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WEPP simulations of dryland cropping systems in small drainages of northeastern Oregon

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Abstract: Computer simulation models are essential tools for evaluating soil erosion potential over large areas of cropland. Small-plot and field-scale evaluations are commonly conducted for federal farm program compliance, but producers are now faced with off-farm water quality concerns. Predicting the potential contribution of upland sediment is of interest to producers and state and federal agencies. The purpose of this study was to evaluate the applicability of the Water Erosion Prediction Project (WEPP) model for quantifying hydrological and erosion processes in the semiarid croplands of the Columbia Plateau. Two headwater drainages managed using conventional inversion tillage (CT) or no-tillage (NT) management techniques were monitored from 2001 through 2007 in the dryland cropping region of northeastern Oregon. The WEPP model was parameterized primarily from field data, including management and weather data. Crop parameters (above-ground biomass and crop yield), water balance components (volumetric soil water, evapotranspiration [ET], and surface runoff), and soil loss were observed and subsequently used to evaluate WEPP simulations. This detailed dataset allowed for a unique opportunity to evaluate not only the WEPP routines for runoff and erosion but also the routine for crop growth, which greatly influences the erodibility and hydraulic conductivity of top soil layers. Graphical and goodness-of-fit analyses indicate that WEPP generated satisfactory estimates for volumetric soil water and crop yields in NT and CT and above-ground biomass production in NT. Gross patterns of ET simulated by WEPP were compatible with those determined using observed precipitation and soil water data. Observed annual runoff and erosion values from both drainages were low (NT: 0.1 mm [0.004 in], 2.5 kg ha^{-1} [0.001 tn ac^{-1}]; CT: 0.9 mm [0.04 in], 72.0 kg ha^{-1} [0.03 tn ac^{-1}]). On average only 0.3% and 0.03% of total precipitation left the catchment as runoff during the six-year study period for CT and NT, respectively. No runoff was predicted by WEPP when default input values for a Walla Walla silt loam soil were used in the model. Simulated runoff and erosion agreed well with field observations after the effective surface hydraulic conductivity K_{eff} and rill erodibility K_r were calibrated. With minimal calibration, the WEPP model was able to successfully represent the hydrology, sediment transport, and crop growth for CT and NT cropping systems in northeastern Oregon during years of below normal precipitation, mild weather, and little runoff.

Key words: conventional tillage—crop growth—no-tillage—runoff—soil loss—Water Erosion Prediction Project (WEPP)

In the last two decades, focus on soil erosion has shifted from in-field soil loss to concerns about off-farm water quality. With this shift, regulatory agencies (US Environmental Protection Agency, tribal agencies, state departments of ecology and environmental quality) have begun evaluating agricultural land as potential nonpoint sources affecting off-farm water quality. In the US Pacific Northwest, a critical concern is degradation of salmonid habitat and infrastructure damage (reservoir and transportation channels) resulting from excessive sedimentation. The scale at which these concerns occur necessarily dictates that these evaluations take place at the drainage, subwatershed, and watershed levels. Identifying effective soil conservation practices will be critical to ensuring that efforts are well-placed and that satisfactory results are obtained in conserving soil and protecting water quality.

Historically, traditional farming practices used for dryland crop production have combined with severe weather events (frozen soil, rain with warm maritime fronts) to produce high erosion rates. Zuzel et al. (1982) reported 31.0 Mg ha^{-1} (13.8 tn ac^{-1}) soil loss from 18.3 m (60 ft) long experimental plots during a five-week period. Soil erosion rates recorded at larger temporal and spatial scales have not been as dramatic. Williams et al. (2009) reported 0.11 Mg ha^{-1} y^{-1} (0.05 tn ac^{-1} yr^{-1}) from four years of data collected in a headwater drainage under traditional tillage practices, although this study was conducted during relatively dry and mild winters. Nagle and Ritchie (2004) reported average erosion rates on the Columbia Plateau of 2.48 Mg ha^{-1} y^{-1} (1.11 tn ac^{-1} yr^{-1}) since 1963, based on Cesium-137 concentrations in soil collected from cropland farmed on a relatively gentle 5% slope in a two year winter wheat/summer fallow rotation.

Annual and long-term averages generally do not provide sufficient information for evaluating aquatic habitat impact, where one large event can cause damage that persists for months or years. The time and effort needed to conduct research at the headwater drainage scale prohibits gathering data on the potential upland contribution to stream sedimentation from the wide variety of cropping systems. To estimate these potential sediment loads requires the use of reliable models that can adequately predict annual and event soil

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Table 1
Soil properties of the Walla Walla silt loam.

Soil property		Description			
Albedo		0.23			
Initial soil saturation (%)		75			
Interrill erodibility (kg s m^{-4})		5.4 × 10^{6}			
Rill erodibility (s m^{-1})	(default)	2.0 × 10^{-2}			
Rill erodibility (s m^{-1})	(calibrated NT, CT)	5.0 × 10^{-3}			
Critical shear (N m^{-2})		3.5			
K_{eff} of surface soil (mm h^{-1})	(default)	4.5			
K_{eff} of surface soil (mm h^{-1})	(calibrated CT)	0.5			
K_{eff} of surface soil (mm h^{-1})	(calibrated NT)	1.2			
Soil depth (m)		0 to 0.3	0.3 to 0.6	0.6 to 0.9	0.9 to 1.2
Sand (% weight)		27.4	35.3	35.3	35.3
Clay (% weight)		11.5	14.0	14.0	14.0
Organic matter (% weight)		2.5	0.83	0.28	0.18
CEC (cmol kg^{-1})		11.3	8.4	8.4	8.4

Notes: NT = no-tillage. CT = conventional inversion tillage. K_{eff} = effective surface hydraulic conductivity. CEC = Cation exchange capacity.

erosion under different management options and geographic conditions.

The Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing 1995) is a process- based model that simulates water erosion by coupling hydrology, hydraulics, erosion mechanics, and plant science. An auxiliary stochastic climate generator, CLIGEN (Nicks et al. 1995), creates climate input files if daily meteorological data are not available or desired to be used. The WEPP model was developed to evaluate hydrologic and erosion impacts under various cropping practices at scales that are appropriate for the headwater drainages (maximum 248 ha [640 ac]) (Flanagan and Nearing 1995) as involved in this study. The WEPP model has been evaluated in multiple locations throughout the United States and the world (Flanagan et al. 2007). However, headwater drainage evaluations of WEPP in the Pacific Northwest have been restricted to forests (e.g., Covert et al. 2005; Dun et al. 2009) or plot scales (Pannkuk et al. 2000; Greer et al. 2006; Singh et al. 2009). Field-scale experimental research, at the drainage or subwatershed scale, has been lacking until recently (Williams et al. 2009). Studies had not been conducted to evaluate WEPP simulations of runoff, erosion, and crop biomass and yield at this scale in the Pacific Northwest.

Physically based soil erosion models quantify infiltration, runoff, and erosion through soil water dynamics and vegetative growth. Therefore, model assessments should include comparisons of simulated and observed runoff and erosion as well as evaluation of simulated crop growth. Such analysis would be a step forward in the development of physically based models that adequately assess management impacts on runoff and sediment yield from small agricultural drainages.

Table 2
Crop rotations for crop years 2001 to 2006.

