MODELING EFFECTS OF CONTRASTING TILLAGE AND MANAGEMENT ON HYDROLOGICAL PROCESSES IN SELECTED SOILS OF THE PACIFIC NORTHWEST US

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the dissertation of PRABHAKAR SINGH find it satisfactory and recommend that it be accepted.

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Chair

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Soil erosion by water is detrimental to fertility and crop yield as well as soil biological and physical properties. Soil erosion could be affected by winter precipitation, intermittent freezing and thawing of soils, steep slopes, and improper management practices as well as combination of these factors. The tillage practices play an important role on infiltration, winter runoff and erosion, and seed-zone water storage. Understanding of hydrological processes is crucial to developing land-use and management plans for reducing runoff and erosion and for conserving seed-zone water. Adequate understanding of hydrological processes is also essential to develop models that can serve as effective predictive tools. The objectives were as follows:

1. to assess the suitability of WEPP, a physically-based erosion model with a newly implemented energy-budget-based winter routine, for quantifying field-observed winter processes;
2. to evaluate winter hydrological and erosion processes as affected by two contrasting tillage practices;

3. to assess the effects of Chemical Fallow (CF) and Reduced-tillage Fallow (RT) on seed- and root-zone water and temperature regimes;
4. to test the Simultaneous Heat and Water (SHAW) model's ability to simulate management effects on soil water and temperature distribution.

Long-term erosion research plots (2003–07) subject to continuous tilled bare fallow (CTBF), and continuous no-tillage (NT), were established at the USDA-ARS Palouse Conservation Field Station near Pullman, WA. The plots were monitored for runoff, erosion, soil temperature and water content, and depths of snow and freeze-thaw as well as climate data. The study with paired CF and RT treatments was conducted in 2003–04 at the Dryland Research Station at Lind, WA.

Field data showed that NT plots generated negligible runoff and erosion compared to CTBF. Frost occurred more frequently and frost depth was deeper in the CTBF compared to the NT. The modified WEPP model could reasonably reproduce major winter processes. Yet it cannot represent all the complicated winter phenomena observed in the field.

The RT treatment retained more seed-zone water during the summer compared to CF. In general, soil temperatures in the CF were higher than the RT. Overall, SHAW proved adequate in simulating seed-zone and whole-profile soil water and temperature.

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CHAPTER 1

INTRODUCTION

1.1 Background

Agriculture lands have been adversely impacted by water erosion due to the removal of topsoil and reduced soil fertility (USDA et al., 1978; Busacca et al., 1985; Schertz et al., 1985; Young et al., 1985; McCool and Busacca, 1999). Off-site sediment deposition in streams, rivers and reservoirs has also negatively affected water quality, storage capacity, and life of open-water habitat (USDA, 1978). On-site erosion control will not only maintain the topsoil but also reduce the off-site damages and associated economic losses (USDA, 1978). In 1937, the Washington Agricultural Experiment Station issued Bulletin 344 entitled "Crop Rotations," with a statement that "Losses from soil erosion are so great that both tillage methods and suitable crops should be employed to reduce to a minimum the destruction from this cause" (Wheeting and Vandecaveye, 1937).

USDA (1978) reported that soil loss rates due to water erosion reached a maximum of 225 to 450 t ha^{-1} yr^{-1} with an average soil loss of 35 t ha^{-1} yr^{-1} in the Palouse region, greatly exceeding the recommended tolerable rates of 5.0–12.0 t ha^{-1} yr^{-1} (USDA SCS, 1982). A combination of factors, including winter precipitation, intermittent freezing and thawing of soils, steep slopes, and conventional management practices, contributed to the high erosion rates (Papendick et al., 1983). Frozen and thawing of soil has been found to be a major factor leading to winter runoff and erosion (McCool, 1990). Understating the dynamic changes in soil hydraulic properties during soil freezing and thawing and their impacts on winter hydrologic and erosion processes can help in proper selection of management practices for reducing runoff and erosion. Adequate knowledge of the winter processes is also essential to developing models that can serve as effective predictive tools.

Tillage-based, winter wheat-summer fallow is the predominant agricultural system on the 1.8-million ha of farmland in the low-precipitation (<350 mm annually) dryland cropping region of the Pacific Northwest (PNW). The primary goal of summer fallow is to store a portion of winter precipitation during the following 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). Tillage operations often bury surface residue, pulverize soil particles and leave the soil highly vulnerable to wind erosion (Papendick, 2004). Alternative management practices are needed to provide necessary seed-zone soil water for winter wheat and to reduce wind erosion.

1.2 PCFS Study

The two replicated treatments of continuous tilled bare fallow (CTBF) and continuous no-till (NT) do not mimic anything that a producer would use on their land. These are extremely different treatments that provide data sets to test relationships in WEPP. The CTBF represents a worst case treatment of agricultural land. The lack of residue addition and, even annual tillage leads to decline in strength of material (SOM) and resistance to erosion. It takes about 3 years before a plot treated in this manner loses the stem pieces and material that physically protects the soil. The spring Barley was seeded across in the spring with intent of adding just a bit of organic material to the surface and then killing it before it added much biomass. However, weather never cooperated with spraying out in a timely manner, and the excess material was burned. The winter wheat plants on the NT plot were always chemically killed and the plots reseeded in the spring in order that we could seed across and have growing material on the area that have been walked on adjacent the plots each winter. When we rolled up the borders each spring, we always damaged part of the plot area. Reseeding with spring crop gave a uniform condition, and residue cover, for no-till seeding winter wheat in the fall. In this study we are comparing two treatments, one very soil damaging, and the other soil conserving, and not comparing the performance of cropping or tillage systems. The goal of this study is how well does WEPP model these widely different treatments.

1.3 Objectives

The goal of this dissertation was to attain a better understanding of the effects of contrasting tillage practices on runoff, erosion and seed-zone water and temperature based on field investigation and modeling. The main models used in this study were the Water Erosion Prediction Project (WEPP; Laflen, 1991; 1997) and Simultaneous Heat and Water (SHAW; Flerchinger and Saxton, 1989a,b). WEPP is a physically-based model developed in the late 1980's for predicting runoff and erosion from field- to watershed scales (Flanagan et al., 1995). SHAW was developed to characterize water and heat flow (coupled simulation of heat and water movement) in the root zone as affected by tillage and residue management (Flerchinger and Saxton, 1989a). These models were applied, modified as needed, and evaluated in this study. The specific objectives were:

1. to evaluate winter hydrological and erosion processes as affected by two contrasting tillage practices, namely, Conventional tilled Black Fallow (CTBF) and No-tillage (NT);
2. to assess the suitability of WEPP (v2004.7), a physically-based erosion model with a newly implemented energy-budget-based winter routine, for quantifying field-observed winter processes (i.e., snow depth, soil frost and thaw, runoff and erosion);
3. To assess the adequacy and performance of WEPP (v2004.7) for water erosion prediction under the physical conditions of the inland Pacific Northwest (PNW) for two contrasting treatments of Conventional Tillage (CT) and No-tillage (NT);
4. to assess the effects of Chemical (no-till) Fallow (CF) and Reduced-tillage Fallow (RT) on seed- and root-zone water and temperature regimes; and
5. to test the SHAW model's ability to simulate management effects on soil water and temperature distribution.

1.4 Thesis Outline

This dissertation includes six chapters. Chapter 1 is an introduction to the dissertation and provides the background information and major objectives of the doctoral study. Chapter 2 presents the effects of two contrasting tillage practices on winter hydrologic and erosion processes and the performance of WEPP (v2006.5) with an alternative winter routine for quantifying field-observed winter processes (*Vadose Zone Journal*, in press). Chapter 3 investigates the adequacy and performance of WEPP (v2004.7) for water erosion prediction (*Vadose Zone Journal 5:261–272, 2006*). Chapter

4 assess the of two tillage practices on conserving seed- and root-zone water in dryland region and the assessment of the ability of the SHAW model in simulating field-observed soil water and temperature (*Applied Engineering in Agriculture*, Accepted). Chapter 5 presents the major conclusions of the dissertation. Appendices include runoff separation technique, literature review on surface sealing and crusting, SAS code and effect of slope aspect in WEPP simulation. References are listed together at the end of the dissertation.

CHAPTER 2

WINTER HYDROLOGICAL AND EROSION PROCESSES IN THE U.S. PALOUSE REGION: FIELD EXPERIMENTATION AND WEPP SIMULATION

2.1 Abstract

Soil erosion by water is detrimental to soil fertility and crop yield as well as the environment. For cold areas, knowledge of winter hydrological processes is critical to determining alternative land-use and management practices for reducing soil loss and protecting land and water resources. Adequate understanding of these processes is also essential to developing models that can serve as effective predictive tools. The objectives of this study were to: (i) evaluate winter hydrological and erosion processes as affected by two contrasting tillage practices; and (ii) assess the suitability of WEPP (Water Erosion Prediction Project), a physically-based erosion model with a newly implemented energy-budget-based winter routine, for quantifying field-observed winter processes. Long-term erosion research plots subject to two tillage treatments: a worst-treatment control, continuous tilled bare fallow (CTBF), and continuous no-tillage seeding of winter wheat after spring cereal (NT), were established at the USDA-ARS Palouse Conservation Field Station near Pullman, WA. The plots were continually monitored for runoff, erosion, soil temperature and water content, and depths of snow and freeze-thaw during October to May of 2003–04 through 2006–07. Field data showed that NT plots generated negligible runoff and erosion compared to CTBF that produced substantially greater runoff and erosion. Further, frost occurred more frequently and frost depth was deeper in the CTBF treatment, likely due to its lack of residue and shallower snow depth, compared to the NT treatment. The modified WEPP model could reasonably reproduce major winter processes (e.g., snow and frost depths, runoff and erosion). 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 the transient soil hydraulic properties and hydrologic and erosion processes.

2.2 Introduction

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 hydrological 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 (PNW) where the majority of the precipitation falls in winter (McCool and Roe, 2005; WRCC, 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, eastern Washington received 59% of the annual precipitation during the winter season of November through March (WRCC, 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 PNW. Davis and Molnau (1973), based on a study conducted at the eastern edge of the Palouse region, found that between 20 and 25 percent of incident precipitation was lost to runoff. Water erosion has led to an average soil loss of 35 t ha^{-1} yr^{-1} with maximum soil loss rates reaching 225 to 450 t ha^{-1} yr^{-1} in the Palouse region (USDA, 1978), which was among the highest in the U.S. and greatly exceeded the recommended tolerable rates of 5.0–12.0 t ha^{-1} yr^{-1} (USDA SCS, 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 was agreeable with the nearly 100 freeze-thaw cycles reported by Hershfield (1974) for the Palouse region.

Freeze-thaw reduces soil cohesive strength (Formanek et al., 1984; Kok and McCool, 1990) and consequently increases soil erodibility (Van Klaveren and McCool, 1998). Frost heave and expansion of soil pores occur frequently during freezing due to 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 is greater for precipitation events under non-frozen 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.

Water Erosion Prediction Project (WEPP) is a physically-based model developed in the late 1980’s for predicting runoff and erosion from field- to watershed scales (Flanagan et al., 1995; Laflen et al., 1997). WEPP 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). However, the original winter routine of WEPP was found inadequate for the PNW (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 (PCFS), 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 2003–04 through 2006–07. 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-tillage (NT) with direct-seeded annual winter wheat (Triticum aestivum L. cv. Madsen; Gledhill, 2002) following no-till spring barley (Hordeum vulgare L.; Gledhill, 2002), were evaluated. The comprehensive data allow for an improved understanding of water movement and heat transfer in the soil profile, and for 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 hydrological 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.

2.3 Materials and Methods

2.3.1 Experimental Site and Field Monitoring

The experimental site was comprised of three pairs of CTBF and NT plots on a south-facing field at the PCFS (46°44′N, 117°8′W, 762 m a.m.s.l.). 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 (fine silty, mixed Mesic-Pachic, Ultic, Haploxeroll). Average annual precipitation (1940–2007) is 531 mm (WRCC, 2008). Two tillage treatments of CTBF and NT were applied. A Roto-vator, with depth of 15–18 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 (of slope gradient 23% and 80 m apart) plots were chosen to measure residue and soil properties and were extensively instrumented for monitoring soil water and temperature, in addition to other hydrologic and erosion processes, in the winter seasons of 2003–04 through 2006–07.

Surface residue properties, including the amount of dry biomass, percent cover, and the height of standing stubble, were measured for the NT treatment each year after harvest. Three measurements were made across 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 prior to residue collection, and were later analyzed to determine percent residue cover using regular grid counting following

McCool et al. (1989). The amount of dry biomass was obtained by weighing the residue samples after oven-drying at 105°C. 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 (2.5 cm diameter and 3 cm length). Undisturbed samples were collected in the 0–0.1 m, 0.1–0.2 m, 0.2–0.4 m, 0.4–0.6 m, 0.6–0.8 m, 0.8–1 m depth intervals, and measurements were made of saturated hydraulic conductivity (K) by the constant-head method (Reynolds et al., 2002), dry bulk density with the core method (Grossman and Reinsch, 2002), and organic matter by dry combustion (Sheldrick, 1984). Particle-size analysis was made 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 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 re-installed 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 (extending to the depth of 1.2 m) containing methylene-blue dye solution, in which dye migrates from freezing point and concentrates in the unfrozen portion of the tube during freezing, provide 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-m3 (600-gallon) at the bottom of each plot. Sediment in the tank was re-suspended 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-liter runoff samples were collected for analysis. These samples were oven-dried to determine sediment concentration and 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 soil water was monitored using individually calibrated ECHO probes (Decagon Devices Inc., 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 Inc., Pullman, WA). 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-minute intervals. The soil temperature profile allowed for separation of runoff events into occurrences with frozen, thawing, or non-frozen conditions, and for verification of the frost-tube measurements.

An automatic weather station was installed between the paired CTBF and NT plots (of 23% slope), measuring precipitation with a tipping-bucket rain gage (Campbell Scientific, Logan, UT), 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, Logan, UT). All weather measurements were made at 15-minute 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 were missing for these periods. A Belfort rain gage (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.

