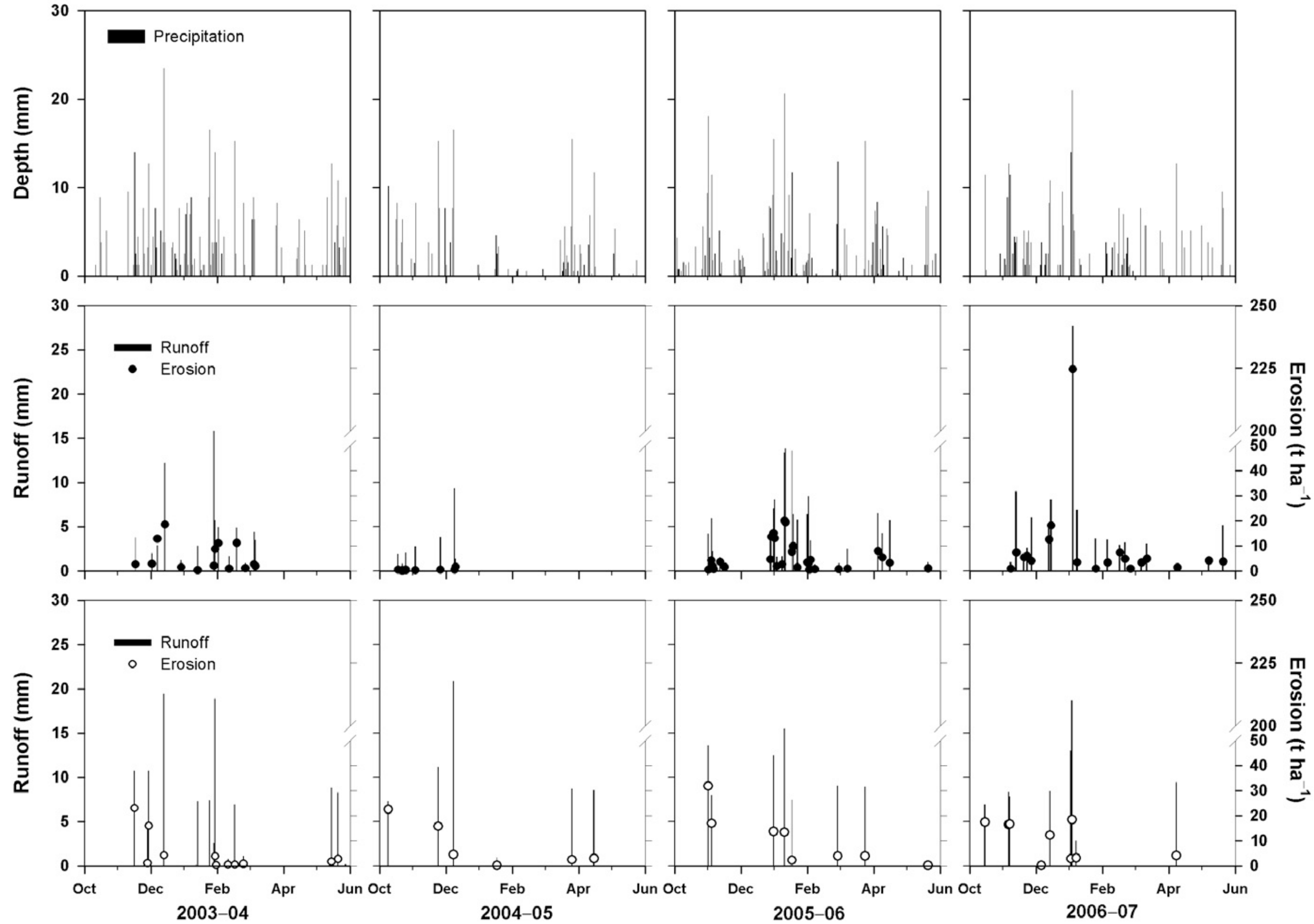

FIG. 1. Observed daily precipitation (top panel), observed runoff and erosion (middle panel), and simulated runoff and erosion (bottom panel) in the continuous tilled bare fallow (CTBF) plot for each monitored period.

(Campbell et al., 1992). Frost depths extended below 100 mm in the CTBF plot during each winter season but did so in only one winter season (2005–2006) in the NT plot. Slightly more frozen-soil days (143 vs. 129 for the entire study period) and much deeper frost depths were observed in the CTBF plot than in the NT plot (Table 4). The frost-tube measurements proved to be valuable indicators of soil freezing, although they tended to respond to soil freezing in a delayed manner (Flerchinger and Saxton, 1989; Greer et al., 2006). More snow on the surface in the NT plot probably provided better insulation and resulted in shallower frost depth on the cold days.