	No-tillage				Conventional tillage	
Crop year	NT1*	NT2, NT3	NT4, NT5	NT6, NT7	CT1	CT2, CT3
2001	Ch	CF	SW	WW	F	F
2002	WW	WW	CF	Ch	WW	WW
2003	CF	Ch	WW	WW	F	F
2004	WW	WW	Ch	CF	WW	WW
2005	DP	CF	SW	WW	F	SW
2006	WW	WW	CF	DP	WW	V†

Notes: Ch = chickpeas. CF = chemical fallow. SW = spring wheat. WW = winter wheat. F = fallow (inversion tillage). DP = dry peas. V = volunteer crop.

* NT = no tillage. CT = conventional inversion tillage. Numbers following NT and CT designate study locations (see figure 1).

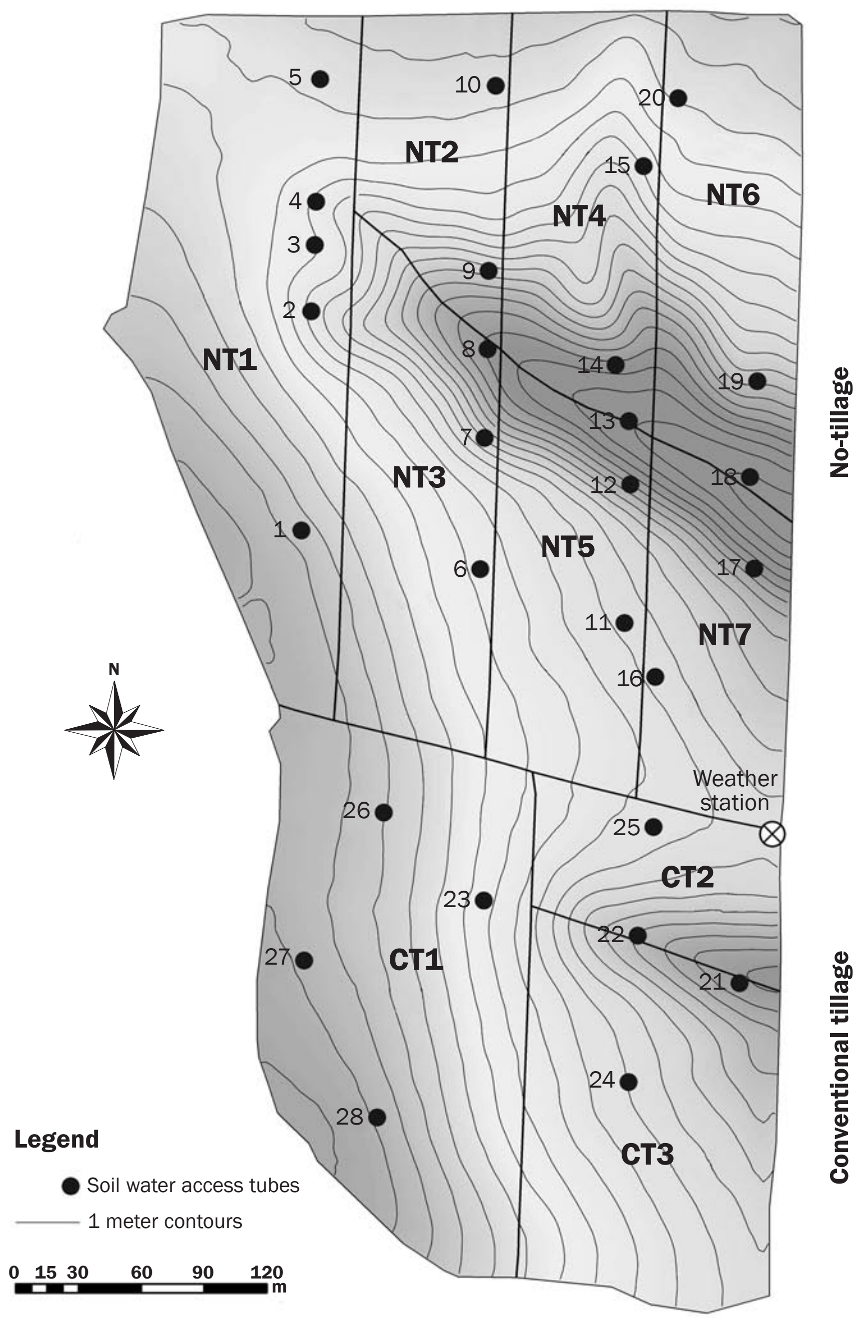
† Producer allowed volunteer wheat to mature. The only tillage was to fertilize the field.

The objective of this study was to evaluate the ability of the WEPP model to quantify surface runoff and sediment yield from conventional and no-tillage cropping systems in small headwater drainages in the dryland region of northeastern Oregon. Because runoff generation and soil erosion prediction in WEPP is highly dependent upon surface conditions (Flanagan and Livingston 1995), we also evaluated the ability of the model to simulate crop yield and above-ground biomass. Specifically, we evaluated the ability of WEPP to simulate (1) the spatial variability in soil water content and evapotranspiration throughout two headwater catchments, (2) surface runoff and sediment yield at the outlet of the catchments, and (3) crop yield and biomass production in two- and four-year winter wheat cropping rotations.

Materials and Methods

Site Description. The study site consisted of two adjacent ephemeral drainages, 6 ha (14 ac) and 11 ha (26 ac), in the Wild Horse Creek watershed (45°49'00"N, 118°38'35"W) 20 km (12.4 mi) northeast of Pendleton, Oregon. The elevation is 530 m (1,750 ft). The soils are well-drained Walla Walla silt loams (coarse-silty, mixed, superactive, mesic Typic Haploxerolls) (table 1). Soil development occurred within a mantle

Figure 1
Hillslopes for WEPP simulations and locations for soil water measurement.



of loess derived from Pleistocene aeolian deposits onto basalt flows of the Miocene Epoch (Johnson and Makinson 1988). These are the only research drainages in existence in the arid and semiarid cropland region of the Pacific Northwest.

Annual air temperatures vary from −34°C to 46°C (−29°F to 115°F), averaging 11°C (52°F). Approximately 70% of the precipitation occurs between November and April resulting from maritime fronts characterized by rainfall (0.5 mm h^{-1} (0.02 in hr^{-1}), and storm durations of three hours (Brown et al. 1983; Williams et al. 1998). Long-term annual precipitation averages 422 mm (16.6 in). Snow cover is transient, with accumulated snow subject to rapid melting by frequent warm fronts. A meteorological station located on the ridge between the drainages recorded precipitation with a tipping-bucket rain gage and 15-minute recordings of air and soil temperature, wind speed and direction, solar radiation, and relative humidity (Oviatt and Wilkins 2002).

Tillage Management. Two crop rotations (table 2), a four-year no-tillage rotation of winter wheat (*Triticum aestivum* L.)–chemical fallow–winter wheat–chickpea (*Cicer arietinum* L.) and a two-year conventional tillage rotation of winter wheat–fallow, were started in October 2000. Each phase of the no-tillage rotation occurred each year on one of four equally sized strips, each subject to a unique management practice, identified in the upper part of figure 1 as hillslopes NT1 to NT7. In 2005 and 2006, dry peas (*Pisum sativum* L.) replaced chickpeas in the no-tillage rotation. From crop years 2001 through 2004, the entire drainage in conventional tillage alternated from fallow (2001, 2003) to crop (2002, 2004). In crop year 2005, the lower half of the drainage corresponding to hillslopes CT2 and CT3 was re-cropped to winter wheat, and the upper half was left as fallow. In crop year 2006, grain lost from the combine during harvest in the lower half of the conventional drainage was left by the producer to mature as a volunteer crop, and the upper half was tilled and planted. Dates and types of tillage are given in table 3. Fertilizer was applied at time of seeding in the no-tillage drainage and in May preceding the fall planting of wheat in the inversion tillage drainage.