2.3.2 WEPP Application

2.3.2.1 WEPP Overview

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

The energy-budget-based winter routine by Lin and McCool (2006) was incorporated into WEPP (v2008.7) 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

$$\downarrow G = \downarrow Rn - \uparrow H - \uparrow LE \tag{1}$$

where G is energy flow into the soil surface, Rn is net radiation, H is sensible heat, and LE is latent heat of vaporization. Energy flow is considered positive in the direction of 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 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, total soil water content (liquid plus ice) and 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, 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

$$Ke = 1/(ff/(Ku \cdot rf) + (1 - ff)/Ku) \tag{2}$$

where Ke 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), Ku 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 soil hydraulic conductivity (Rawls et al., 1990; Philip, 1998; Ruan et al., 2001). In this study, adjustment of saturated hydraulic conductivity for the CTBF was made by applying the adjustment factor of 0.01 if the daily rainfall amount exceeds a threshold value of 10 mm and 0.5 otherwise. Such adjustments were not made for the NT because we assumed that the residue cover reduces the impact of raindrops and helps retain soil infiltration capacity.

2.3.2.2 WEPP Inputs and Simulation

The WEPP model was executed to simulate the winter hydrologic and erosion processes for 2003–04 through 2006–07 under the CTBF and NT conditions. WEPP requires four sets of input data: climate, slope, soil and management. WEPP climate inputs include daily precipitation (in break-point 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 2 NW station. Data from the Belfort rain gage 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 (azimuth 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 2.1 summarizes soil inputs for the WEPP simulation.

Information on 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 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 2.2.

Table 2.1: 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).

2.3.3 Statistical Analysis

Non-parametric Wilcoxon rank-sum tests were conducted using SAS (SAS Institute Inc., 2004) to determine differences in mean field-measured daily soil liquid-water content between the CTBF and NT treatments for each monitored period. These tests (significance level 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 non-normality and lack of independence typically associated with daily soil water and temperature data.

2.4 Results and Discussion

2.4.1 Field-observed Winter Processes

During the monitored periods of 2003–04 through 2006–07, 75 runoff and erosion events were observed in the CTBF plot (Fig. 2.1) as compared to three in the NT plot. In total, the CTBF plot generated 323 mm of runoff and 547 t ha^{-1} of eroded sediment for the entire study period whereas both runoff and erosion were negligible (0.5 mm and 0.2 t ha^{-1}) from the NT plot (Table 2.3). The amount of runoff and 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 been built up due to continuous no-tillage 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 Greer et al. (2006) and Cruse et al. (2001).

Table 2.2: Management inputs used in the WEPP simulations for the continuous tilled bare fallow (CTBF) and no-tillage (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
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

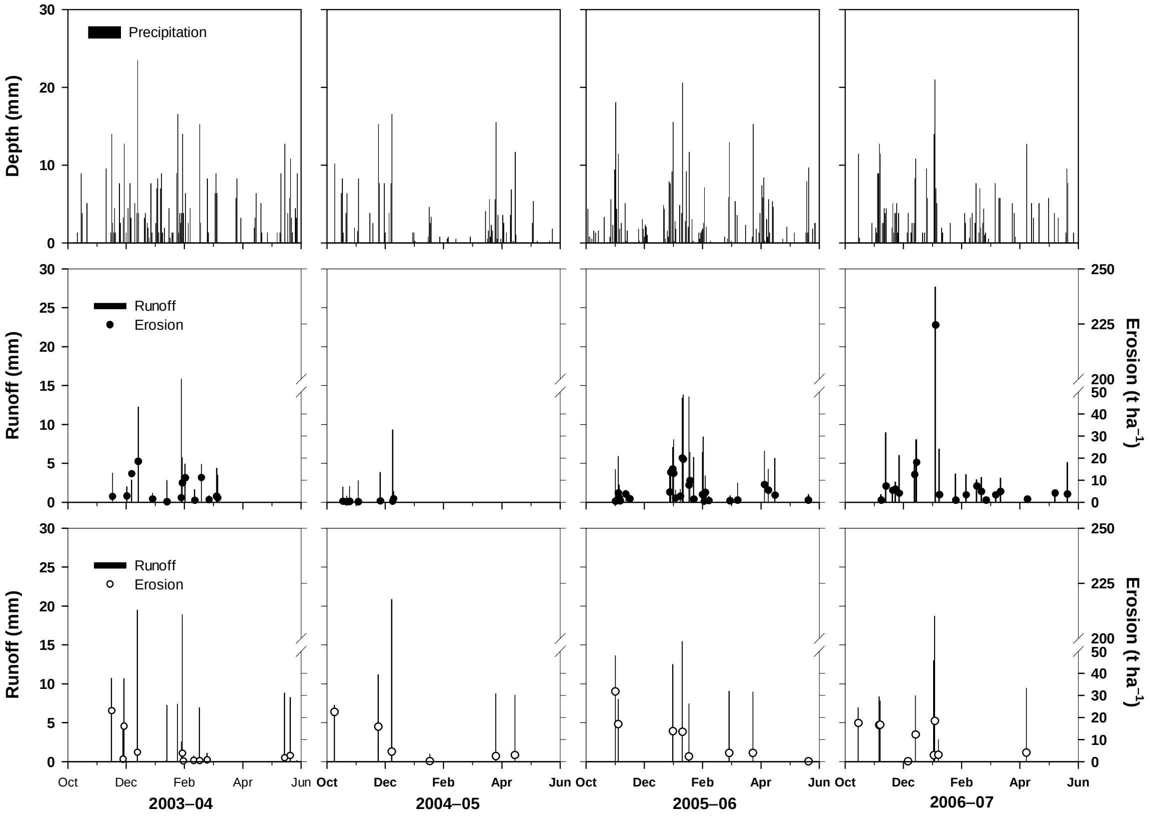

Figure 2.1: Observed daily precipitation (top panel), observed runoff and erosion (middle panel), and simulated runoff and erosion (bottom panel) in the continuous tilled bare fallow (CTBF) plot for each monitored period.

A large runoff and erosion event occurred on January 2–3, 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 t 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 2006–07. Similar results were also found for the two replicate CTBF plots (26.0 and 25.8 mm of runoff and 148 and 124 t ha^{-1} of erosion, respectively). The NT plot, on the other hand, generated negligible runoff (0.13 mm) and no erosion, while the two replicate plots generated neither runoff nor erosion.

Daily soil temperatures at different depths in the CTBF and the NT plots, averaged from the 15-minute records, are shown in Fig. 2.2. Damping fluctuations of soil temperature with depth was observed (Fig. 2.2). Wilcoxon rank-sum test results indicated that soil temperatures at different depths under the CTBF and NT did not differ for each monitored period (P-value ranging 0.08–0.49), with the difference between mean daily soil temperatures of the CTBF and NT always below 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, as compared with the CTBF plot.

Table 2.3: Observed runoff and erosion and WEPP-simulated surface runoff (*R*), soil evaporation (*Es*), plant transpiration (*Ep*), deep percolation (*Dp*), subsurface lateral flow (*Q*), change in soil water (Δθ) and erosion for each monitored period under the continuous tilled bare fallow (CTBF) and no-tillage (NT) treatments.

		Observed[‡]		Simulated						
	P[†]	*R*	Erosion	*R*	*Es*	*Ep*	*Dp*	*Q*	Δθ	Erosion
	mm	mm	t ha^{-1}	mm	mm	mm	mm		mm	t ha^{-1}
		CTBF								
2003–04	417	67 (52, 62)	77 (35, 21)	108	233	0	42	0	34	53
2004–05	214	22 (2, 0)	3 (0.2, 0)	57	153	0	6	0	−2	48
2005–06	360	137 (102, 118)	150 (95, 92)	75	231	0	28	0	26	85
2006–07	336	97 (74, 89)	317 (214, 175)	76	211	0	27	0	22	90
		NT								
2003–04	417	0.3 (0, 0.5)	0.2 (0, 0.001)	36	108	160	30	22	61	0.03
2004–05	214	0 (0, 0)	0 (0, 0)	0	42	177	0	0	−5	0
2005–06	360	0.1 (0, 0.1)	0 (0, 0)	0	103	158	43	0	56	0
2006–07	336	0.1 (0, 0)	0 (0, 0)	0	91	149	45	1	50	0

[†] Precipitation values were for the monitored period of October to 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.

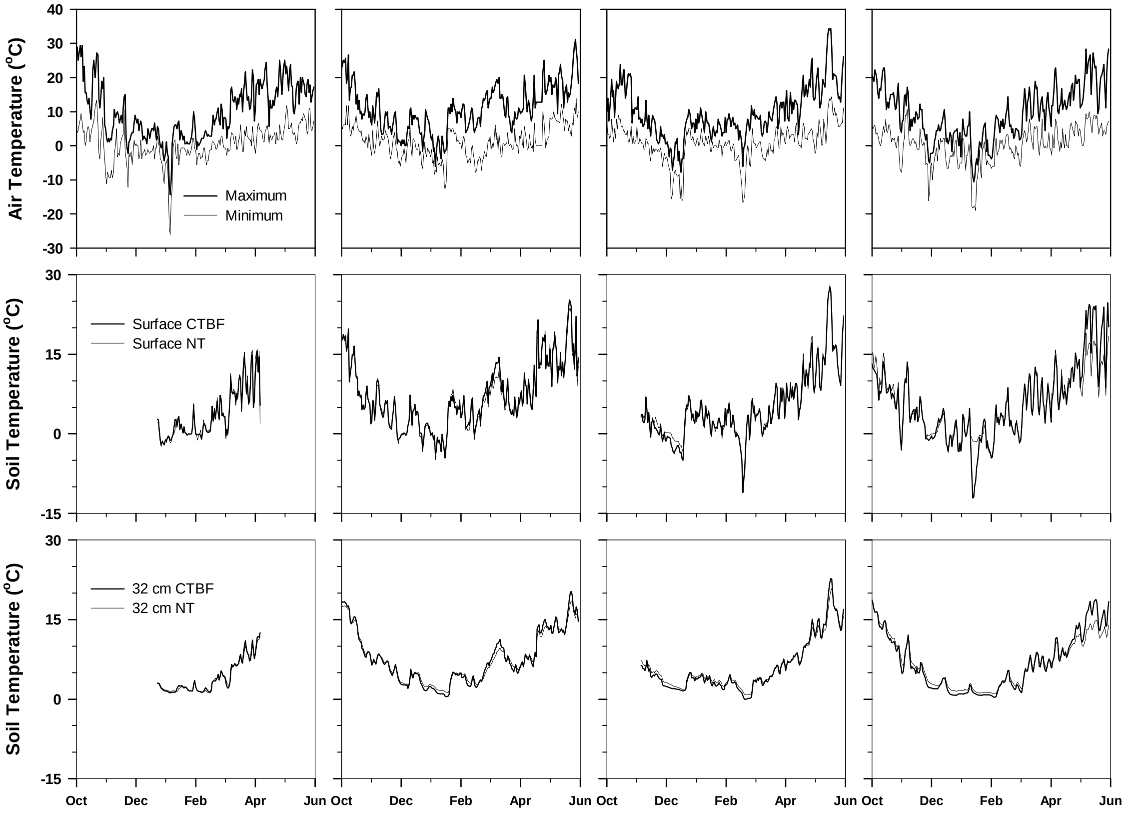

Figure 2.2: Observed air temperature (top panel), observed soil temperature at the 4-cm (middle panel) and 32-cm (bottom panel) depths for the continuous tilled bare fallow (CTBF) and the no-tillage (NT) for each monitored period.

Field-observed depths of snow, frost and thaw at the CTBF and NT plots are shown in Figs. 2.3 and 2.4, respectively. Snow depths were deeper in the NT plot than in the CTBF plot (Table 2.4) as a consequence of the greater snow capture and holding capacities by wheat residue (standing stubble in particular) than bare soil (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 (2005–06) in the NT plot. Slightly more frozen-soil days (143 vs 129 for the entire study period) yet much deeper frost depths were observed in the CTBF plot than in the NT plot (Table 2.4). The frost-tube measurements proved valuable indicators of soil freezing, although they tended to respond to soil freezing in a delayed manner (McCool and Molnau, 1984; Flerchinger and Saxton, 1989; Greer et al., 2006). More snow on the surface in the NT plot likely 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 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.

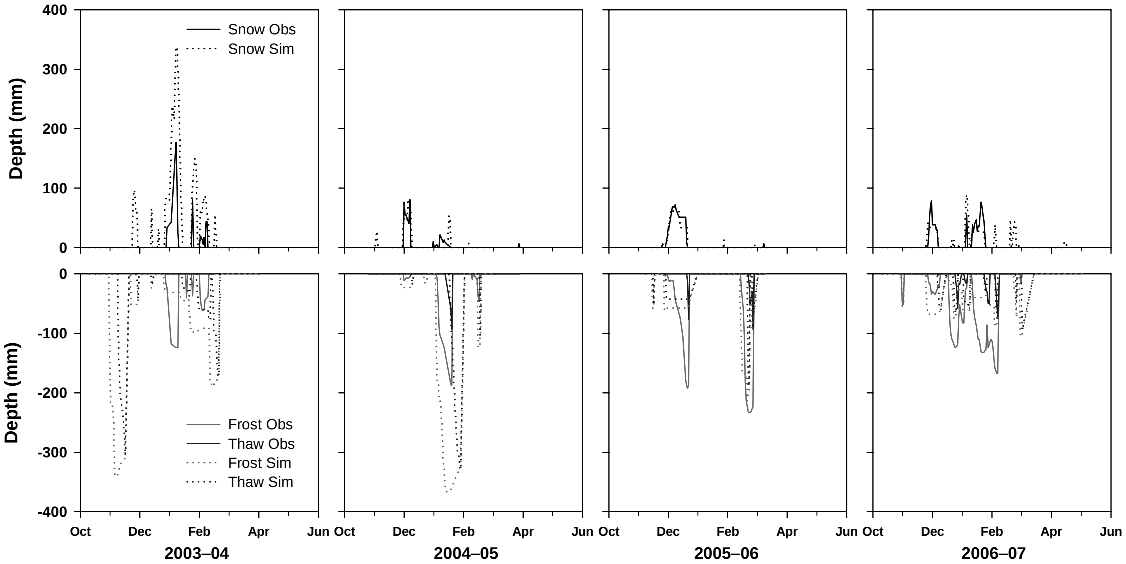

Figure 2.3: Observed and simulated snow depths (top panel), and frost and thaw depths (bottom panel) in the continuous tilled bare fallow (CTBF) plot for each monitored period. The observed frost and thaw depths were based on frost-tube readings. All events were captured during each monitored period, except those before December 23, 2003.

