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Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX

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ABSTRACT

Simulation models are increasingly used to analyze the impact of agricultural management at the watershed-scale. In this study, the Agricultural Policy/Environmental eXtender (APEX) model was tested using long-term (1976–1995) data from two watersheds (W2 and W3) at the USDA Deep Loess Research Station near Treynor, Iowa. The two watersheds were cropped with continuous corn (*Zea mays* L.) and managed with conventional-tillage at W2 (34.4 ha) and ridge-till at W3 (43.3 ha). The monthly runoff and sediment yield were calibrated for the two watersheds during 1976–1987 by adjusting the curve numbers, curve number index coefficient, RUSLE *C* factor exponential residue and height coefficients, and erosion control practice factor for grassed waterways. Soil organic carbon values in the top 0.15 m soil layer were calibrated for the two watersheds in 1984 by adjusting the microbial decay rate coefficient. Model validation was conducted from 1988 to 1995. The calibrated model was able to reasonably replicate the monthly and yearly surface runoff and sediment yield for both watersheds for the validation period, with Nash–Sutcliffe efficiencies (EF) larger than 0.62 except for the EF of 0.41 for monthly sediment yield comparison at W3. The errors between the predicted and observed means were all within ±6% for runoff and sediment yield; predicted soil organic carbon in the 0.15 m soils in 1994 were within 10% of the observed values for both watersheds. The percentage error between the predicted and observed average corn grain yields was −5.3% at W2 and −2.7% at W3 during the 20-year simulation period. Scenario analyses were also conducted to assess the benefits of ridge-till over conventional-tillage. Over the 20 years, the predicted benefit of ridge-till versus conventional-tillage on surface runoff reduction was 36% in W2 and 39% in W3, and about 82–86% sediment yield reduction in both watersheds. The cumulative soil organic carbon losses from sediment were reduced about 63–67%. The long-term benefit of ridge-till over conventional-tillage was also quantified as a minimum corn grain yield increase of 3.8%. The results of this study indicate that APEX has the ability to predict differences between the two tillage systems. The modeling approach can be extended to other watersheds to examine the impacts of different tillage systems.

1. Introduction

Agriculture is the primary focus of water quality and erosion control in the U.S. Agricultural practices affect water quality/quantity, crop productivity, and soil quality. Various incentives and education efforts to prevent the loss of nutrient-rich topsoil have resulted in the reduction of erosion from U.S. croplands and Conservation Reserve Program land by 32% between 1982 and 1997 (USDA-NRCS, 1997). Field monitoring is often used to evaluate and acquire knowledge of the impacts of management practices on productivity and environment. However, field research can be prohibitively costly and time consuming to perform across all possible landscape, climate, management practice, and cropping system combinations (Chung et al., 1999; Davis et al., 2000). Monitoring studies conducted at a watershed-scale are difficult to replicate in the way that traditional plot-scale research is designed, in order to compare responses of alternative management practices using only field observations. However, computer simulation models provide an efficient and effective alternative for evaluating the effects of agricultural practices on soil and water quality at the watershed level.

Simulation models have been extensively applied to study the impacts of agricultural management practices. Examples of such applications include predicting soil erosion effects associated with

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alternative land uses at a northwestern China watershed using the Agricultural Policy/Environmental eXtender (APEX) model by Wang et al. (2006a), quantifying the impacts of conservation tillage, strip intercropping, and other practices for two watersheds in central Iowa, USA using the Soil and Water Assessment Tool (SWAT) model (Vache et al., 2002), and analyzing the effectiveness of agricultural BMPs for sediment reduction in the Mississippi Delta using AnnAGNPS (Yuan et al., 2002). These and other models vary in complexity and flexibility, and provide different capabilities in representing agricultural systems and subsequently quantifying the impact of these systems over a range of climate, soil, and landscape conditions. Many models simulate BMPs using simple removal fractions, which do not allow in-depth depictions of different management practices.

The APEX model (Williams and Izaurralde, 2006) is a farm/small watershed and BMP model that simulates extensive land management (Borah et al., 2006). APEX is an extended and expanded version of the Environmental Policy Impact Climate (EPIC) model (Williams, 1990; Izaurralde et al., 2006). The field scale model, EPIC, has been extensively tested and applied for a wide variety conditions in the U.S. and other regions (e.g., China, Austria) as described in Gassman et al. (2005) and has also been applied at a global scale (Liu et al., 2007). APEX is based on state-of-the-art technology taken from several mature and well-tested models. For example, the soil carbon cycling submodel was developed following the approach used in the Century model Parton et al. (1993, 1994) as reported by Izaurralde et al. (2006), the pesticide component was derived from the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987), and the plant competition component was originally developed in the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al., 1992).

APEX can provide a consistent approach for evaluating various land management strategies at scales ranging from field to farm to small watersheds. It is a continuous simulation model that runs typically on a daily time-step. The individual field simulation uses the functions originally developed in EPIC, which simulate hydrology, erosion/sedimentation, weather, soil temperature, crop growth/plant competition, nutrients, pesticides, and agricultural management such as nutrient management, tillage operations, alternative cropping systems and irrigation. In addition to the EPIC functions, APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to a watershed outlet. APEX also has groundwater and reservoir components. APEX can also be configured for simulating the effects of buffers, filter strips, grassed waterways, intensive grazing scenarios, land application of manure removal from livestock feedlots, and other structural conservation practices. The flexibility of APEX has led to its adoption within the Conservation Effects Assessment Project (CEAP) for national assessment, which is designed to estimate the benefits obtained from USDA conservation programs at the national level (Mausbach and Dedrick, 2004). APEX has continued to be expanded and refined to reflect the knowledge advance in multiple areas of agriculture ranging from soil physics to micrometeorology and agricultural management. However, continuous testing and validation against as much field-specific data as possible is needed, to provide increased confidence in supporting ongoing APEX applications such as the CEAP national assessment and for guidance in selecting most suitable parameters to depict different management systems (Chung et al., 1999).

Long-term watershed studies dating back to the mid-1960s at the Deep Loess Research Station near Treynor, Iowa provide excellent data for testing simulation models and exploring management alternatives. The Treynor watersheds represent the Deep Loess hills region (Major Land Resource Area 107) which covers about 4.9 million ha in western Iowa and northwestern Missouri (USDA-NRCS, 2006). Short and/or long-term evaluations of different combinations of cropping systems and conservation practices have been reported for the Treynor watersheds in many studies including Alberts and Spomer (1985), Burwell et al. (1974), Cambardella et al. (2004), Karlen et al. (1999), Moorman et al. (2004), Kramer et al. (1999), Schuman et al. (1973), Steinheimer and Scoggin (2001), Steinheimer et al. (1998a,b), Thomas et al. (2004), Tomer et al. (2005), and Chung et al. (1999). These studies were conducted using descriptive, statistic, autoregressive, or simulation methods, indicating collectively that the Deep Loess hills are vulnerable agricultural landscapes where soil and crop management practices can impact water quality/quantity and soil quality. However, no long-term model-based scenario analyses have been performed for the Treynor watersheds, which provide the ability to isolate the effects of management practices on flow, sediment, and nutrient losses.