Above-ground biomass and crop yields were determined during harvest in late July each year of the study. Above-ground biomass was hand harvested from 1 m^2 (10.8 ft^2) plots taken in a stratified random regime corresponding to landscape position (ridge top, shoulder slope, midslope, foot slope, and bottom). Sample size for each crop (table 2) varied from 10 to 50 plots per year. Crop yields were determined from whole-field samples (total yield per crop per year) based on truck-scale receipts.

Soil Water, Runoff, and Erosion Measurements. Beginning in 2003, a total of 20 soil volumetric water content measurements were taken in each drainage capturing post-harvest, midwinter, spring, and early summer conditions during each crop year using neutron thermalization (Topp 2002). Access tubes were installed to depths of 2.44 m (96 in) or to an impermeable calcareous horizon (figure 1). Runoff was measured with 23 cm (9 in) Parshall flumes located

Table 3
Tillage operations of dry biomass (DB) and crop yields (CY).

		Tillage							Yield (kg m^{-2})*	
Year	Hillslope	PT	ST_1	ST_2	ST_3	ST_4	Planting	Harvest	DB	CY
2001	NT1†	4/2‡					4/17	8/21	0.33	0.11
	NT2, NT3								0.00	0.00
	NT4, NT5						3/22	8/6	0.89	0.42
	NT6, NT7						10/20	8/6	0.91	0.39
	CT1, CT2, CT3								0.00	0.00
2002	NT1						10/15	7/30	0.65	0.23
	NT2, NT3						10/15	7/30	1.21	0.43
	NT4, NT5								0.00	0.00
	NT6, NT7						4/9	7/30	0.23	0.07
	CT1, CT2, CT3	3/15 ‖	3/25	5/10	6/15	9/10	10/10	7/30	1.20	0.44
2003	NT1	8/14							0.00	0.00
	NT2, NT3	8/14					4/4	8/27	0.40	0.01
	NT4, NT5						10/22	8/24	1.23	0.46
	NT6, NT7	9/20					10/22	8/25	1.14	0.41
	CT1, CT2, CT3								0.00	0.00
2004	NT1						10/15	7/29	1.41	0.62
	NT2, NT3						10/15	7/29	1.32	0.58
	NT4, NT5	2/4					4/1	9/7	0.46	0.17
	NT6, NT7	9/4							0.00	0.00
	CT1, CT2, CT3	3/15§	3/25	5/10	6/15	9/10	10/10	7/30	0.99	0.46
2005	NT1	10/6	4/6‖				4/3	7/28	—	0.16
	NT2, NT3	10/6							0.00	0.00
	NT4, NT5						10/2	8/5	0.95	0.38
	NT6, NT7						10/2	8/5	1.40	0.60
	CT1						7/28		0.00	0.00
	CT2, CT3	9/5	10/5				10/15	7/28	1.19	0.36
2006	NT1	10/5					10/27	7/27	1.19	0.43
	NT2, NT3	9/27					10/27	7/27	1.20	0.49
	NT4, NT5								0.00	0.00
	NT6, NT7	9/27	4/14				4/12	7/25	—	0.16
	CT1	4/15§	5/15	6/15	7/10	9/15	10/20	7/28	1.76	0.74
	CT2, CT3		9/20					7/28	1.13	0.48

Notes: PT = primary tillage. ST = secondary tillage. — = missing data.

* Dry biomass (residue and grain) was taken as the average of 25 bundles from each crop; grain yield was determined from combine harvest.

† NT = no tillage. CT = conventional inversion tillage. Numbers following NT and CT designate study locations (see figure 1). Crop rotations are explained in table 2.

‡ Management in no-tillage other than planting included residue management to shake weed seeds to the ground and lay standing residue prone without disturbance to soil surface.

§ Tillage operations in winter wheat occurred previous year.

‖ Dry green peas were rolled after planting with a roller harrow.

at the outlet of each drainage. In October 2006, the Parshall flume in the conventional drainage was replaced with a drop-box weir (Bonta 1998) to adequately mix and transport the large volume of sediment. Flow stage was recorded using ultrasonic distance sensors, and flow rate was calculated using a standard rating curve (Bonta 1998; USDI Bureau of Reclamation 2001). Runoff samples were collected with flow-activated, commercial storm water samplers using a liquid level switch at a stage of 1 cm (0.4 in) or greater. Samples (0.5 L [0.1 gal]) were collected every 40 minutes for up to eight hours of continuous runoff. Samples were analyzed for suspended sediment concentrations (Glysson and Grays 2002). Deep percolation for the study region has been found to be negligible (Chen and Payne 2001), and therefore, cumulative evapotranspiration (ET) between two sampling dates for soil water can be estimated from observed precipitation, surface runoff, and changes in soil water. In this study, we used this approach to estimate ET in each drainage.

$$ET = P - \Delta S - RO \,, \tag{1}$$

where P is precipitation, ΔS is change in soil water, and RO is runoff.

Water Erosion Prediction Project Model Description, Input, and Assessment. The WEPP watershed model is most suitable for

Table 4
Observed and simulated annual water balance in depth (mm) for each water year (October 1 to September 30).

Year	Observed				Simulated		
	Precipitation	Runoff	Change of soil water*	Estimated ET	Runoff	ET	Deep percolation
No-tillage							
2001	296	0	—	—	0	378	100
2002	245	0	—	—	0	285	10
2003	364	0.38	—	—	0.45	336	0
2004	423	0	45	402	0	411	10
2005	257	0.13	−16	281	0	291	0
2006	455	0.05	5	459	0	426	0
Average†	340	0.09	25	380	0.08	354	20
Conventional tillage							
2001	296	0	—	—	0.28	173	0
2002	245	0	—	—	0	392	0
2003	364	1.17	—	—	3.55	193	0
2004	423	3.94	−29	476	4.59	546	14
2005	257	0.34	−32	274	0	232	0
2006	455	0	−31	478	0.79	493	0
Average	340	0.91	−31	410	1.54	338	2

Notes: ET = evapotranspiration. — = no observation.

* Based on post-harvest soil water content measurements taken before the onset of fall rainfall.

† The averages were made over the observation period.

simulating hydrologic and soil erosion processes for areas up to 248 ha [640 ac]) (Laflen et al. 1991; Flanagan and Nearing 1995; Ascough et al. 1997; Baffaut et al. 1997). Hillslope processes are simulated by using up to 10 distinct overland flow elements to represent the variability in cropping, management, and soil characteristics. Within each overland flow element, the following are simulated: water balance (surface runoff, ET, subsurface lateral flow, deep percolation, and soil water redistribution), soil erosion, plant growth, and changes in soil properties by tillage or other management. Runoff and eroded soil from the hillslopes are routed through the channel network to the watershed outlet. The model accepts long-term daily climate data or single-storm event data. An auxiliary climate generator program, CLIGEN (Nicks et al. 1995), creates long-term climate files if daily meteorological data are not available. More thorough descriptions of the WEPP model are available (USDA ARS 2009) and in recent publications (e.g., Hunt and Wu 2004; Pieri et al. 2006; Singh et al. 2009). In this research, the drainages were manually subdivided into hillslopes, each as a single overland flow element, to describe gross differences in crop rotations and tillage operations (figure 1).