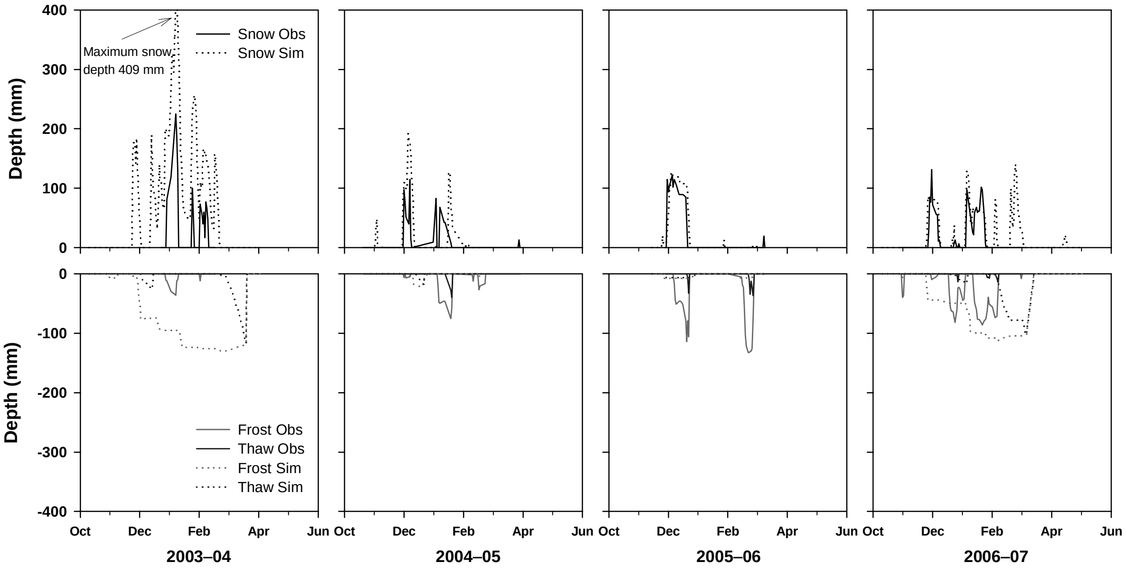

Figure 2.4: Observed and simulated snow depths (top panel), and frost and thaw depths (bottom panel) in the no-tillage (NT) plot for each monitored period. The observed frost and thaw depths were based on frost-tube readings. All events were captured during each monitored period, except those before December 23, 2003.

Table 2.4: Observed and simulated maximum snow and frost depths and total frozen-soil days for each monitored period under the continuous tilled bare fallow (CTBF) and no-tillage (NT) treatments.

	Observed[†]			Simulated		
	Max. snow depth mm	Max. frost depth mm	Frozen-soil days	Max. snow depth mm	Max. frost depth mm	Frozen-soil days
			CTBF			
2003–04	177	124	24	338	340	86
2004–05	80	187	26	81	366	44
2005–06	72	234	36	65	214	39
2006–07	78	167	57	89	106	72
			NT			
2003–04	225	36	14	409	130	128
2004–05	114	75	32	192	21	29
2005–06	123	132	29	127	8	40
2006–07	131	86	54	140	113	105

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

A noticeable response of soil liquid-water content to rainfall events was observed for both the CTBF and NT treatments (Figs. 2.1 and 2.5). As the ECHO probes only measure liquid-water content, the field-measured water content decreased as soil froze. Consequently, soil water content measured when 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 10–20 Dec, 2005 and 14–25 Feb, 2006 (Figs. 2.3 and 2.4), when sharp decreases in measured liquid-water content occurred as shown by the 4-cm measurements (Fig. 2.5). 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 2004–05 was much drier compared to the others, which, however, did not appear to have had an impact on the measured soil liquid-water content.

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 during each monitored period, except 2006–07 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 the CTBF than under the NT ($P < 0.0001$). Soil liquid-water content in the field was affected by many factors. The CTBF produced substantially more runoff compared to the NT, which likely resulted from less infiltration into the soil. On the other hand, deeper frost depth in the CTBF and underestimates of total water content by ECHO probes under freezing conditions both could contribute to the lower measured liquid-water contents in the CTBF. Irrigation of the CTBF plot before

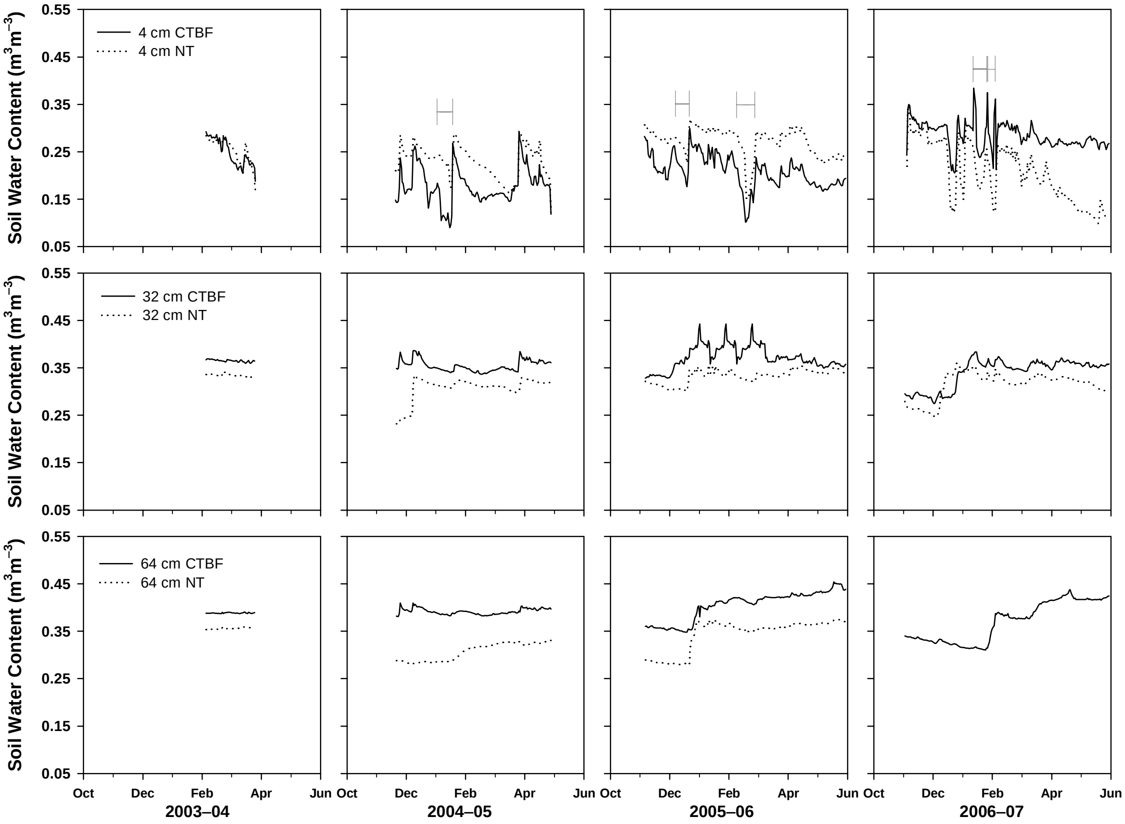

Figure 2.5: Observed soil liquid-water content at the 4-, 32-, and 64-cm depths (top, middle, and bottom panels, respectively) for the continuous tilled bare fallow (CTBF) and the no-tillage (NT) treatments for each monitored period. NOTE missing data at the 64-cm depth in the NT for 2006-07. The marks in the top panel indicate frost periods where soil liquid-water content measurements were affected by ice formation.

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 non-frozen 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 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 overlaying a solid frozen layer, can cause erosion at high rates. 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. 2.1) reflected such mechanisms. Rainfall-induced snowmelt on frozen soil (with a soil surface temperature at 0 °C, Fig. 2.2; snow on the surface, Fig. 2.3; and daily rainfall of 2.5 mm, Fig. 2.1) produced more runoff (15.8 mm) and less erosion (1.9 t ha^{-1}) in the first event on January 27, 2004. In the following event on January 28, with a daily rainfall of 3.8 mm (snow on the surface), less runoff (6.0 mm) but more erosion (8.7 t ha^{-1}) was generated due to rain on thawed soil.

Table 2.5 presents all the runoff events categorized into those with non-frozen, frozen and thawed soil conditions based on frost-tube readings and field-measured soil temperature data for the CTBF. In this study, we define a frozen soil condition as one with the surface soil temperature below 0 °C and a frost layer being present; a thawed condition as one with the soil fully or partially thawed from the surface; and a non-frozen condition as one with soil temperature above 0 °C and having reconsolidated after a

Table 2.5. Runoff and erosion events for each monitored period under the continuous tilled bare fallow (CTBF) plot on the 23% slope separated into those with non-frozen, frozen, and thawed soil conditions.

	2003–04	2004–05	2005–06	2006–07	Total
			Non-frozen		
No. of events	3	5	25	10	43 (57)[†]
Runoff, mm	6	11	111	20	148 (44)
Erosion, t 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, t 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, t ha^{-1}	32	2	56	279	369 (65)

[†] Shown in parentheses are percentages of the total.

previous thaw (for 2 days). 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 several hours under rapid evaporation. Therefore, judgment was exercised in categorizing the field-observed runoff events.

Non-frozen, 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 non-frozen events was substantial, which was likely a consequence of reduced infiltration capacity due to surface sealing and crusting.

2.4.2 WEPP-Simulated Winter Processes

For the monitored period of 2003–04, measurement of earlier frost depths were missed due to late installation of the frost tubes. For the CTBF treatment, WEPP over-predicted the frost depth and frozen-soil days for 2003–05, and the predictions were reasonable for 2005–07 (Fig. 2.3, Table 2.4). For the NT treatment, WEPP substantially over-predicted frost depth and frozen-soil days for the monitored periods of 2003–04 and 2006–07. WEPP under-predicted frost depth for the other monitored periods but the predictions of frozen-soil days were adequate (Fig. 2.4, Table 2.4). 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 (Figs. 2.3 and 2.4). 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, WEPP-simulated snow depth may not always be representative of field conditions.

For the CTBF, WEPP over-predicted runoff for the monitored periods of 2003–05 and under-predicted it during the third monitored period (Fig. 2.1, Table 2.3). WEPP over-predicted erosion for the monitored period of 2004–05 and under-predicted it for the last two monitored periods (Fig. 2.1, Table 2.3). For the first monitored period, WEPP over-predicted the frost depth in November 2003, which led to two over-predicted erosion events. The over-predicted snow depths resulted in high snowmelt runoff with little to no erosion in December and January 2004. The overall outcome was over-estimated runoff and a rather agreeable erosion prediction. The winter of 2004–05 was relatively dry with field-observed runoff and erosion being low. WEPP over-predicted 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 compared to 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 January 2–3, 2007 discussed earlier. In fact, WEPP slightly over-predicted the amount of runoff for this two-day event (32 vs 28 mm) yet WEPP significantly under-predicted the erosion (21 vs 224 t ha^{-1}) due to description of soil detachment capacity as a linear function of rill erodibility and flow shear stress.

For the NT treatment, WEPP predictions of runoff and erosion were highly agreeable with field measurements (Table 2.3), except for the first monitored period for which WEPP over-predicted runoff as a result of its over-prediction of snow depth, frost depth and frozen-soil days (Table 2.4). WEPP-simulated and field-observed erosion were both negligible for all four years.

Figure 2.6 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 2004–05 (Fig. 2.6). For the CTBF, 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, WEPP simulated near-saturation total soil water contents for the period of January–March 2004, which was in disagreement with field-observed soil water content of less than 0.35 m^3 m^{-3} at 4- and 32 cm (Fig. 2.5) under predominantly non-frozen conditions (Fig. 2.4). The reason was that WEPP incorrectly simulated continuous frost for this period (Fig. 2.4). Consequently, there would be no downward movement of soil water during this simulated frost period. Upon the simulated thawing of the top soil layer around March 19, 2004 (Fig. 2.4), 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. 2.6).