This study builds on the previous research performed for the Treynor watersheds, especially the application of EPIC by Chung et al. (1999), by incorporating both model testing and scenario analyses. The EPIC and APEX models share a mostly common parameter set, and thus the previously developed EPIC parameters were also used in the APEX simulations reported here to the extent possible. However, enhanced methods of simulating tillage and the Universal Soil Loss Equation (USLE) crop management "C" factor (Wischmeier and Smith, 1978) are used in APEX (and latest EPIC versions), versus the EPIC model used by Chung et al. (1999). Accounting for grassed waterways present in the watersheds was also performed in this study which allows for assessment of sediment losses at the watershed outlets, which Chung et al. (1999) could not evaluate. Thus, specific attention is focused on the effects of tillage, *C* factor calculations, and sediment delivery in the current study. The main objectives of this study were: (1) to calibrate and validate APEX using the long-term (1976–1995) field study data from two Treynor watersheds (conventional-tillage versus ridge-till), and (2) to quantify the long-term benefits of ridge-till versus conventional-tillage on runoff, sediment yield, crop, and soil organic carbon by conducting scenario analyses.

2. Methods and materials

2.1. Model description

APEX is a physically based and continuous daily time-step model that was developed to predict the impact of various land management strategies on water supply and quality, erosion and sediment yield, soil quality, plant productivity and pests in whole farm/small watershed. A watershed can be subdivided into multiple subareas to assure that each subarea is relatively homogeneous in terms of soil, slope, land use, management, and weather. APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. APEX also has groundwater and reservoir components. The routing mechanisms provide for evaluation of interactions between subareas involving surface runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. A complete description of all components can be found in Williams and Izaurralde (2006). A brief description of the runoff, water-induced sediment yield, tillage, and carbon submodels is provided here.

Surface runoff is predicted for daily rainfall using a modification of the NRCS curve number method (USDA-NRCS, 2004b). In APEX, the S retention parameter in the curve number method is linked to a continuous soil moisture accounting procedure. The value of the retention parameter is related to soils, land use, management, slope, and soil antecedent moisture conditions. The S parameter should be linked to a sound continuous soil moisture accounting procedure to be used in continuous hydrologic modeling (Kannan et al., 2008). Two options are available in APEX to simulate the S parameter, which are computed as either a function of soil moisture parameters as described in Williams (2008) or potential evapotranspiration (Kannan et al., 2008). In this study the S parameter was calculated based on the approach described by Kannan et al. (2008) using the modified equation:

$$S = S_{\text{prev}} + \text{PET} \times \exp\left(-\text{CNIC} \times \frac{S_{\text{prev}}}{S_{\max}}\right) - P + Q + Q_{\text{return}} + Q_{\text{drainage}} + \text{SST} + \text{PKRZ} \quad (1)$$

where S is the retention parameter for a given day (mm), S_{prev} is the retention parameter at the previous day (mm), PET is the potential evapotranspiration for the day (mm d^{-1}), CNIC is the weighting coefficient (or curve number index coefficient) used to calculate the retention coefficient for daily curve number calculations dependent on plant evapotranspiration, $S_{\max}$ is the maximum value the retention parameter can achieve (mm) which is associated with curve number CN1 for moisture condition 1 (dry), P is rainfall depth on the previous day (mm), Q is surface runoff on the previous day (mm), Q_{return} is quick return flow on the previous day (mm), Q_{drainage} is drainage flow on the previous day (mm), SST is the moisture storage in soil on the previous day (mm), and PKRZ is percolation on the previous day (mm).

Peak runoff rate, which is the maximum runoff flow rate that occurs with a given rainfall event, is calculated using a modified rational formula. The rational formula is:

$$q_{\text{p}} = \frac{C \times i \times \text{WSA}}{360} \quad (2)$$

where q_{p} is the peak runoff rate (m^3 s^{-1}), C is the runoff coefficient, i is the rainfall intensity (mm h^{-1}) for the watershed's time of concentration, and WSA is the watershed area (ha). The runoff coefficient can be calculated for each storm as the ratio of runoff Q (mm) to the rainfall for the day, R_{day} (mm):

$$C = \frac{Q}{R_{day}} \quad (3)$$

The rainfall intensity, i, is the average rainfall rate during the time of concentration. It can be calculated with the equation:

$$i = \frac{R_{\text{TC}}}{\text{TC}} \quad (4)$$

where TC is the watershed's time of concentration (h), and R_{TC} is the amount of rainfall during the time of concentration (mm). An analysis of rainfall data from the Weather Service's TP-40 (Hershfield, 1961) for various durations and frequencies showed that the amount of rainfall during the time of concentration is proportional to the amount of rainfall during the 24-h period (Neitsch et al., 2005). The value of R_{TC} can be calculated as:

$$R_{\text{TC}} = \alpha_{\text{TC}} \times R_{\text{day}} \quad (5)$$

where α_{TC} is the fraction of daily rainfall that occurs during the time of concentration.

Therefore, the modified rational formula used in APEX to estimate peak flow rate is obtained by substituting Eqs. (3)–(5) into Eq. (2):

$$q_{\text{p}} = \frac{\alpha_{\text{TC}} \times Q \times \text{WSA}}{360 \times \text{TC}} \quad (6)$$

APEX offers seven options for simulating erosion/sediment yield. The APEX MUST option was used in this study. The MUST equation (Williams and Izaurralde, 2006) was developed from sediment concentration bases and uses runoff variables to replace the rainfall erosion index in the USLE. The runoff variables increased the prediction accuracy, which eliminated the need for a delivery ratio (Williams and Izaurralde, 2006). The equation is described as:

$$Y = 2.5 \times (Q \times q_{\text{p}})^{0.5} \times \text{EK} \times \text{CVF} \times \text{PEC} \times \text{SL} \times \text{ROKF} \quad (7)$$

where Y is the sediment yield (t ha^{-1}) on a given day, Q is the runoff volume (mm), q_{p} is the peak runoff rate (mm s^{-1}), EK is the soil erodibility factor, CVF is the crop management C factor, PEC is the erosion control practice factor, SL is the slope length and steepness factor, and ROKF is the coarse fragment factor. The peak runoff rate is an indicator of the erosive power of a storm and is calculated as shown in Eq. (6).

An enhanced CVF factor approach is used in APEX in which daily CVF factor calculations are performed internally as a function of above ground crop-residue, crop height, standing live biomass of the crop, and soil surface random roughness, without the requirement of a minimum CVF factor input value. This contrasts with the original method used in earlier versions of EPIC and APEX, in which unique minimum CVF factor values were required to be input for different tillage systems as was described by Chung et al. (1999) for their EPIC simulation study. Because plant cover varies during the plant growth cycle, APEX calculates the CVF for all days when runoff occurs using the above ground crop-residue, crop height, standing live crop biomass, and soil surface random roughness as follows:

$$\text{CVF} = \exp(-0.026 \times (\text{RRUF} - 6.1)) \times \text{FRSD} \times \text{FBIO} \quad (8)$$

where RRUF is the soil surface random roughness in mm, FRSD is the crop-residue factor, FBIO is the growing biomass factor. FRSD and FBIO factors are calculated:

$$\text{FRSD} = \exp(-\text{CVRSc} \times \text{CVRS}) \quad (9)$$

$$\text{FBIO} = 1.0 - \exp(-\text{CPHTc} \times \text{CPHT}) \times \frac{\text{STL}}{\text{STL} + \exp(1.175 - 1.748 \times \text{STL})} \quad (10)$$

where CVRS is the above ground crop-residue (t ha^{-1}), CVRSc and CPHTp are coefficients in the exponential functions, CPHT is the crop height in m, and STL is the standing live biomass of the crop (t ha^{-1}).