The WEPP (version 2008.9) simulations were conducted using climate data collected at the research drainages from 2001 through 2006. Break-point climate input for the simulation was developed from the tipping-bucket precipitation data and 15-minute temperature, relative humidity, wind speed, and wind direction recorded at the study site. Soil input was taken from the WEPP database for a Walla Walla silt loam (table 1). The topography for each hillslope was built from elevation data acquired using a survey-grade, real-time kinematic global positioning system total station. The dates of each tillage operation as well as planting and harvest were input to the model (table 3). The amount of disturbance for specific tillage implements (e.g., tillage depth, ridge height, and spacing) was also measured and used as input to the model. The crop growth parameters for winter wheat, spring wheat, and grass were taken directly from the WEPP User Summary (Flanagan and Livingston 1995). The crop-growth parameters for chickpea were prepared based on those for soybean in the WEPP database. A perennial grass was used to represent weed growth and to simulate soil water dynamics that occurred between harvest and spring herbicide applications.

Previous WEPP applications suggested that the effective surface hydraulic conductivity K_{eff} and rill erodibility K_r are crucial parameters affecting surface runoff and erosion (Greer et al. 2006; Pieri et al. 2006; Singh et al. 2009). In this study, K_{eff} and K_r were calibrated for runoff and erosion simulation during a period of below-normal precipitation and low runoff. Effective surface hydraulic conductivity was manually adjusted to a smaller value than found in the WEPP database to capture the major observed runoff events, while generating fewer minor runoff events that were not observed. Rill erodibility was also manually adjusted to a smaller value for the erosion amount simulated for individual events to be more agreeable with observed values. Hence, WEPP runs were made first using soil properties taken directly from the WEPP database and then with calibrated K_{eff} and K_r.

Water balance (surface runoff, ET, and volumetric soil water content), soil erosion, and above-ground biomass and crop yield values simulated by WEPP were evaluated against measured values using graphical plots and statistical analyses. Observed volumetric soil water and estimated ET for each drainage were compared with WEPP–simulated results. Furthermore, WEPP–simulated and field-observed annual runoff, sediment yield, above-ground biomass, and crop yield were compared. Additionally, root mean square deviation (*RMSD*) (equation 2) and an efficiency index of percent bias (*PBIAS*) (equation 3) were computed to assess the ability of the WEPP model to reproduce hydrologic and erosion field observations.

$$RMSD = \sqrt{\sum_{i=1}^{n} (x_{s,i} - x_{o,i})^2 / n} \quad , \tag{2}$$

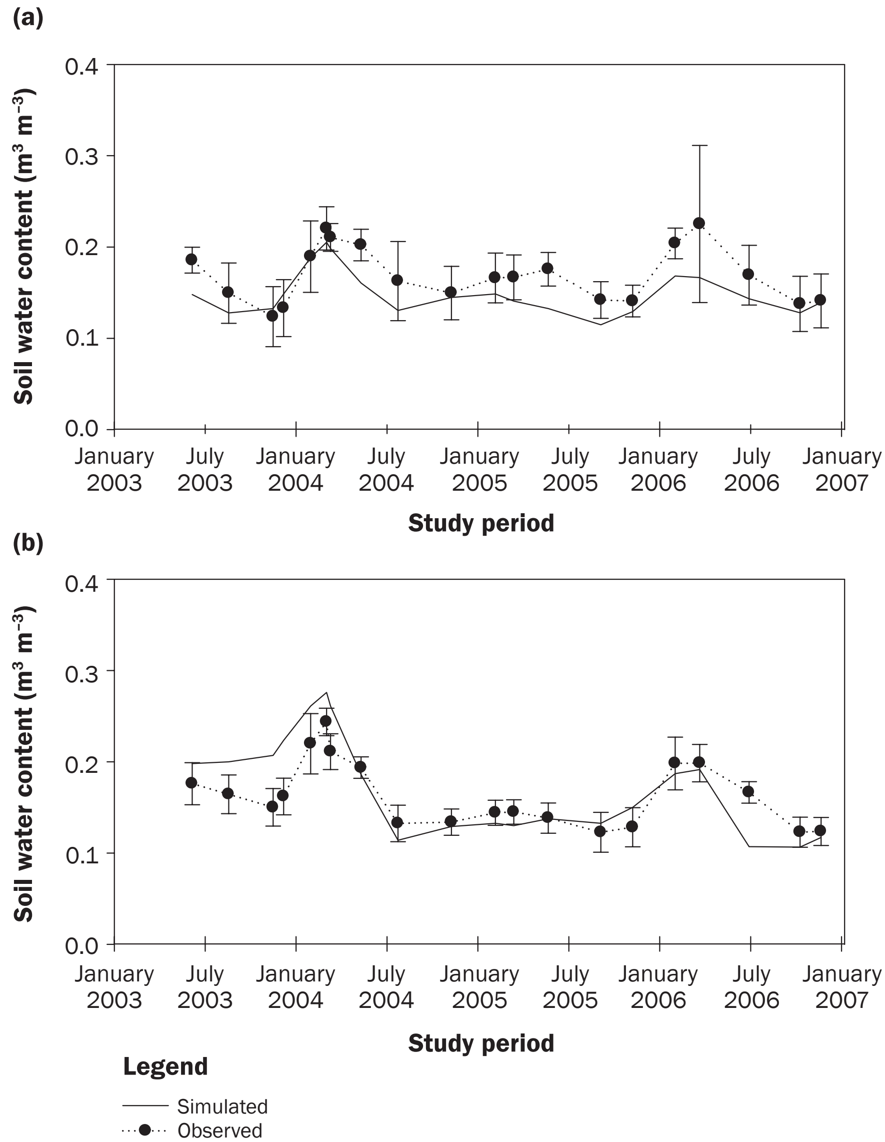
$$PBIAS = \frac{\sum_{i=1}^{n} (x_{o,i} - x_{s,i})}{\sum_{i=1}^{n} x_{o,i}} \times 100\% \ , \tag{3}$$

where $x_{s,i}$ and $x_{o,i}$ are simulated and observed values for a given day of sampling, and n is the number of days of observations. Sample means and standard deviations for volumetric soil water and above-ground biomass for each drainage were calculated and presented in graphical form.

In addition, nonparametric Wilcoxon two-sample tests were performed using Statistical Analysis Systems (SAS Institute Inc 2004) to compare the differences between the field-observed runoff and erosion events under the two management practices, NT and CT, and between the simulated results and field observations. The nonparametric tests were chosen due to the non-normality and lack of independence of the data.

Figure 2

Observed and simulated soil water content for (a) no-tillage (NT) drainage and (b) conventional inversion tillage (CT) drainage. Error bars represent standard deviations of soil water measurements on a given day.