WEPP-simulated water balance (Table 2.3) showed that, overall, runoff is substantially larger, and soil evaporation is more than doubled, under the CTBF than under the NT. However, combined soil evaporation and plant transpiration, namely evapotranspiration (ET), is higher under the NT. WEPP simulated 6–42 mm per

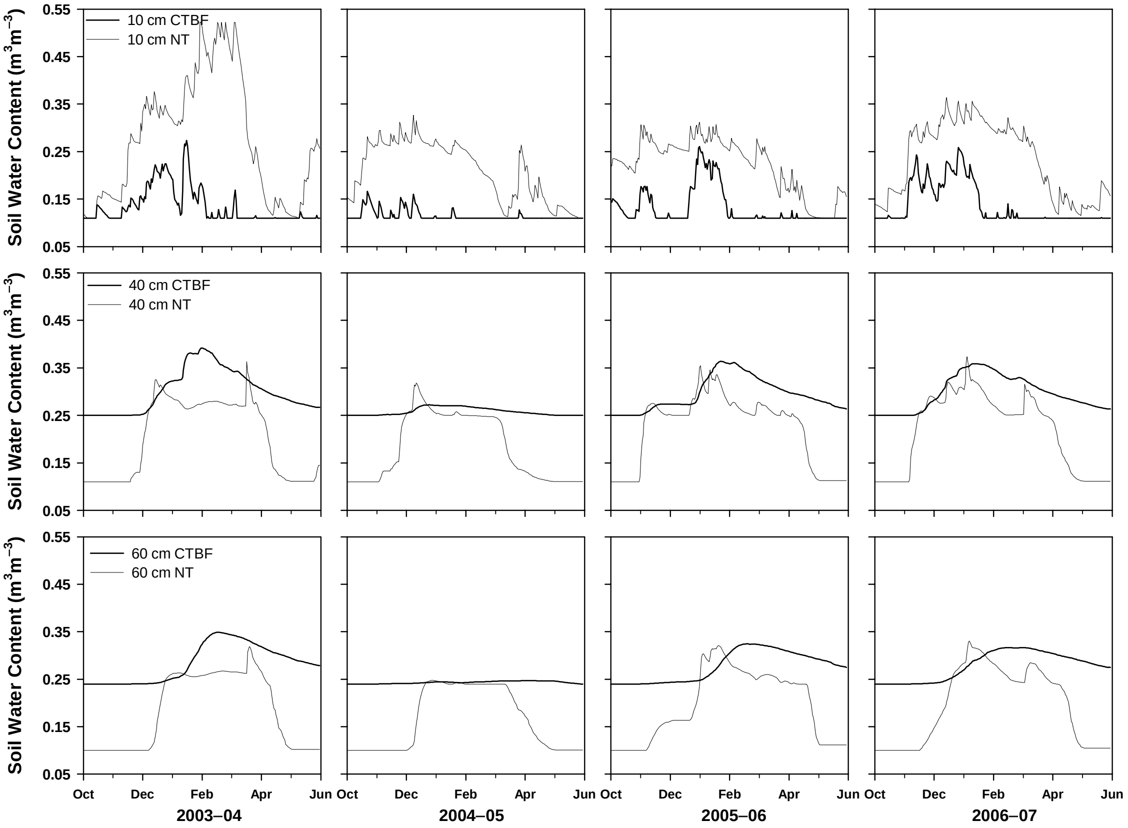

Figure 2.6: Simulated total soil water content at the 10-, 40-, and 60-cm depths (top, middle, and bottom panels, respectively) for the continuous tilled bare fallow (CTBF) and the no-tillage (NT) treatments for the monitored period.

monitored period of deep percolation below the 1-m soil profile for the CTBF and 0–45 mm for the 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 surface, may range from less than 3 to 10 mm yr^{-1} depending on the homogeneity of the regolith in the Pullman area.

2.5 Conclusions

This study aimed to evaluate winter hydrological 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, compared to the NT treatment. The CTBF generated significant amounts of runoff and erosion whereas the NT produced negligible runoff and erosion. For the study period, the majority of the runoff events occurred under non-frozen conditions, yet the thawed events resulted in most of the soil erosion under the CTBF.

The WEPP model, with an alternative energy-budget-based winter routine, could well reproduce field-measured snow depths for the monitored periods (October to May) for 2004–2007 for both the CTBF and NT. WEPP reproduced 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 the CTBF, but performed poorly for each monitored period for the NT. For the CTBF, WEPP over-predicted runoff for the first two monitored periods and under-predicted it for the last two monitored periods, and mostly under-predicted erosion. For the NT, WEPP predictions of runoff and erosion were generally in good agreement with field measurements.

WEPP showed the 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, non-frozen 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.

CHAPTER 3

WEPP SIMULATION OF OBSERVED WINTER RUNOFF AND EROSION IN THE U.S. PACIFIC NORTHWEST

3.1 Abstract

The Palouse area of the Northwestern Wheat and Range Region suffers high erosion throughout the winter season. The excessive soil loss is a result of a combination of winter precipitation, intermittent freezing and thawing of soils, steep land slopes, and improper management practices. Soil strength is typically decreased by the cyclic freeze and thaw, particularly during the period of thawing. When precipitation occurs over these freeze-thaw cycles, soil is easily detached and moved downslope. This study was aimed at improving the knowledge of winter hydrology and erosion in the Pacific Northwest (PNW) through combined field experimentation and mathematical modeling. Surface runoff and sediment were collected for three paired field plots under conventional tillage and no-till, respectively. Additionally transient soil moisture and temperature at various depths were continuously monitored for two selected plots. These data were used to assess the suitability and performance of the USDA's WEPP (Water Erosion Prediction Project), a physically-based erosion model, under the PNW winter conditions. Field observations revealed that minimal erosion was generated on the no-till plots, whereas erosion from the conventionally tilled plots largely exceeded the tolerable rates recommended by the Natural Resources Conservation Service. The WEPP model could

reasonably reproduce certain winter processes (e.g., snow and thaw depths and runoff) after code modification and parameter adjustment. Yet it is not able to represent all the complicated processes of winter erosion as observed in the field. Continued field and laboratory investigation of dynamic winter runoff and erosion mechanisms are necessary so that these processes can be properly represented by physically-based erosion models.

3.2 Objectives

The main purpose of this paper was to report the field experimental results from the 2003–2004 winter season at the PCFS, and to use this field data to assess the adequacy and performance of WEPP for water erosion prediction under the physical conditions of the inland PNW.

3.3 Methods

- Experimental Site
- Field Instrumentation and Monitoring
- WEPP simulations
    - Model description
    - WEPP Inputs
    - WEPP Runs

3.4 Results

Table 3.1: Physical properties of Palouse silt loam measured for the CT Plot 1.

Layer	Depth	$K^{\dagger}$	OM	ρ_b	Sand	Clay
	m	10^{-5} m s^{-1}	%	g cm^{-3}	%	%
1	0–0.1	3.94‡ (1.73)§	4.25 (0.198)	1.32 (0.09)	19.97 (0.03)	13.54 (0.02)
2	0.1–0.2	1.48 (0.25)	3.51 (0.417)	1.32 (0.08)	14.59 (0.01)	16.06 (0.002)
3	0.2–0.4	1.15 (0.16)	3.18 (0.344)	1.38 (0.08)	24.21 (0.02)	13.12 (0.02)
4	0.4–0.6	2.12 (0.16)	3.55 (0.185)	1.47 (0.16)	39.03 (0.02)	8.80 (0.008)
5	0.6–0.8	4.44 (0.28)	3.28 (0.308)	1.41 (0.03)	19.36 (0.02)	13.58 (0.02)
6	0.8–1.0	1.29 (0.14)	2.73 (0.741)	1.57 (0.06)	18.21 (0.01)	12.72 (0.01)

[†] *K*, saturated hydraulic conductivity, OM, organic matter content, ρ_b, soil dry bulk density.

[‡] The *K* value for the surface layer was slightly higher than those measured in some previous studies, e.g., Fuentes et al. (2004) reported a range of *K* as arithmetic or geometric means of 3.6×10^{-6}–2.7×10^{-5} m s^{-1} for the Palouse silt loam under conventional tillage over a period of two years.

[§] Numbers in parentheses are one standard deviation calculated from 3–12 soil samples.

Table 3.2: Important soil, slope and cultural practice parameters used in the WEPP simulations.

Parameter	Value
Hillslope configuration	
Number of overland flow elements (OFEs)	1
Profile aspect (clockwise from north), degrees	182
Representative profile width, m	3.7
Number of slope points on the OFE	11
Length of the OFE, m	24.7
Present soil properties	
Texture	Silt loam[†]
Number of soil layers	6
Albedo	0.08
Initial saturation of soil porosity, m m^{-1}	0.9
Baseline interrill erodibility, kg s m^{-4}	4.32×10^{6}
Baseline rill erodibility, s m^{-1}	6.55×10^{-3}
Baseline critical shear, N m^{-2}	0.74
Effective hydraulic conductivity of surface soil, m s^{-1}[‡]	3.94×10^{-5}
Cultural practice[§]	
Land use	Cropland
Plant name	Spring wheat, Winter wheat
Canopy cover coefficient	5.2
Base daily air temperature, °C	4
Growing degree days to emergence, °C	60
Height of post harvest standing residue; cutting height, m	0.152
Plant stem diameter at maturity, m	6.4×10^{-3}
Radiation extinction coefficient	0.65
Standing to flat residue adjustment factor (wind, snow)	0.99
Maximum Darcy Weisbach friction factor for living plant	3
Growing degree days for growing season, °C	1700

Harvest index	0.42
Maximum Canopy height, m	0.91
Decomposition constant to calculate mass change of both root biomass and above-ground biomass	8.5×10^{-3}
Optimal temperature for plant growth, °C	15
Plant specific drought tolerance	0.25
In row plant spacing, m	0.005
Maximum root depth, m	0.3
Root to shoot ratio	0.25
Period over which senescence occurs, days	14
Maximum leaf area index	5
Rill and interrill tillage intensity for non-fragile crops	0.1
Number of rows of tillage implement	20
Ridge height value after tillage, m	2.54×10^{-2}
Ridge interval, m	0.2
Random roughness value after tillage, m	0.12
Fraction of surface area disturbed	0.85
Bulk density after last tillage, 1.5×10^{3} kg m^{-3}	1.15
Initial canopy cover[¶]	0
Days since last tillage	105
Days since last harvest	119
Initial frost depth, m	0.12
Initial residue cropping system	Fallow
Cumulative rainfall since last tillage, mm	101.6
Initial ridge height after last tillage, m	2.54×10^{-2}
Initial ridge roughness after last tillage, m	0.01
Initial snow depth, m	2.54×10^{-2}
Depth of primary tillage layer, m	0.2

[†] Texture information includes sand and clay percentage which is shown in Table 2.1.

[‡] The effective saturated hydraulic conductivity, with an initial value of 3.94×10^{-5} m s^{-1} from the laboratory measurements, was internally adjusted for field conditions such as wormhole and tillage and for winter conditions.

[§] All the plant physiological parameters were from the WEPP User Summary (Flanagan and Livingston, 1995). For spring wheat and winter wheat, these parameters are the same.

[¶] The initial conditions correspond to the field conditions at the beginning of 2002.

Table 3.3: WEPP-predicted surface runoff (R), soil evaporation (E_s), deep percolation (D_p), and erosion in comparison with field observation during Nov 17, 2003–Mar 6, 2004. In all runs, subsurface lateral flow was zero.

WEPP Run	K_f, τ_c [†] changes	Precip. mm	R mm	E_s [‡] Mm	D_p mm	Erosion t ha^{-1}
1	$K_f = 0.1K$ $\tau_c = 0.74$ Pa	270.6	0.0	141.1	75.0	0.0
2	$K_f = 0.0001K$ $\tau_c = 0.74$ Pa	270.6	37.2	116.5	54.1	8.5
3	$K_f = 0.00005K$ $\tau_c = 0.74$ Pa	270.6	62.7	103.5	41.4	11.6
4	$K_f = 0.00005K$ $\tau_c = 0.1$ Pa	270.6	62.7	103.5	41.4	34.4
Observed	--	270.6	66.7	--	--	69.7

[†] K_f, minimum saturated hydraulic conductivity under winter (freezing soil) conditions, taken as a fraction (default value of 0.1) of K, the effective saturated hydraulic conductivity under non-winter conditions, in the original WEPP code. τ_c, soil critical shear stress.

[‡] No plant transpiration was predicted as the field was under fallow without winter crop.

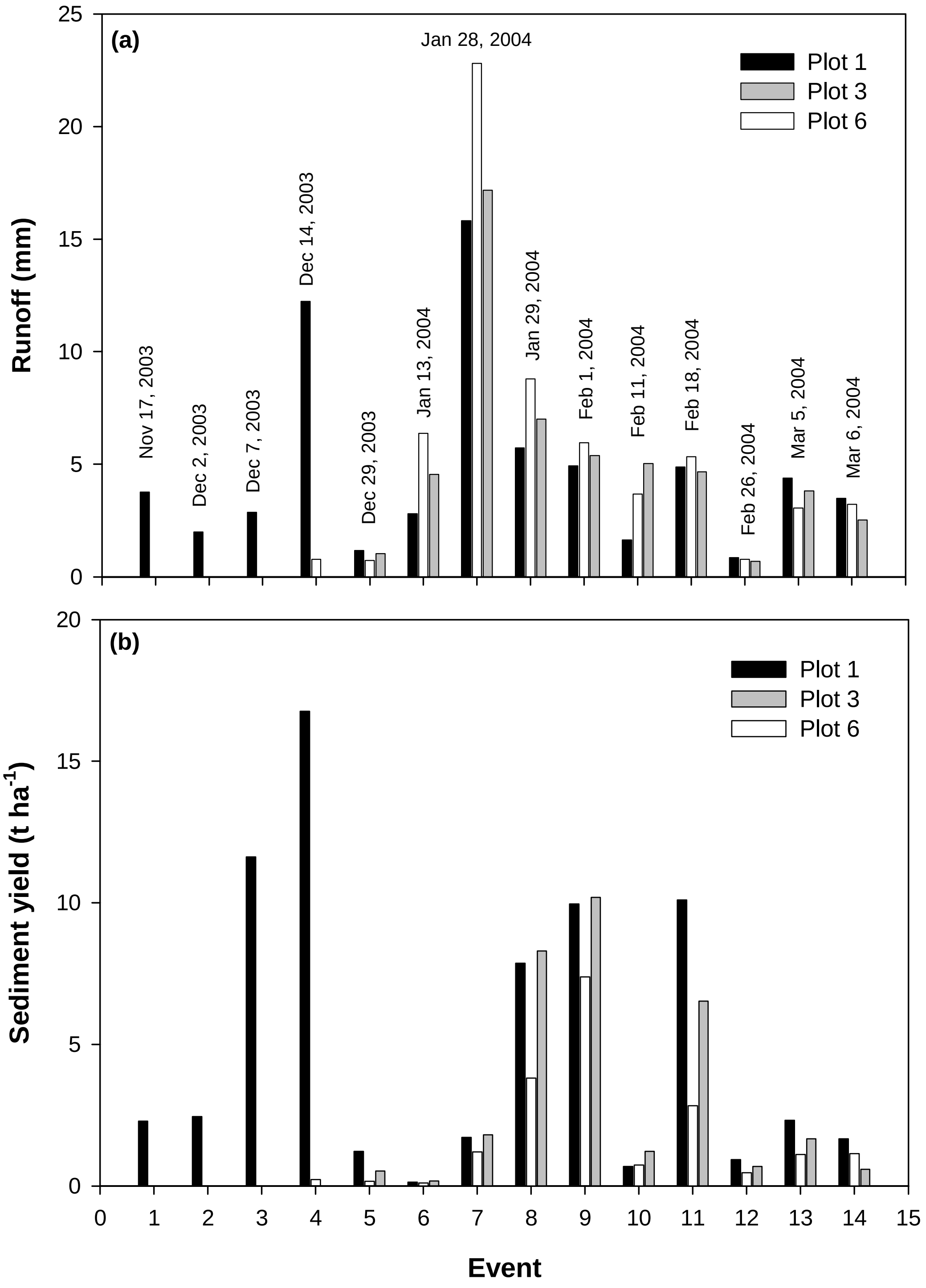

Figure 3.1: Observed (a) runoff and (b) erosion from conventional tillage (CT) plots.