The tillage component has functions of mixing nutrients and crop-residues within the tillage depth, converting standing residue to flat residue, simulating the change in bulk density, ridge height and surface roughness. The tillage mixing equation is:

$$X(i) = (1 - \text{EF}) \times X_0(i) + \text{EF} \times \text{SMX}_0 \times \frac{Z(i)}{\text{TLD}} \quad (11)$$

where X is the amount of the material in layer i after mixing (kg ha^{-1}), X_0 is the amount of the material in layer i before mixing (kg ha^{-1}), EF is the mixing efficiency of the tillage operation (0–1), TLD is the tillage depth (m), SMX_0 is the sum of the material in TLD before mixing (kg ha^{-1}), and $Z(i)$ is the depth of the layer i (m). Converting standing residue to flat residue is accomplished with the equation:

$$\text{STD} = \text{STD}_0 \times \exp(-56.9 \times \text{TLD} \times \text{EF}) \quad (12)$$

where STD_0 and STD are the standing residue weights before and after tillage in (t ha^{-1}).

APEX simulates the coupled cycling of carbon and nitrogen in soil by splitting the carbon and nitrogen contained in soil organic matter into microbial (or active), slow and passive compartments. Organic residues added to the soil surface or below ground are split into two litter compartments: metabolic and structural. Leaching equations currently are used to move organic materials from surface litter to subsurface layers. APEX calculates potential transformations based on substrate-specific rate constants, temperature, and water content. Lignin content and soil texture also affect some of these transformations (e.g., structural litter and biomass). The potential transformation of carbon in structural litter on the surface and in subsurface soil layers is calculated as a function of the carbon content in structural litter, the rate of potential transformation of structural litter under optimal conditions, a control of the lignin fraction of structural litter, and a combined factor expressing the effects of temperature, soil water content, oxygen, and tillage on biological processes (Izaurralde et al., 2006). This combined factor is determined differently from the temperature and water controls on decomposition used in the Century model and is calculated as below:

$$\mathrm{CS} = \mathrm{MDRC} \times \sqrt{\frac{\mathrm{STMP} \times \mathrm{SWF}}{\mathrm{STMP} + \exp(5.059 - 0.2504\mathrm{STMP})}} \times \mathrm{OX} \times \exp(6 \times (\mathrm{BD} - \mathrm{BDP})); \quad \mathrm{CS} \leq 10 \tag{13}$$

$$\mathrm{SWF} = 0.1 \times \left(\frac{\mathrm{ST}}{\mathrm{WP}}\right)^2; \quad \mathrm{ST} < \mathrm{WP}$$
$$\mathrm{SWF} = 0.1 + 0.9 \times \sqrt{\frac{(\mathrm{ST} - \mathrm{WP})}{(\mathrm{FC} - \mathrm{WP})}}; \quad \mathrm{ST} > \mathrm{WP} \tag{14}$$

$$\mathrm{OX} = \frac{1.0 - 0.9 \times Z_5}{(Z_5 + \exp(16.79 - 0.0196 \times Z_5))} \tag{15}$$

where CS is the combined factor, MDRC is the microbial decay rate coefficient, STMP is soil temperature (°C) at the center of a soil layer, SWF is the soil water factor, OX is oxygen, BD is the soil layer bulk density ($\mathrm{t\,m^{-3}}$), BDP is the soil layer tillage/compaction affected bulk density ($\mathrm{t\,m^{-3}}$), ST is the soil water content in the root zone (mm), WP is the wilting point soil water content (mm), FC is the field capacity soil water content (mm), and Z_5 is the depth to the center of a soil layer (mm).

2.2. Study watersheds

The data used in this study were collected from two watersheds (denoted as W2 and W3) of the National Soils Tilth Laboratory, Deep Loess Research Station, U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS). They are located about 6 km apart near the town of Treynor in Pottawattamie County (N 41°9′, W 95°38′) (Fig. 1) and were established in 1964 to determine how various soil conservation practices affect runoff and water-induced soil erosion (Karlen et al., 1999). Each of the watersheds forms the origin of a perennial, first-order stream (Tomer et al., 2005). The primary soils within the watersheds include Typic Hapludolls (fine-silty, mixed, superactive, mesic Typic Hapludolls), Typic Udorthents (fine-silty, mixed, superactive, calcareous, mesic Typic Udorthents), and Cumulic Hapludolls (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) (Table 1). These soils have moderate to moderately rapid permeability and no restrictions for plant root development. The Typic Hapludolls soil cover about 60% of the soil surface of the two watersheds.

Table 1
Dominant soils in watersheds W2 and W3

	Area (ha)	Percentage of dominant soil (%)				
		Typic Hapludolls[a]	Typic Udorthents[b]		Cumulic Hapludolls[c]	
		Monona series	Ida series	Dow series	Napier series	Kennebec series
W2	34.4	59.7	16.4	3.7	11.4	8.8
W3	43.3	65.7	9.0	0.9	16.0	8.4

[a] Fine-silty, mixed, superactive, mesic Typic Hapludolls.
[b] Fine-silty, mixed, superactive, calcareous, mesic Typic Udorthents.
[c] Fine-silty, mixed, superactive, mesic Cumulic Hapludolls.

Corn (*Zea mays* L.) was grown continuously on W2 from 1964 to 1995. Bromegrass (*Bromis inermis* L.) interseeded with alfalfa was grown on W3 from 1964 to 1971. Then W3 was cropped with continuous corn during 1972–1995. Approximately 94% of both watersheds were cropped, with perennial grass waterways located in the main valley drainage ways and on some valley side slopes (Steinheimer et al., 1998b).

The outlet of each watershed was instrumented with a broad-crested, V-notch weir (Fig. 1) and water-stage recorder to measure surface and base flow. Samples were collected during runoff events using automatic samplers located above the weirs. The location of these samplers was such that they could effectively sample the concentrated runoff leaving the watershed coming directly from the fields via overland flow, while eliminating the contribution of bank and gully erosion between these samplers and the weirs (Moorman et al., 2004).