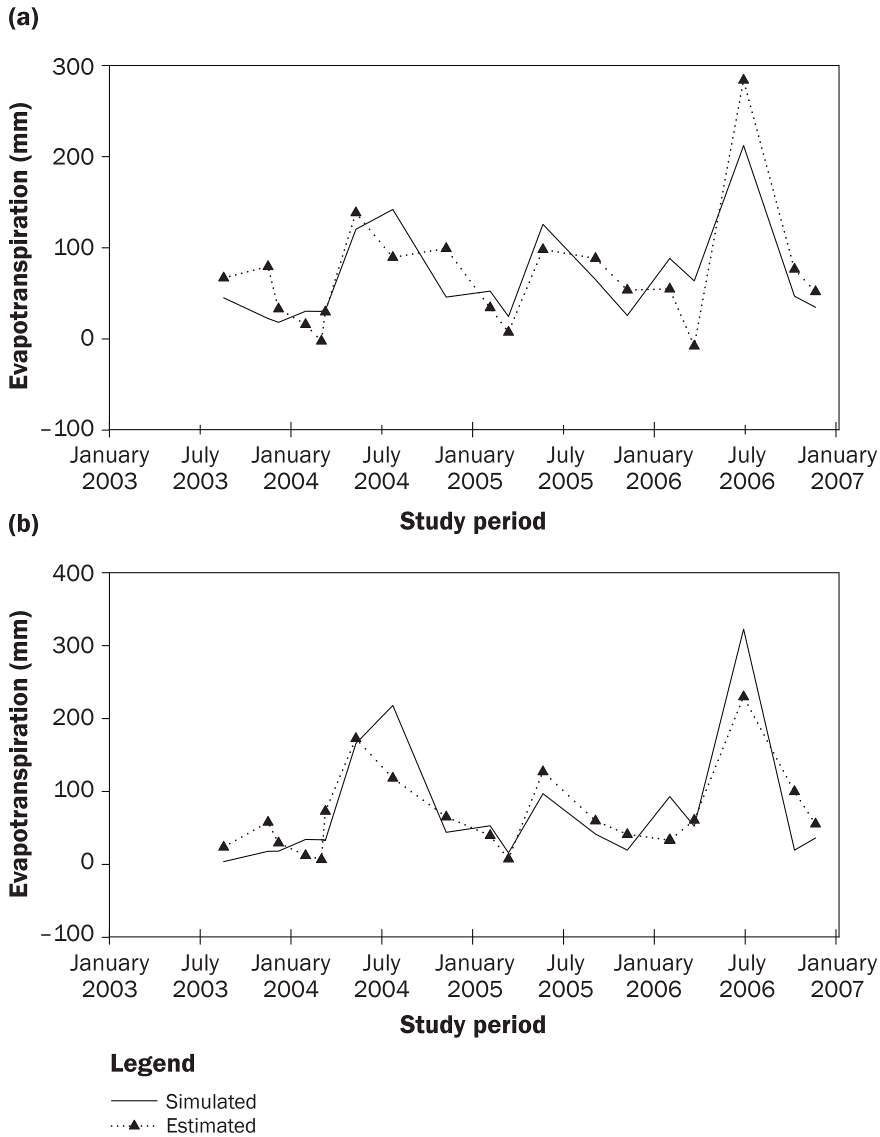
Results and Discussion

Water Balance and Soil Erosion. The annual water balance indicated that surface runoff was extremely low during this study. Mild weather conditions prevailed from 2001 through 2006 (Williams et al. 2009). Minimum temperatures were higher than normal in 2001, 2002, 2003, and 2006, and precipitation was below the long-term average in 2001, 2002, 2003, and 2005. As a result, fewer events occurred under rain on frozen or thawing soil conditions that typically cause large runoff and erosion events in this region (Williams et al. 2009). On average, less than 0.3% and 0.03% of the total annual precipitation left the drainages as surface runoff under CT and NT, respectively (table 4). During the study period, nearly all the precipitation either evaporated or was transpired through crop growth. Soil water content declined to wilting point due to *ET* during summer and recovered in the winter and spring (figures 2 and 3). Throughout the six-year study period (October 2000 to December 2006), only three years had measurable runoff (tables 4 and 5). Three of the six observed events in the NT drainage and six of the 14 events in the CT drainage occurred while the soil was frozen (table 5). Wilcoxon two-sample tests indicated significant differences in the field-observed runoff events (Z-score 3.87, p-value 0.0001) and erosion events (Z-score 3.31, p-value 0.0009) between the NT and CT drainages.

The WEPP simulated no runoff or erosion events for the NT and CT drainages when the default soil properties of a Walla Walla silt loam soil from the WEPP database were used. Low runoff and sediment yields, as observed in this study, pose challenges to erosion models (Nearing et al. 1999). In a comparison of USLE, RUSLE, and WEPP with 1,600 plot-years of measured data, Tiwari et al. (2000) showed that each model somewhat underpredicted soil loss. For example, WEPP predicted a sediment yield of 1,110 kg ha^{-1} (0.50 tn ac^{-1}) where 3.6 kg ha^{-1} (0.02 tn ac^{-1}) was measured in a small 0.49 ha (1 ac) no-tillage corn experimental watershed in Coshocton, Ohio (Liu et al.

Figure 3

Estimated and simulated evapotranspiration (*ET*) for (a) no-tillage (NT) drainage and (b) conventional inversion tillage (CT) drainage. The *ET* was estimated as precipitation – change in soil water – runoff.



1997). Zhang et al. (1996) applied the WEPP model to 290 annual values and obtained an average of 21,800 kg ha^{-1} (9.72 tn ac^{-1}) for the measured soil loss, with an average magnitude of prediction error of 13,400 kg ha^{-1} (5.98 tn ac^{-1}), or approximately 61% of the mean. Based on an assessment of soil loss data representing thirteen soil types and locations, Nearing et al. (1999) reported that the coefficient of variation (ratio of standard deviation to mean) may increase by more than tenfold when average soil loss decreased from 2,000 to 100 kg ha^{-1} (0.89 to 0.04 tn ac^{-1}).

Alternatively, underestimation of runoff and erosion, as in this study, could result from the unique interaction of low rainfall energy and soil processes associated with multiple freezing and thawing events throughout the winter in the US Pacific Northwest. In this region, soil surface sealing typically results from slaking, or exfoliation of soil peds rather than from direct raindrop impact. Surface sealing was observed in the field areas of localized overland flow during low-intensity, short-duration rain showers. Pikul and Aase (2003) measured a 10-fold reduction in saturated hydraulic conductivity due to surface sealing in fine-sandy-loam and loam soils in Montana. Using data from long-term experimental plots located in Pendleton, Oregon, Wuest et al. (2005) showed that small differences in aggregate stability caused by small differences in total carbon (C) and total nitrogen (N) had profound effects on infiltration rates, which persisted for several weeks after the last occurrence of frozen soil leading to increased runoff and erosion (Williams 2004, 2008). The default hydraulic properties in WEPP are based on empirical pedo-transfer functions largely developed in regions where these conditions do not exist. Therefore, calibration of key soil properties is important for site-specific applications.

Because the algorithms in WEPP for the effects of freeze and thaw on slaking and surface sealing have not been well developed or verified for the Pacific Northwest, the vertical effective hydraulic conductivity at the soil surface (K_{eff}) and rill erodibility (K_r) were calibrated to improve the agreement between WEPP–simulated and field-observed runoff and erosion events. With K_{eff} adjusted to 10% and 30% of the default value for CT and NT, respectively, and K_r reduced by 75% for both the CT and NT, WEPP generated one runoff and erosion event for the NT and seven for the CT. The one event and three large events simulated for the NT and CT, respectively, corresponded directly to observed winter events, typical of the study region (table 5). For the NT drainage, all six observed runoff events were smaller than 0.5 mm (0.02 in). The WEPP model reproduced the largest event. For the CT drainage, WEPP reproduced three large events. Two simulated large events on January 31, 2003, and January 28, 2004, were due to high rainfall intensity, and the third on January 23, 2004, was due to rain-on-snow. The WEPP model did not properly model the small events in that certain small events were simulated, but not observed, while some observed were not simulated (table 5), suggesting the complexity of the dynamic changes in soil properties and the need for improving the representation of such dynamics.

