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In search of long-term sustainable tillage and straw mulching practices for a maize-winter wheat-soybean rotation system in the Loess Plateau of China

Zhou Li[a,b], Xingfa Lai[a,b], Qian Yang[a,b], Xuan Yang[a,b], Song Cui[c], Yuying Shen[a,b,*]

[a] State Key Laboratory of Grassland Agro-ecosystems, Lanzhou 730020, China
[b] College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, China
[c] School of Agribusiness and Agriscience, Middle Tennessee State University, Murfreesboro, TN 37132, USA

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ABSTRACT

Development of sustainable agronomic practices and increasing crop water use efficiency (WUE) under the realm of water scarcity and climate change have become the major focuses in the semiarid Loess Plateau region of China. This 7-yr (2001–2007) study investigated the effects of conservation tillage practices and residue management on crop yield, WUE, soil organic carbon (SOC), soil water storage, economic return, and determined the contribution of various environmental factors on crop WUE under a two-year cycle spring maize (*Zea mays* L.)-winter wheat (*Triticum aestivum* L.)-summer soybean (*Glycine max* L.) rotation cropping system. Treatments included conventional tillage (T) as control, conventional tillage followed by straw mulching (TS), no tillage (NT) and no tillage followed by straw mulching (NTS). Averaged over years and species, the overall crop yield was greatest under TS treatment, which was 17 9 and 5% significantly greater than NT, T and NTS treatments, respectively. Additionally, TS treatment resulted in comparable or greater crop WUE than other treatments starting from 2004. Soil moisture storage was not significantly affected by treatments but varied greatly across different soil depths throughout the growing season. Soil organic carbon was significantly increased by straw mulching treatments (NTS and TS) beginning at 2004. In all, NTS treatment provided the greatest economic return on a system basis. Our simulation modeling results indicated that biomass and net radiation are the most important factors in determining WUE in the semiarid Loess Plateau of China.

1. Introduction

The sustainability and resilience of Chinese agriculture have been greatly challenged by the rapid population growth and substantial economic development in recent years, particularly in the semiarid crop production regions of China. The Loess Plateau is a major agricultural region located in the northwest of China, with an average annual rainfall below 600 mm and a total area of 648,700 km^2 accounting for about 6.8% of Chinese territory (Shan, 1993). Like other dry regions in the world, water scarcity and climate change are the most important ecological factors limiting agricultural productivity (Zhang et al., 2014). A study by Deng et al. (2015) showed that during 1961–2010, the annual mean temperature on the Loess Plateau has increased at an average rate of 0.32 °C every ten years, which could cause significant increase in evapotranspiration and alteration of energy/carbon balance of terrestrial ecosystems. Meanwhile, Yan (2015) reported that annual precipitation in this region has declined at an average rate of 0.751 mm yr^{-1} during 1961–2014 and IPCC (Intergovernmental Panel on Climate Change) also found that the precipitation reduction could reach 5% per decade at certain recorded sites in the Northwest China during 1951–2010 (IPCC 2013). Thus, designing and developing sustainable cropping systems that can maintain productivity, better tolerate extreme weather conditions, and use production inputs (particularly water) more efficiently have become the major focuses in this region (Trumbore et al., 1996; Grace and Rayment, 2000; Midgley et al., 2004).

On a global scale, incorporating crop rotations with limited or no tillage have become very popular in cropping system studies. Riedell et al. (2013) found that maize (*Zea mays* L.)-soybean (*Glycine max* L.)-wheat (*Triticum aestivum* L.)/alfalfa (*Medicago sativa* L.) rotations with conservation tillage provided better soil health, seed yield, and kernel mineral concentration than maize monoculture. Likewise, Huang et al. (2003a) found that pea/millet (*Panicum miliaceum*)/maize/maize rotation with conservation tillage practices provided significantly improved crop WUE on the Loess Plateau. In an economic study, Katsvairo and Cox (2000) suggested that soybean–maize rotation with low chemical inputs and limited tillage could provide similar net economic return compared with conventional tillage. Although crop rotation and

* Corresponding author at: State Key Laboratory of Grassland Agro-ecosystems, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, China.
E-mail address: yy.shen@lzu.edu.cn (Y. Shen).