Soil freezing is a complex process, as reported in multiple previous studies. The factors affecting soil freezing include soil texture, antecedent water content, surface cover type, and tillage practices. The effect of frost on water infiltration can also be complicated, depending on numerous factors. Boll (1988) discovered that lower antecedent soil water content led to a higher equilibrium infiltration rate of, and less water migration within, frozen soils. Two rain-on-frozen-soil events were observed on 4 Feb. 2004 and 1 Feb. 2007. Both events had a rainfall of 6.4 mm but generated different amounts of runoff, 3.5 mm in the former and 5 mm in the latter.

A noticeable response of soil liquid-water content to rainfall events

TABLE 3. Observed runoff and erosion and WEPP-simulated surface runoff (R), soil evaporation (E_s), plant transpiration (E_p), deep percolation (Dp), subsurface lateral flow (Q), change in soil water ($\Delta\theta$), and erosion for each monitored period under the continuous tilled bare fallow and no-till treatments.

Season	P†	Observed‡		Simulated						
		R	Erosion	R	E_s	E_p	Dp	Q	$\Delta\theta$	Erosion
	——mm——		Mg ha^{-1}	——mm——					mm	Mg ha^{-1}
			Continuous tilled bare fallow							
2003–2004	417	67 (52, 62)	77 (35, 21)	108	233	0	42	0	34	53
2004–2005	214	22 (2, 0)	3 (0.2, 0)	57	153	0	6	0	−2	48
2005–2006	360	137 (102, 118)	150 (95, 92)	75	231	0	28	0	26	85
2006–2007	336	97 (74, 89)	317 (214, 175)	76	211	0	27	0	22	90
			No-till							
2003–2004	417	0.3 (0, 0.5)	0.2 (0, 0.001)	36	108	160	30	22	61	0.03
2004–2005	214	0 (0, 0)	0 (0, 0)	0	42	177	0	0	−5	0
2005–2006	360	0.1 (0, 0.1)	0 (0, 0)	0	103	158	43	0	56	0
2006–2007	336	0.1 (0, 0)	0 (0, 0)	0	91	149	45	1	50	0

† Precipitation values for the monitored period of October–May.

‡ For each period, the first value is for the plot on the 23% slope; the second and third values (in parentheses) are for plots on the 24 and 17% slopes, respectively.