The simulated six-year average sediment yield of 84 kg ha^{-1} (0.04 tn ac^{-1}) for CT and 0.3 kg ha^{-1} (0.0001 tn ac^{-1}) for NT matched well with the observed values of 72.0 kg ha^{-1} (0.03 tn ac^{-1}) and 2.5 kg ha^{-1} (0.001 tn ac^{-1}) for CT and NT, respectively (figure 4).

Results from the statistical analyses comparing WEPP–simulated and field-observed

Table 5

Observed and simulated runoff and erosion events during October 2000 to December 2006. The Water Erosion Prediction Project simulated events presented here after calibration of soil properties K_{eff} and K_r.

Date*	Precipitation (mm)	Intensity (mm h⁻¹) Maximum	Intensity (mm h⁻¹) Average	Duration (h)	Runoff (mm) Observed	Runoff (mm) Simulated	Sediment yield (kg ha⁻¹) Observed	Sediment yield (kg ha⁻¹) Simulated
No-tillage								
1/29/03	10.9	2.9	0.8	13.8	0.1		2.5	
1/30/03	14.6	6.5	0.7	21.2	0.2		4.1	
1/31/03	**14.9**	**8.7**	**1.8**	**8.1**	**0.2**	**0.4**	**8.2**	**1.6**
1/18/05†	4.4	31.0	0.7	5.9	0.1		<0.1	
12/22/05†	3.8	4.2	0.2	19.6	<0.1		<0.1	
12/30/05†	20.3	5.2	0.9	23.6	<0.1		<0.1	
Annual average					0.1	0.07	2.5	0.3
Conventional tillage								
6/12/01	*9.65*	*25.0*	*1.7*	*5.7*		*0.3*		*2.2*
1/26/03	15.5	6.5	0.7	21.7	0.3		14.2	
1/29/03	10.9	2.9	0.8	13.8	0.4		22.2	
1/30/03	14.6	6.5	0.7	21.2	0.5		73.5	
1/31/03	**14.9**	**8.7**	**1.8**	**8.1**	**‡**	**3.5**	**‡**	**381.1**
11/29/03	*16.26*	*5.2*	*2.8*	*5.8*		*0.2*		*26.3*
12/13/03	*16.5*	*5.0*	*0.9*	*18.4*		*0.2*		*11.3*
1/23/04†	**26.6**	**5.1**	**0.9**	**31.3**	**‡**	**2.6**	**‡**	**49.5**
1/26/04†	0.76	0.8	0.4	2.1	0.3		2.7	
1/28/04†	**19.3**	**4.3**	**0.5**	**39.4**	**0.6**	**1.7**	**43.7**	**34.0**
2/6/04	9.4	3.3	0.9	10.0	0.3		8.7	
2/16/04	12.7	2.9	1.1	11.6	0.6		138.3	
2/17/04	6.3	3.3	0.3	20.51	0.3		47.6	
2/24/04	9.2	13.0	0.9	9.9	0.3		53.5	
4/15/04	24.6	12.5	3.5	7.0	0.3		§	
6/8/04	21.1	6.5	3.6	5.9	1.3		§	
1/18/05†	4.4	31.0	0.7	5.9	0.3		0.3	
12/22/05†	*3.8*	*4.2*	*0.2*	*19.6*		*0.8*		*0.0*
Annual average					0.9	1.6	67.5	84.1

* Data in bold face and normal font are those for which WEPP (Water Erosion Prediction Project) produced or failed to reproduce the observed events, respectively. Data in Italic are those for which WEPP predicted an event that was not observed.

† Runoff and soil erosion associated with frozen or thawing soil.

‡ Stage failure due to freezing in the stilling well and intake line of stormwater samplers.

§ Event observed but no sediment data collected due to malfunctioning of samplers.

Table 6

Statistical tests comparing WEPP (Water Erosion Prediction Project) simulation results and field observations. Analysis of runoff and sediment yield were conducted after calibration of K_{eff} and K_r for the Walla Walla silt loam in the WEPP database.

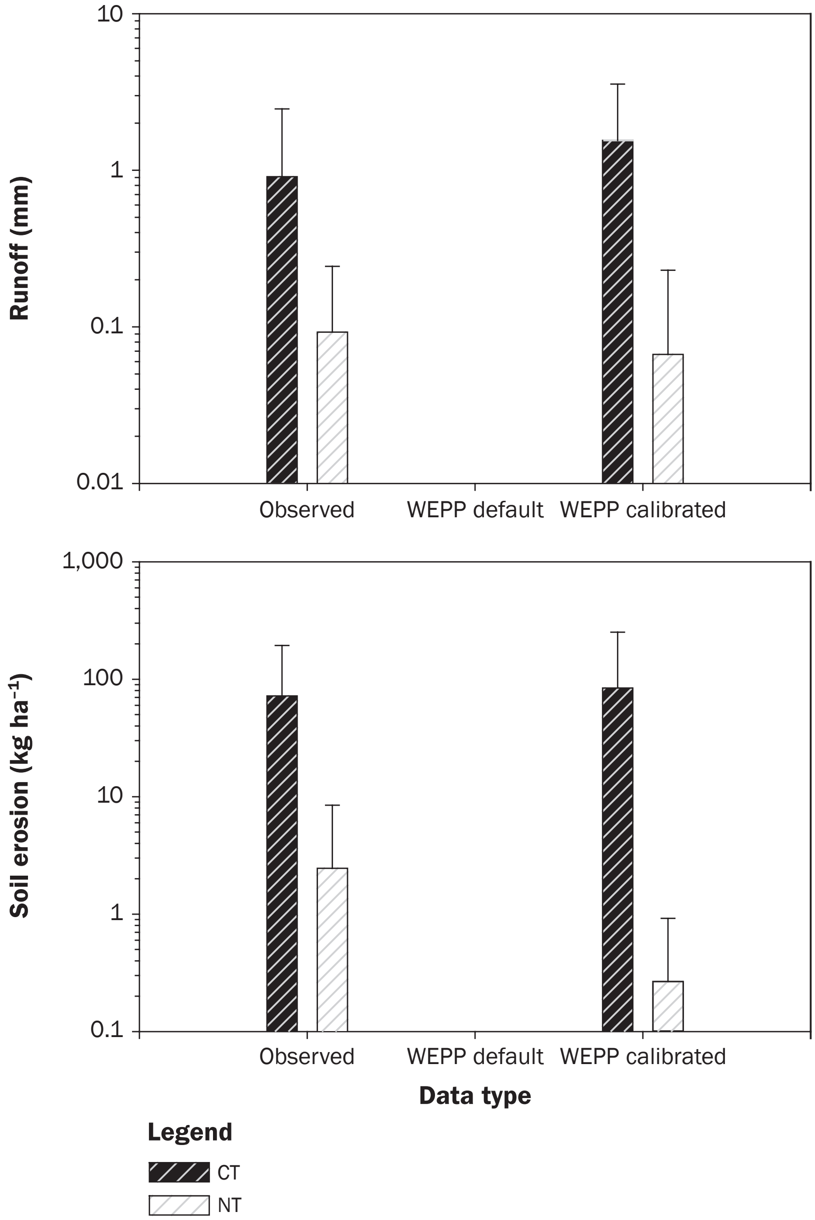
Treatment	Observed Sample size	Observed Standard deviation	*RMSD*	Wilcoxon test* *Z*-score	Wilcoxon test* *p*-value
No-tillage					
Above-ground biomass (kg m⁻²)	6	0.23	0.14	−0.40	0.69
Crop yield (kg m⁻²)	6	0.08	0.09	−0.56	0.57
Soil water content (m³ m⁻³)	20	0.03	0.03	1.99	0.05
ET (mm)	19	57	44	0.79	0.43
Annual runoff (mm)	6	0.2	0.06	0.53	0.60
Annual sediment yield (kg m⁻¹)	6	5.5	5.4	0.00	1.0
Conventional tillage					
Above-ground biomass (kg m⁻²)	4	0.23	0.60	−1.28	0.20
Crop yield (kg m⁻²)	4	0.13	0.07	−0.08	0.94
Soil water content (m³ m⁻³)	20	0.03	0.03	−0.11	0.91
ET (mm)	19	65	37	0.29	0.77
Annual runoff (mm)	6	1.7	1.1	−0.50	0.62
Annual sediment yield (kg m⁻¹)	6	130	150	−0.27	0.79