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conservation tillage have long been known for their economic and ecological benefits, effects of integrating different tillage and crop residue retention practices on the system-based productivity and sustainability are less well known particularly in the semiarid Loess Plateau region of China (Shao et al., 2016; Zhang et al., 2016a). Furthermore, the mechanism and contribution of various environmental factors on crop WUE as well as their interaction with different management practices in the semiarid environment have rarely been systematically studied.

Thus, this study was conducted to (1) study the effects of different conservation tillage/crop residue retention practices and changes of relevant environmental factors on crop yield, WUE, SOC, soil moisture change, and economic return of a spring maize-winter wheat-summer soybean rotation system on the Loess Plateau; (2) employ path analysis to investigate the interplay and contribution of various environmental factors on crop WUE, which is of great importance to producers and researchers in this region.

2. Materials and methods

2.1. Site description

A 7-yr tillage × residual straw mulching study was conducted in a spring maize-winter wheat-summer soybean rotation system at the Qingyang Loess Plateau Research Station of Lanzhou University (35°39′N, 107°51′E; elevation 1298m) from 2001 to 2007. The average long-term annual temperature ranges from 8 to 10 °C. The minimum and maximum temperatures are 39 °C and −22.4 °C, respectively. Mean annual accumulated heat unit is 3446 ° days. The growing season for major warm-season crops extends from March to October for about 255 days with 110 frost-free days on average. Annual precipitation is between 480–660 mm, and average annual pan evaporation is 1504 mm. The dominant soil type is sandy loam with an average field water-holding capacity of 0.223 cm^3/cm^3 and permanent wilting point of 0.07 cm^3/cm^3 determined using methods described by Cassel and Nielsen (1986) and Colla et al. (2000).

2.2. Experimental design and crop management

This study was a randomized complete block design with four blocks and a factorial treatment structure (two tillage practices × two straw mulching practices; 4 blocks × 4 treatments = 16 plots). The entire experiment was conducted within a bulk field with each plot measured as 52 m^2 (4 × 13 m) in area. The distance between two adjacent blocks and plots was measured as two and one meter, respectively. Treatments were imposed on an existing maize-wheat-soybean rotation cropping system based on different tillage and residue management practices, including conventional tillage (T), conventional tillage followed by straw mulching (TS), no tillage (NT), and no tillage followed by straw mulching (NTS). Crop rotations started after a summer soybean production in 2001 and was designed as a spring maize-winter wheat-summer soybean cycle. Each cycle spans two years and was repeated three times for a total of six years (2001, soybean monoculture; 2002–2003, 2004–2005, 2006–2007, spring maize-winter wheat-summer soybean rotations).

Farmlands in the Loess Plateau region of China typically feature small size, steep slope, and long distance to primary highway and country road systems, thus, preventing the usage of large farm equipment (e.g. combine harvester) and greatly favoring human labor (Huang et al., 2003b; Shao et al., 2016). Farmers typically collect crop residues after harvest and either burn them in the field or use as animal feed or fuel for heating (Komarek et al., 2015). Very few farmers return crop residues back to the field as a way to improve crop productivity and soil health. Additionally, little scientific information relating to residue management is available for guiding the decision making processes of local farmers. In our study, we used hand planting or specially designed planters/drills for small-plot seeding. All plots were sampled and harvested by hand in accordance with common farming practices adopted by farmers in the local region.