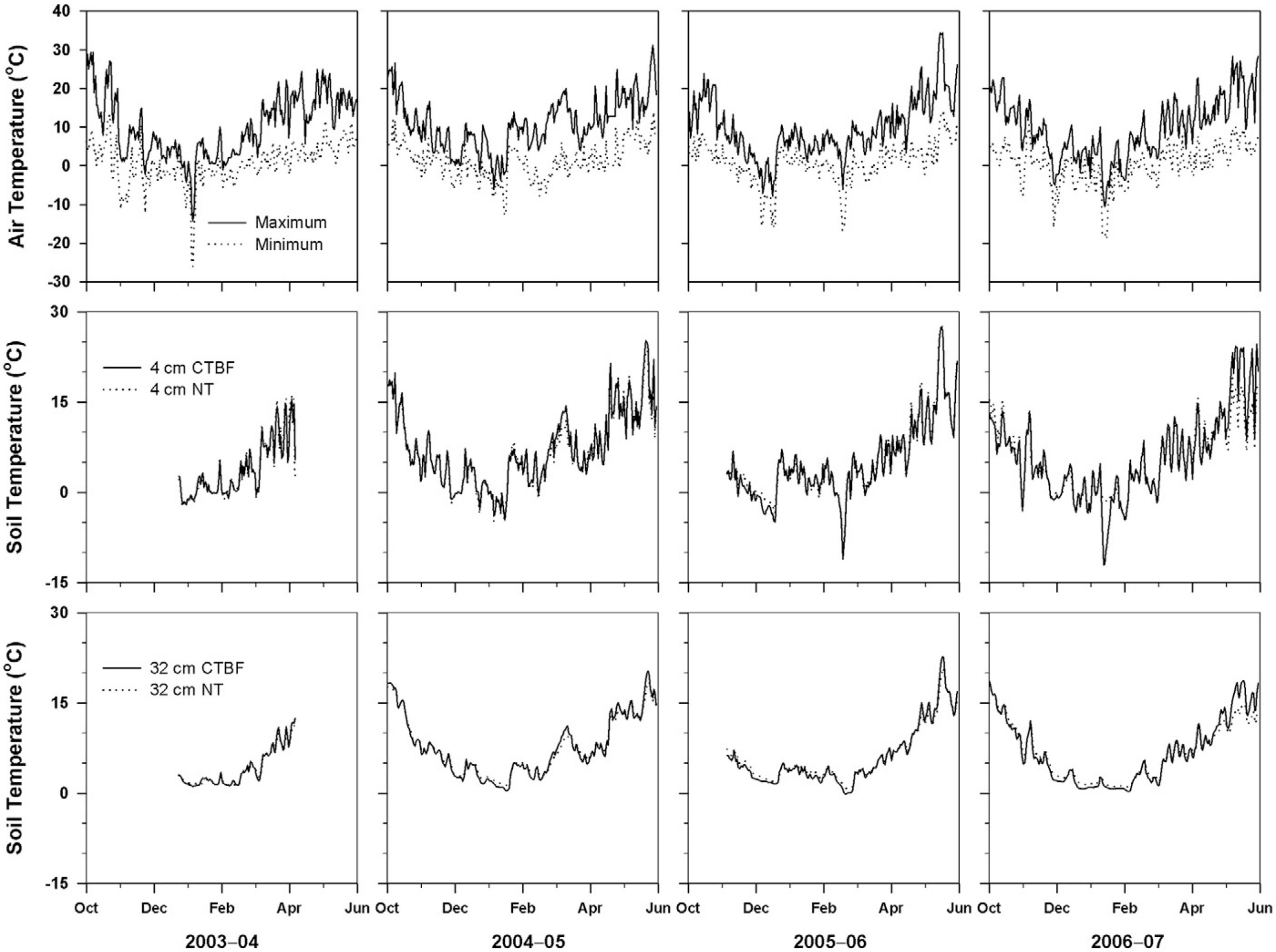

FIG. 2. Observed air temperature (top panel) and observed soil temperature at the 4-cm (middle panel) and 32-cm (bottom panel) depths for the continuous tilled bare fallow (CTBF) and the no-till (NT) plots for each monitored period.

was observed for both the CTBF and NT treatments (Fig. 1 and 5). As the ECHO probes only measure liquid-water content, the field-measured water content decreased as soil froze. Consequently, soil water content measured when the soil was frozen did not represent the total soil water content. A decrease in measured soil liquid-water content due to freezing was consistently observed during the frost period. Two such examples were for the periods of 10 to 20 Dec. 2005 and 14 to 25 Feb. 2006 (Fig. 3 and 4), when sharp decreases in measured liquid-water content occurred, as shown by the 4-cm measurements (Fig. 5). In contrast, soil liquid-water contents at the deeper depths of 32 and 64 cm did not show such abrupt changes. The monitored period of 2004–2005 was much drier than the others, which probably led to decreased soil water content at the shallow depths but did not appear to have had an impact on the deeper depth.

Wilcoxon rank-sum test results showed that measured soil liquid-water contents at various depths in the top 16 cm were significantly lower ($P < 0.0001$) under the CTBF than under the NT treatment during each monitored period, except 2006–2007 for which CTBF had a higher soil liquid-water content. For the deeper depths of 32 and 64 cm, soil liquid-water contents were significantly greater under CTBF than under NT ($P < 0.0001$). Soil liquid-water content in the field was affected by many factors. The CTBF treatment produced substantially more runoff than the NT treatment, which probably resulted from less infiltration into the soil. On the other hand, deeper frost depth under CTBF and underestimates of total water content by the ECHO probes under freezing conditions could both contribute to the lower measured liquid-water contents under CTBF. Irrigation of the CTBF plot before tillage in both 2003 and 2005 adds further complexity in interpreting the measured soil liquid-water content.

Several complicated mechanisms appeared to cause runoff and erosion. Runoff occurred due to rainfall or snowmelt or both on unfrozen or frozen soil, or due to thawing from the surface. In each case, the soil erosion rate differed due to changes in soil erodibility under different soil freeze–thaw conditions. Soil erodibility is extremely low when the soil is completely frozen, but it becomes high if the soil surface is thawed. Rainfall, even of a relatively small amount, on a thawed bare soil overlying a solid frozen layer can cause high rates of erosion. The reason is that, generally, the water content of thawed soil is high, soil strength is low, and the subsurface frozen layer impedes infiltration. Two successive runoff and erosion events at the end of January 2004 in the CTBF plot (Fig. 1) reflected such mechanisms. Rainfall-induced snowmelt on frozen soil (with a soil surface temperature at 0°C, Fig. 2; snow on the surface, Fig. 3; and daily rainfall of 2.5 mm, Fig. 1) produced more runoff (15.8 mm) and less erosion (1.9 Mg ha^{-1}) in the first event on 27 Jan. 2004. In the following

