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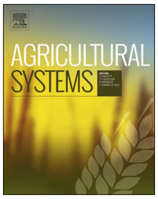

Modelling the effects of conservation tillage on crop water productivity, soil water dynamics and evapotranspiration of a maize-winter wheat-soybean rotation system on the Loess Plateau of China using APSIM

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ABSTRACT

Information relating to the accurate quantification of the impacts of long-term conservation tillage practices on the crop yields and water use patterns of rainfed rotational cropping systems under global climate change is urgently required. The objectives of this study were to calibrate and evaluate APSIM (Agriculture Production System sIMulator) to accurately predict crop growth and development of a maize-winter wheat-soybean rotation, and to investigate the effects of conservation tillage on grain yield, water productivity and evapotranspiration on the Loess Plateau of China. This study integrated APSIM-based simulation modelling and field-level data collected from a maize-winter wheat-soybean rotation system under conventional tillage (CT) and no tillage with stubble retention of the previous crop (NTR) in Xifeng, Gansu, China. APSIM was successfully calibrated and evaluated using the root mean square error (RMSE) and index of agreement (d), indicating good performance on simulating the crop yield, dry matter biomass and soil water dynamic of the three crops for both CT and NTR treatments. Under the long-term scenario simulations (50 a, 25 rotation phases in total), the results showed that NTR improved soil water storage by 0–159 mm (72 mm on average; $P < 0.01$) of soil water storage before each rotation phase. The grain yield and biomass of winter wheat were significantly improved under the NTR treatment (1805 and 4309 kg ha^{-1} on average), but changes in maize or soybean were not significant ($P > 0.05$). On a system basis, the NTR treatment had significantly greater plant transpiration (T_c) and T_c/system water supply (WS_{sys}), but lower soil evaporation (E_s), evapotranspiration (ET), and ET/WS_{sys} than treatment CT did. Additionally, T_c and E_s for maize production were not significantly different between the two treatments. Grain yield water productivity (WP_Y) and biomass water productivity (WP_B) in wheat and soybean were substantially improved by 1.9–8.0 kg ha^{-1} mm^{-1} ($P < 0.05$) under treatment NTR. In general, we advocated that conservation tillage has indicated great potential for improving crop/water productivity and soil water storage under rainfed conditions in the semiarid Loess Plateau region of China.

1. Introduction

Conservation tillage is defined as any agricultural practice that aims to conserve soil moisture and reduce soil erosion by leaving soil surface covered by crop residues and/or subsoil less disturbed (Fowler and Rockström, 2001). Common conservation tillage practices, including no tillage, subsoil tillage, reduced or shallow tillage, subsoil tillage with straw mulching/retention, etc., have been adopted in many regions around the world (Awada et al., 2014; Xie et al., 2016). Previous research has indicated that conservation tillage could mitigate the effects of dry spells (Barron et al., 2003), increase crop productivity (Awada et al., 2014), and improve the improve physical, chemical, and biological properties of soil (Singh et al., 2005). Thus, there has been increased attention on incorporating conservation tillage practices into conventional management practices in recent years. Yield advantages observed under conservation tillage in the arid/semiarid environments were mainly attributed to reduced water loss, improved soil water holding capacity, and enhanced nutrient availability (Martinez et al., 1995; Busari et al., 2015; Nyakudya and Stroosnijder, 2015). Improved crop water productivity (WP) was also reported across various

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agroecosystems globally (Barron et al., 2003; Su et al., 2007; Liu et al., 2013). However, some studies noted that neither no tillage nor straw mulching could actually increase crop yield (Mupangwa and Jewitt, 2011; Pittelkow et al., 2015; Ernst et al., 2016). Furthermore, Strudley et al. (2008) and Lal et al. (2004) summarized that conservation tillage could cause soil compaction and reduce infiltration of soil water. Therefore, the effects of conservation tillage on crop production depend greatly on many environmental and ecological factors, and obtaining site-specific data is essential for predicting/estimating agronomic productivity and ecological consequences on a system level.

The Loess Plateau is a quintessential dry-land agronomic region of China, where the intensity and duration of solar radiation and the diurnal temperature variation provide suitable environmental conditions for the production of many dry-land or water-conserving crop species/varieties in the nation. Precipitation is the main water input and the most limiting factor for crop production in this region (Shan and Chen, 1993). Annual precipitation of the Loess Plateau region ranges from 200 to 750 mm, with approximately 70% of precipitation occurring from June to September often in the form of heavy or scattered thunderstorms. Meanwhile, the quantity and distribution pattern of precipitation have changed dramatically in the past decade, posing great challenges for successful crop production in this region. In particular, the increased incidence of extreme weather events such as prolonged droughts and intense rainstorms has been observed more often in the most recent years (Ren et al., 2018), leading to increased severity of soil crusting and erosion, causing significant nutrient loss, compromised soil structure and reduction of soil fertility (Mueller and Pfister, 2011). Therefore, if the productivity and ecological function of the Loess Plateau region are to be sustained, new managerial practices that are less consumptive of farming inputs and natural resources such as conservation tillage practices are essential. Previous studies have focused on the effect of using conservation tillage in continuous monoculture cropping systems in semiarid regions of the Loess Plateau (Su et al., 2007; Zhang et al., 2014; Xie et al., 2016). However, information relating to the effects of conservation tillage on predominant rotational cropping systems [for example, maize (*Zea mays* L.)- winter wheat (*Triticum aestivum* L.)- soybean (*Gyleine* max L.) rotations] from a long-term view, is limited.

Process-based crop models are frequently used as a scientific tool to investigate the impacts of changes in managerial and environmental factors on crop production. The APSIM (Agriculture Production System sIMulator) framework is one of the most widely used process-based models for simulating crop production, risk management, and crop adaptation under various cropping system studies (Keating et al., 2003; Singh et al., 2011; Archontoulis et al., 2014a). By linking of crop growth with soil hydrological processes, APSIM has been successfully used to predict the productivity of many crop species, including maize (Archontoulis et al., 2014b), wheat (Bassu et al., 2009), soybean (Archontoulis et al., 2014a), and several other agronomic crops (Chen et al., 2008; Masikati et al., 2014). However, information relating to modelling rotational multispecies systems remains limited.

Taken together, there is an urgent need to accurately quantify and model the effects of conservation tillage practices on the yield and water use pattern of the maize-winter wheat-soybean rotation systems on the Loess Plateau of China. In this study, we integrated APSIM-based simulation modelling and long-term field data from a maize-winter wheat-soybean rotation system to: 1) calibrate and evaluate APSIM for accurately predicting crop growth and development of a maize-winter wheat-soybean rotation system under conservation or conventional tillage practices; 2) investigate the effects of conservation tillage on the soil water content, grain yield, and water productivity of the three crops under projected weather condition; and 3) evaluate the effects of conservation tillage on evapotranspiration at the system scale.

2. Materials and methods

2.1. Experimental site

The field experiment component of this study was conducted at the Qingyang Loess Plateau Research Station of Lanzhou University (35°40′N, 107°52′E; altitude 1298 m) in Xifeng, Qingyang City, in Gansu Province of China (Fig. S1). Agriculture in this area is mainly rainfed with a semiarid climate featuring predominant summer precipitation as well as dry and cold winter seasons (BSk in the Köppen climate classification; Peel et al., 2007). The average annual precipitation is 546 mm, with an average of 255 frost-free days per year. The mean annual temperature ranges from 8 °C to 10 °C, and the mean annual total sunshine hours ranges from 2300 to 2700 h. The soil is classified as Heilu (a very deep loess sandy loam of the Los Orthic Entisols based on the FAO soil classification; FAO, 1990). The groundwater depth is below 50 m. The weather data, including daily maximal and minimal air temperature, daily precipitation and daily solar radiation, was obtained from the Meteorologic Bureau of Xifeng (the distance between the meteorological station and the experimental site is 19.6 km).

2.2. Experimental design

During the seven growing seasons (2001–2007, meanwhile the seventh maize, winter wheat and soybean seasons were harvested in 2007, 2008 and 2007, respectively; Fig. S2) of a maize-winter wheat-soybean rotation, the effects of two tillage treatments were continuously investigated, including conventional tillage (CT treatment) and conservation tillage (no tillage with previous crop's stubble retention; NTR treatment). Each treatment was replicated four times in a randomized complete block design with a total of 16 plots. Each plot was 52 m^2 (4 m × 13 m) in area. There were 2-m spaces between adjacent blocks and 1-m spaces between adjacent plots. Maize was sown in late April and harvested in late September, followed by winter wheat, which was harvested in the early July of the next year. After winter wheat harvesting, soybean was planted and generally harvested in late October. There were two separate sequences of rotations both initiated in 2001 (Fig. S2).

Soil was plowed to a 20-cm depth before sowing and after harvesting of each crop in the CT treatment, whereas no tillage was used for the NTR treatment throughout the growing seasons. All three crop's residues were harvested, ground or cut into 5–10 cm fragments. For the NTR treatment, all soybean and wheat residues and 50% of the maize residues within each plot were returned back to the field. This practice closely mimics the traditional local labor-intensive farming methods in China, which involve very little usage of large farming equipment such as combine harvesters. Farmers typically harvest maize and soybean by hand and feed stubble to livestock or use them for winter heating and cooking purposes. There is a very small portion of farmers who incorporate straw mulching into their predominant management practices.

The cultivars and seeding rates for all three crops used in this study were 'Zhongdan2' at 30 kg ha^{-1} (6.93 plants m^{-2}), 'Xifeng24' at 187 kg ha^{-1}, and 'Fengshou12' at 15 kg ha^{-1}, for maize, winter wheat, and soybean, respectively. All crops were sown using a small no-till seeder (5–6 rows at a1.2-m width) designed by the China Agricultural University. For maize, 54 kg N ha^{-1} and 60.3 kg P_2O_5 ha^{-1} and 138 kg N ha^{-1} was applied before planting and at the booting stage (Feekes' scale 8), respectively. For winter wheat, the fertilizer application at sowing was 54 kg N ha^{-1} and 60.3 kg P_2O_5 ha^{-1}, and 69 kg ha^{-1} N was applied at the jointing stage (Feekes' scale 6). For soybean, a one-time application of 27.7 kg ha^{-1} of P_2O_5 was added. Weeds in all plots were removed periodically by hand, and no irrigation water was supplied throughout the growing season in each year.