2.3. Model inputs

APEX inputs included weather, land use, planting and harvesting dates, tillage type and dates, fertilizer applications, soil properties by layer, site information and watershed characteristics. The weather variables necessary for driving the model are daily precipitation, maximum and minimum air temperature, and solar radiation. The average wind speed and average relative humidity are also required if the Penman or Penman-Monteith methods are used to estimate potential evaporation (Williams, 2008). The Hargreaves method (Hargreaves and Samani, 1985) was used to estimate potential evapotranspiration in this study, which was also chosen for the CEAP study. Measured daily precipitation, and maximum and minimum air temperature, were used for the 20-year (1976–1995) simulation period. Precipitation measurements were obtained from universal recording rain gauges (three rain gauges for W2 and two for W3) placed around the perimeter of each watershed (Fig. 1). The precipitation amounts were determined using area weighting for each gauge based on the Thiessen polygon method (Thiessen, 1911). The average annual precipitation for the simulation period (1976–1995) was 808 mm for W2 and 772 mm for W3. Small variations in annual precipitation often occurred between the watersheds (Fig. 2). Annual precipitation ranged from 441 to 1314 mm during 1976–1995. The average daily maximum temperature of the warmest month (July) was 30 °C, and the average daily minimum temperature of the coldest month (January) was −10 °C. Daily solar radiation inputs were generated internally in APEX using monthly weather statistics developed for Oakland, IA (available in the APEX weather database). Soil properties by layer for the dominant soil type, Typic Hapludolls (Monona series), were used for APEX simulation (Table 2). The layer depth, bulk density, wilting point, field capacity, percentage sand, percentage silt, and percentage organic carbon were primarily from USDA (1991) with bulk density for the upper

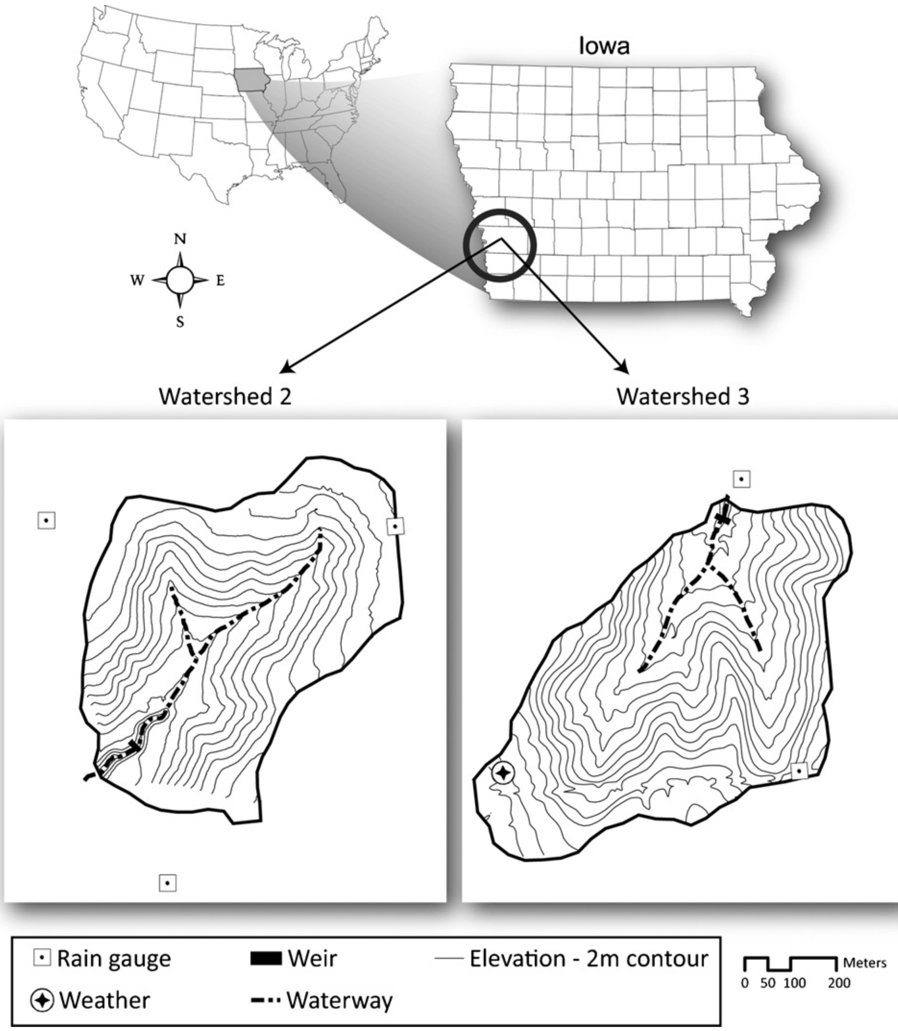

Fig. 1. Location of watersheds W2 and W3 of the Deep Loess Research Station in southwest Iowa, and locations of rain gauges, weirs, waterways, and weather station (temperature and other data) within each watershed (adapted from Tomer et al., 2005).

20 cm updated from the mean values measured by Kramer and Grossman (1992). Soil pH values were obtained from the Monona soil data included in the APEX soil database with the upper 20 cm pH values updated based on measurements made in 1989 and 1995 (Kramer, 1995, personal communication, USDA-ARS, National Soil Tilth Laboratory, Deep Loess Research Station, Council Bluffs, IA). The continuous corn production for the conventionally tilled W2 and ridge-tilled W3 were managed quite similarly, except for the differences in tillage. The W2 was farmed on the contour when feasible. The conventional-tillage operations consisted of moldboard plowing for primary tillage prior to the early 1980s. Deep disking was used thereafter around mid-April to incorporate corn residue, followed by a shallow disking or field cultivation about two weeks later, immediately before planting, to

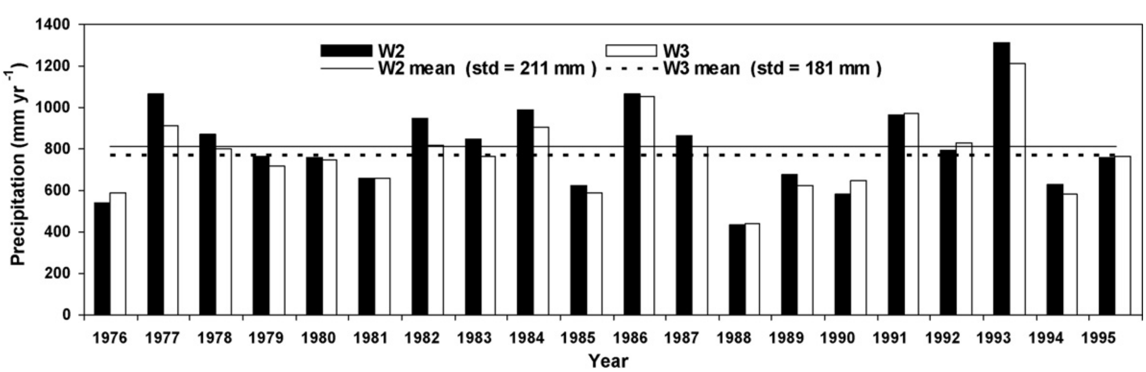

Fig. 2. Annual precipitation in watersheds W2 and W3 of the Deep Loess Research Station.