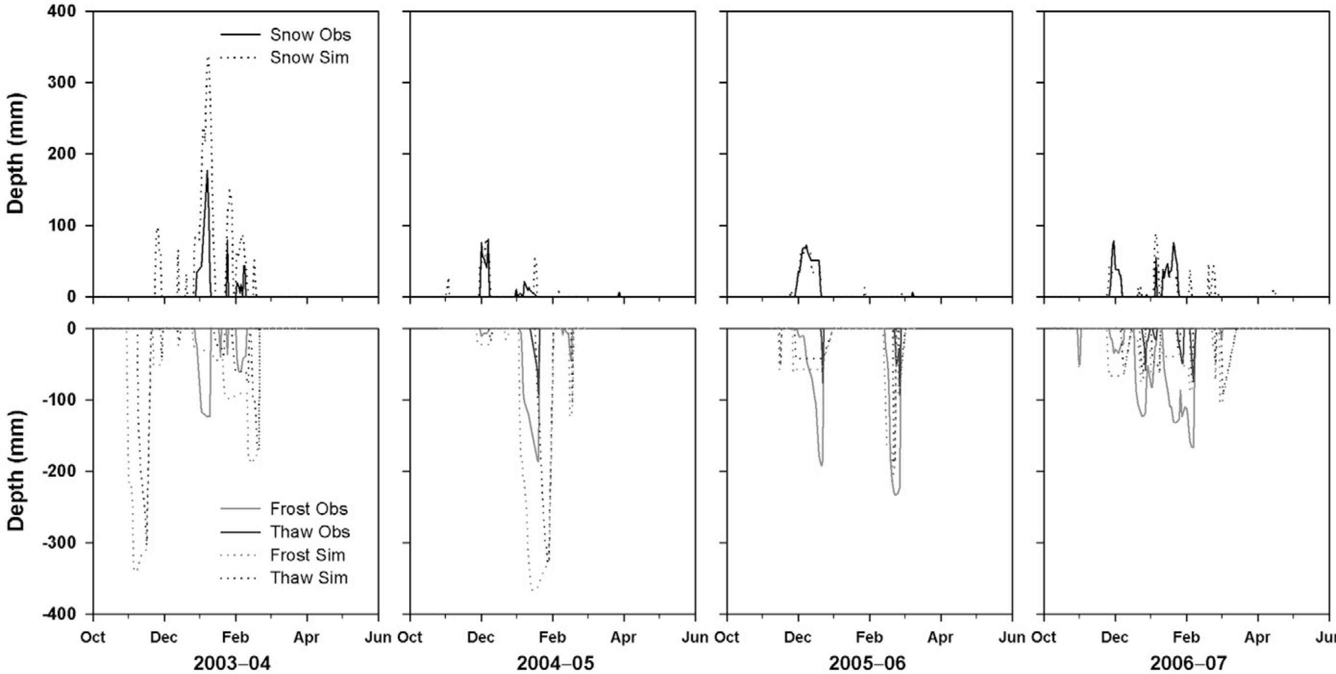

Fig. 3. Observed (Obs) and simulated (Sim) snow depths (top panel) and frost and thaw depths (bottom panel) in the continuous tilled bare fallow (CTBF) plot for each monitored period. The observed frost and thaw depths were based on frost-tube readings. All events were captured during each monitored period, except those before 23 Dec. 2003.

event on 28 January, with a daily rainfall of 3.8 mm (snow on the surface), less runoff (6.0 mm), but more erosion (8.7 Mg ha^{-1}) was generated due to rain on thawed soil.

Table 5 presents all the runoff events categorized into those with unfrozen, frozen, and thawed soil conditions based on frost-tube readings and field-measured soil temperature data for the CTBF. In this study, we defined a frozen soil condition as one with the surface soil temperature below 0°C and a frost layer present; a thawed condition was one with the soil fully or partially thawed from the surface; and an unfrozen condition was one with the soil temperature above 0°C and having reconsolidated after a previous thaw (for 2 d). Kok and McCool (1990) reported that soil shear strength may change substantially during winter freeze–thaw cycles, and a thaw-weakened soil may reconsolidate within