Grain yield and dry matter biomass of three crops were determined by manually harvesting, threshing, and air-drying three randomly selected quadrat samples from within each plot every year measured as 0.76, 0.3, and 0.25 m^2 for maize, winter wheat and soybean, respectively. These samples exclude the two peripheral rows to minimize edge effects. The gravimetric soil water storage [0–30 and 30–200 cm; measured by a neutron probe (NMM, Campbell pacific, HP503)] was measured separately for each crop at the sowing and harvesting periods of each growing season, and recorded at least once per month during the two sequences of rotations (Shen, 2004; Yang et al., 2010).

2.3. APSIM parameters collection and evaluation

In this study, APSIM version 7.4 (available at www.apsim.info) in conjunction with crop modules APSIM-Maize, Wheat and Soybean was used to simulate crop development and production. In particular, APSIM is pluggable model that could accommodate a wide array of submodules according to different factors such as crop species, hydrological conditions, and residual management practices. In our study, the SOILWAT2 module was used to model water infiltration and movement in the soil, and the RESIDUE module was used to simulate the effects of crop residues on water balance and soil nutrition (Keating et al., 2003).

The phenological parameters of crops were calculated by detailed crop phenology and weather data obtained from field-level experiments (Table 1) in which Shen (2004) and Chen et al. (2008) have successfully calibrated APSIM-Maize, Wheat and Soybean modules in the semiarid Loess Plateau environment of China during 2001–2002.

In SOILWAT2, the cascading water balance was established based on CERES (Crop Environment Resource Synthesis) and PERFECT (Productivity, Erosion, and Runoff, Functions to Evaluate Conservation Techniques; Probert et al., 1998). CERES was originally designed to simulate crop growth in response to climate, soil, genotype and management practices (Ritchie, 1972; Jones and Kiniry, 1986), while PERFECT is a model that integrates the dynamics of soil and crop processes and their interactions (Littleboy et al., 1992). The main modelling parameters in conjunction with soil bulk density (BD), drained upper limit (DUL) and low limit (LL) were determined by Shen (2004) using the methods described by Dalgliesh and Foale (1998; Table 2). It is noteworthy to mention that tillage cannot affect SOILWAT2 directly, but through its impacts on the status of surface residues, which could further change soil water balance/dynamics.

In SOILWAT2, potential total evapotranspiration (ET_o) is calculated daily using an equilibrium evaporation concept modified by Priestley and Tylor (1972), and Jones and Kiniry (1986). Soil evaporation (E_s) and plant transpiration (T_c) were calculated separately. In particular, E_s was estimated based on Ritchie's evaporation model (Ritchie, 1972), which assumes that E_s takes place in two stages represented by two parameters: U and CONA. U represents the amount of cumulative E_s when the surface soil water supply is greater than the atmospheric demand; CONA is an empirical coefficient which depends greatly on soil hydraulic properties and potential evapotranspiration (Ritchie, 1972), The relationship between E_s and CONA could be formulated as:

$$E_s = CONA \times t^{1/2} \tag{1}$$

where the rate of E_s during the second stage is specified by the parameter CONA as a function of the square root of time (t). T_c was estimated based on the transpiration efficiency (TE; the ratio of biomass production to the quantity of water transpired) and vapor pressure deficit (VPD; Keating et al., 1999). Meanwhile, the sum of E_s and T_c represents evapotranspiration (ET) [exclusive of surface runoff and deep drainage under 200 cm, as described by Sun et al., 2015]

APSIM-RESIDUE treats crop residues on the soil surface as a separate component from the soil organic matter pool (Probert et al., 1998; Thorburn et al., 2001). The effect of crop residues on runoff was evaluated based on the USDA (United States Department of Agriculture) curve number (CN) method (runoff-curve-number method) adapted from Glanville et al. (1984). CN is a collective term describing a family of curves that relate total runoff (Q) to total rainfall (P) according to a soil moisture retention parameter (S).

$$Q = (P - 0.2S)^2/(P + 0.8S) \quad P > 0.2S \tag{2}$$

$$CN = [1000/(10 + S/25.4)] \tag{3}$$

The moisture retention parameter, S, used in Eq. 2 is calculated based on antecedent soil moisture conditions predicted by a moisture balance submodel. CN values are used to express S on a scale from zero to 100 (Eq. 3). CN at average antecedent soil moisture content (CN2) is used in the model to adjust the relationships between S and soil moisture according to soil types and treatments (e.g., CT or NTR). Value of CN2 in the current study is 75.

The rate of residue decomposition is controlled by first-order kinetics:

$$\frac{dR}{dt} = -kR \tag{4}$$

R, t and k were the mass of residue per unit area, time and the rate coefficient, respectively. The rate coefficient k is a unitless scalar calculated as:

$$k = D_{\max} F_{C:N} F_{temp} F_{moist} F_{contact} \tag{5}$$

where $D_{\max}$, $F_{\mathrm{C:N}}$, F_{temp}, F_{moist} and F_{contact} are rate coefficient controlling factors (scaled from 0 to 1). $D_{\max}$ represents the maximum decomposition rate coefficient and the other four factors account for the limitations to decomposition under different residual C:N ratio, soil temperature, moisture and residue-soil contact conditions, respectively (Thorburn et al., 2001). The default values for the parameters in RESIDUE were used in this study.

The performance indices/statistics were calculated separately for both the calibration and evaluation processes based on the data collected from the long-term field experiment component of this study. The variables of interest include crop grain yield, biomass production and soil water status at two different layers (0–30 cm and 30–200 cm).

Table 1

Values of the main parameters used in APSIM-based (Agriculture Production System sIMulator) modelling of the three crops. The simulation was carried out based on field-level data collected from experiments conducted in Xifeng, Gansu Province, China.

Crop (cultivar)	Reference	Parameter	Validated value	Base value
Winter wheat (Xifeng24)	Shen, 2004; Chen et al. (2008)	Thermal time to floral initiation/°C d	955	955
		Thermal time from floral initiation to start filling/°C d	62.5	155
		Thermal time from filling to maturity/°C d	650	580
Maize (Zhongdan2)	Shen, 2004	Thermal time to floral initiation/°C d	543	500–700
		Thermal time from floral initiation to start filling/°C d	70	0–1000
		Thermal time from filling to maturity/°C d	787	0–1000
Soybean (Fengshou12)	Shen, 2004	Thermal time to floral initiation/°C d	410	0–1000
		Thermal time from floral initiation to start filling/°C d	50	0–1000
		Thermal time from filling to maturity/°C d	630	0–1000

Note: validated values were derived from field experiments; base values were derived from the base cultivars in crop modules.

Table 2
Main characteristics of soil at the experimental site in Xifeng, Gansu Province, China (Shen, 2004; Yang, 2009).

Parameter	Soil layer (cm)						
	0–10	10–30	30–60	60–90	90–120	120–150	150–200
Plant available water (mm)	17	26	48	36	45	42	70
Drained upper limit (mm mm^{-1})	0.31	0.29	0.30	0.26	0.29	0.28	0.28
Crop lower limit (mm mm^{-1})	0.14	0.12	0.13	0.13	0.14	0.14	0.14
Bulk density (g cm^{-3})	1.30	1.21	1.42	1.26	1.24	1.26	1.29
Soil pH	8.7	8.7	8.7	8.6	8.7	8.8	8.9
Initial soil organic carbon (SOC) (g kg^{-1})	6.88	6.11	5.87	6.02	4.56	3.56	2.98
Initial soil nitrate nitrogen (NO_3-N) (mg kg^{-1})	38.47	23.06	9.12	4.34	5.22	4.46	3.69

Table 3
Observed phenology stages, grain yield and biomass for a maize-winter wheat-soybean rotation from the experiment field in Xifeng, Gansu Province, China during the growing seasons in 2001–2007 (Shen, 2004; Yang, 2009; Yang et al., 2010).

Treatment	Season	Calibration or evaluation	Maize		Winter wheat		Soybean	
			Grain yield (kg ha^{-1})	Biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Biomass (kg ha^{-1})	Biomass (kg ha^{-1})	Grain yield (kg ha^{-1})
CT	2001 (2001 – 2002)	Calibration	7649	16,121	4357	9797	4761	1987
	2002 (2002 – 2003)	Calibration	9050	25,500	3358	8073	1715	557
	2003 (2003–2004)	Evaluation	9133	15,267	1523	4509	2400	1012
	2004 (2004–2005)	Evaluation	7471	14,350	3548	7555	1948	566
	2005 (2005–2006)	Evaluation	9688	18,223	2860	6893	2937	1167
	2006 (2006–2007)	Evaluation	3918	8359	3864	8578		
	2007 (2007–2008)	Evaluation	10,485	18,918	3450	7934	2644	972
NTR	2001 (2001–2002)	Calibration	7422	16,506	4551	10,681	4712	2105
	2002 (2002–2003)	Calibration	9252	25,785	3066	7674	1607	365
	2003 (2003–2004)	Evaluation	9961	18,724	1412	4469	2507	1179
	2004 (2004–2005)	Evaluation	7733	15,127	3643	8062	3318	1245
	2005 (2005–2006)	Evaluation	8812	16,465	2385	5711	3539	1497
	2006 (2006–2007)	Evaluation	3974	8958	3730	7905		
	2007 (2007–2008)	Evaluation	10,650	18,356	3522	8495	3862	1785

Note: grain yield and biomass were measured annually; Feekes' scales for emergency, flowering and maturity were 1, 10.51 and 11.4, respectively. The seasons in brackets in column "season" were winter wheat seasons. There were no significant differences between treatments for grain yield and biomass ($P > 0.05$). CT: conventional tillage; NTR: no tillage with retention of the previous crop's stubble.