Table 2
Soil properties by layer for the Typic Hapludolls (Monona) soil

	Layer							
	1	2	3	4	5	6	7	8
Depth (m)	0.05	0.20	0.35	0.50	0.85	1.10	1.55	1.80
Bulk density (Mg m^3)	1.08[a], 0.87[b]	1.25	1.38	1.26	1.28	1.35	1.41	1.44
Wilting point (m m^{-1})	0.13	0.13	0.13	0.12	0.12	0.11	0.11	0.12
Field capacity (m m^{-1})	0.25	0.25	0.26	0.26	0.26	0.28	0.27	0.28
Sand (%)	4.3	4.1	3.7	5.1	5.4	6.1	6.3	6.4
Silt (%)	68.7	68.3	68.9	70.2	70.3	73.0	71.4	73.5
Soil pH	5.5	5.5	7.3	7.4	7.6	8.0	8.0	8.0
Organic carbon (%)	1.97[a], 2.30[b]	1.21	0.68	0.38	0.30	0.24	0.17	0.16

[a] Values for W2 watershed.
[b] Values for W3 watershed.

smooth the seedbed and to incorporate herbicides in early May (Karlen et al., 1999; Chung et al., 1999). During the growing season, one or two cultivations were performed for weed control. The W3 was farmed on the contour with corn planted on top of small ridges. One or two cultivations were performed in the furrows between ridges to control weeds. The annual N application ranged from 154 to 237 kg ha^{-1} (average annual value of 190 kg ha^{-1}) at W2 and from 128 to 190 kg ha^{-1} (average annual value of 164 kg ha^{-1}) at W3 during the 1976–1995 simulation study. Fertilizer was generally applied in April or early May. The APEX field operation file was configured based on the above information. In this study, both watersheds were assumed homogeneous with an average slope of 8.4% and a single dominant soil type (Monona) similar to the assumptions made by Chung et al. (1999).

2.4. Model calibration

Runoff calculations in APEX are strongly influenced by both the curve number (CN2) and curve number index coefficient (CNIC) (Wang et al., 2005, 2006b). The erosion/sediment component is sensitive to the RUSLE *C* factor exponential residue coefficient (CVRSc) (Wang et al., 2006b) and height coefficient (CPHTc). The soil C dynamics are sensitive to microbial decay rate coefficient (MDRC) (Wang et al., 2005). These parameters including their suitable ranges are listed in Table 3 and were considered in the calibration process. The APEX calibration was first performed for surface runoff using observed monthly data from 1976–1987 by adjusting (CN2) and CNIC (in Eq. (1)). The CNIC is used to calculate the retention coefficient for daily curve number calculations dependent on plant potential evapotranspiration. Agricultural tillage influences the partitioning of rainfall into runoff and infiltration (Radcliffe et al., 1988; Rhoton et al., 2002). The curve numbers for the two watersheds were adjusted relative to the standard value of 75 (USDA-NRCS, 2004a). Ridge-tillage encourages infiltration and decrease runoff, thus the curve number reduction for the ridge-tilled W3 was greater than that of the curve number for W2, because it was managed with conventional-tillage. During calibration, the value of the curve number index coefficient was adjusted within the APEX recommended default range of 0.5–1.5 (Table 3), but the adjustment was kept the same for the two watersheds. The curve numbers and CNIC were refined during calibration until the percentage error between the observed and predicted average monthly runoff were within ±5% for both watersheds.

Monthly sediment yield calibration was performed following runoff calibration for the same period of 1976–1987 by adjusting two exponential coefficients in the RUSLE CVF factor equation: CVRSc, which is used in estimating the residue effect on the *C* factor, and CPHTc, which is used in estimating the crop height effect on the CVF factor. The adjustments for the two exponential coefficients were kept the same for the two watersheds (two tillage systems), which provides a test to see if APEX can accurately simulate different tillage practices using the same set of RUSLE *C* factor coefficients while recalculating the daily *C* factor for all runoff days. The erosion control practice factor PEC (in Eq. (2)) for the grassed waterways practice was set to 0.83, which is close to the practice factor of 0.84 in Fiener and Auerswald (2006).

Continuous records of measured soil organic carbon were not available for the calibration period. The soil organic carbon values in the top 0.15 m soil in 1984 in the two watersheds were used to adjust the microbial decay rate coefficient MDRC (in Eq. (13)). The CVRSc and CPHTc were adjusted within APEX default ranges of 0.5–1.5 and 0.1–3.0 (Table 3), respectively, until the percentage error between the observed sediment yield and the predicted average values were within ±5% at both watersheds. Then, the MDRC was adjusted within the APEX recommended range of 0.05–1.5 (Table 3) until the percentage error between predicted and observed soil organic carbon values in the top 0.15 m soil in 1984 were within ±10% at both watersheds.

Table 3
Calibrated APEX model parameters

APEX file	Calibrated parameter (symbol in APEX code, Eq No.)	Parameter description	Calibrated value	Range (source)
Parameter file (parm2110.dat)	CNIC (parm(42), Eq. (1))	Curve number index coefficient used to calculate the retention coefficient for daily curve number calculations, regulating the effect of plant potential evapotranspiration in driving the NRCS curve number retention parameter	0.5	0.5–1.5 (Williams et al., 2004)
	CVRSc (parm(46), Eq. (9))	RUSLE *C* factor exponential residue coefficient used in the RUSLE *C* factor equation for estimating the residue effect	1.5	0.5–1.5 (Williams et al., 2004)
	CPHTc (parm(47), Eq. (10))	RUSLE *C* factor exponential height coefficient used in the RUSLE *C* factor equation for estimating crop height effect	0.17	0.1–3.0 (Williams et al., 2004)
	MDRC (parm(70), Eq. (13))	Microbial decay rate coefficient	0.95	0.05–1.5 (Williams et al., 2004)
Field operation file	CN2	Curve number for moisture condition 2 (or average curve number	72 (for W2) 68 (for W3)	75 (USDA-NRCS, 2004a)

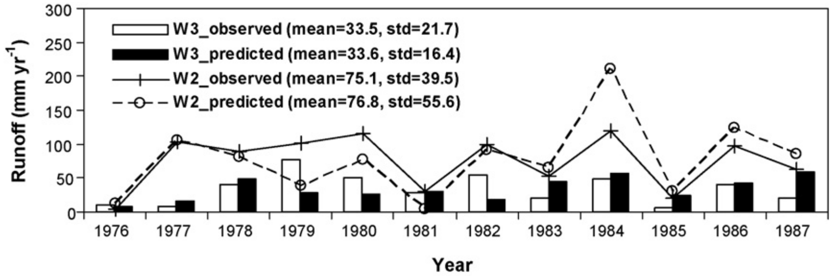

Fig. 3. Predicted versus observed annual surface runoff for watersheds W2 and W3 for the calibration period.