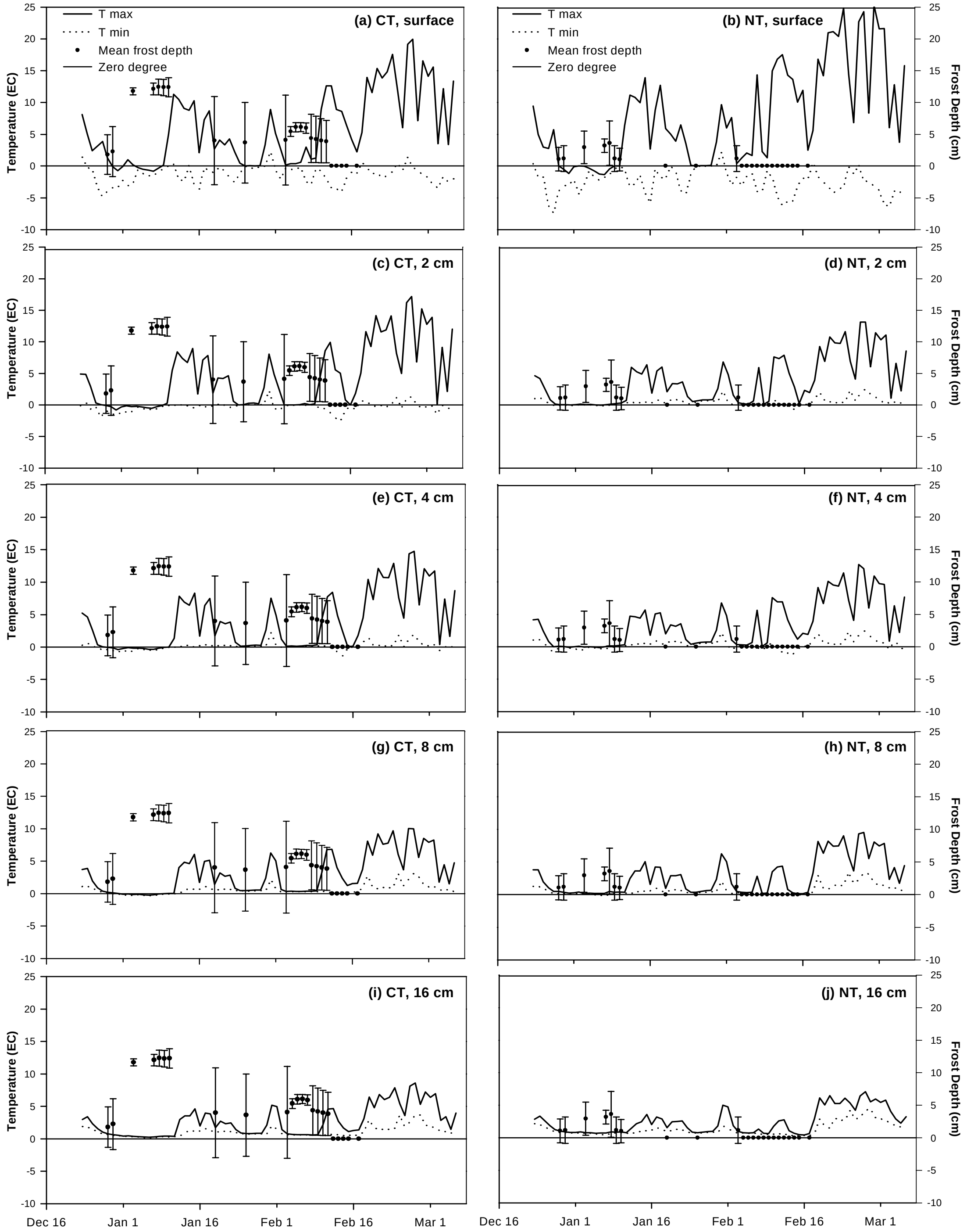

Figure 3.2: Soil temperature profile and frost depths under conventional tillage (CT Plot 1, in panels a, c, e, g, and i) and no-till winter wheat (NT Plot 2, in panels b, d, f, h, and j) for different depths.

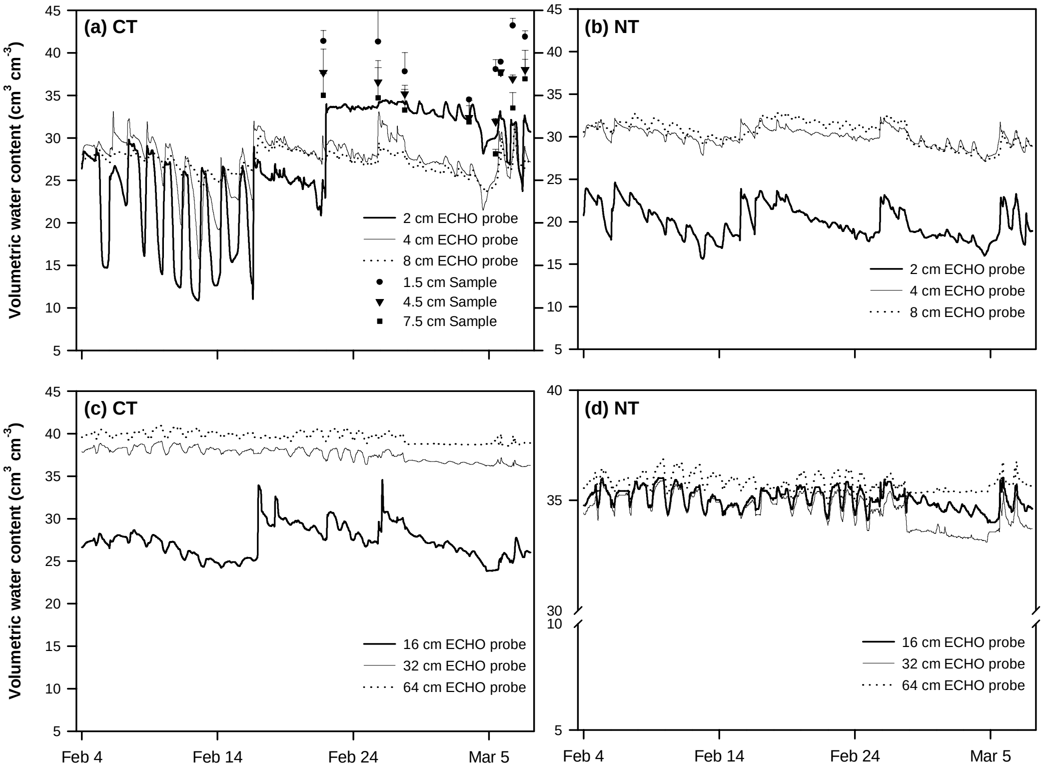

Figure 3.3: Volumetric soil water content recorded by ECHO probes and undisturbed soil core sampling under conventional tillage (CT, in panels a and c) and no-till winter wheat (NT, in panels b and d) for different depths.

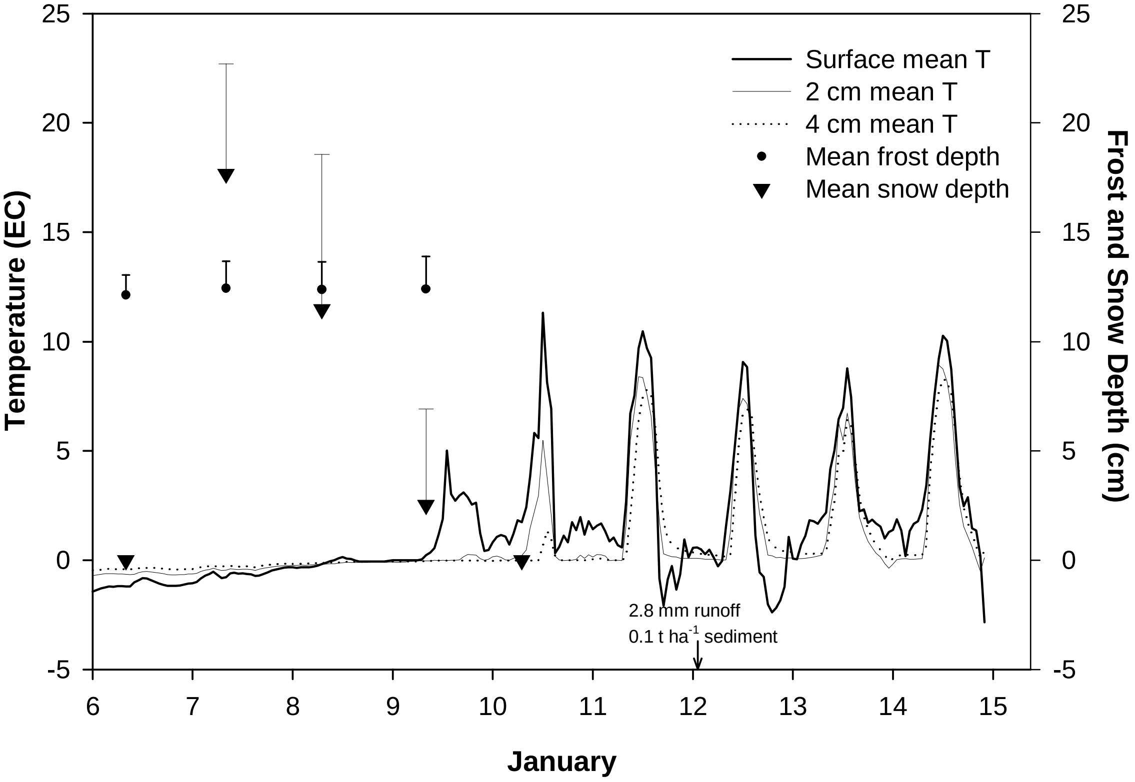

Figure 3.4: A runoff event due to soil thawing and snowmelt on 12 January 2004.

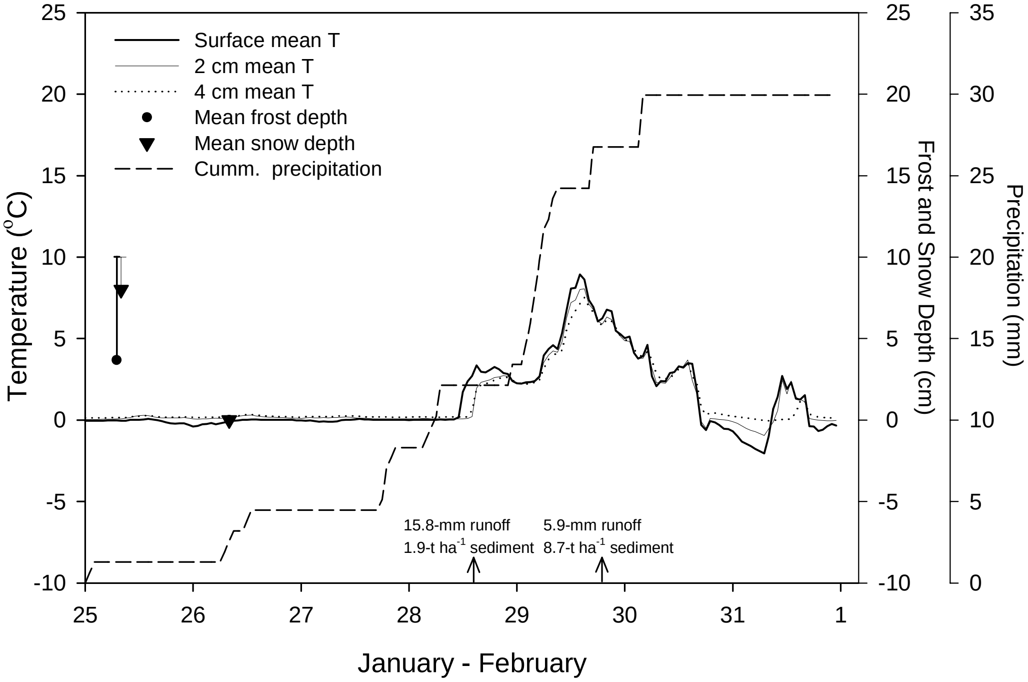

Figure 3.5: Successive runoff events caused by rain on snow followed by rain only on 28–29 January 2004.