The experimental data (Sect. 2.2) during the growing seasons in 2001–2002 and 2003–2007 were used for calibration and evaluation, respectively (the values of soil water storage measured before 25, April 2003 were used for calibration, and the others were used for evaluation). The root mean square error (RMSE) and index of agreement (d; a standardized measure of the degree of model prediction error that varies between 0 and 1) were calculated as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2} \tag{6}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \overline{O}_i| + |O_i - \overline{O}_i|)^2} \tag{7}$$

where O_i, P_i and $\overline{\text{O}}$ are observed, simulated, and mean of observed values, respectively. N is the number of observations in the dataset.

2.4. Scenario analysis

The production of maize-winter wheat-soybean rotation under the two treatments (CT and NTR) at the experimental site during 1961–2010 (50 years) was simulated using APSIM based on recorded long-term weather data. Management practices used in the simulation were in accordance with the field experiment (described in Sect. 2.2). As the first crop of each rotation sequence, maize in the scenario simulations had a specific sowing time window (April 15–25) and a requirement of accumulated precipitation (10 mm) for planting (Smith et al., 2016). The initial soil water storage was 100% of plant available water (Table 2). Initial NO_3-N and SOC were set according to observed values in previous studies conducted at this research site (Yang, 2009; Table 2).

Grain yield and biomass production of all three crops under both treatments were simulated and recorded. Meanwhile, the crop water productivity (WP) was calculated based on grain yield (WP_Y) and biomass (WP_B) using the following equations:

$$WP_Y = Y/WS \tag{8}$$

$$WP_B = B/WS \tag{9}$$

$$WS = GSP + SW_i - SW_t \tag{10}$$

where Y and B represent grain yield and biomass, respectively, WS represents the water supply for a single growing season, and GSP is growing-season precipitation. SW_i and SW_t are soil water storage at sowing and harvesting, respectively (0–200 cm soil layer).

The effects of treatments were investigated based on the outputs of APSIM simulations. Soil water dynamics were analyzed. The simulated E_s, T_c, and ET in each rotation phase were used to characterize the effects of conservation tillage on crop water use. The system-level water supply (WS_{sys}) that included ET amounts and unproductive water loss (surface runoff and deep drainage under 200 cm) for each rotation phase was calculated as:

$$WS_{sys} = P + SW_{sys,i} - SW_{sys,t} \tag{11}$$

In Eq. 11, P is the precipitation amount during a rotation phase, and $SW_{sys,i}$ and $SW_{sys,t}$ are the simulated soil water storage at the beginning and the end of a certain rotation phase, respectively (in the 0–200 cm soil layer). The proportions of T_c and ET with respect to WS_{sys} were

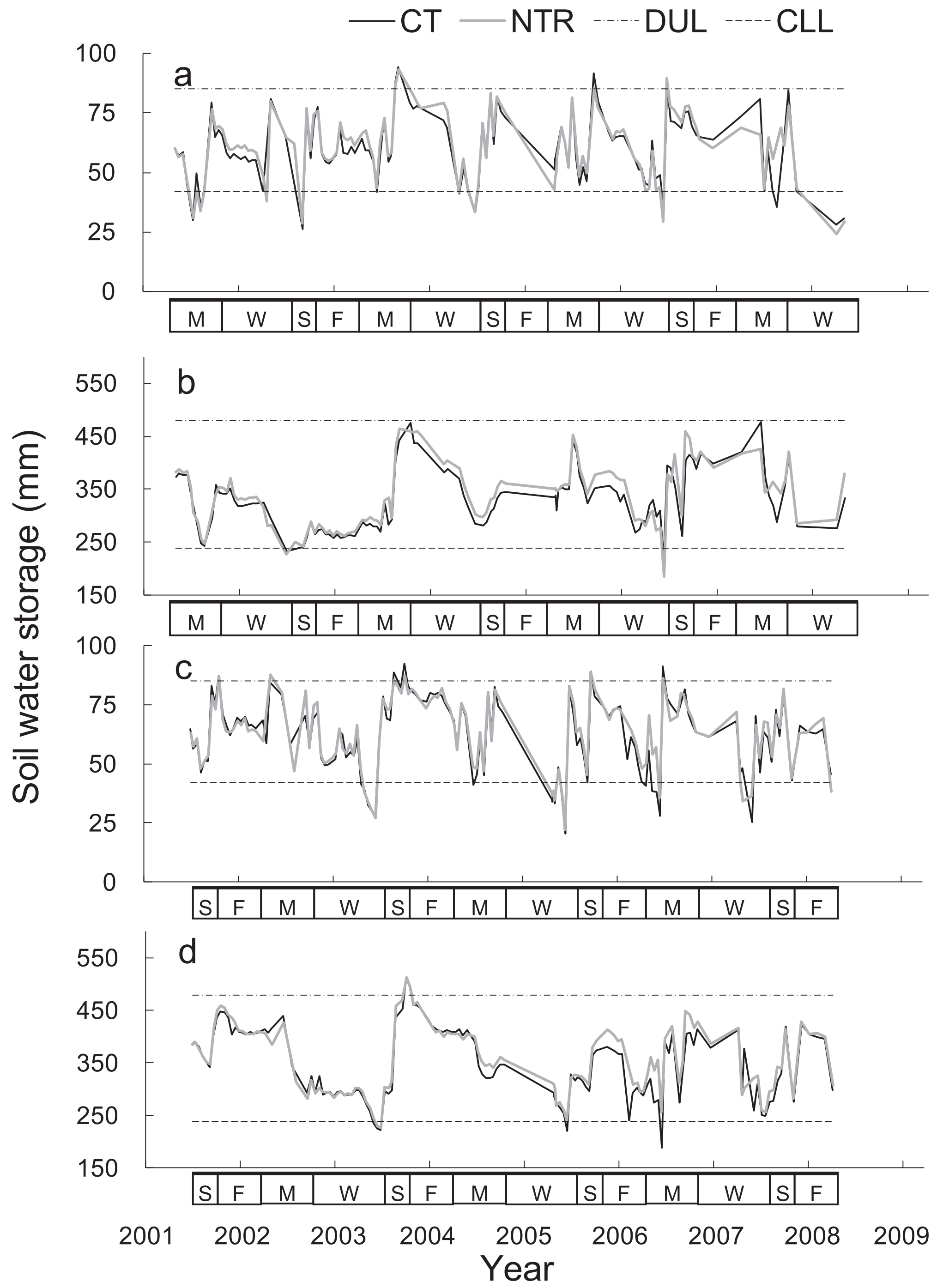

Fig. 1. Soil water storage of the two sequences of maize-winter wheat-soybean rotation, collected from a: crop sequence 1 in the 0–30 cm soil layer, b: sequence 1 in the 30–200 cm soil layer, c: sequence 2 in the 0–30 cm soil layer, and d: sequence 2 in the 30–200 cm soil layer in a rotational cropping study conducted in Xifeng, Gansu Province, China during the growing seasons in 2001–2007 (Yang et al., 2010). CLL and DUL represent crop lower limit and drained upper limit, respectively. CT and NTR represent the conventional tillage and no tillage with retention of the previous crop's stubble, respectively. The abbreviated symbols under the X-axes represent crop sequences (M: maize; W: winter wheat; S: soybean; F: fallow).

calculated as T_c/WS_{sys} and ET/WS_{sys} (%), respectively.

3. Results

3.1. Field-level data summary

For maize and winter wheat, grain yield and biomass production in the field experiment were mostly similar between the CT treatment and NTR (Table 3). For soybean, greater grain yield (16.5–120.0% higher) and biomass (4.5–70.3% higher) were found in the NTR treatment than in CT. Additionally, it should be noted that significant crop loss was detected for soybean production in 2006 likely due to hare grazing across both treatment plots.

Soil water dynamics of the two treatments showed similar trends during the growing seasons in 2001–2007 for both sequences and appeared to mirror precipitation patterns (Fig. 1). The results showed that NTR improved soil water storage by 3.6% and 2.7% in the 0–30 cm layer for sequences 1 and 2, respectively. Additionally, NTR improved soil water storage by 3.3% and 4.6% in the 30–200 cm layer for sequences 1 and 2, respectively. In particular, the NTR treatment typically provided greater soil water storage from October to the following April in each year compared with CT, leading to more water for the following crop phase (e.g., maize or wheat; Fig. 3).