2.5. Model evaluation and scenario analysis

The calibrated model was continuously run for the validation period (1988–1995) using the same parameter values as identified in the calibration process. Both graphical comparisons and statistical measures between simulated and observed values including the mean, standard deviation, R^2, Nash–Sutcliffe efficiency (EF) (Nash and Sutcliffe, 1970), and percent error of mean were used to evaluate the model performance. The calibrated and validated model was then used for long-term (1976–1995) scenario analyses to quantify the benefits of ridge-till over conventional-tillage on runoff, sediment yield, crop grain yield, and soil organic carbon over a 20-year period. The scenario simulations were conducted by replacing the conventional-tillage at W2 (W2 baseline) with ridge-till (scenario at W2) and the ridge-till at W3 (W3 baseline) with conventional-tillage (scenario at W3) in two separate runs. The effects of alternative tillage systems were estimated by comparing the APEX outputs between baseline and scenario at both watersheds.

3. Results and discussion

3.1. Model calibration

The APEX monthly surface runoff and sediment yield calibrations were performed for 1976–1987 for both W2 and W3 by adjusting the model parameters that have significant effects on runoff (CN2 and curve number index coefficient) and sediment (RUSLE *C* factor exponential residue and height coefficients and PEC) (Table 3). The APEX model was set up for batch run, in which W2 was run first followed by running W3 using the same APEX parameter file. This guarantied that the same adjustment of model parameters in the parameter file (Table 3) was used for both watersheds. However, the adjustments of the CN2 value for the W3 ridge-till system were different from the W2 conventional-tillage CN2 adjustments, because the NRCS curve number method (USDA-NRCS, 2004b) was used to partition precipitation between infiltration and surface runoff.

The runoff related parameters were calibrated first until the simulated average monthly surface runoff was within ±5% of the observed values at both W2 and W3. Sediment yield was calibrated following runoff calibration. The calibration phase resulted in a value of 0.5 for the curve number index coefficient, 1.5 for RUSLE *C* factor exponential residue coefficient, 0.17 for RUSLE *C* factor exponential height coefficient), and a CN2 value of 72 for W2 and 68 for W3 (Table 3). The CN2 value was reduced 4% from the standard tabulated CN2 value of 75 (USDA-NRCS, 2004a) for W2 and 9% for W3. Studies by Rawls et al. (1980) and Rawls and Richardson (1983) also indicated necessary reduction to represent the impacts of different residue cover levels on the partition of rainfall between surface runoff and infiltration. The microbial decay rate coefficient was adjusted followed sediment yield calibration by calibrating the soil organic carbon values at both W2 and W3 in 1984 until the percentage errors between predicted and observed values were within ±10% at both watersheds, which resulted in a value of 0.95 for the microbial decay rate coefficient.

The observed values and predicted outputs for the calibration period are summarized in Table 4. The percentage errors between the predicted and observed mean monthly surface runoff and sediment yield were all within ±5% and within ±10% for soil organic carbon in top 0.15 m soil in 1984 at both watersheds. In general, the model results and field observations demonstrate that both surface runoff and sediment yield increased in the conventionally tilled W2 as compared to the ridge-tilled W3 (Table 4, and Figs. 3 and 4). The difference of average annual observed surface runoff between W2 and W3 is 42 mm yr^{-1} while APEX predicted a difference of 43 mm yr^{-1} during the calibration period. The difference of average annual observed sediment yield between W2 and W3 is 16.4 Mg ha^{-1} yr^{-1} versus the APEX-predicted difference of 15.6 Mg ha^{-1} yr^{-1}. APEX reasonably tracked the annual trends of surface runoff and sediment yield for both watersheds (Figs. 3 and 4). Ridge-tillage increases crop-residue and the orientation of ridges along the contour encourage

Table 4
Observed versus predicted runoff, sediment yield, and soil organic carbon for the calibration period (1976–1987)

	Runoff (mm month^{-1})		Sediment (Mg ha^{-1} month^{-1})		Soil organic carbon (Mg ha^{-1} yr^{-1})	
	W2	W3	W2	W3	W2	W3
Observed mean	6.26	2.79	1.54	0.18	22.3	35.1
Observed std	14.61	8.26	6.08	0.90	2.7	2.1
Predicted mean	6.40	2.80	1.48	0.18	23.9	32.0
Predicted std	15.07	6.52	5.60	0.68	–	–
R^2	0.51	0.38	0.43	0.35	–	–
EF	0.41	0.35	0.36	0.32	–	–
% Error	2.3	0.3	−4.2	−1.9	7.3	−8.7

Mean of soil organic carbon in top 0.15 m soil in 1984 based on about 50 observations (Cambardella et al., 2004).

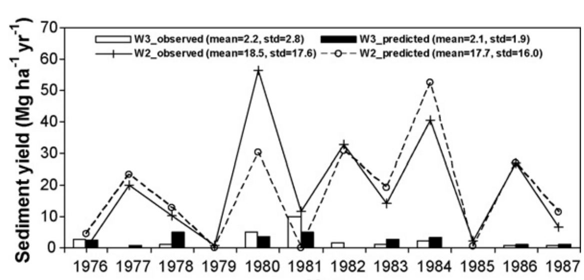

Fig. 4. Predicted versus observed annual sediment yield for watersheds W2 and W3 for the calibration period.

Table 5
Evaluations of observed versus predicted runoff and sediment yield for the validation period (1988–1995)

	Watershed	Monthly ($N = 96$)		Yearly ($N = 8$)		% Error[b]
		R^2	EF[a]	R^2	EF	
Runoff	W2	0.68	0.62	0.97	0.95	5.7
	W3	0.76	0.72	0.98	0.96	−5.2
Sediment yield	W2	0.63	0.62	0.90	0.89	5.9
	W3	0.41	0.41	0.66	0.65	−5.3

[a] Nash–Sutcliffe efficiency (Nash and Sutcliffe, 1970).
[b] Percentage error between the observed and predicted average monthly values.

rainfall to infiltrate into the soil, resulting in reduced surface runoff and water-induced soil erosion.

3.2. Model validation

3.2.1. Surface runoff and sediment yield

The calibrated model was validated against a second set of observed surface runoff and sediment yield for 1988–1995. The summary statistics (Table 5) indicate that the predicted surface runoff and sediment yield were in good agreement with observed values for both watersheds. The EF values ranged from 0.41 to 0.72 and R^2 from 0.41 to 0.76 for the monthly comparisons while the annual comparisons resulted in EF and R^2 values ranging from 0.65 to 0.96 and 0.66 to 0.98, respectively. The percentage errors between the predicted and observed mean surface runoff and sediment yield were all within ±6%.

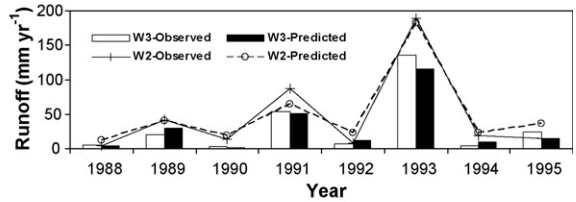

Fig. 7. Predicted verse observed annual surface runoff for watersheds W2 and W3 during the validation period.