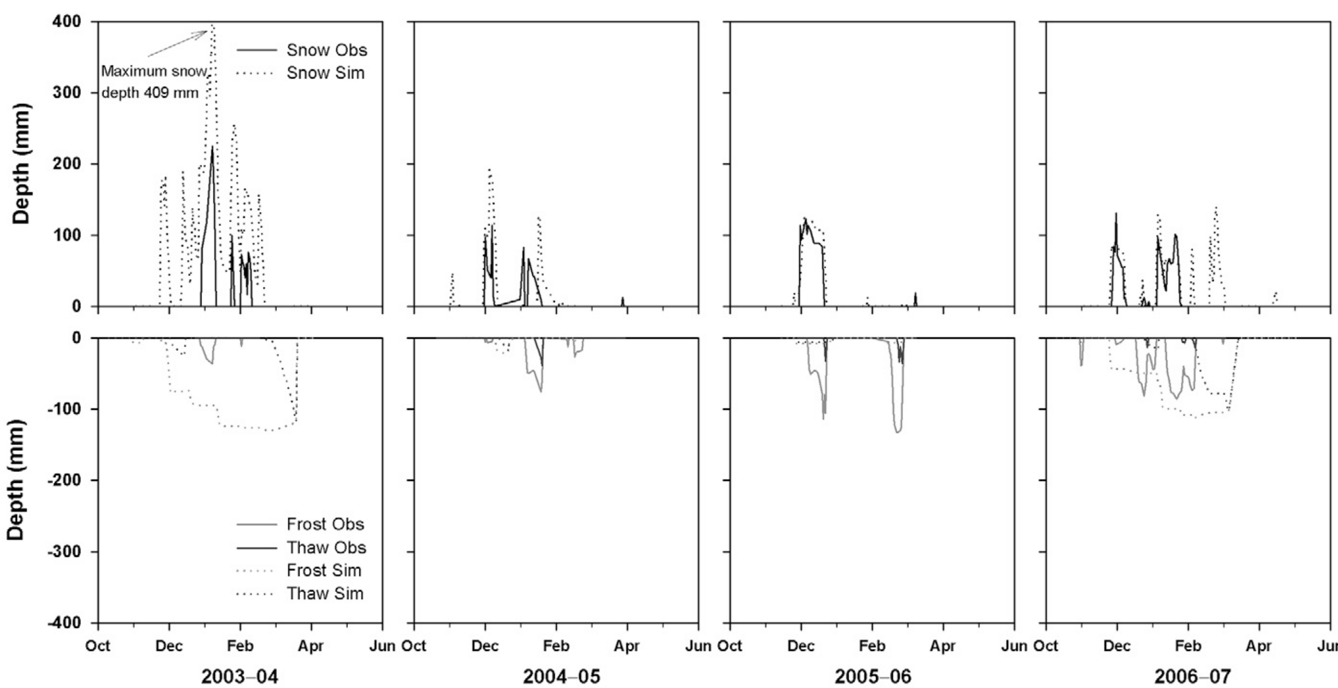

Fig. 4. Observed (Obs) and simulated (Sim) snow depths (top panel) and frost and thaw depths (bottom panel) in the no-till (NT) plot for each monitored period. The observed frost and thaw depths were based on frost-tube readings. All events were captured during each monitored period, except those before 23 Dec. 2003.

Table 4. Observed and simulated maximum snow and frost depths and total frozen-soil days for each monitored period under the continuous tilled bare fallow and no-till treatments.

Season	Observed†			Simulated		
	Max. snow depth	Max. frost depth	Frozen soil	Max. snow depth	Max. frost depth	Frozen soil
	mm	mm	d	mm	mm	d
			Continuous tilled bare fallow			
2003–2004	177	124	24	338	340	86
2004–2005	80	187	26	81	366	44
2005–2006	72	234	36	65	214	39
2006–2007	78	167	57	89	106	72
			No-till			
2003–2004	225	36	14	409	130	128
2004–2005	114	75	32	192	21	29
2005–2006	123	132	29	127	8	40
2006–2007	131	86	54	140	113	105

† Values are for individual plots on the 23% slope.

several hours under rapid evaporation. Therefore, judgment was exercised in categorizing the field-observed runoff events.

Unfrozen, frozen, and thawed events accounted for 57, 12, and 31% of the total events, and they produced 44, 9, and 47% of runoff and 28, 7, and 65% of erosion, respectively. Evidently, rain-on-thawing-soil events were the primary contributor to runoff and erosion that occurred during the entire study time. On the other hand, rainfall-excess runoff produced from unfrozen events was substantial, which was probably a consequence of reduced infiltration capacity due to surface sealing and crusting.

WEPP-Simulated Winter Processes

For the monitored period of 2003–2004, measurement of earlier frost depths were missed due to late installation of the frost tubes. For the CTBF treatment, WEPP overpredicted the frost depth and frozen-soil days for 2003–2005, and the predictions were reasonable for 2005–2007 (Fig. 3, Table 4). For the NT treatment, WEPP substantially overpredicted both frost depth and frozen-soil days for the monitored periods of 2003–2004 and 2006–2007. The WEPP model underpredicted frost depth for the other monitored periods but the predictions of frozen-soil days were adequate (Fig. 4, Table