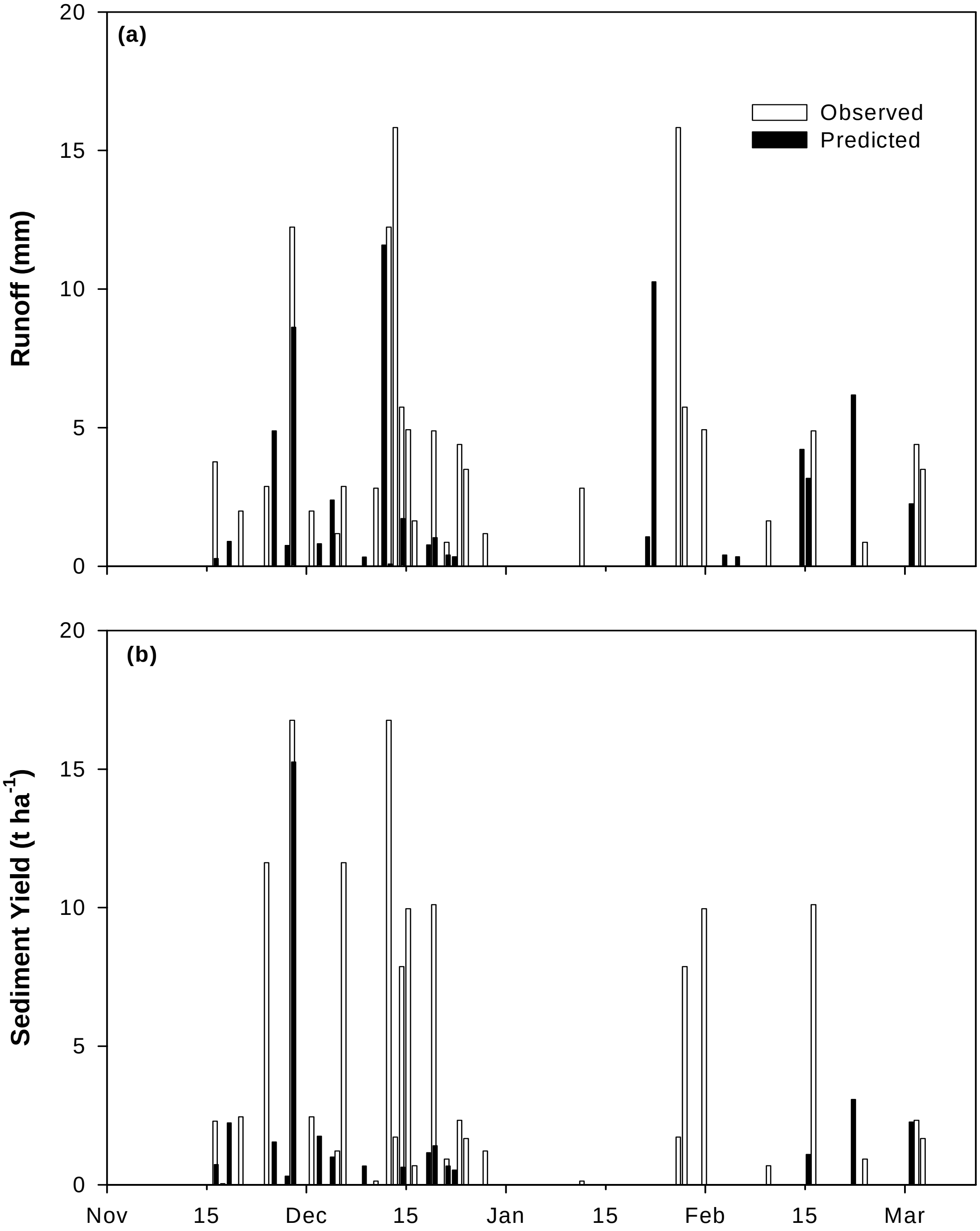

Figure 3.6: (a) Observed and (b) WEPP-predicted runoff and erosion for Plot 1 under conventional tillage.

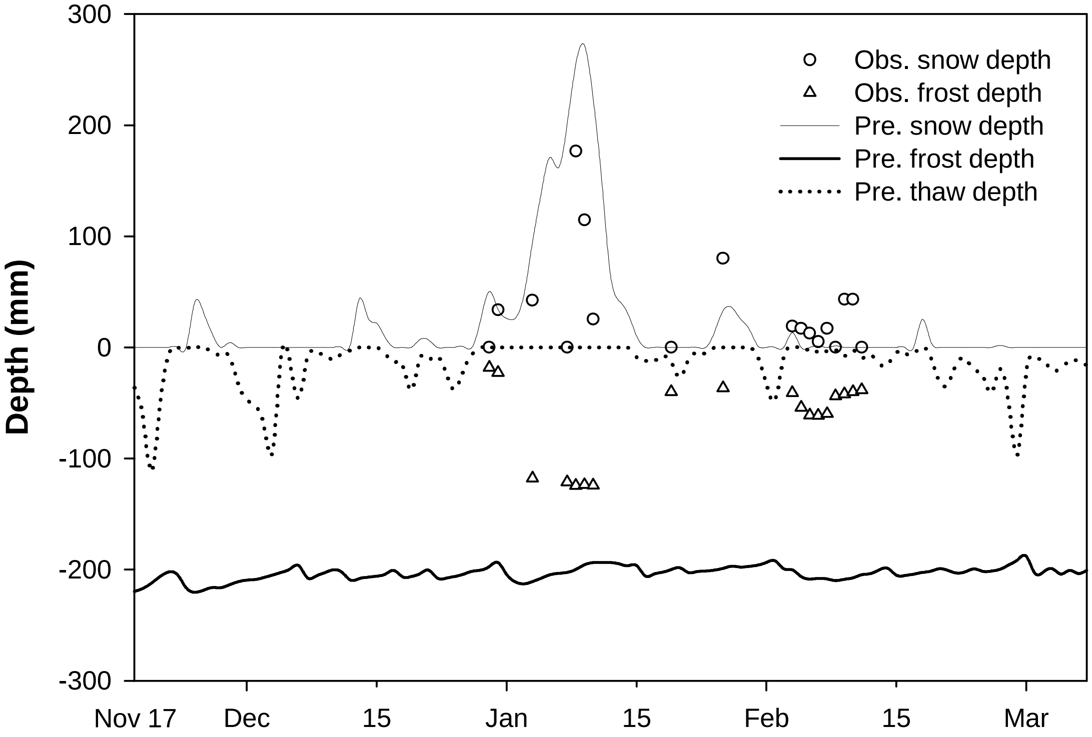

Figure 3.7: Comparison of field-observed and WEPP-predicted snow, frost, and thaw depths. No event-based thawing depths were recorded during the field experimentation. Note that frost tubes were not installed until late December.

3.5 Conclusion

The unique winter climatic conditions, steep topography, and winter wheat cropping with conventional tillage combine to create large winter runoff and erosion events in the Palouse area of the Northwestern Wheat and Range Region. This study focused on detailed field monitoring and modeling of runoff and erosion events from two different management practices at the PCFS near Pullman, WA, over the 2003–2004 winter season.

In addition to surface runoff and erosion, soil water and temperature profiles were continuously monitored to provide information on soil moisture and temperature conditions under which runoff and erosion occurred. In general, the no-till plots generated little to no runoff and no erosion throughout the season. The conventionally tilled plots, however, all produced considerably higher runoff and erosion exceeding the NRCS recommended tolerable rate. Differences in runoff and erosion existed among the three CT plots, possibly reflecting the lingering influence from a previous study and the naturally occurring spatial variation.

Two main mechanisms causing runoff and erosion were observed in the field. First, runoff and erosion may result solely from soil thawing and snowmelt. Without any precipitation input, the presence of frozen soil layers could prevent infiltration of snowmelt, causing saturation-excess runoff and erosion. Second, when rain fell on a snow-covered frozen ground, runoff would start as a consequence of the rain input and snowmelt. Higher-rate erosion was evident when the additional rainfall caused substantial increase in soil moisture and lowered soil erosion resistance. Such successive events may not happen frequently but are very dynamic and can generate considerable amounts of sediment from uncovered surfaces.

The USDA's WEPP model contains a physically-based winter routine to simulate snow cover and soil frost and thaw. Although WEPP could reasonably reproduce certain winter processes (snow and thaw depths) after code modification and parameter adjustment, it is not yet able to represent all the complex processes of winter erosion, as observed in the inland PNW. Improved knowledge of heat and water migration during the freezing-thawing processes is needed to better quantify soil strength changes, and thus soil erosion, over the winter season. Future efforts should focus on laboratory and field investigation of the dynamic winter runoff and erosion, so that these processes can be properly represented by physically-based erosion model.

CHAPTER 4

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

4.1 Abstract

A 2-year rotation of winter wheat (*Triticum aestivum* L.)-summer fallow is the dominant cropping system in the low-precipitation (<350 mm annual) dryland region of the Pacific Northwest (PNW), USA. Traditional, tillage-based summer fallow relies on a soil mulch to disrupt capillary continuity to conserve seed-zone water required 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 finely-divided soil aggregates and 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 from April 2003 to March 2004. The RT treatment retained more seed-zone water during the summer compared to CF, which was consistent with relevant literature for Mediterranean environments and of critical importance to farmers for successful early establishment of winter wheat. During the wet

winter months, CF gained more water than RT because of later planting of winter wheat, and thus less water use. SHAW-simulated water contents followed the general trend of the field data. The model under-predicted soil water content for CF and over-predicted for RT. However, absolute differences between observed and simulated soil water contents were mostly less than 0.03 m^3/m^3. SHAW slightly under-predicted soil temperature during the dry summer months and over-predicted for the wet (November–December) period. Still, soil temperatures were in general properly described by the SHAW model 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.

4.2 Objectives

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.

4.3 Methods

- Treatments
- Instrumentation and Monitoring
- The SHAW Model
- SHAW Model Parameters and Simulations
- Statistical Analysis

4.4 Results

Table 4.1: 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[1]	0.18[1]
Albedo of residue	0.23[2]	0.23[2]
Wind-profile surface-roughness		
Parameter for momentum transfer (cm)	0.6[3]	0.4[1]
Wind-profile roughness parameter for		
momentum transfer with snow cover (cm)	0.15[4]	0.15[4]
Exponents for calculating albedo of moist soil	0[4]	0[4]

[1] for tilled soil (Campbell and Norman, 1998)
[2] from Fernhout and Kurtz (1999).
[3] for no-till plot (Flerchinger, 2000b).
[4] from Flerchinger (2000b).

Table 4.2: Measured soil properties under chemical fallow and reduced-tillage fallow. Errors denote one standard deviation of 3 replicates.

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[1]	42.4
	60	46.3	44.0
Silt (%wt.)	2.5	47.0	48.3
	10	47.0	48.3
	30	47.7[1]	51.8
	60	48.4	50.2
Clay (%wt.)	2.5	6.1	6.1
	10	6.1	6.1
	30	5.8[1]	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

[1] 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.

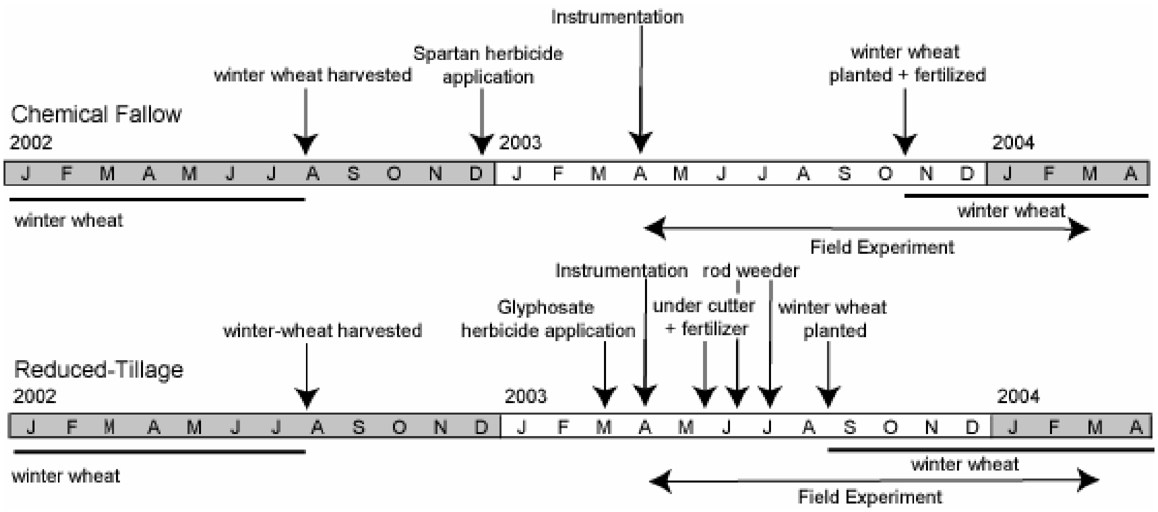

Figure 4.1: Management operations for the chemical fallow (CF) and reduced-tillage fallow (RT).

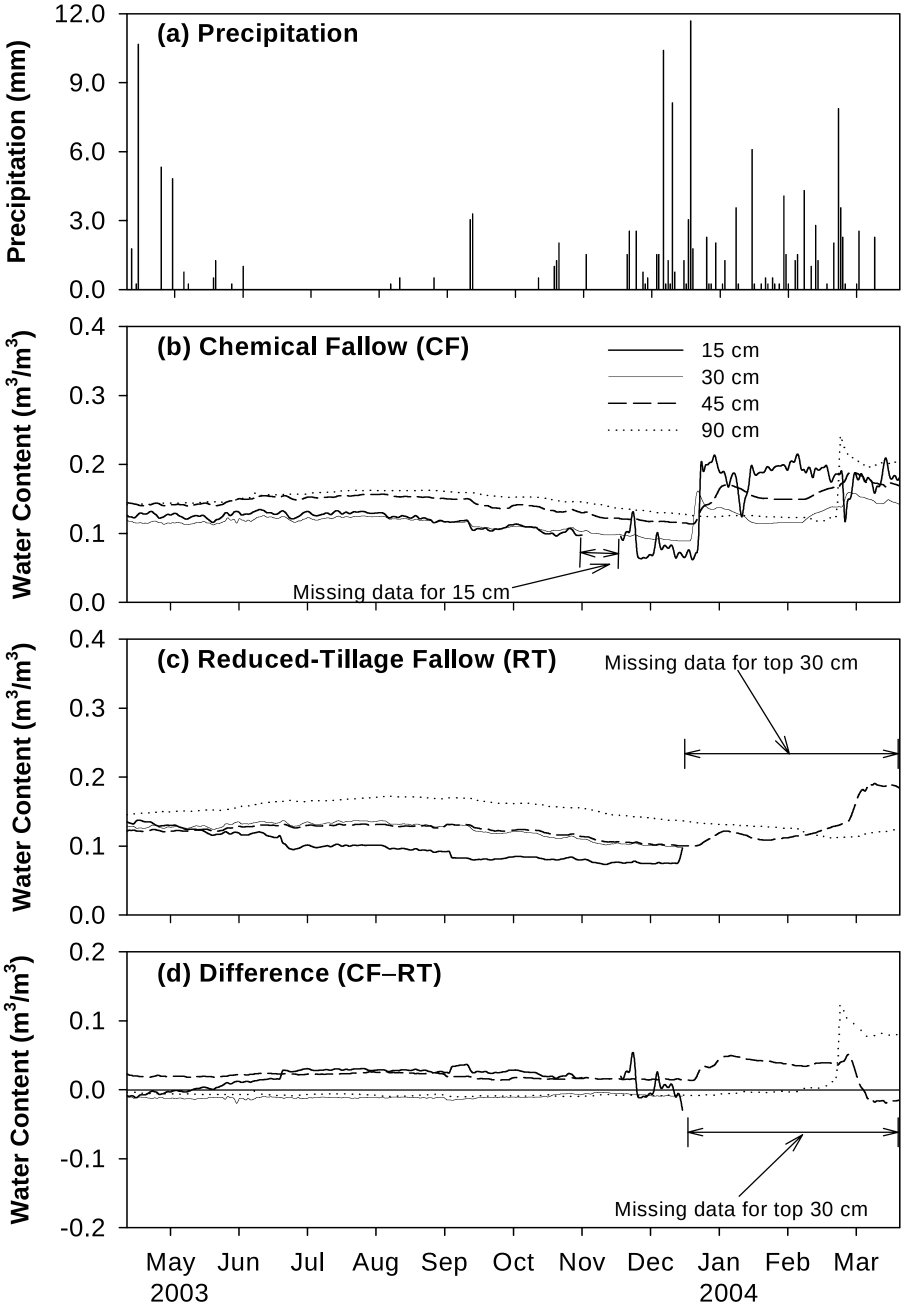

Figure 4.2: (a) Observed daily precipitation; observed water content at different depths using Echo probe data under (b) chemical fallow (CF) and (c) reduced-tillage fallow (RT); and (d) difference in water content between CF and RT.