3.2. Model evaluation

3.2.1. Biomass accumulation and grain yield

Maize grain yield and biomass production showed good agreement

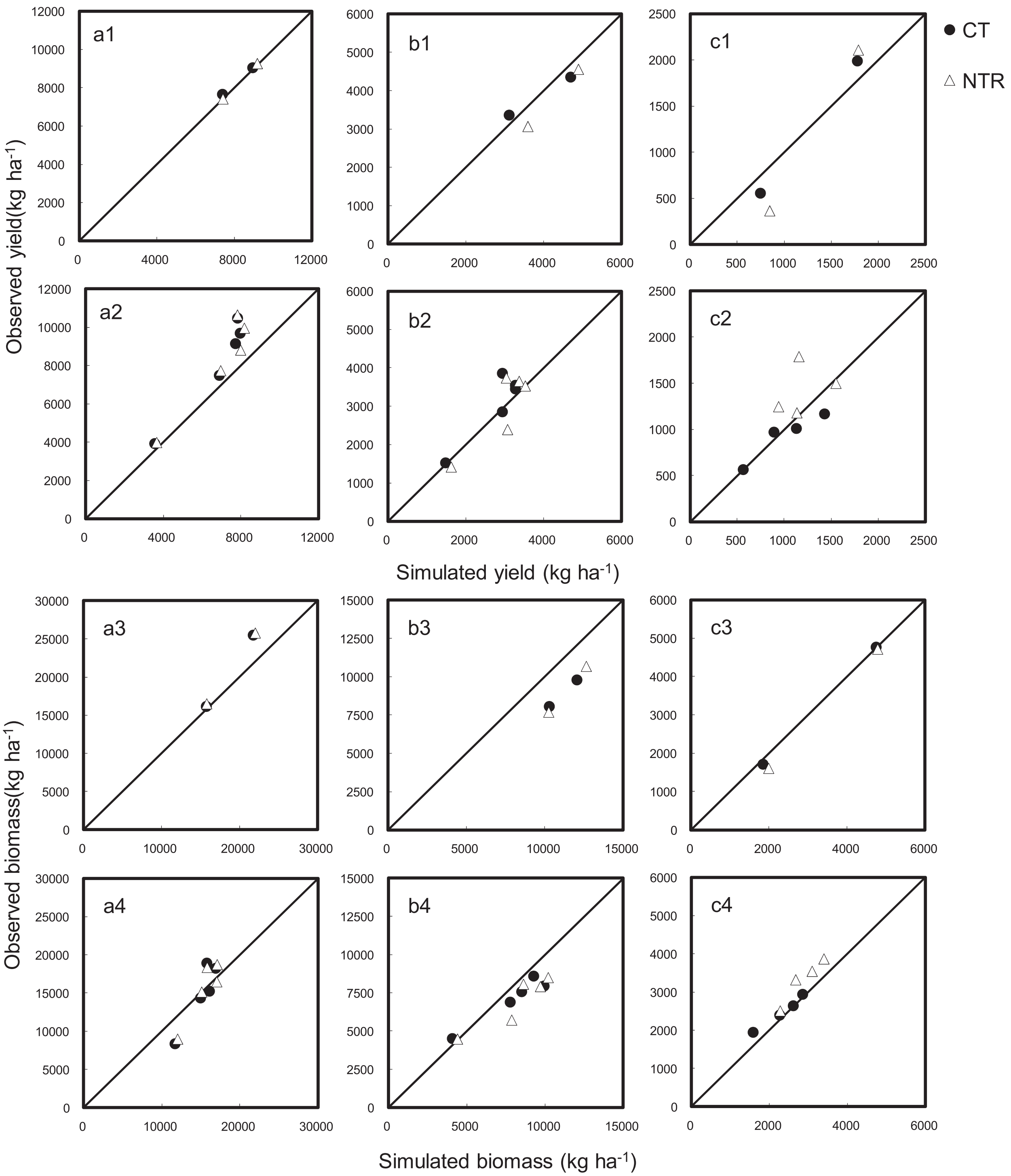

Fig. 2. Model calibration (2001–2002) and evaluation (2003–2007) of grain yield and biomass of maize, winter wheat and soybean in a maize-winter wheat-soybean rotation. a1–a4 represent calibration of the maize grain yield, evaluation of maize grain yield, calibration of maize biomass and evaluation of maize biomass, respectively; b1–b4 represent calibration of wheat grain yield, evaluation of wheat grain yield, calibration of wheat biomass and evaluation of wheat biomass, respectively; c1–c4 represent calibration of soybean grain yield, evaluation of soybean grain yield, calibration of soybean biomass and evaluation of soybean biomass, respectively. CT: conventional tillage; NTR: no tillage with retention of the previous crop's stubble. The 1:1 line is shown in each case.

between simulated and observed values in both calibration (2001–2002) and evaluation (2003–2007; Fig. 2 and Table 4). The RMSE valus for maize grain yield and biomass production were 53–1583 kg ha^{-1} and 1954–2701 kg ha^{-1}, respectively, while d values were 0.87–0.98 and 0.84–0.89, respectively, indicating close agreement between the simulated and observed values (Table 4).

For the calibration of winter wheat, RMSE values of biomass reached 2248 and 2290 for CT and NTR, respectively, while d values were only 0.52 and 0.67 (Table 4). However, the results of model evaluation indicated strong agreement. RMSE values of grain yield were 437 and 462 kg ha^{-1} for CT and NTR, respectively, while the RMSE values of biomass production were 1137 and 1489 kg ha^{-1} for CT and NTR, respectively (Fig. 2; Table 4). The d values were also high and ranged from 0.85 to 0.92.

Table 4
The statistics of calibration and evaluation for grain yield, biomass, and soil water storage during the growing seasons in 2001–2007.

Data	Tillage treatment	Calibration		Evaluation	
		RMSE	d	RMSE	d
Maize grain yield	CT	193 kg ha^{-1}	0.98	1583 kg ha^{-1}	0.87
	NTR	53 kg ha^{-1}	0.99	1578 kg ha^{-1}	0.87
Maize biomass	CT	2673 kg ha^{-1}	0.89	2167 kg ha^{-1}	0.84
	NTR	2701 kg ha^{-1}	0.89	1954 kg ha^{-1}	0.86
Wheat grain yield	CT	293 kg ha^{-1}	0.95	437 kg ha^{-1}	0.92
	NTR	447 kg ha^{-1}	0.91	462 kg ha^{-1}	0.91
Wheat biomass	CT	2248 kg ha^{-1}	0.52	1137 kg ha^{-1}	0.90
	NTR	2290 kg ha^{-1}	0.67	1489 kg ha^{-1}	0.85
Soybean grain yield	CT	200 kg ha^{-1}	0.97	149 kg ha^{-1}	0.92
	NTR	406 kg ha^{-1}	0.91	351 kg ha^{-1}	0.58
Soybean biomass	CT	98 kg ha^{-1}	0.99	198 kg ha^{-1}	0.95
	NTR	276 kg ha^{-1}	0.99	463 kg ha^{-1}	0.80
Soil water storage in 0–30 cm, sequence 1	CT	9.4 mm	0.80	11.0 mm	0.85
	NTR	9.6 mm	0.79	10.7 mm	0.86
Soil water storage in 0–30 cm, sequence 2	CT	8.9 mm	0.82	11.4 mm	0.87
	NTR	8.8 mm	0.80	10.8 mm	0.88
Soil water storage in 30–200 cm, sequence 1	CT	24.4 mm	0.88	47.9 mm	0.70
	NTR	24.8 mm	0.88	52.1 mm	0.74
Soil water storage in 30–200 cm, sequence 2	CT	17.1 mm	0.98	46.2 mm	0.87
	NTR	15.8 mm	0.98	52.9 mm	0.82

Note: calibration and evaluation were based on the experimental data (Sect. 2.2) during the growing seasons in 2001–2002 and 2003–2007, respectively. RMSE: root mean square error; d: index of agreement. CT: conventional tillage; NTR: no tillage with retention of the previous crop's stubble.

The results of model calibration and evaluation for soybean were generally satisfactory, but some large deviations were also found in grain yield under the NTR treatment during model evaluation (RMSE = 351 kg ha^{-1}, and d value = 0.58; Table 4). This is mainly caused by the underestimation of soybean grain yield in 2007 (35% lower than the true value).

In all, APSIM was able to predict the production of these three crops well, but it tended to overestimate grain yield and biomass production of winter wheat (Fig. 2) and underestimate those of maize and soybean in most cases (Fig. 2).

3.2.2. *Soil water dynamics*

Both model calibration and evaluation indicated good agreement between simulated and observed soil water storage (Fig. 3 and Table 4). In particular, RMSE values for the 0–30 cm soil layer were 8.8–9.6 mm and 10.7–11.4 mm in calibration and evaluation, respectively, while d values ranged from 0.79 to 0.88 (Table 4). Overall, simulated soil water storage was slightly higher than observed field data for the 0–30 cm soil layer.

For the 30–200 cm soil layer, the RMSE and d values in calibration were 15.8–24.8 mm and 0.88–0.98, respectively. Meanwhile, the RMSE values in evaluation were 46.2–52.9 mm, while d values ranged from 0.70 to 0.87 (Table 4).

3.3. *Scenario analysis*

The semiarid climate of the Loess Plateau region features erratic long-term annual precipitation and temperature patterns (Fig. 4). In 1961–2010, the mean precipitation from November to the next June was only 176.3 mm, while the amount during July, August, September and October reached 350.3 mm. The annual cumulative precipitation decreased by 21.0 mm decade^{-1} and the annual average temperature increased by 0.30 °C decade^{-1} in these 50 years. Although these trends were determined insignificant at the level of 5% using the Mann-Kendall test (Mann, 1945; Kendall, 1975), they still had posed great challenges for crop production in this region.

3.3.1. *Soil water storage*

As shown in Fig. 5, there were large differences in the long-term simulated soil water storage data in the 0–200 cm soil profile between the two treatments. Soil water was better preserved after peak precipitation period (usually emerged from July to September) in the NTR treatment, leading to great increase in soil water content. Therefore, soil water storage was significantly greater in the NTR treatment than in CT from October to the following spring in the 50 year period. Furthermore, we also found that soil water storage was usually greater in the NTR treatment than in CT during the winter fallow period after soybean harvesting, improving 0–159 mm (72 mm on average; $P < 0.01$) at the beginning of each rotation phase.

3.3.2. *Grain yield and biomass*

The long-term scenario simulations showed that the NTR treatment improved winter wheat grain yield and biomass by 1805 and 4309 kg ha^{-1} on average ($P < 0.01$; Fig. 6). During extremely dry growing seasons, including the years 1966, 1980, 1982, 1986 and 2000, when seasonal precipitation was below 220 mm (while the average precipitation for winter wheat production based on current simulations was 282 mm), NTR notably improved wheat grain yield and biomass by 76.2–1440.6% and 65.4–835.6%, respectively.