Notes: *RMSD* = root mean square deviation. *ET* = evapotranspiration.

* Significance level $\alpha = 0.05$.

Figure 4

Annual averages and standard errors of annual runoff and soil erosion demonstrating improvement in WEPP (Water Erosion Prediction Project) performance through the calibration of effective hydraulic conductivity and rill erodibility parameters.



Notes: NT = no-tillage drainage. CT = conventional inversion tillage.

runoff and sediment yield are shown in table 6. Compared to the standard deviations of field observations, the *RMSD* values were smaller in terms of simulated runoff and were similar in terms of simulated annual sediment yield for the CT and NT. The Wilcoxon tests showed no significant difference between the simulated and observed annual runoff and sediment yield for both drainages. Overall, with adjustment to K_{eff} and K_r, WEPP–simulated annual runoff and soil erosion closely matched the observed values, and reflected the differences due to the two different tillage treatments.

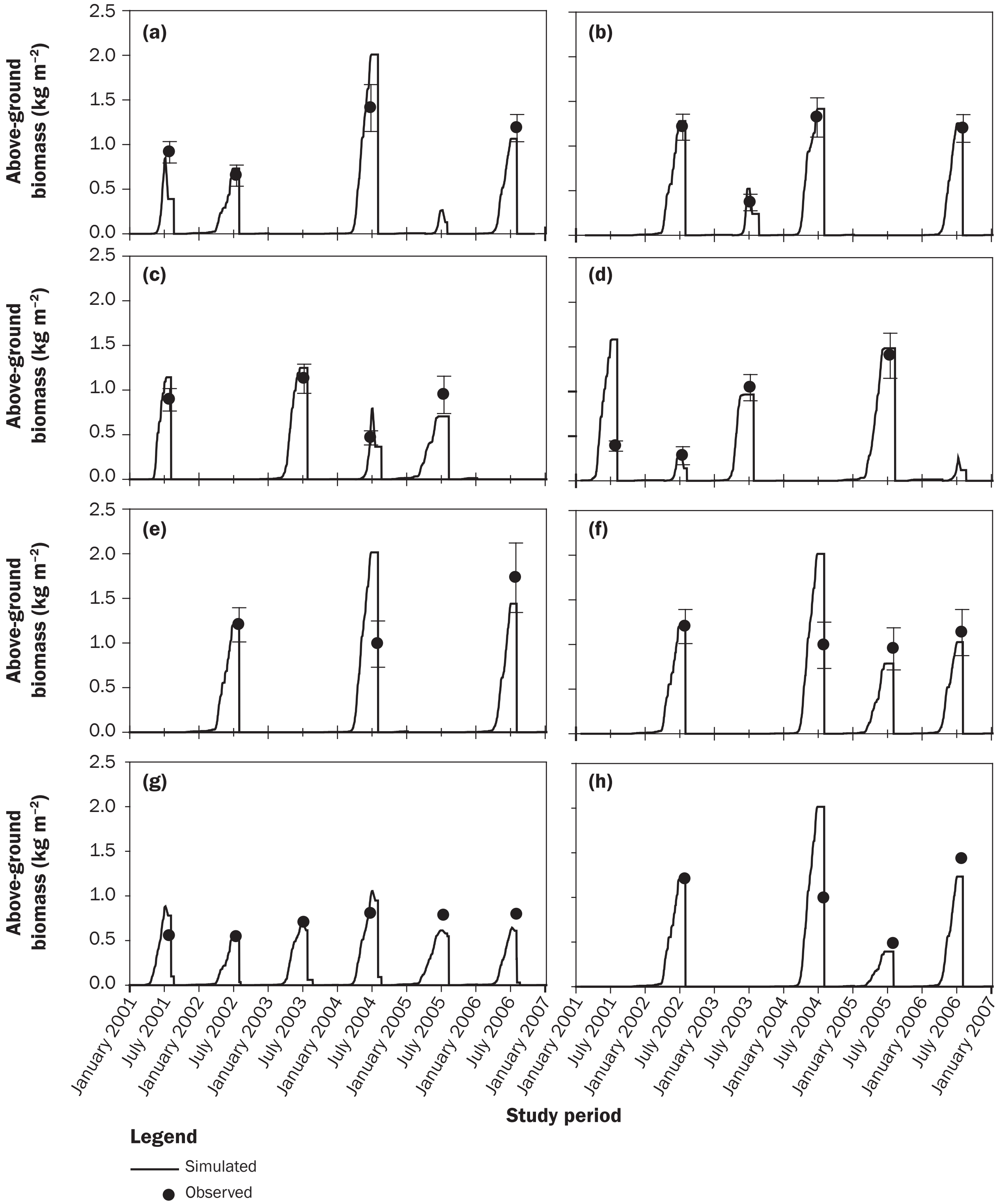
The WEPP model satisfactorily simulated volumetric soil water and *ET* for both drainages, even without adjustment to K_{eff} due to the negligible surface runoff from both the CT and NT (table 6, figures 2 and 3). The *RMSD* for volumetric soil water content was 0.03 for both drainages (with corresponding standard deviations of 0.03), with an underprediction (*PBIAS*) of 8% in the CT and overprediction of 9% in the NT. This error is immaterial considering that the standard deviation of measured daily volumetric soil water content within a drainage changed between 0.01 and 0.08 with time (figure 2). The *RMSD* values for predicted and estimated *ET* (CT = 37 mm [1.46 in], NT = 42 mm [1.65 in]) were smaller than the standard deviations of 65 mm (2.56 in) and 57 mm (2.24 in) for the CT and NT, respectively. The WEPP model overpredicted *ET* by 4% in the CT and underpredicted *ET* by 1% in the NT. Wilcoxon two-sample tests indicate no significant differences between WEPP–simulated and field-observed (or estimated) soil water content and *ET*. Reliable prediction of *ET* is especially important in the dryland farming areas of the US Pacific Northwest where growers routinely practice summer tillage or chemical fallow to limit evaporation losses.