All plots were managed similarly except for treatment practices. All crops were planted and harvested by hand except for winter wheat (different planters were used under conventional tillage and no-till treatments). For T and TS treatments, all plots were plowed at a 30-cm depth before each planting using a chisel plow followed by manual mixing, smoothening, and conditioning using hand tools (e.g. shovels, hoes, and rakes). Soils under NT and NTS treatments remained undisturbed throughout the experimental period. Within each crop rotation cycle, ‘Zhongdan NO. 2’ maize was hand-planted in early April at a seeding rate of 30 kg ha^{-1} (Pure Live Seed, PLS) with a row spacing of 0.40 m. Starter fertilizer (diammonium phosphate, 18-46-0) was applied by hand at a rate of 300 kg ha^{-1} at planting. Urea N fertilizer (46-0-0) was applied at a rate of 300 kg ha^{-1} when the majority of maize plants reached V6 development stage (Abendroth et al., 2011). Maize was harvested manually in September and the remaining stalks were removed from the field by hand (T and NT) or shredded into 15-cm long pieces using a corn stalk shredder and returned evenly back to the original plots (TS and NTS).

‘Xifeng NO.24’ winter wheat was planted in late September immediately after maize harvest using a ‘Jinniu 2BF’ no-till drill (Jinniu Manufacturing Co., Qingyang, Gansu Province, China) under no-till treatments (NT and NTS) or a Xingnong drill (Xiguan Manufacturing Co., Baoji, Shanxi Province, China) after tillage treatments (T and TS). The seeding rate was 187 kg ha^{-1} PLS with a row spacing of 0.15 m. Starter fertilizer (diammonium phosphate) was applied at a rate of 300 kg ha^{-1} below the seed using a fertilizer coulter attached to the drill. Urea fertilizer was surface-broadcasted by hand at a rate of 150 kg ha^{-1} at the green-up stage (Feekes 4–5; Miller, 1999). Wheat was hand-harvested in late June of the following year with 30-cm tall stubbles left in the field. Depending on treatments, stalks within each plot were either removed (T and NT) or returned back to the field after reaping (TS and NTS).

‘Fengshou NO.12’ soybean was planted manually at a rate of 15 kg ha^{-1} PLS with a row spacing of 0.25 m immediately after winter wheat harvest in late June or early July. Banded starter fertilizer (Calcium superphosphate, 0–26-0) was applied at a rate of 63 kg ha^{-1}. Hand harvesting of soybean was completed by late October. The remaining stalks were either removed (T and NT) or left in the field (TS and NTS) according to treatment. All plots were hand-weeded periodically throughout the growing season and a one-time broadcast application of 3 kg ha^{-1} a.i. of Triadimefon [1-(4-Chlorophenoxy)-3,3-dimethyl-1-(1H-1,2,4-triazol-1-yl)-2-butanone] was used in 2003 for an insect outbreak.

2.3. Data collection

2.3.1. Meteorological measurements

Meteorological data were recorded using a weather monitoring system installed at the center of the experiment field. Particularly, ambient air temperature and relative humidity were measured using a HMP-50 Probe (Campbell Sci., Inc. Logan, UT). Net radiation was measured by a net radiometer (CNR-I, Kipp and Zonen Inc., Saskatoon, Saskatchewan, Canada). Rainfall was recorded using a rain gauge (TE525MM, Campbell Sci., Inc. Logan, UT). All variables were measured every ten seconds and 30-min average values were stored by a CR5000 data-logger (Campbell Sci., Inc. Logan, UT).

2.3.2. Crop yield

At each harvest, maize, wheat and soybean samples were taken randomly from three quadrats within each treatment replicate away from the plot edges during maturity stage for calculating crop yield, measured as 0.76, 0.3 and 0.25 m^2, respectively. Sampling protocol for each crop was exactly the same as what was described in Section 2.2.

All samples were reaped, threshed, and winnowed manually. Fresh weight of grain was recorded immediately following harvesting and then dried in an oven at a temperature of 40 °C to a constant weight to calculate grain yield.