For maize, the NTR treatment had average increases in grain yield and biomass of 1459 and 2846 kg ha^{-1}, respectively. In five extreme drought years (1979, 1987, 1995, 1997 and 2001), both maize grain yield and biomass were still at least 5% higher than those under CT, while precipitation during maize growth was < 285 mm (average precipitation requirement for maize production was 355 mm). Additionally, extreme improvement was found in maize production in 1987 and 1997, including 846.6% and 207.3% (for 1987 and 1997) increases for grain yield and 331.4% and 179.6% increases for biomass, respectively. A total of one failure was recorded under NTR in 2009, whereas three failures were found under CT in 1973, 1995 and 2009.

NTR improved soybean grain yield and biomass production by 270 and 549 kg ha^{-1} ($P > 0.05$) on average. Additionally, NTR notably improved grain yield and biomass by 16.4–106.4% and 16.4–78.3% in the growing seasons whose total precipitation falls below 210 mm (1972, 1986, 1994 and 2002). Meanwhile, the average precipitation requirement for soybean production was 334 mm.

3.3.3. *Water productivity*

Due to the insignificant change in WS caused by tillage treatments ($P > 0.05$), WP_Y and WP_B for all three crops generally agreed with grain yield and biomass fluctuations (Fig. 6). The averaged WP_Y and WP_B of winter wheat were 3.3 and 8.0 kg ha^{-1} mm^{-1} greater in the NTR treatment than in CT ($P < 0.05$), respectively. Meanwhile WP_Y and WP_B of soybean were 1.9 and 4.1 kg ha^{-1} mm^{-1} greater in the NTR treatment than in CT ($P < 0.05$), respectively. Averaged over all maize seasons, WP_Y and WP_B were 3.2 and 5.6 kg ha^{-1} mm^{-1} greater in the treatment NTR than in CT ($P > 0.05$), respectively.

3.3.4. *Evapotranspiration*

The system T_c in NTR was significantly greater (37.3% greater on average) than in CT ($P < 0.05$), meanwhile the system E_s in the NTR treatment was 36.3% lower than in CT ($P < 0.05$; Fig. 7). For the different crop periods within each rotation, the average T_c values for maize, winter wheat and soybean period were 8.2%, 55.2% and 32.4% greater in the NTR treatment than in CT (extreme values that exceeded 100% were eliminated), respectively. Meanwhile, the average E_s values for maize, winter wheat and soybean period were 16.0%, 52.1% and 50.3% lower in the NTR treatment than in CT, respectively. The decrease of system ET under NTR (6.2% on average) was also significant compared with CT ($P < 0.05$; Fig. 7). Additionally, despite the

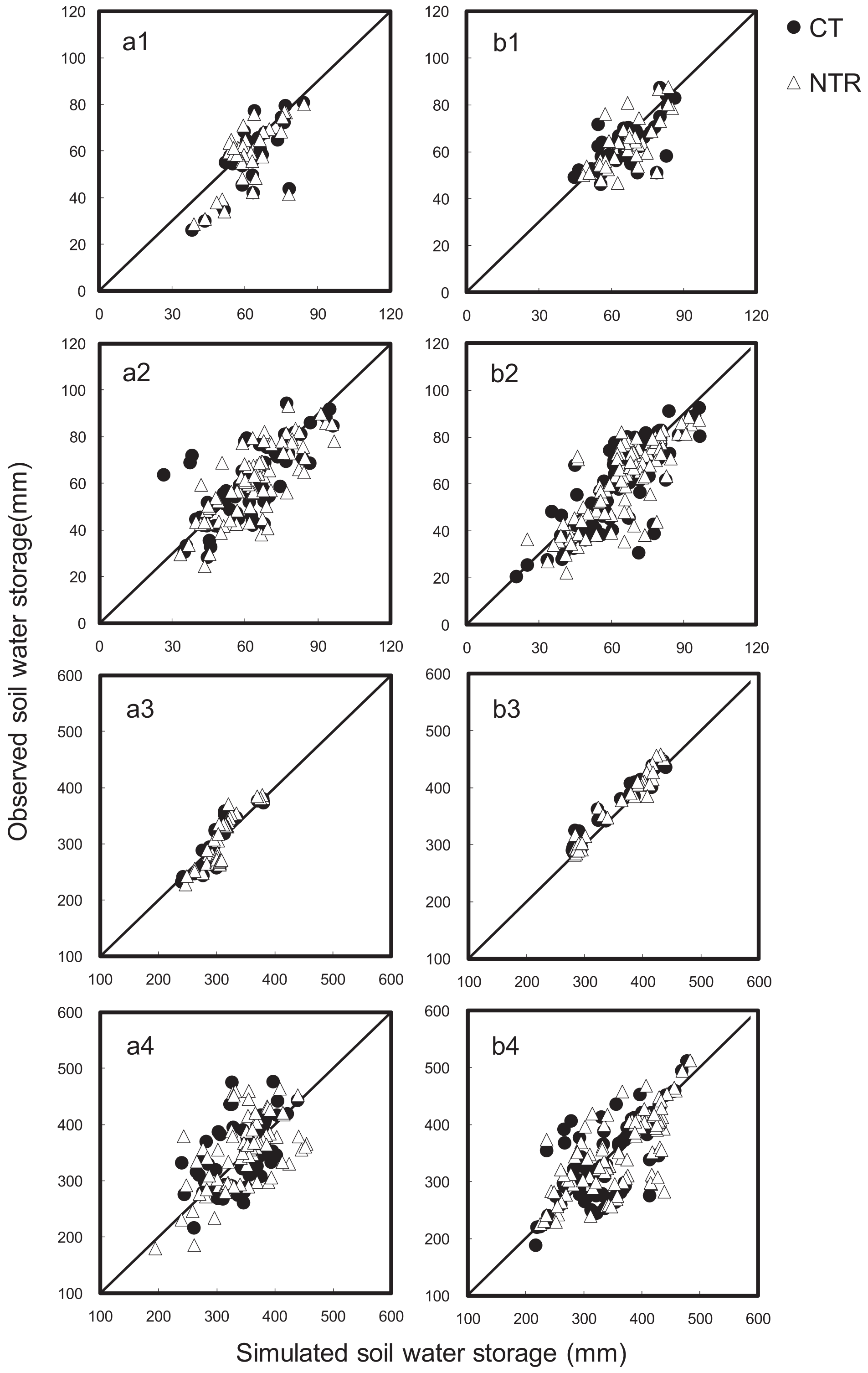

Fig. 3. Model calibration (2001–2002) and evaluation (2003–2007) of soil water storage in the 0–30 cm and 30–200 cm soil layers of a maize-winter wheat-soybean rotation. a1–a4 represent calibration of soil water storage in the 0–30 cm layer of sequence 1, evaluation of soil water storage in the 0–30 cm layer of sequence 1, calibration of soil water storage in the 30–200 cm layer of sequence 1, and evaluation of soil water storage in the 30–200 cm layer of sequence 1, respectively; b1–b4 represent calibration of soil water storage in the 0–30 cm layer of sequence 2, evaluation of soil water storage in the 0–30 cm layer of sequence 2, calibration of soil water storage in the 30–200 cm layer of sequence 2, and evaluation of soil water storage in the 30–200 cm layer of sequence 2, respectively. CT: conventional tillage; NTR: no tillage with retention of the previous crop's stubble. The 1:1 line is shown in each case.

differences of $SW_{sys,i}$ and SW_{sys}, WS_{sys} values were similar between both treatments ($P > 0.05$).

T_c/WS_{sys} varied from 19.4% to 52.5% and from 39.6% to 70.7% for CT and NTR, respectively. ET/WS_{sys} varied from 84.4% to 99.8% and from 69.5% to 99.8% for CT and NTR, respectively. These values all differed significantly between the two treatments ($P < 0.05$; Fig. 7), indicating that conservation tillage provided better crop water use.

4. Discussion

4.1. Model evaluation

Although APSIM cannot fully consider the complexity and dynamics among various factors that control crop production on a cropping system level (Peake et al., 2014), the results from this study suggested that APSIM was suitable for estimating the crop growth and soil water dynamics of a maize-winter wheat-soybean rotation under the rainfed conditions of the Loess Plateau.

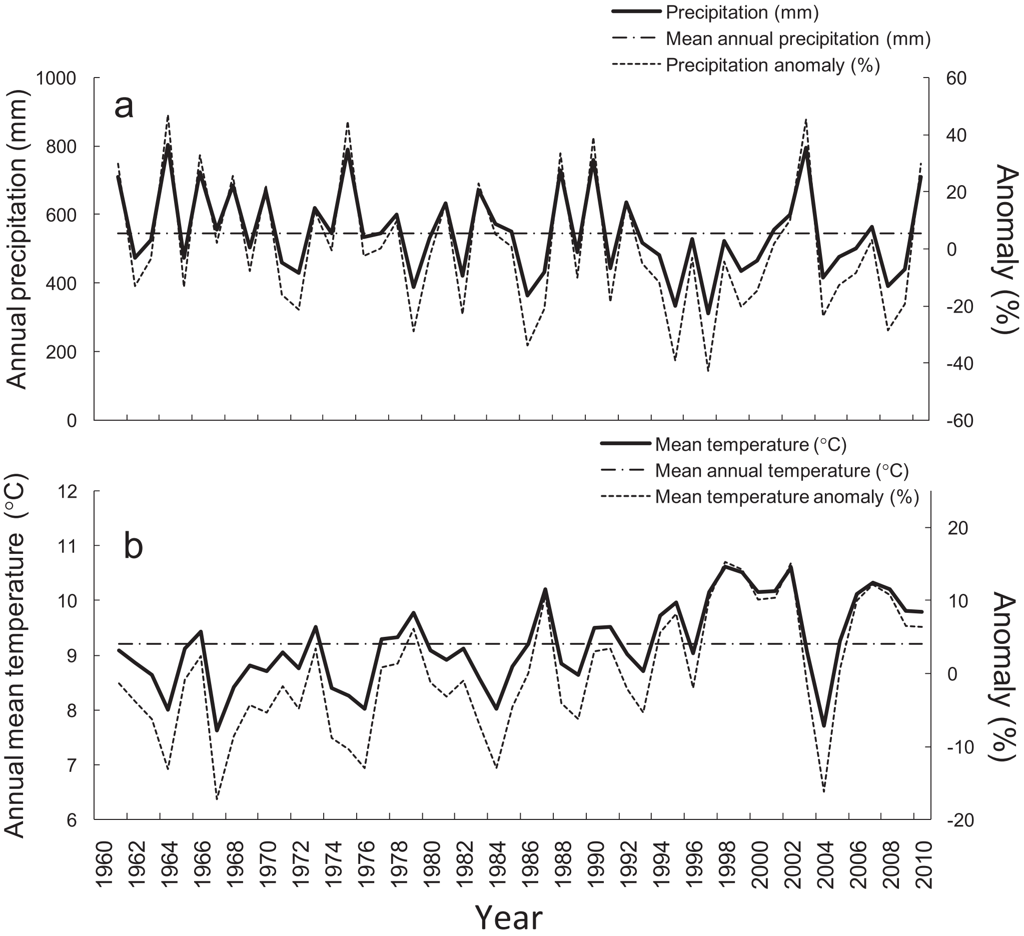

Fig. 4. Annual precipitation and mean yearly temperature during 1961–2010 in Xifeng, Gansu Province, China. a: annual precipitation; b: mean annual temperature.