Comparisons of the measured and predicted cumulative monthly surface runoff for both watersheds are shown in Fig. 5. The predicted cumulative runoff closely matched the cumulative measured runoff. During the 8-year validation period, APEX predicted a difference of average annual surface runoff between W2 and W3 of 16 mm yr^{-1}, which is comparable with the observed difference of 20 mm yr^{-1}. The cumulative monthly sediment yield for the two watersheds was compared in Fig. 6. The sediment yield was greater from the conventionally tilled W2 relative to the ridge-tilled W3, which was consistent with historical observations for the two watersheds. The predicted difference of average annual sediment yields between W2 and W3 was 2.14 Mg ha^{-1} yr^{-1}, which was close to the observed difference of 2.37 Mg ha^{-1} yr^{-1} for the validation period. APEX reliably tracked the annual level of observed surface runoff for both watersheds (Fig. 7) and also

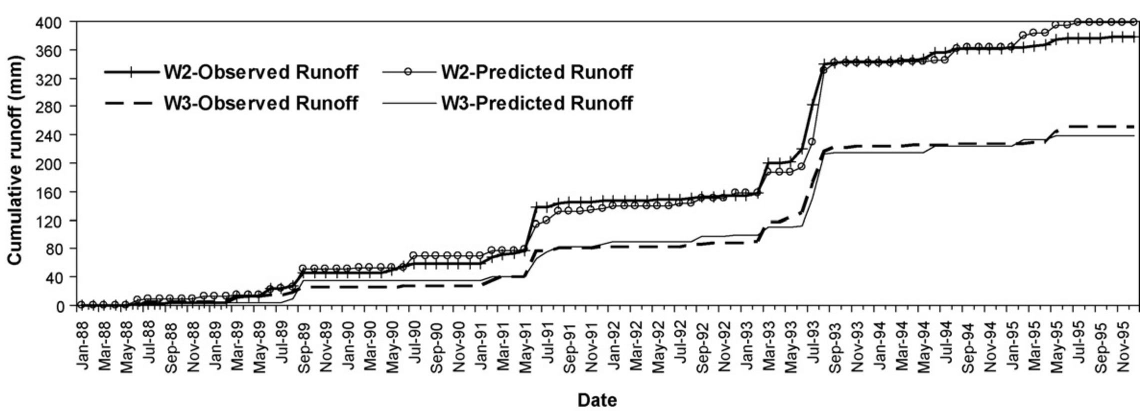

Fig. 5. Predicted verse observed surface runoff cumulated by month for watersheds W2 and W3 for the validation period.

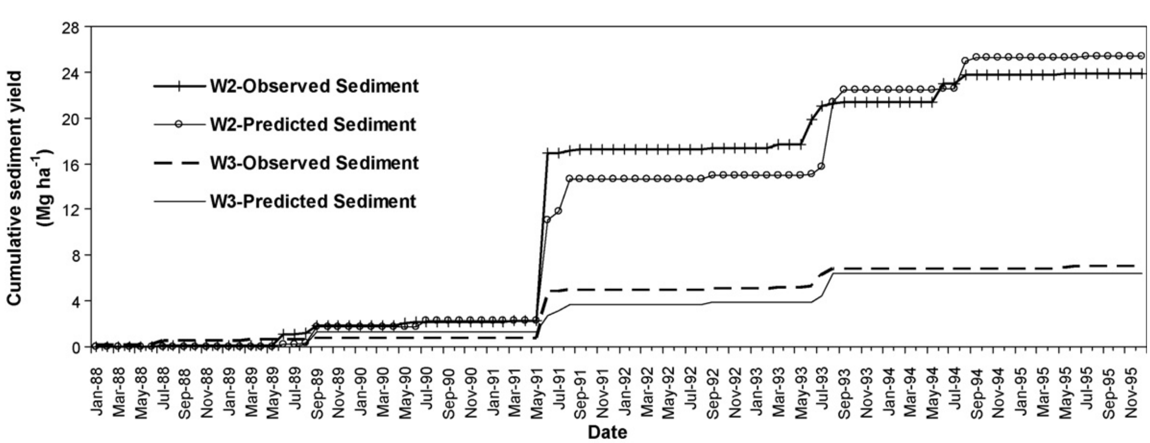

Fig. 6. Predicted verse observed sediment yield cumulated by month for watersheds W2 and W3 for the validation period.

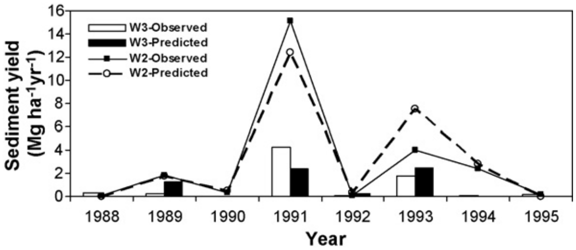

Fig. 8. Predicted verse observed annual sediment yield for watersheds W2 and W3 during the validation period.

reasonably captured the annual pattern between the observed and predicted sediment yield (Fig. 8). The runoff in 1991 was moderate in comparison to 1993 (Fig. 7). However, the sediment yield was higher in 1991 than in 1993 (Fig. 8). This is due to the difference in seasonal precipitation in the 2 years. For example, the total precipitation was 966 mm in 1991 compared to 1314 mm in 1993 at W2. However, over 21% of the 1991 precipitation was concentrated in June, 1991 (45 mm on June 1 and 78 mm on June 5). However, in 1993, over 21% precipitation was concentrated in July and 25% in August after much of the corn canopy had developed. Significant runoff occurred in June 1991 and in August 1993 (Fig. 5). However, corn was planted on May 11 and thus cover from the corn crop had not yet fully developed by June 5, 1991. Therefore, sediment yield was significant in June, 1991 (Fig. 6).

The results indicate that the APEX model is capable of reasonably capturing the runoff and sediment yield differences between the conventionally tilled W2 and ridge-tilled W3 using the same set of RUSLE *C* factor coefficients. Thus, the APEX model provides an enhanced methodology to more directly simulate tillage effects with the recalculation of the daily *C* factor for all runoff days.

3.2.2. Corn grain yield and soil organic carbon

The time series of observed and uncalibrated predicted corn grain yield for the whole simulation period are plotted in Fig. 9. In most years, the predicted values matched the observed values reasonably well for both watersheds (Fig. 9). The percentage errors between the predicted and observed average corn grain yields during 1976–1995 were −4.9% at W2 and −3.0% at W3. Both the APEX results and field observations show that average annual corn grain yield harvested from the ridge-tilled W3 was higher than that from the conventionally tilled W2. Water and nitrogen are often the most limiting crop production factors. There was no nitrogen stress simulated in APEX for either watershed, but water stress was simulated for both W2 and W3. Higher water stress was predicted for W2 as compared to W3, which resulted in the higher simulated corn grain yields for W3. This result was confirmed by Logsdon et al. (1999), who report that greater rainfall use efficiency occurred for W3 relative to W2, based on annual paired comparison of the two watersheds during 1972–1994. The higher rainfall use efficiency for W3 is due to greater residue cover, which results in reduced evaporation, reduced surface runoff, and increased infiltration.

The effect of the residue management was also clearly reflected in long-term soil carbon levels in both soils. The change of organic carbon in the surface soils (0–15 cm) were compared with observed data in 1994 (Table 6). The soil organic carbon changes were well represented by APEX with simulated values within 10% of observed values in 1994.