2.3.3. Soil moisture level and crop water use efficiency

Soil moisture was measured every 2 weeks in the following layers: 0–10, 10–20, 20–30, 30–60, 60–90, 90–120, 120–150, and 150–200 cm using a neutron probe (NMM, Campbell pacific, HP503), The neutron probe readings were converted into volumetric water content according to the calibration curve. Samples at 0–10 cm were oven-dried at 105 °C for 48 h for calculating gravimetric soil water content. Seasonal evapotranspiration (ET, mm) was computed using the field water balance Eq. (1)

$$\mathrm{ET} = \mathrm{P} - \Delta\mathrm{S} \quad (1)$$

where P is precipitation (mm) and ΔS is the change in stored soil water of the soil profile (mm). Compared to conventional field water balance equation, our simplified version omitted many components including irrigation, upward flow into the root zone, surface runoff, and downward drainage out of the root zone. This is because on the Loess Plateau, the groundwater table remained at a depth of about 50 m below the surface, so the upward flow into the root was negligible. Runoff was never considered at this experimental site due to the lack of precipitation and flat topography. Additionally, there were no heavy rains or water logging events during the growing season, so drainage was assumed to be insignificant (Shen et al., 2009). Last but not the least, the entire study was conducted on a rainfed system, therefore, no irrigation was included. Water-use efficiency was calculated as (Hussain and Al-Jaloud, 1995):

$$\mathrm{WUE} = \mathrm{Y}/\mathrm{ET} \quad (2)$$

where Y is crop grain yield (kg ha^{-1}).

2.3.4. Soil organic carbon

Soil carbon samples were collected annually from the 0–10-cm top soil layer at 5-cm intervals during each harvesting season using an auger. Therefore, two sets of soil samples (during wheat and soybean harvesting seasons) were collected during odd years (2003, 2005, and 2007) and one from even years (2002, 2004, and 2006) and the initial year (2001). We averaged the soil carbon data collected from wheat and soybean harvests during odd yeas for consistency purposes. During each sampling, three sampling locations were randomly selected from within each plot. Therefore, six individual soil samples were collected from within each plot (3 locations × 2 depths). Then, all three samples from the same horizon (0–5 cm or 5–10 cm) were pooled into one sample and mixed evenly for analysis. Thus, each plot would have two pooled samples in total. The collected soil samples were dried at 36 °C for 48 h and passed

through a 2-mm sieve. Soil organic carbon concentration was determined by the external heating potassium dichromate oxidation method ($K_2Cr_2O_7$-H_2SO_4; Page et al., 1982). Specifically, each soil sample was weighed at 0.25 g and added in a test tube. Then, 5 ml of 0.167 M potassium dichromate and 5 ml of concentrated sulfuric acid were added and heated in a 180 °C oil bath for 5 min. After completion of the reaction, the excess potassium dichromate was titrated with 1.0 M ferric sulfate and the total potassium dichromate consumed was calculated to estimate total carbon dioxide emission.

2.4. Statistics and modeling

Statistical analyses were conducted using the MIXED procedure in SAS 9.4. All data was analysed as a Randomized Complete Block Design. Block effect was treated as random and year effect was treated as fixed effect to account for the erratic weather pattern on the Loess Plateau of China. Data were averaged over the years if no year-by-treatment interactions were detected. Differences were compared using Fisher's Least Significant Difference (LSD) method and evaluated at a $P = 0.05$ significance level. The relationships between WUE and various environmental factors were modeled by Path Analysis implemented using the CORR and REG procedures in SAS 9.4. Decision coefficient R^2 (j) (Eq. (3)) was used to quantify the comprehensive effect of environmental factor (X_J) on WUE (y). R^2(j) not only contains the effect of the direct decision function (R_j^2) of y on X_J, but also includes the indirect determination coefficient (ΣR_{ji}) associated with X_J.

$$R_{(j)}^2 = R_j^2 + \sum_{j \neq i} R_{ji}^2 \quad (3)$$

$$R_j^2 = b_j^{*2} \quad (4)$$

$$R_{ji}^2 = 2b_j^* r_{ji} b_i^* \quad (5)$$

Where b_j is the direct effect of X_J on y, which is equal to the direct path coefficient of X_J to Y, $2b_jr_{ji}b_i$ is the indirect effect of other environmental factors X_i on Y by X_J, which is equal to the indirect path coefficient. Contributive effect of each variable on y was represented by the absolute value of its corresponding $R_{(j)}^2$ values. The sign of R^2(j) indicated whether there is a positive or negative correlation between X_J and Y. The variable with the largest $R_{(j)}^2$ value was the main decision variable, or the main decision-making factor and the smallest variable (typically the one with the negative $R_{(j)}^2$) became the main restrictive variables, or called the main confined factor.