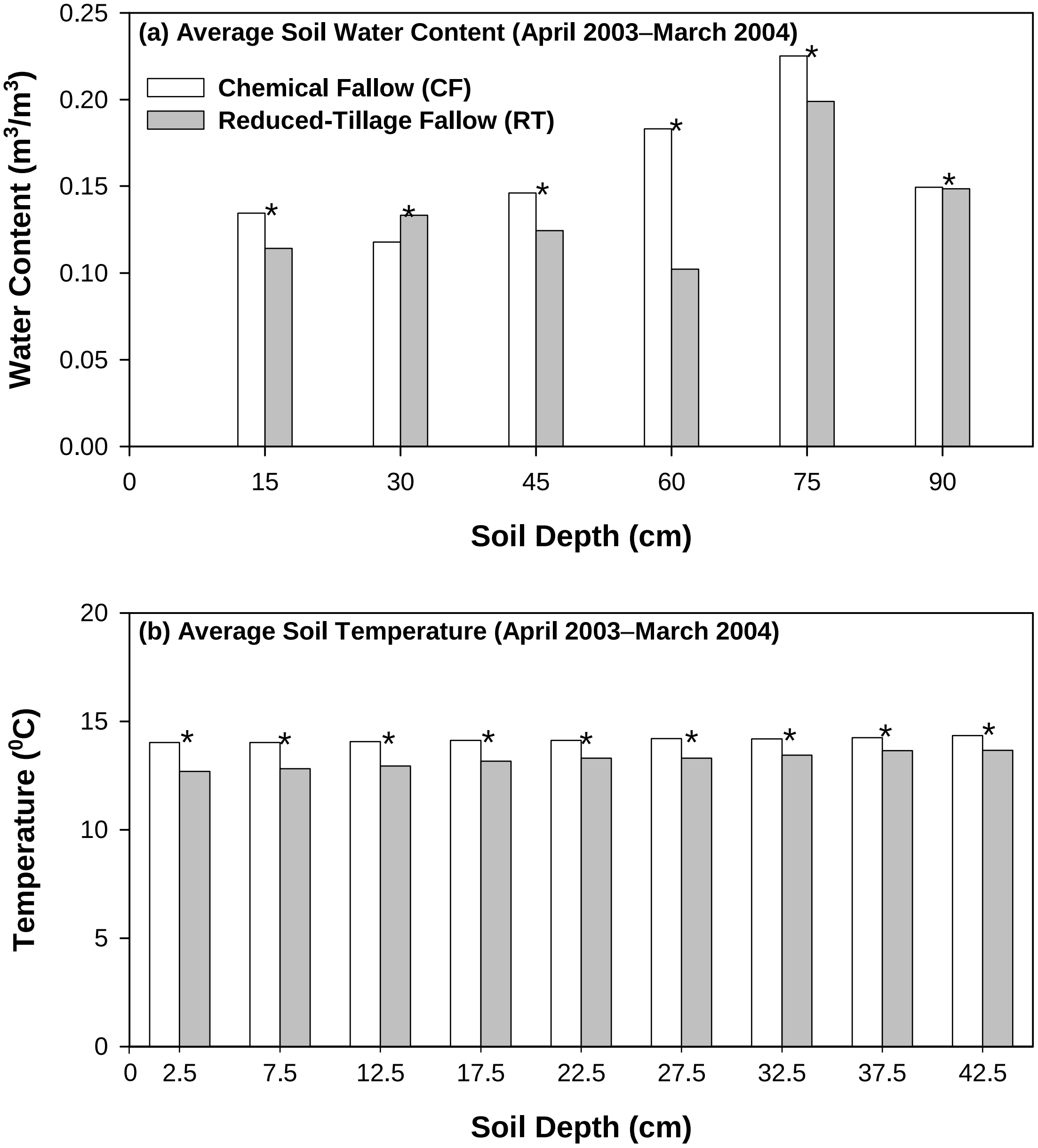

Figure 4.3: Averaged (a) water contents and (b) soil temperatures for chemical fallow (CF) and reduced-tillage fallow (RT) for April 11, 2003-March 14, 2004 at different measurement depths. Asterisks denote significant difference at 5% level.

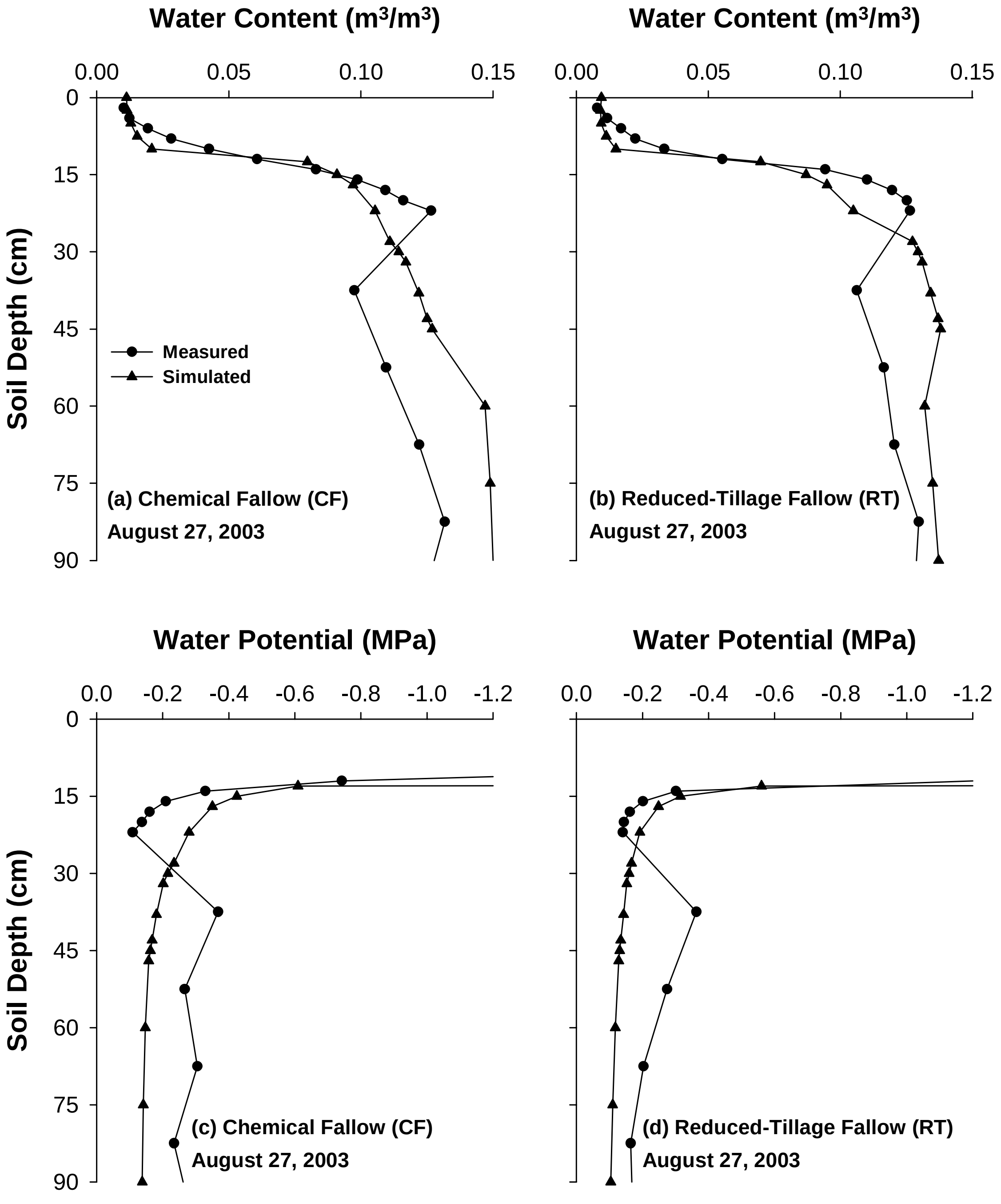

Figure 4.4: (a and b) Observed (gravimetric sampling) vs. simulated water contents and (c and d) observed vs. simulated water potentials for chemical fallow (CF) and reduced-tillage fallow (RT) on August 27, 2003.

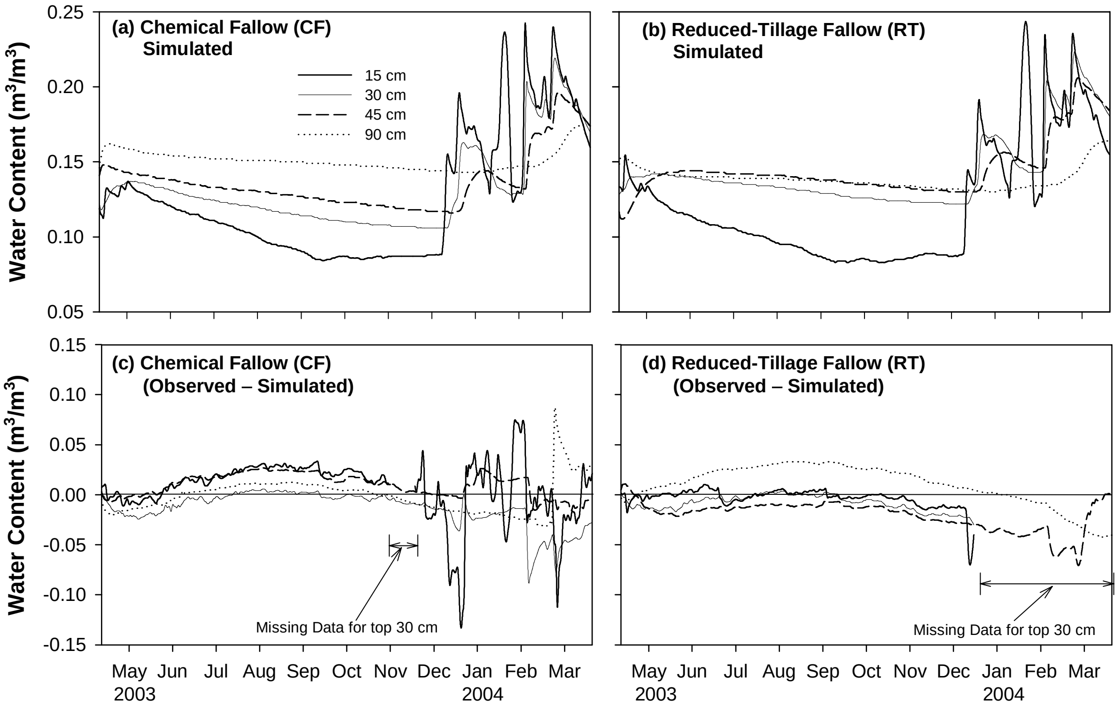

Figure 4.5: (a and b) Simulated water contents for chemical fallow (CF) and reduced-tillage fallow (RT) and (c and d) differences between observed and simulated data.

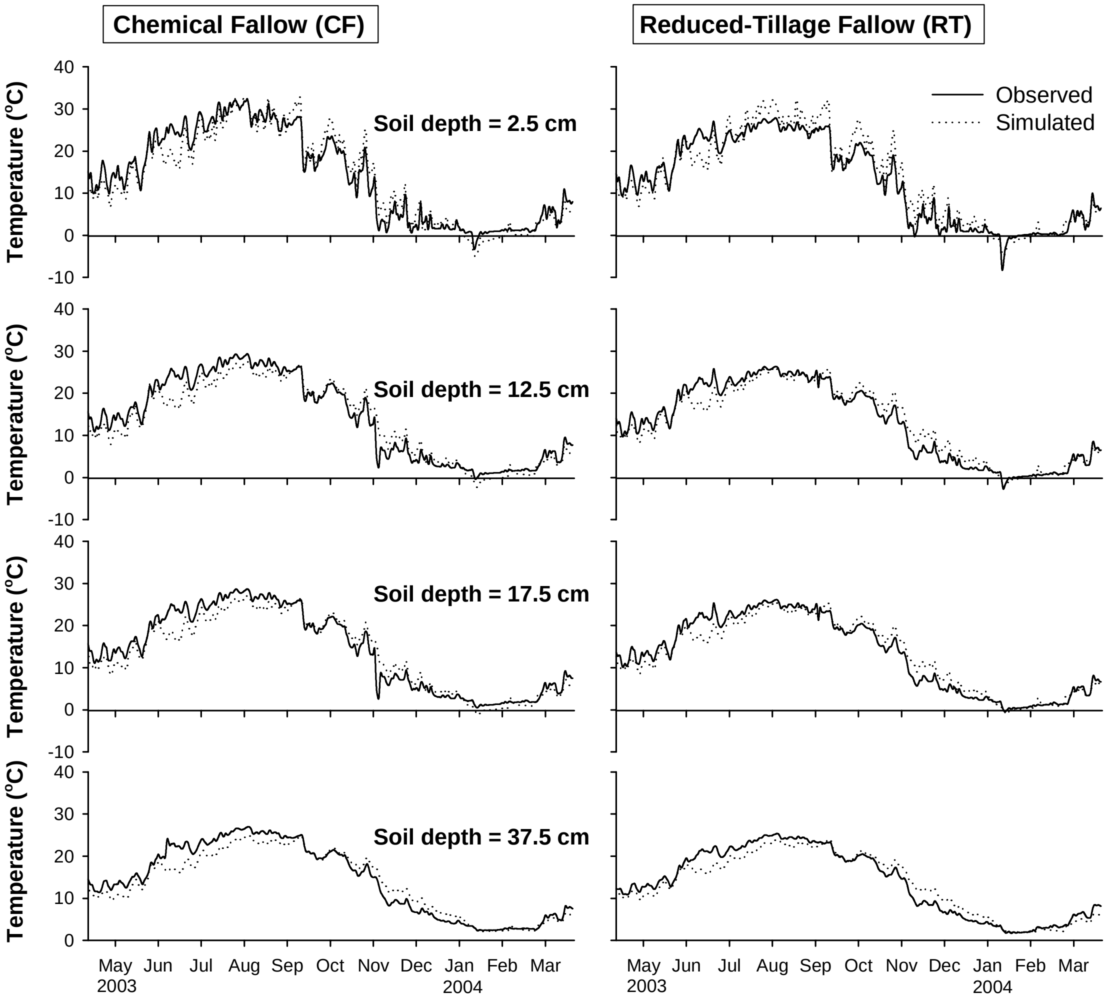

Figure 4.6: Observed and simulated soil temperatures (daily averages) at different depths for chemical fallow (CF) and reduced-tillage fallow (RT).