3.3. Benefits of ridge-till over conventional-tillage

The long-term (1976–1995) effects of ridge-till were compared with that of conventional-tillage at both watershed conditions by conducting scenario simulations after the completion of the model testing phase. The baselines were set according to the historical tillage systems used for each watershed; i.e., conventional-tillage for W2 and ridge-tillage for W3. The predicted benefit of ridge-till versus conventional-tillage for surface runoff reduction was 36% in W2 and 39% in W3 during the 20-year simulation period. The corresponding predicted sediment yields were reduced 86% in W2 and 82% in W3 by using ridge-till instead of a conventional-tillage system (Table 7). The long-term benefits were also quantified as an average annual corn grain yield increase of 3.8% in W2 and 4.7%

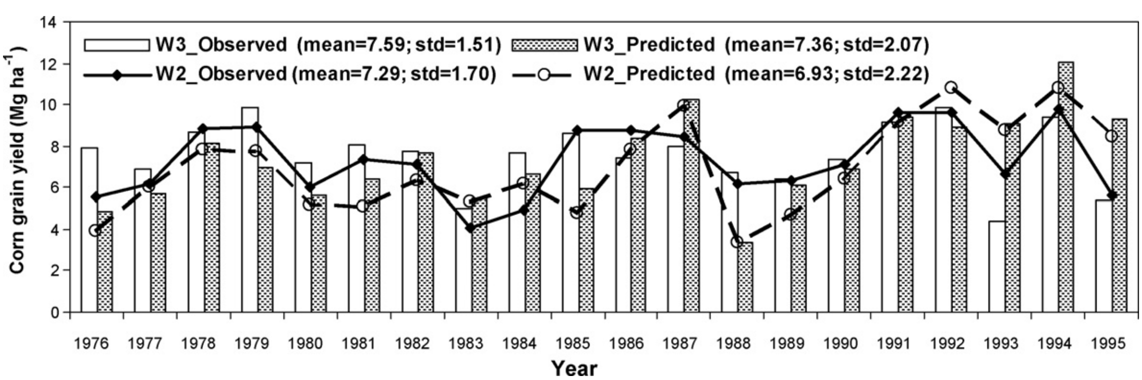

Fig. 9. Simulated verse observed corn grain yield for watersheds W2 and W3 during the simulation period.

Table 6
Observed and predicted corn grain yield and soil organic carbon in the top 0.15 m soil

	Year	W2			W3		
		Observed (Mg ha^{-1})	Predicted (Mg ha^{-1})	% Error	Observed (Mg ha^{-1})	Predicted (Mg ha^{-1})	% Error
Corn grain yield	1976–1995	7.29	6.93	−4.9	7.59	7.36	−3.0
Soil organic carbon	1994	26.6[a]	29.1	9.2	34.7[a]	36.4	5.0

[a] Mean of soil organic carbon in top 0.15 m soil based on about 50 observations (Cambardella et al., 2004).

Table 7
Simulated benefits of ridge-till over conventional-tillage at watersheds W2 and W3 from 1976 to 1995

	W2				W3			
	Baseline (conventional-till)	Scenario (ridge-till)	Benefit[b]		Baseline (ridge-till)	Scenario (conventional-till)	Benefit[b]	
			Amount	%			Amount	%
Runoff								
Observed (mm yr^{-1})	63.9	–			32.7	–		
Predicted (mm yr^{-1})	66.0	42.6	−23.5	−35.5	32.4	52.2	−20.2	−38.6
% Error	3.3	–			−0.9	–		
Sediment yield								
Observed (Mg ha^{-1} yr^{-1})	12.30	–			1.51	–		
Predicted (Mg ha^{-1} yr^{-1})	11.90	1.71	−10.20	−85.7	1.49	8.87	−7.28	−82.1
% Error	−3.2	–			−1.8	–		
Corn grain yield								
Observed (Mg ha^{-1} yr^{-1})	7.29	–			7.59	–		
Predicted (Mg ha^{-1} yr^{-1})	6.93	7.19	0.26	3.8	7.38	7.04	0.32	4.7
% Error	−4.9	–			−2.7	–		
Cumulative SOC[a] loss in sediment								
Predicted (Mg ha^{-1})	6.38	2.13	−4.25	−66.6	2.01	5.41	−3.40	−62.8

[a] Soil organic carbon.
[b] Benefits were estimated as model output differences between ridge-till and conventional-till practices at both watersheds.

in W3 and a reduction in cumulative soil organic carbon loss by 67% in W2 and 63% in W3.

The benefits of ridge-till system have been noted in other studies (Ginting et al., 1998; Owens et al., 2002). For example, Ginting et al. (1998) showed that the ridge-tillage system resulted in about 45% annual runoff reduction and 97% annual sediment loss reduction compared with conventional-tillage based on a short-term (1992–1994) field study on 12 erosion plots cropped with corn at the West Central Experiment Station in Morris, MN. Corn grain yield was also found to increase by 3.2% in 1994 (Ginting et al., 1998).

The benefits clearly reflect the effects of the different tillage systems used for each watershed. The remarkable performance of ridge-till in watersheds on such an erosion-prone area (Alberts and Spomer, 1985; Kramer et al., 1999; Laflen et al., 1990) demonstrates the potential for such a system to reduce runoff and erosion to that of a sustainable system. Residue cover was reported near or over 90% for the ridge-till system and about 10% for the moldboard plow system (Ginting et al., 1998; Hansen et al., 2000). Because much of the surface is covered by crop-residue and a mulch of decaying organic matter (Laflen et al., 1990), the runoff volume is reduced and the interrill erosion is also greatly reduced.

4. Conclusions

Agricultural tillage influences the partitioning of precipitation into surface runoff and infiltration. Conservation tillage systems which leave more crop-residue on the soil surface can effectively reduce water and sediment loss. The APEX model was applied to estimate the long-term effects of ridge-till versus conventional-tillage in two watersheds at the USDA Deep Loess Research Station near Treynor, Iowa. The model was calibrated and validated with reasonable accuracy. Scenario analyses indicate that runoff can be reduced by 36%–39%, sediment yield by 82% to 86%, and cumulative soil organic carbon loss from sediment by 63%–67%, by applying ridge-till instead of conventional-tillage for the two watersheds. Also, a minimum average annual corn grain yield increase of 3.8% was predicted by converting conventional-tillage to ridge-till. The performance of ridge-till in both watersheds demonstrates the potential to use conservation tillage on an erosion-prone area for reducing runoff and sediment loss for sustainable agricultural productivity.

The APEX simulations of surface runoff, sediment yield, crop grain yield, and soil organic carbon demonstrate the utility of using the model for estimating the long-term response to different tillage management strategies. The results further indicate that the enhanced tillage and daily CVF factor calculation approaches used in the APEX model are capable of reasonably simulating a variety of responses to different tillage practices, when using the same set of RUSLE *C* factor coefficients for the two watersheds. Overall, the study shows that APEX can be successfully applied to evaluate the impacts of different tillage systems.

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