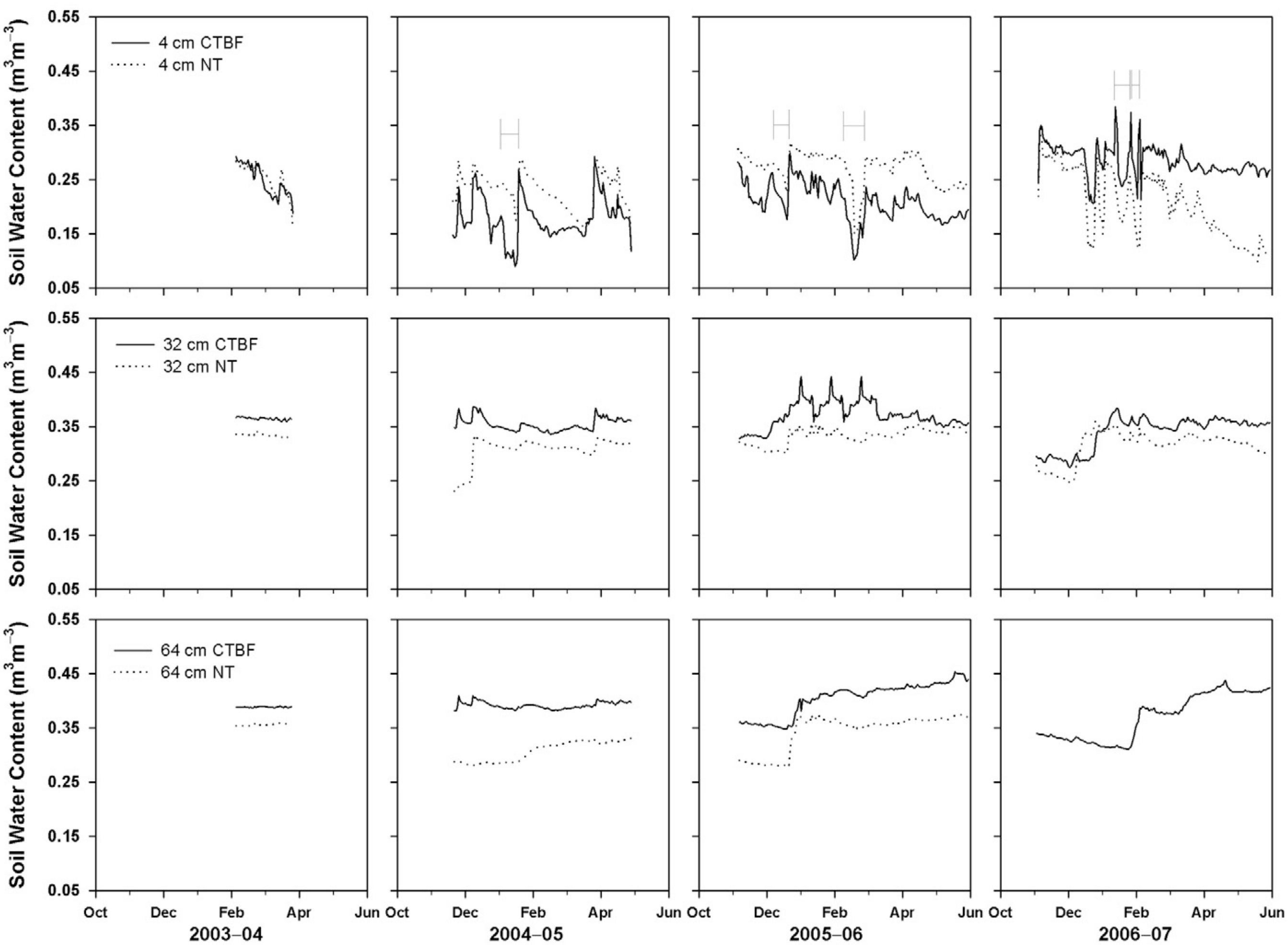

Fig. 5. Observed soil liquid-water content at the 4-, 32-, and 64-cm depths (top, middle, and bottom panels, respectively) for the continuous tilled bare fallow (CTBF) and no-till (NT) treatments for each monitored period. Note missing data at the 64-cm depth in the NT for 2006–2007. The marks in the top panel indicate frost periods where soil liquid-water content measurements were affected by ice formation.

Table 5. Runoff and erosion events for each monitored period under the continuous tilled bare fallow plot on the 23% slope separated into those with unfrozen, frozen, and thawed soil conditions.

Parameter	2003–2004	2004–2005	2005–2006	2006–2007	Total
			Unfrozen		
No. of events	3	5	25	10	43 (57)†
Runoff, mm	6	11	111	20	148 (44)
Erosion, Mg ha^{-1}	17	1	106	31	155 (28)
			Frozen		
No. of events	6	0	1	2	9 (12)
Runoff, mm	21	0	1	10	32 (9)
Erosion, Mg ha^{-1}	29	0	2	7	38 (7)
			Thawed		
No. of events	5	2	7	9	23 (31)
Runoff, mm	40	11	39	68	158 (47)
Erosion, Mg ha^{-1}	32	2	56	279	369 (65)

† Percentage of the total in parentheses.

4). For both the CTBF and NT, WEPP simulations and field observations of snow depth were in reasonable agreement, except for the first monitored period for which simulated maximum snow depths nearly doubled the observed depths (Fig. 3 and 4). In our simulation we did not account for snow drift, yet the experimental site was situated on a windward slope in an open field. Hence, the WEPP-simulated snow depth may not always be representative of field conditions.