4.5 Conclusions

This study showed that tillage management significantly affected soil water and temperature in summer fallow in the PNW. Detailed measurements on August 27, 2003 revealed 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.

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.

CHAPTER 5

CONCLUSIONS

The goal of this dissertation was to attain a better understanding of the effects of tillage practices on runoff, erosion and seed-zone water and temperature based on field investigation and modeling. The predictive models (WEPP and SHAW) were applied, modified as needed, and evaluated in this study. The conclusions from this study are:

1. The continuous tilled bare fallow (CTBF) and continuous no-tillage (NT) treatment produced shallower snow depth and deeper frost depth, compared to the NT treatment.
2. The CTBF generated significant amounts of runoff and erosion whereas the NT produced negligible runoff and erosion.
3. For the study period, the majority of the runoff events occurred under non-frozen conditions, yet the thawed events resulted in most of the soil erosion under the CTBF.
4. The WEPP model showed the potential as a modeling tool for assessing the effect of management practices on winter hydrologic and erosion processes.
5. 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.

6. The RT treatment showed an advantage compared to the CF (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).
7. 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.

APPENDICES

APPENDIX A

Separation of Runoff and Erosion Events

The runoff and erosion events were categorized into non-frozen, frozen and thawed soil conditions based on frost-tube readings and field-measured soil temperature data for the CTBF. We have defined a frozen soil condition as one with the surface soil temperature below 0 °C and a frost layer being present; a thawed condition as one with the soil fully or partially thawed from the surface; and a non-frozen condition as one with soil temperature above 0 °C and having reconsolidated after a previous thaw (for 2 days). 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 several hours to few days depending on climate conditions. Therefore, personal judgment was exercised in categorizing the field-observed runoff events.

For some runoff events, the soil surface would thaw during the event, and soil loss would increase accordingly. In one such event, severe soil loss was observed due to frozen soil layer beneath the thawed soil surface. Such events were categorized as thawed events. For confirmed frozen soil events, soil loss was observed, so sediment concentration was also used to separate frozen and thawing events.

Non-frozen, 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. The 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 non-frozen events was substantial, which was likely a consequence of reduced infiltration capacity due to surface sealing and crusting.

Example:

Non-frozen event – Most of the events were non-frozen. The event in January 31, 2006 produced 6.5 mm of runoff and 3.4 t ha^{-1} of erosion. There was no frost prior and at the onset of the rainfall.

Frozen event – Rainfall-induced snowmelt on frozen soil (with a soil surface temperature at 0 °C) produced more runoff (15.8 mm) and less erosion (1.9 t ha^{-1}) in the first event on January 27, 2004.

Thawed event – A large runoff and erosion event occurred on January 2–3, 2007. When the rainfall started, the ground was frozen and the continuous rainfall (35 mm in total) caused thawing of the surface soil, and produced 27.7 mm of runoff and 224.4 t ha^{-1} of erosion. This event was also an example for rainfall on a thawed bare soil overlaying a solid frozen layer. Due to lack of data, we could not able to further separate the events into thawing and thawed conditions.

APPENDIX B

Surface Sealing and Crusting

The orientation and packing of dispersed soil particles that have disintegrated from the soil aggregates due to the impact of rain drops is surface sealing. Surface crusts is defined as the deposition of soil particles, suspended in water, on the soil surface as the water infiltrates or evaporates (McIntyre, 1958a,b). Surface sealing and crusting had been used in literatures simultaneously/interchangeably. Bradford et al., (1987) defined the surface sealing as initial phase or wetting phase in crust formation and crusting as the subsequent drying phase.

The impact of rain drops on the soil breaks the aggregates, compact the soil, reduced the average pore size and the dispersed clay particles migrated into the soil with infiltrating water (McIntyre, 1958a,b; Agassi et al., 1985, Ben-Hur et al., 1985). Crust-seal formed on the soil surface reduces the infiltration of water into bare soil (McIntyre, 1958a,b; Morin and Benyamini, 1977). The thickness of the crust layer vary from 1 to 5 mm and decrease in hydraulic conductivity of the layer by two order of magnitude lower than that of the soil below (McIntyre, 1958a,b; Sharma, 1980). Chahinian et al., (2006) reported that the crust hydraulic conductivity is only 10 times lower than that of the subsoil. Several studies have been devoted to characterizing and modeling the process (Hillel and Gardner, 1970; Ahuja, 1973, 1983; Chu et al., 1986; Bradford et al., 1987; Rawls et al., 1990; Philip 1998) due to its importance in determining infiltration, runoff and soil loss, and soil chemical transfer to overland flow.

An approximate solution of infiltration into crusted soil was obtained by using Green-Ampt approach (Hillel and Gardner, 1970; Ahuja, 1983). Rawls et al., (1990) developed the crust factor for a wide range of soils to incorporate the effect of crust into the Green-Ampt effective hydraulic conductivity. Philip (1998) used quasi-analytic methods to analyze ponded infiltration into crusted soils and stated that the approximations and simplifications (neglect of gravity, replacing the crust with a hydraulic resistance and use of the Green-Ampt model) in the previous studies are unnecessary and obscure or distort the dynamics of infiltration into crusted soils. Philip (1998) described surface crust as a throttle on infiltration that can result in greatly reduced level of soil wetting and therefore severely limiting the water in the root zone.

Effect of soil surface sealing and crusting on soil loss rates was investigated by Knapen et al., (2008). Knapen et al., (2008) observed no effect of sealing and crusting on critical flow shear stress but substantial reduction in soil erodibility. Soil erodibility decreases exponentially with increasing cumulative rainfall. With 100 mm of cumulative rainfall, surface sealing and crusting reduces the soil erodibility by 10% to up to 70% for dry and wet topsoil, respectively. Bajracharya and Lal (1998 and 1999) and Ruan et al., (2001) investigated the diminishing effect of residue and natural vegetation on crust formation. A detailed study of surface seal formation and its effect on infiltration rate and hydraulic conductivity in PCFS will be very helpful for better understanding of the process. The study will also be helpful in better parameterization of the model and its modification.

APPENDIX C

SAS Code

Wilcoxon Rank-Sum Test

```
*********************************************
DATA temp;
INFILE 'C:\singh\wc0607.prn';
INPUT type $ depth temp;
run;
proc npar1way data=temp; * non-parametric test;
title 'BF_2 cm vs. NT_2 cm, 2006-07';
where depth=2;
class type;
var temp;
run;
proc npar1way data=temp; * non-parametric test;
title 'BF_4 cm vs. NT_4 cm, 2006-07';
where depth=4;
class type;
var temp;
run;
proc npar1way data=temp; * non-parametric test;
title 'BF_8 cm vs. NT_8 cm, 2006-07';
where depth=8;
class type;
var temp;
run;
*********************************************
```

Sample of input data file used for statistical analysis (wc0607.prn):
Column 1: Tillage practice (Black Fallow or No-tillage)
Column 2: Soil depth
Column 3: Field measured water content (or temperature)

```
BF      2  10.44
BF      2  15.11
BF      2  20.44
BF      2  24.37
BF      4  13.57
BF      4  21.66
BF      4  22.53
```

```
BF        4   24.57
BF        8   16.47
BF        8   26.83
BF        8   27.75
BF        8   29.04
NT        2    4.55
NT        2    9.95
NT        2   15.62
NT        2   20.52
NT        4   10.88
NT        4   14.84
NT        4   14.55
NT        4   13.61
NT        8   11.23
NT        8   17.47
NT        8   17.98
NT        8   18.74
```

Sample Output File:

```
          BF_4 cm vs. NT_4 cm, 2005-06     16:22 Thursday, July 3, 2008

                          The NPAR1WAY Procedure

                 Wilcoxon Scores (Rank Sums) for Variable temp
                        Classified by Variable type

                        Sum of      Expected       Std Dev          Mean
          type      N       Scores      Under H0      Under H0          Score

          BF      208       43136.0       43368.0    1226.13716    207.384615
          NT       208       43600.0       43368.0    1226.13716    209.615385

                      Average scores were used for ties.

                         Wilcoxon Two-Sample Test

                      Statistic            43136.0000

                      Normal Approximation
                      Z                     -0.1888
                      One-Sided Pr <  Z        0.4251
                      Two-Sided Pr > |Z|       0.8502
```

```
                    t Approximation
                    One-Sided Pr <  Z         0.4252
                    Two-Sided Pr > |Z|        0.8503

                 Z includes a continuity correction of 0.5.
```

Signed-Rank Test

```
************************************************
Data prabh1;
Input cf rt;
Diff=cf-rt;
Cards;
0.141416309   0.145171246
0.142003857   0.145333075
0.142381543   0.146466205
0.142591364   0.146574091
0.142843182   0.147275513
0.142843182   0.14770722
0.142633319   0.14770722
0.142549408   0.14770722
0.142381543   0.14770722
0.142003857   0.147761163
0.141961859   0.147761163
0.142423499   0.147761163
0.142969049   0.148678412;
Proc Univariate Normal;
run;
************************************************
```

Sample Output File:

```
       The SAS System          09:38 Sunday, August 19, 2007

                      The UNIVARIATE Procedure
                         Variable:  cf

                           Moments

          N                   339           Sum Weights             339
          Mean             -0.1108668       Sum Observations    -37.583836
          Std Deviation     0.02841972      Variance            0.00080768
```

```
Skewness          -0.0615844      Kurtosis          -0.5956294
Uncorrected SS     4.43979469    Corrected SS       0.27299606
Coeff Variation    -25.634121      Std Error Mean     0.00154355
```

```
          Tests for Location: Mu0=0

     Test          -Statistic-    -----p Value------

     Student's t    t   -71.826    Pr > |t|    <.0001
     Sign           M    -169.5    Pr >= |M|   <.0001
     Signed Rank    S    -28815    Pr >= |S|   <.0001
```

Table C.1: Nonparametric statistical analysis of soil water content and temperature at different depth during each monitored period.

	Depth	Water Content		Soil Temperature	
	cm	*Z*-value	*P*-value	*Z*-value	*P*-value
2003–04	2	8.786	0.0001	-1.114	0.1326
	4	-0.195	0.4227	-0.475	0.3175
	8	-7.843	0.0001	0.033	0.4870
	16	-8.774	0.0001	-0.451	0.3259
	32	8.456	0.0001	-0.202	0.4201
	64	8.457	0.0001	-1.441	0.0748
	100	--	--	-2.127	0.0167
2004–05	2	6.166	0.0001	0.095	0.4620
	4	-10.854	0.0001	0.252	0.4004
	8	-14.832	0.0001	0.047	0.4812
	16	-13.431	0.0001	0.498	0.3093
	32	15.467	0.0001	-0.343	0.3658
	64	15.467	0.0001	-0.592	0.2770
	100	--	--	-1.292	0.0982
2005–06	2	-4.626	0.0001	-0.656	0.2559
	4	-14.356	0.0001	-0.189	0.4251
	8	1.329	0.0919	-0.322	0.3738
	16	2.614	0.0045	-0.312	0.3777
	32	14.436	0.0001	-1.327	0.0923
	64	12.393	0.0001	-2.120	0.0135
	100	--	--	-2.185	0.0145
2006–07	2	16.100	0.0001	0.353	0.3619
	4	10.689	0.0001	0.168	0.4332
	8	6.615	0.0001	0.225	0.4108
	16	10.503	0.0001	0.015	0.4941
	32	12.309	0.0001	-0.965	0.1672
	64	-14.091	0.0001	-1.258	0.1042
	100	--	--	-1.441	0.0748

APPENDIX D

Effect of Slope Aspect on WEPP Simulation

The WEPP model was run using the input files (same input files as for Chapter 2) with change n aspect from south to north. The simulated results were presented in tables as follows:

Table D.1: Predicted runoff and erosion with maximum snow, frost and thaw depths for the CTBF.

	Runoff mm	Erosion t ha^{-1}	Snow mm	Frost mm	Frozen-soil days
2003–04	159	45	342	1000	171
2004–05	55	46	84	1000	126
2005–06	102	106	64	1000	151
2006–07	115	89	74	1000	168

The WEPP-simulated results for north facing plot showed that the simulated runoff was higher than the south facing plot (413 vs. 316) but the simulated erosion was fairly similar (286 vs. 276) for the four monitored period. Simulated snow depths for north and south facing plot were similar but the simulated frost depths and frozen-soil days were substantially higher for north facing plot (Table D1). On north facing plot, the

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