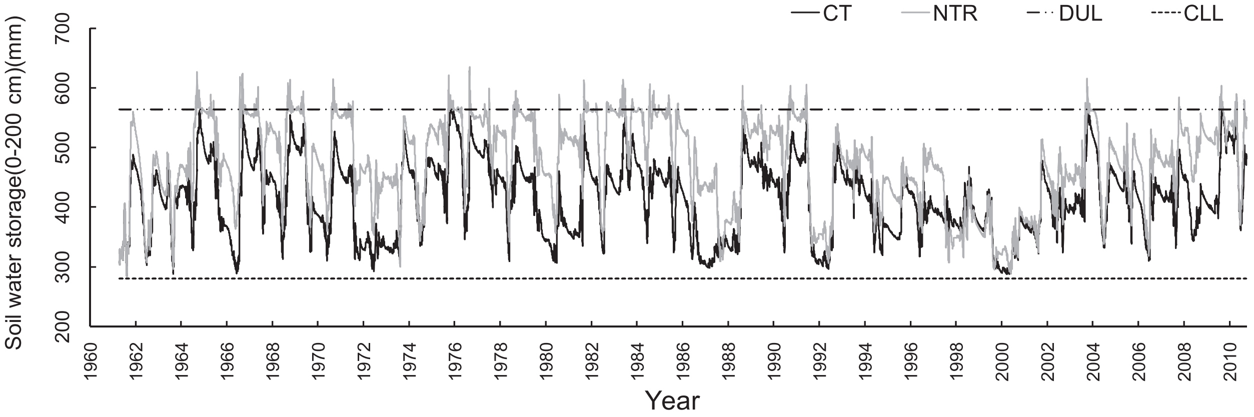

Fig. 5. Simulated soil water dynamics in the 0–200 cm soil layer in maize-winter wheat-soybean rotation during 1961–2010. DUL: drained upper limit; CLL: crop lower limit. CT: conventional tillage; NTR: no tillage with retention of the previous crop's stubble.

Both the grain yield and biomass of winter wheat were overestimated by APSIM. This might be due to impacts of natural disasters (e.g. prolonged drought, severe storm, etc.) which can greatly reduce yield in field conditions but is not considered by APSIM (Asseng et al., 2004; Bassu et al., 2009). Another popular explanation is that the APSIM-Wheat module tends to overestimate the early-season growth of winter wheat (Chen et al., 2010), leading to an exaggerated prediction of wheat grain yield and biomass at the end of the growing season.

The APSIM model underestimated grain yield and biomass of maize and soybean in most cases, which is highly consistent with other studies (Mohanty et al., 2012; Archontoulis et al., 2014b; Masikati et al., 2014). Mohanty et al. (2012) and Peake et al. (2014) speculated that this might be caused by the fact that APSIM underestimated N uptake for both maize and soybean, resulting in inaccurate predictions in grain yield. Another reason would be the underestimated radiation use efficiency (RUE) associated with those default parameter values in APSIM simulations (Archontoulis et al., 2014b).

Overall, there were no significant differences of grain yield and biomass production between CT and NTR in field measurements, as well as model calibration and evaluation processes. This lack of differences could be caused by the offsetting effect between increased soil health caused by residual retention and increased compaction due to

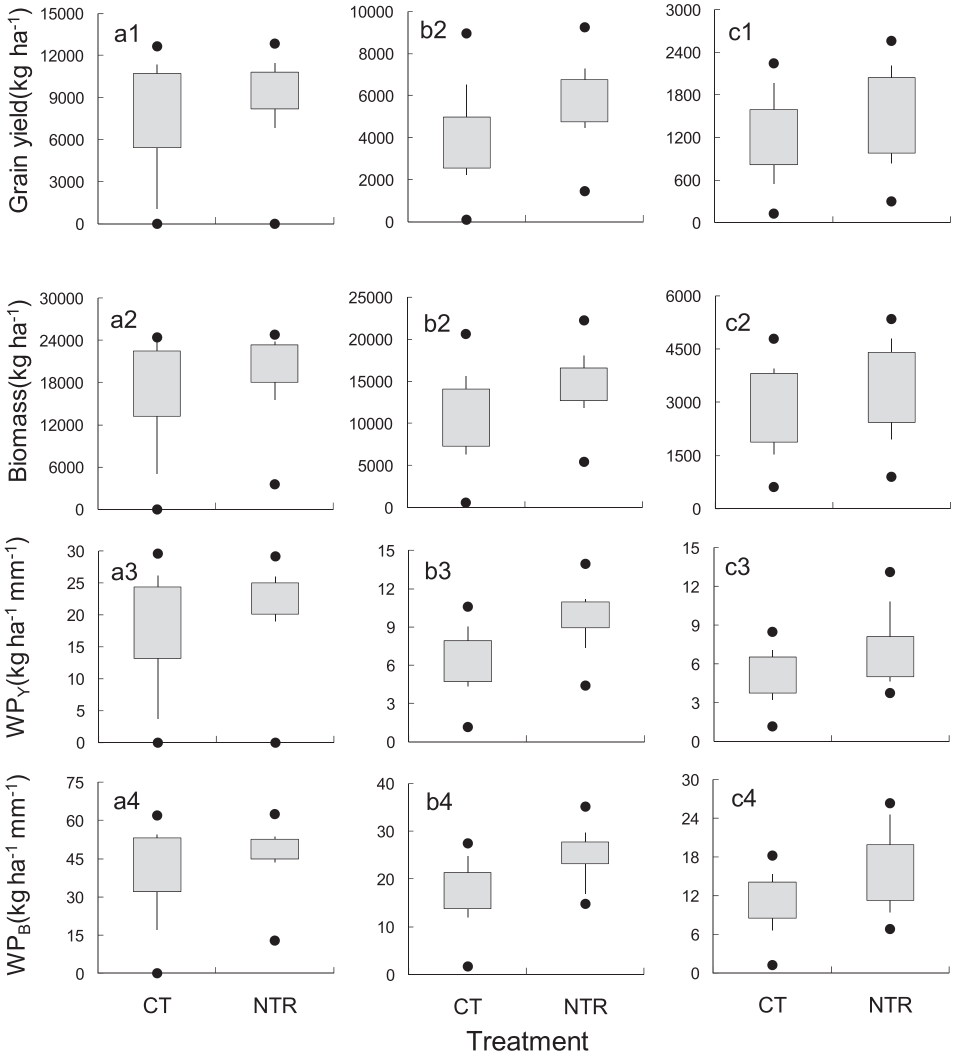

Fig. 6. Grain yield, dry matter biomass, grain yield water productivity (WP$_Y$) and dry matter biomass water productivity (WP$_B$) for maize, winter wheat and soybean crops in a maize-winter wheat-soybean rotation during 1961–2010. Box boundaries indicate the 75th and 25th percentiles; whisker caps indicate the 90th and 10th percentiles. Dots show extreme values. a1, a2, a3, and a4 represent maize yield, biomass, WP$_Y$ and WP$_B$, respectively; b1, b2, b3, and b4 represent winter wheat yield, biomass, WP$_Y$ and WP$_B$, respectively; c1, c2, c3, and c4 represent soybean yield, biomass, WPy and WP$_B$, respectively. CT: conventional tillage; NTR: no tillage with retention of the previous crop's stubble.

the lack of tillage. On the other hand, seven years of NTR could still not significantly improve grain yield and biomass production. For the experimental data of 2007, we also noted that soybean in NTR has already presented much greater grain yield and biomass production than in CT. However, the APSIM evaluation indicated little response to this: the model seemed to neglect this benefit of NTR due to high growing-season precipitation (reached 376 mm).

APSIM could predict the beneficial of NTR on soil water storage. Moreover, the overestimation of soil water storage in the 0–30 cm profile was probably caused by the errors associated with the larger variability of field measurements than in the 30–200 cm profile (Mohanty et al., 2012). Mupangwa and Jewitt (2011) also noted that the USDA Curve Number approach utilized in the APSIM framework was not able to consider the antecedent moisture condition in the model calibration processes. Alternatively, the default U and CONA values (Eq. 1), which might cause underestimated E_s, resulted in higher soil water storage in modelling prediction. Further improvements on the robustness and applicability of APSIM on simulating the hydrological dynamics of different cropping systems are warranted.