2.5. Economic analysis

This study considered the production budget for establishment, treatment implementation, maintenance, and harvest of different crops. Equipment-based farming operations (e.g. planting and tillage) were mainly carried out by regional Farmers' Cooperative and Extension Service agencies near the Loess Plateau Research Station. The hourly service charge included costs associated with labor, fossil fuel, capital recovery of equipment (depreciation and interest), insurance, machine storage, as well as repairing and maintenance of equipment. Material costs (seeds, fertilizers, herbicides, and straw residues) were calculated based on purchasing records from local farming supply companies or regional farmers' Cooperative and Extension Service agencies. Costs for labor-based operations such as fertilization, herbicides application, residual spreading, and harvesting were calculated based on standard individual hourly earnings at 3.64 USD/d at Xifeng, China during the experimental period and number of days required to complete the tasks. A detailed breakdown of costs is presented in Table 2. Output value/ha was calculated based on grain yield (kg ha^{-1}) under each treatment and market price of maize, wheat, and soybean grain obtained from China's National Agricultural Market Service Database (http://datacenter.cngrain.com) averaging at 0.15, 0.18, and 0.36 USD kg^{-1}, respectively.

3. Results

3.1. Meteorological characteristics

Monthly precipitation and long-term (1961–2013) average values at the study site during 2001–2007 are shown in Fig. 1. With the exception of yr 2002 and 2007, monthly precipitations from July to September accounted for more than 60% of the annual precipitation. Annual precipitation in of 2001 agreed with the long-term average. More rainfalls were observed in 2002, 2003, and 2007, which were 10, 46, and 5% higher than the long-term average, respectively; while values in 2004, 2005, and 2006 were 21, 13, and 8% lower than the long-term average, respectively. Changing patterns of total net radiation were similar at the study area during 2001–2007 (Fig. 2), which generally

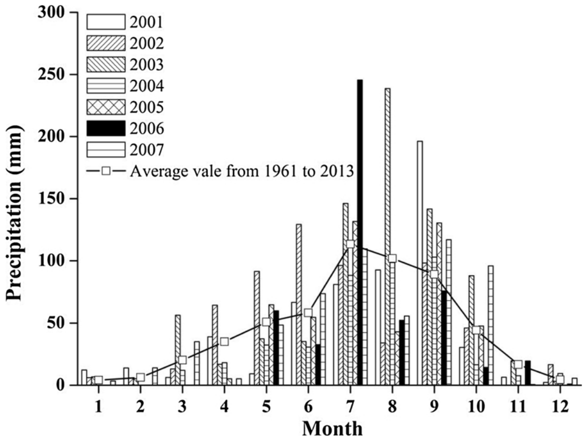

Fig. 1. Monthly rainfall from 2001 to 2007 and long-term average monthly rainfall (1961–2001) at the Qingyang Research Station, Gansu, China.

peaked between May and July due to the high solar elevation angle. Total net radiation in 2003 and 2007 was 6% and 10% lower than the long-term average, respectively. In 2001, 2002, 2004, 2005, and 2006, net radiation was 6, 13, 4, 8, and 4% higher than the long-term average, respectively. Monthly temperature patterns were similar during 2001–2007 at the study site, which also agreed with the long-term values (Fig. 3). Maximum monthly average temperature generally occurred in July and August, and minimum in January. During the experimental period, monthly average temperature ranged from −6.8 to 23.1 °C. The overall average annual temperature was 9.2 °C.