Drainage-Scale Above-Ground Biomass and Crop Yield. Above-ground biomass and crop yield in this region is predominately influenced by available soil water during the growing season. Above-ground biomass and crop yield were well simulated by the WEPP model for the NT cropping system throughout the study period and were overpredicted for the wet year 2004 for the CT cropping system (figures 5 and 6). The WEPP 2008.9 only considers available water, which was sufficient in crop year 2004, as a limiting factor for crop growth. Consideration of additional limiting factors, such as nutrients, would help improve WEPP simulation of crop growth. Over the six years of this research, average annual above-ground biomass was overpredicted (*PBIAS*: 6% for CT and 7% for NT). The *RMSD* of the simulated above-ground biomass was smaller than the standard deviation of the measured value for the NT, but it was larger for the CT due to WEPP's overprediction for year 2004.

Yields for all crops within the CT and NT drainages averaged over 2001 to 2006 were 0.39 and 0.26 kg m^{-2} (58 and 39 bu ac^{-2}), respectively, with an annual overprediction of 9% for the CT and 12% for the NT (figure 6). The *RMSD* of simulated crop yield was 0.07 and 0.09 kg m^{-2} (10 and 13 bu ac^{-1}) for the CT and NT treatments, respectively, with corresponding standard deviations of 0.13 and 0.08 kg m^{-2} (19 and 12 bu ac^{-1}).

Figure 5

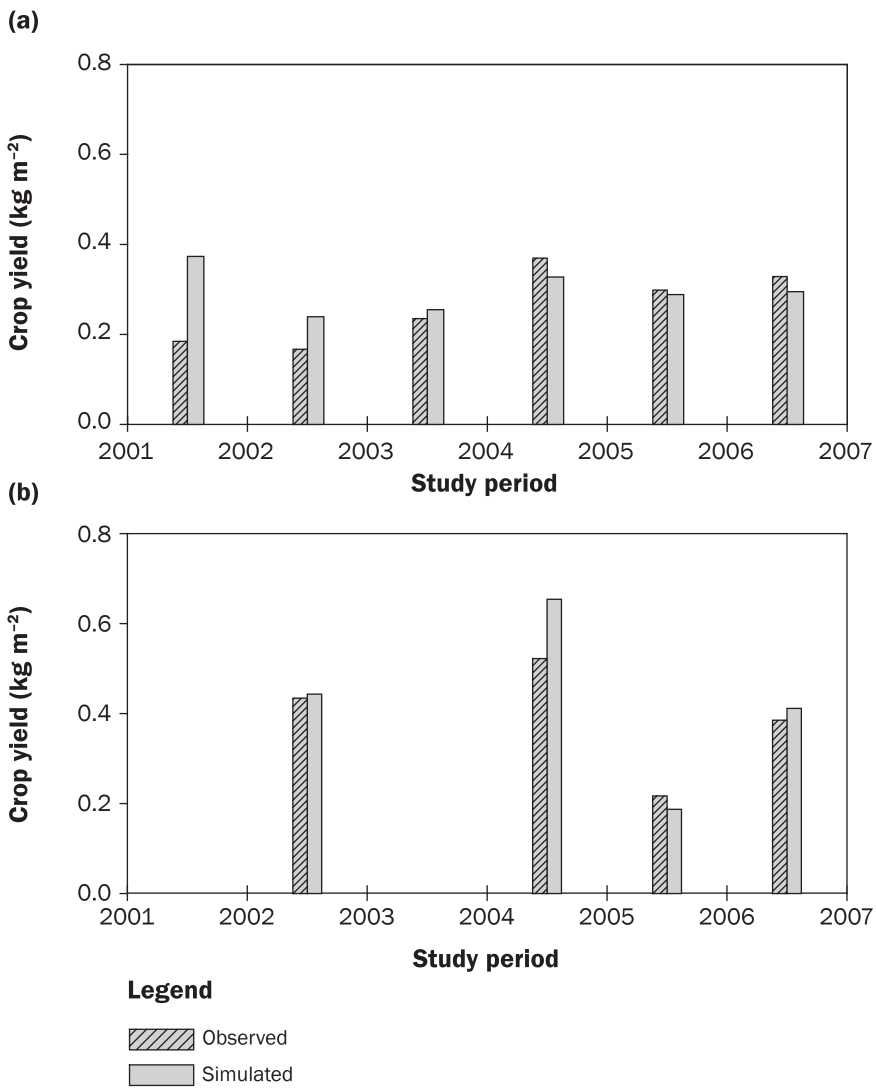
Observed and simulated above-ground biomass for (a) NT1, (b) NT2 and NT3, (c) NT4 and NT5, (d) NT6 and NT7, (e) CT1, (f) CT2 and CT3, (g) NT drainage, and (h) CT drainage. Averages and standard deviations in panels (a) through (f) were calculated from multiple-field samples. Drainage annual averages in panels (g) and (f) were calculated from component hillslope values.



Notes: NT = no tillage. CT = conventional inversion tillage. Numbers following NT and CT designate study locations (see figure 1).

Figure 6

Observed and simulated crop yield for (a) no-tillage (NT) drainage and (b) conventional inversion tillage (CT) drainage. Note fallow years 2001 and 2003 under the CT. Observed averages were calculated from component hillslope values. Crop yields for the CT in 2002 and 2004 were single, whole-field values.



For the NT, a considerable overestimation of crop yield in 2001 and 2002 was likely due to low and untimely precipitation that resulted in low crop production (figure 6). Overall, WEPP reasonably described plant growth, a key component for adequate simulation of runoff and erosion processes.

Summary and Conclusions

Water balance (volumetric soil water, *ET*, and runoff), soil loss, above-ground biomass, and crop yield from two headwater drainages under NT and CT treatments in northeastern Oregon were simulated with WEPP, a physically based water erosion prediction model developed by the USDA. The simulation was conducted using observed weather as well as crop and tillage management data together with measured topography and soil properties. Without calibrating any vegetation parameters in the model, WEPP was able to reproduce field-measured crop yields within 9% and 12% for the CT and NT cropping systems, respectively. Above-ground biomass, soil water content, and *ET* were also adequately predicted. The error in predicted soil water content and *ET* was in the range of measurement error.

Overall crop yield and above-ground biomass predictions agreed well with observations. Over-prediction of above-ground biomass during one wet year in the CT system suggests the need for consideration of additional limiting factors, such as nutrients, to improve WEPP simulation of crop growth.

Using the default soil parameters in the WEPP database without adjustment, WEPP predicted no runoff or erosion events for the two study drainages where 0.03% or 0.3% of the overall precipitation became runoff. With calibration of the effective hydraulic conductivity and rill erodibility, WEPP was able to generate observed major runoff and erosion events and to simulate the differences in the hydrologic and erosion processes under the two tillage treatments. Nonparametric statistical tests indicated no significant difference between the simulated and observed data for un-calibrated simulations of seasonal *ET*, change in soil water content, above-ground biomass, and crop yield, and calibrated simulations of annual runoff and sediment yield, suggesting the adequacy of the WEPP results, in periods of below normal precipitation, mild weather conditions, and low runoff.

Confounding the performance of WEPP in modeling the hydrologic and erosion processes in this study were a combination of low rainfall intensities, long-duration storms, and a high frequency of soil freezes and thaws during winter. Our ability to evaluate and parameterize the WEPP model for application across the dryland farming region of the US Pacific Northwest would be enhanced in the future by additional large plot- and drainage-scale cropping system research.

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