For the CTBF, WEPP overpredicted runoff for the monitored periods of 2003–2005 and underpredicted it during the third monitored period (Fig. 1, Table 3). The WEPP model overpredicted erosion for the monitored period of 2004–2005 and underpredicted it for the last two monitored periods (Fig. 1, Table 3). For the first monitored period, WEPP overpredicted the frost depth in November 2003, which led to two overpredicted erosion events. The overpredicted snow depths resulted in high snowmelt runoff with little to no erosion in December and January 2004. The overall outcome was overestimated runoff and a rather agreeable erosion prediction. The winter of 2004–2005 was dry, with field-observed runoff and erosion being low. The WEPP model overpredicted both runoff and erosion from three large events that were not observed. For the third monitored period, the simulated runoff and erosion were about half of the observed values because WEPP generated fewer runoff events than observed events (8 vs. 33). For the last monitored period, WEPP-simulated and observed runoff was in reasonable agreement (76 vs. 97 mm); however, WEPP could not reproduce the observed rain-on-thawing-soil event on 2–3 Jan. 2007 discussed above. In fact, WEPP slightly overpredicted the amount of runoff for this 2-d event (32 vs. 28 mm) yet significantly underpredicted the erosion (21 vs. 224 Mg ha^{-1}) due to the description of the soil detachment capacity as a linear function of flow shear stress.

For the NT treatment, WEPP predictions of runoff and erosion were highly agreeable with field measurements (Table 3), except for the first monitored period for which WEPP overpredicted runoff as a result of its overprediction of snow depth, frost depth, and frozen-soil days (Table 4). The WEPP-simulated and field-observed erosion were both negligible for all 4 yr.

Figure 6 shows WEPP-simulated total soil water content, including both liquid water and ice contents, at 10-, 40-, and 60-cm depths for each monitored period under the CTBF and NT. The simulated results clearly show the recharge of the soil profile during all the winter seasons, except the winter season of 2004–2005 (Fig. 6). For the CTBF treatment, WEPP simulated relatively low total soil water content for the top layer because evaporation was assumed to withdraw water mainly from this layer. For the NT treatment, WEPP simulated near-saturation total soil water contents for the period of January to March 2004, which was in disagreement with a field-observed soil water content of <0.35 m^3 m^{-3} at the 4- and 32-cm depths (Fig. 5) under predominantly unfrozen conditions (Fig. 4). The reason was that WEPP incorrectly simulated continuous frost for this period (Fig. 4). Consequently, there would be no downward movement of soil water during this simulated frost period. Upon the simulated thawing of the topsoil layer around 19 Mar. 2004 (Fig. 4), the simulated total water content in this layer decreased rapidly, causing recharge to, and increase in total soil water content of, the deeper layers (Fig. 6). The WEPP-simulated soil water contents at the deeper depths were much lower under NT (at about 0.11 m^3 m^{-3}, the permanent wilting point) than under CTBF throughout May to November. This result could be due to excessive crop root uptake simulated by WEPP. Field measurements showed comparatively higher water contents at these depths (range of 0.25–0.35 m^3 m^{-3}) for November 2004.

The WEPP-simulated water balance (Table 3) showed that, overall, runoff is substantially larger and soil evaporation is more than doubled under CTBF than under NT. Combined soil evaporation and plant transpiration, namely evapotranspiration, however, is slightly higher under NT. The WEPP model simulated 6 to 42 mm per monitored period of deep percolation below the 1-m soil profile for CTBF and 0 to 45 mm for NT. O'Geen et al. (2005) reported, based on a study involving hydrometric measurements, natural tracers, and stratigraphic observations, that recharge to the topmost unconfined aquifer, more than 10 m below the surface, may range from <3 to 10 mm yr^{-1} depending on the homogeneity of the regolith in the Pullman area.

Conclusions

This study aimed to evaluate winter hydrologic and erosion processes as affected by two contrasting tillage practices and to assess the suitability of the USDA's WEPP model for quantifying the field-observed winter processes. Field measurements of runoff and erosion as well as the depths of snow, soil frost, and thaw suggested that the effects of tillage practices on winter hydrologic and erosion processes were evident and prominent.

The CTBF treatment produced shallower snow depth and deeper frost depth than the NT treatment. The CTBF generated significant amounts of runoff and erosion, whereas NT produced negligible runoff and erosion. For the study period, the majority of the runoff events occurred under unfrozen conditions, yet the thawed events resulted in most of the soil erosion under CTBF.