4.2. Effects of conservation tillage on grain yield and biomass

Similar to previous modelling/field studies (Awada et al., 2014; Singh et al., 2011), conservation tillage resulted in significantly greater winter wheat grain yield and biomass production than conventional tillage across 25 rotation phases. This finding contradicted the results provided by Pittelkow et al. (2015), who pointed out that under rainfed conditions, the crop yield of NTR might be similar or lower than conventional tillage. In contrast, Huang et al. (2006) considered that at the field level, reductions in soil evaporation and accelerated accumulation of organic matter under NTR could significantly increase crop yield. APSIM seemed to be more responsive towards the beneficial effects of NTR when simulating crop yield due to stubble decomposition (refer to Eq. 4).

Our results also showed that conservation tillage could provide substantially greater grain yield and biomass production of maize or soybean under dry seasons due to better soil water retention (Liu et al., 2013; Zhang et al., 2014). Similar to winter wheat, this finding contradicted the field-level results (maize yield of 2001 and soybean yield of 2002 in NTR were lower than in CT). We speculated that 2001–2002 belongs to the first rotation cycle for field experiments and the twenty-first rotation cycle for long-term simulation, respectively. This appears to be a case of that the effects of straw mulching on yield and biomass production might take a much longer time before they became detectable (Li et al., 2018).

Additionally, a large amount of precipitation during the late season of maize and soybean greatly limited the use of water supplements, thus potentially hindering the effects of the NTR treatment on crop productivity. Alternative crop species or varieties that are more responsive to conservation tillage and late-season precipitation should be explored and incorporated into cropping system production on the Loess Plateau of China.

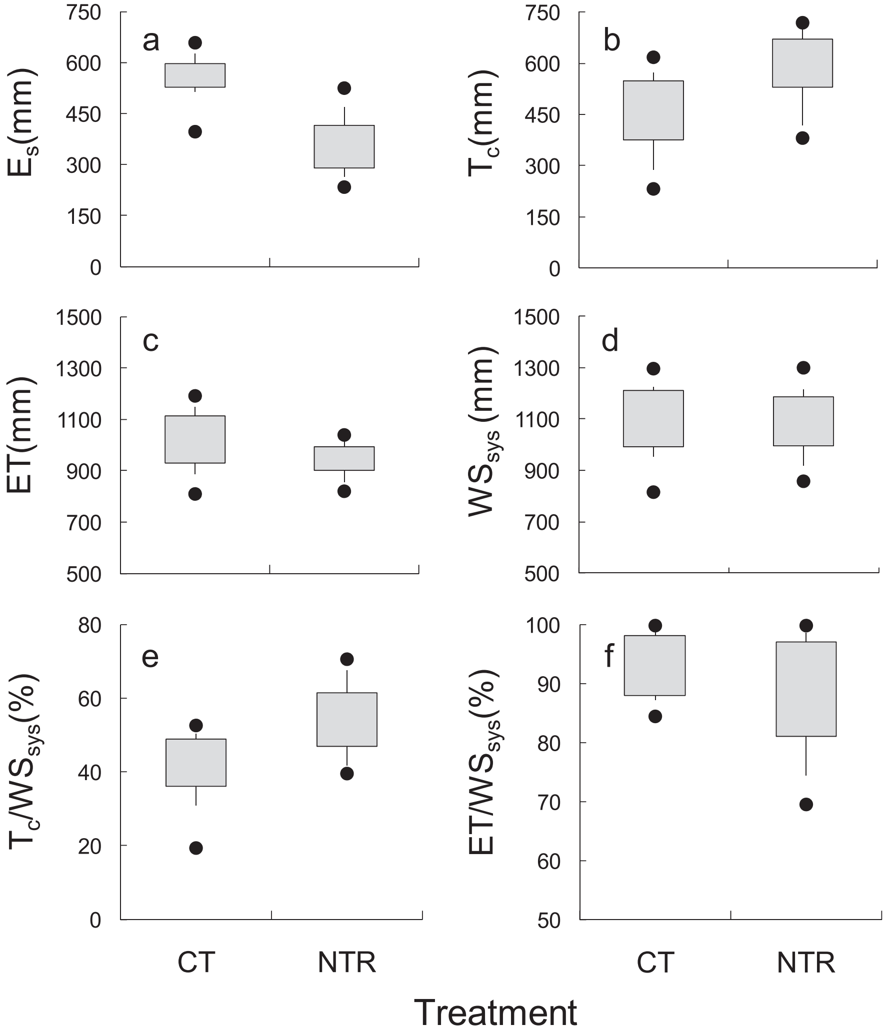

Fig. 7. System soil evaporation (E_s), plant transpiration (T_c), evapotranspiration (ET), water supply (WS_{sys}), system plant transpiration (T_c)/system water supply (WS_{sys}) and evapotranspiration (ET)/system water supply (WS_{sys}) for all maize-winter wheat-soybean rotation cycles during 1961–2010. Box boundaries indicate the 75th and 25th percentiles; whisker caps indicate the 90th and 10th percentiles. Dots show extreme values. a: E_s; b: T_c; c: ET; d: WS_{sys}; e: T_c/WS_{sys}; f: ET/WS_{sys}. CT: conventional tillage; NTR: no tillage with retention of the previous crop's stubble.

4.3. *Effects of conservation tillage on soil water and evapotranspiration*

The scenario simulations of our study verified that conservation tillage played an important role in enhancing the soil water holding capacity and improving the soil water storage of each rotation phase when preplanting (which was the final condition of the previous phase, too). They also implied that conservation tillage would not significantly increase WS_{sys} compared with conventional tillage.

Singh et al. (2011) suggested that conservation tillage could lead to lower E_s in APSIM simulations because the APSIM model actually considers the effects of conservation tillage on reducing system E_s as well as enhancing T_c and T_c/WS_{sys}. Thus, the advantages of NTR could be precisely modeled using APSIM (Busari et al., 2015; Monzon et al., 2006; Singh et al., 2005; Choudhary et al., 2013), which agrees with our findings in this research. Our results also revealed that the water saved from reduced E_s under conservation tillage was not fully diverted to T_c (especially for maize), otherwise, system ET and ET/WS_{sys} values should be similar between CT and NTR.

Significantly larger T_c and smaller E_s values were found for winter wheat and soybean production under the NTR treatment compared with the CT treatment. Interestingly, maize T_c and E_s values were not significantly different between CT and NTR (Fig. 7). These results were primarily caused by the differences in residue management practices and the variation in environmental conditions. For wheat and soybean, seeding was conducted immediately after harvesting of the previous crops. Their early and/or mid growing seasons were typically in the rainy season of this region. For maize, the limited quantity of previous crop's stubble influenced the effects of conservation tillage on the T_c and E_s.

4.4. *Effects of conservation tillage on water productivity*

Similar to our findings, former modelling/field studies indicated significantly greater wheat and soybean WP under conservation tillage compared with conventional tillage (Martinez et al., 1995; Su et al., 2007; Powers et al., 2011). The increased WP under conservation tillage was caused by the combined effect of grain yield and WS.

In addition, although the NTR treatment presented greater soil water storage than CT, the increased moisture retention failed to increase the maize grain yield and biomass to a significant degree (He et al., 2016). The greater WS (derived from higher $SW_{sys,i}$; Eq. 10) under conservation tillage also offset the improvements in WP_Y and WP_B. Thus, identifying better conservation tillage practices other than no-till approaches is important for the enhancement of maize WP in a semiarid environment (Masikati et al., 2014).

5. Conclusion

Based on field-level data, we successfully evaluated the initial parameterization of crop thermal time accumulation, the crop growth process, and soil water balance components (runoff, drainage, and evapotranspiration) of APSIM under conventional and no-till maize-winter wheat-soybean rotation systems on the Loess Plateau of China.

The long-term scenario simulations based on a maize-winter wheat-soybean rotation showed that no tillage with previous stubble retention provided higher soil water storage before each rotation phase compared with conventional tillage. Conservation tillage could also greatly improve the grain yield and biomass of wheat across 25 rotation cycles. There are discrepancies between the field observations and the results from the long-term simulations. This finding might be caused by the different duration of NTR implementation, and/or the limitation of the APSIM framework per se.

Significantly greater system T_c, T_c/WS_{sys} and lower E_s, ET and ET/WS_{sys} were detected under conservation tillage treatment on a system basis, but for maize, T_c and E_s were not significantly changed by different treatments. The water productivity of wheat and soybean was greatly affected by NTR. In addition, maize water productivity was insignificant between CT and NTR.

In all, we advocate that conservation tillage could potentially improve field productivity, and benefit crop water use and soil water storage on a cropping system level under rainfed conditions. Meanwhile some alternative crop species or varieties that are more responsive to conservation tillage should be explored and incorporated into predominant rotation cropping systems. More research efforts should focus on refining and improving APSIM's robustness and accuracy under different environmental conditions and management practices. Innovative and creative modelling approaches as well as high-throughput phenotyping data acquisition technology will be needed to build powerful decision-making tools and/or forecasting models for the future.

Conflict of interest statement

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.08.005.

References

Archontoulis, S.V., Miguez, F.E., Moore, K.J., 2014a. A methodology and an optimization tool to calibrate phenology of short-day species included in the APSIM PLANT model: application to soybean. Environ. Model. Softw. 62, 465–477.

Archontoulis, S.V., Miguez, F.E., Moore, K.J., 2014b. Evaluating APSIM maize, soil water, soil nitrogen, manure, and soil temperature modules in the Midwestern United States. Agron. J. 106 (3), 1025–1040.

Asseng, S., Jamieson, P.D., Kimball, B., Pinter, P., Sayre, K., Bowden, J.W., Howden, S.M., 2004. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO_2. Field Crop Res. 85, 85–102.

Awada, L., Lindwall, C.W., Sonntag, B., 2014. The development and adoption of conservation tillage systems on the Canadian Prairies. Int. Soil Water Conserv. Res. 2 (1), 47–65.

Barron, J., Rockstrom, J., Gichuki, F., Hatibu, N., 2003. Dry spell analysis and maize for two semi-arid locations in east Africa. Agric. For. Meteorol. 117 (1–2), 23–37.