The WEPP model, with an alternative energy-budget-based winter routine, could well reproduce field-measured snow depths for the monitored periods (October–May) for 2004–2007 for both CTBF and NT. The WEPP model reproduced

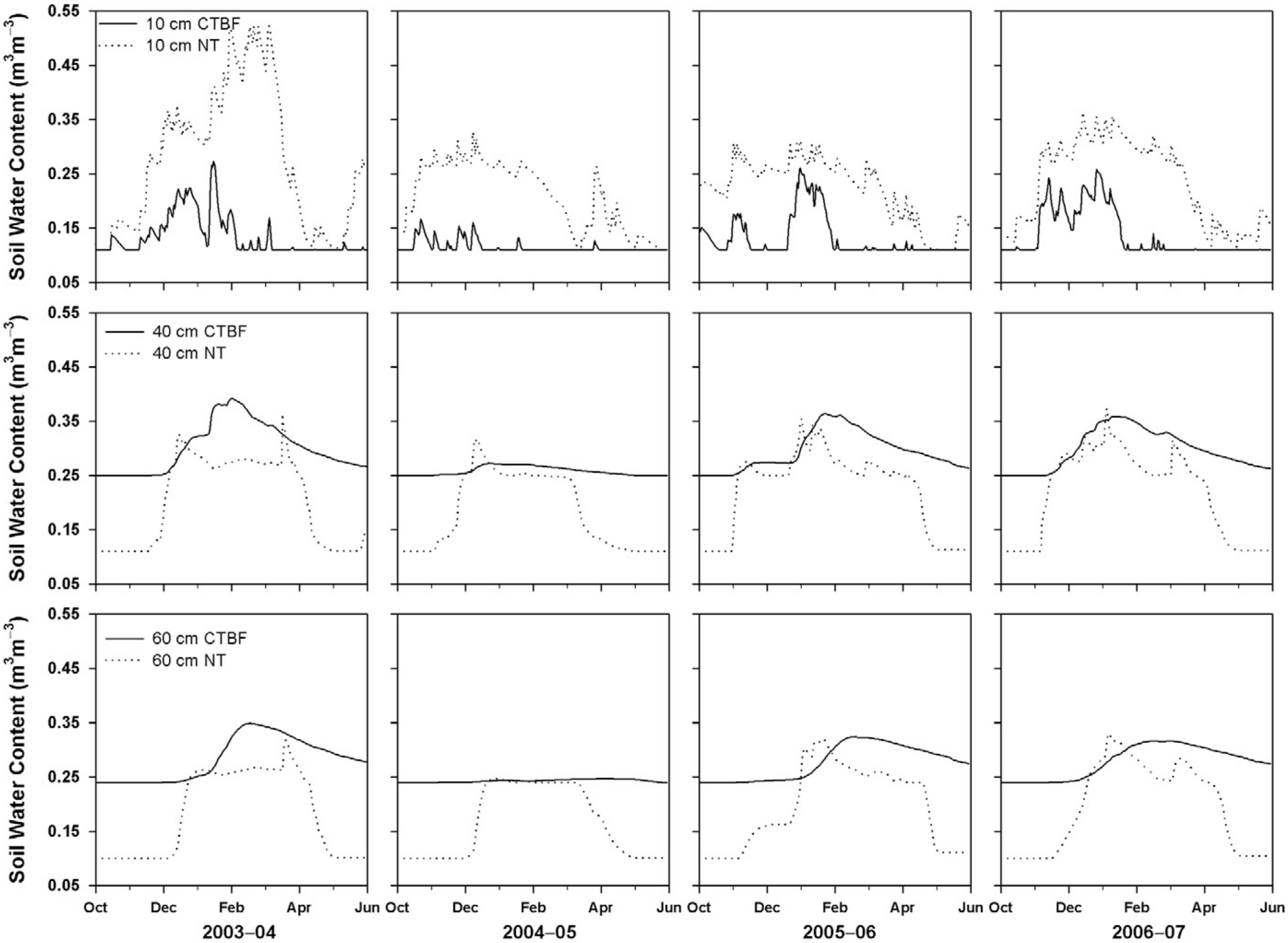

Fig. 6. Simulated total soil water content at the 10-, 40-, and 60-cm depths (top, middle, and bottom panels, respectively) for the continuous tilled bare fallow (CTBF) and no-till (NT) treatments for the monitored period.

the field-observed frost and thaw depths as well as the number of frozen-soil days reasonably well for the monitored periods of 2005–2007 for CTBF, but performed poorly for each monitored period for NT. For CTBF, WEPP overpredicted runoff for the first two monitored periods and underpredicted it for the last two monitored periods, and mostly underpredicted erosion. For NT, WEPP predictions of runoff and erosion were generally in good agreement with field measurements.

The WEPP model showed potential as a modeling tool for assessing the effect of management practices on winter hydrologic and erosion processes. Yet it is not able to represent all the complicated winter phenomena observed in the field. Snow accumulation and melt and soil freeze–thaw are complex processes that are affected by many factors. Dramatic changes in soil resistance to erosion of frozen, unfrozen, and thawed soil surfaces at the time of rainfall or snowmelt or both could complicate the erosion processes, posing great challenges to modeling. Continued efforts are needed to further improve the ability of WEPP to properly account for soil freeze and thaw and thus the transient soil hydraulic properties and hydrologic and erosion processes.

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