Bassu, S., Asseng, S., Motzo, R., Giunta, F., 2009. Optimising sowing date of durum wheat in a variable Mediterranean environment. Field Crop Res. 111 (1–2), 109–118.

Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. Int. Soil Water Conserv. Res. 3, 119–129.

Chen, W., Shen, Y.Y., Robertson, M.J., Probert, M.E., Bellotti, W.D., 2008. Simulation analysis of lucerne-wheat crop rotation on the Loess Plateau of Northern China. Field Crop Res. 108 (2), 179–187.

Chen, C., Wang, E., Yu, Q., 2010. Modeling wheat and maize productivity as affected by climate variation and irrigation supply in North China Plain. Agron. J. 102 (3), 1037–1049.

Choudhary, V.K., Kumar, P.S., Bhagawati, R., 2013. Response of tillage and in situ moisture conservation on alteration of soil and morpho-physiological differences in maize under Eastern Himalayan region of India. Soil Tillage Res. 134, 41–48.

Dalgliesh, N., Foale, M., 1998. Soil Matters [M]. Cranbrook Press, Toowoomba, AUS.

Ernst, O.R., Kemanian, A.R., Mazzillia, S.R., Cadenazzi, M., Dogliotti, S., 2016. Depressed attainable wheat yields under continuous annual no-tillagriculture suggest declining soil productivity. Field Crop Res. 108, 107–116.

FAO, 1990. Soil Map of the World: Revised Legend. World Soil Resources Report 60. Food and Agriculture Organization of the United Nations, Rome.

Fowler, R., Rockström, J., 2001. Conservation tillage for sustainable agriculture, an agrarian revolution gathers momemtum in Africa. Soil Tillage Res. 61 (01), 93–107.

Glanville, S.G., Freebairn, D.M., Silburn, D.M., 1984. Using curve numbers from simulated rainfall to describe the runoff characteristics of contour bay catchments. In: Conference on Agricultural Engineering, Bundaberg, Queensland, 27–30 August 194. Institution of Engineers, Australia.

He, G., Wang, Z., Li, F., Dai, J., Li, Q., Xue, C., Cao, H., Wang, S., Malhi, S., 2016. Soil water storage and winter wheat productivity affected by soil surface management and precipitation in dryland of the Loess Plateau, China. Agric. Water Manag. 171, 1–9.

Huang, G.B., Guo, Q.Y., Zhang, R.Z., Pang, L., Li, G., Chan, K.Y., Yu, A.Z., 2006. Effects of conservation tillage on soil moisture and crop yield in a phased rotation system with spring wheat and field pea in dryland. Acta Ecol. Sin. 26 (4), 1176–1185 (in Chinese with English abstract).

Jones, C.A., Kiniry, J.R., 1986. A Simulation Model of Maize Growth and Development [M]. Texas A&M University Press, College Station, USA.

Keating, B.A., Robertson, M.J., Muchow, R.C., Huth, N.I., 1999. Modelling sugarcane production systems. I. Development and performance of the sugarcane module. Field Crop Res. 61, 253–271.

Keating, B.A., Carberry, P.S., Hammer, G.L., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18 (3/4), 267–288.

Kendall, M.G., 1975. Rank Correlation Methods [M]. Griffin, London, UK.

Lal, R., Griffin, M., Apt, J., Lave, L., Morgan, M.G., 2004. Managing soil carbon. Science 304 (5669), 393.

Li, Z., Yang, X., Cui, S., Yang, Q., Yang, X., Li, J., Shen, Y., 2018. Developing sustainable cropping systems by integrating crop rotation with conservation tillage practices on the Loess Plateau, a long-term imperative. Field Crop Res. 222, 164–179.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L., Leslie, J.K., 1992. Impact of soil-erosion on production in cropping systems.1. Development and validation of a simulation-model. Soil Res. 30, 757–774.

Liu, S., Yang, J.Y., Zhang, X.Y., Drury, C.F., Reynolds, W.D., Hoogenboom, G., 2013. Modelling crop yield, soil water content and soil temperature for a soybean-maize rotation under conventional and conservation tillage systems in Northeast China. Agric. Water Manag. 123 (10), 32–44.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13, 245–259.

Martinez, C.C., O'Leary, G.J., Connor, D.J., 1995. Stubble retention and nitrogen fertilisation in a fallow-wheat rain-fed cropping system. 1. Soil water and nitrogen conservation, crop growth and yield. Soil Tillage Res. 34 (2), 79–94.

Masikati, P., Manschadi, A., Rooyen, A., 2014. Maize-mucuna rotation: an alternative technology to improve water productivity in smallholder farming systems. Agric. Syst. 123, 62–70.

Mohanty, M., Probert, M.E., Reddv, K.S., Dalal, R.C., Mishra, A.K., Rao, A.S., Sinh, M., Menzies, N.W., 2012. Simulating soybean-wheat cropping system: APSIM model parameterization and validation. Agric. Ecosyst. Environ. 152, 68–78.

Monzon, J.P., Sadras, V.O., Andrade, F.H., 2006. Fallow soil evaporation and water storage as affected by stubble in sub-humid (Argentina) and semi-arid (Australia) environments. Field Crop Res. 98 (2–3), 83–90.

Mueller, E.N., Pfister, A., 2011. Increasing occurrence of high-intensity rainstorm events relevant for the generation of soil erosion in a temperate lowland region in Central Europe. J. Hydrol. 411 (3–4), 266–278.

Mupangwa, W., Jewitt, G.P.W., 2011. Simulating the impact of no-till systems on field water fluxes and maize productivity under semi-arid conditions. Phys. Chem. Earth 36 (14–15), 1004–1011.

Nyakudya, I.W., Stroosnijder, L., 2015. Conservation tillage of rainfed maize in semi-arid Zimbabwe: a review. Soil Tillage Res. 145, 184–197.

Peake, A., Huth, N.I., Carberry, P.S., Raine, S.R., Smith, R.J., 2014. Quantifying potential yield and lodging-related yield gaps for irrigated spring wheat in sub-tropical Australia. Field Crop Res. 158 (2), 1–14.

Peel, M.C., Finlayson, B.L., Mcmahon, T., 2007. Updated world map of the Koppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 4 (2), 1633–1644.

Pittelkow, C.M., Liang, X., Linquist, B.A., Groenigen, K.J., Lee, J., Lundy, M.E., Gestel, N., Six, J., Venterea, R.T., Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517 (7534).

Powers, S.E., Ascough II, J.C., Nelson, R.G., Larocque, G.R., 2011. Modeling water and soil quality environmental impacts associated with bioenergy crop production and biomass removal in the Midwest USA. Ecol. Model. 222 (14), 2430–2447.

Priestley, C.H.B., Tylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100 (2), 81–92.

Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C., Strong, W.M., 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Syst. 56 (1), 1–28.

Ren, J., Peng, S., Cao, Y., Huo, X., Chen, Y., 2018. Spatiotemporal distribution characteristics of climate change in the loess plateau from 1901 to 2014. J. Nat. Resour. 33 (4), 621–633 (In Chinese with English abstract).

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204–1213.

Shan, L., Chen, G.L., 1993. The Theory and Practice of Dryland Agriculture in the Loess Plateau of China [M]. Science Press, Beijing, CN (in Chinese).

Shen, Y.Y., 2004. Component Dynamics of the Soil and Crop Within Lucerne-wheat Rotation Systems [D]. Doctoral Dissertation. Sun Yat-sen University, Guangzhou (In Chinese with English abstract).

Singh, Y., Singh, B., Timsina, J., 2005. Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. Adv. Agron. 85 (04), 269–407.

Singh, B., Gaydonb, D.S., Humphreysc, E., Eberbach, P.L., 2011. The effects of mulch and irrigation management on wheat in Punjab, India-evaluation of the APSIM model. Field Crop Res. 124, 1–13.

Smith, A., Snapp, S., Dimes, J., Gwenambira, C., Chikowo, R., 2016. Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. Agric. Syst. 145, 139–149.

Strudley, M.W., Green, T.R., Ascough II, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: state of the science. Soil Tillage Res. 99, 4–48.

Su, Z., Zhang, J., Wu, W., Cai, D., Lv, J., Jiang, G., Huang, J., Gao, J., Hartmann, R., Gabriels, D., 2007. Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on the Loess Plateau, China. Agric. Water Manag. 87 (3), 307–314.

Sun, H.Y., Zhang, X.Y., Wang, E.L., Chen, S., Shao, L., 2015. Quantifying the impact of irrigation on groundwater reserve and crop production - a case study in the North China Plain. Eur. J. Agron. 70, 48–56.

Thorburn, P.J., Probert, M.E., Robertson, F.A., 2001. Modelling decomposition of sugarcane surface residues with APSIM-residue. Field Crop Res. 70, 223–232.

Xie, J., Chen, J., Sun, G., Zha, T., Yang, B., Chu, H., Liu, J., Wan, S., Zhou, C., Ma, H., Bourque, C.P.A., Shao, C., John, R., Ouyang, Z., 2016. Ten-year variability in ecosystem water use efficiency in an oak-dominated temperate forest under a warming climate. Agric. For. Meteorol. 218-219, 209–217.

Yang, J., 2009. Response of System Components to Conservation Tillage Practice in a Maize-wheat-soybean Rotation on the Qingyang Loess Plateau [D]. Master's Dissertation. Lanzhou University, Lanzhou (In Chinese with English abstract).

Yang, J., Shen, Y., Nan, Z., Gao, C., Niu, Y., Wang, X., Luo, C., Li, G., 2010. Effects of conservation tillage on crop yield and carbon pool management index on top soil within a maize-wheat-soy rotation system in the Loess Plateau. Acta Agron. Sin. 19 (1), 75–82 (in Chinese with English abstract).

Zhang, S., Sadras, V., Chen, X., Zhang, F., 2014. Water use efficiency of dryland maize in the Loess Plateau of China in response to crop management. Field Crop Res. 163, 55–63.