3.2. Crop yield

Three crop rotations (three spring maize-winter wheat-summer soybean cycles) were completed following a summer soybean production in 2001. Averaged over years, the overall grain yield (sum of the average annual grain yield of all three crops) was greatest under TS treatment, which was 17% ($P < 0.05$), 9% ($P < 0.05$) and 5%

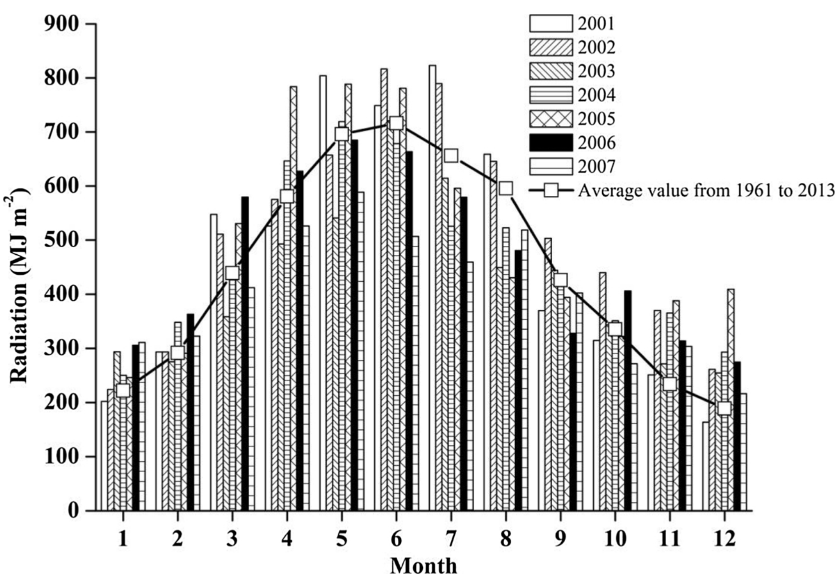

Fig. 2. Monthly net radiation from 2001 to 2007 and long-term average monthly radiation (1961–2013) at the Qingyang Research Station, Gansu, China.

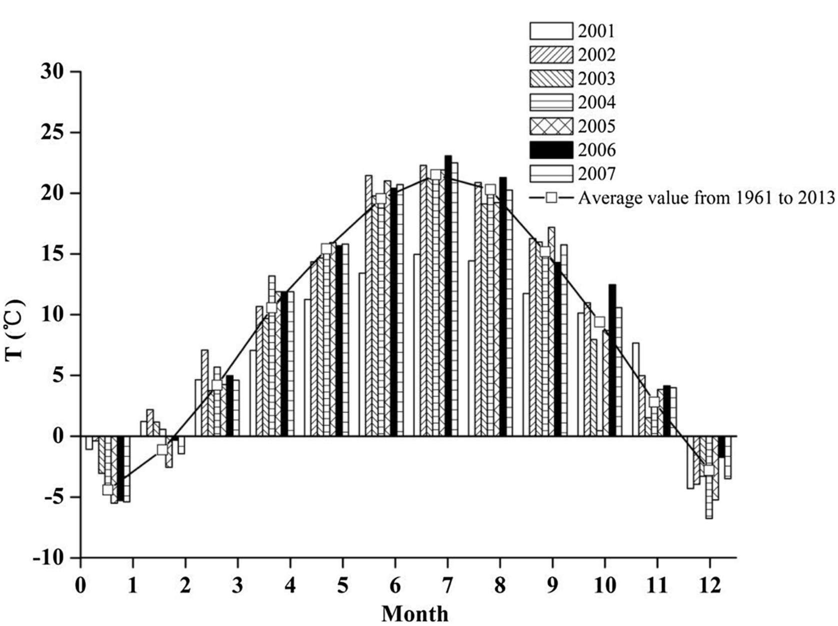

Fig. 3. Monthly temperature from 2001 to 2007 and long-term average monthly temperature (1961–2013) at the Qingyang Research Station, Gansu, China.

Table 1
Grain yield of maize, winter wheat and soybean of a rotation system under different tillage and crop residue retention treatments during 2001–2007 at Xifeng, Gansu, China. Letters separate means based on $P < 0.05$ level by pair-wise comparison within each harvesting season.

Harvesting Time	Grain (Mg ha^{-1})	T[a]	TS	NT	NTS
October 2001	Soy	1.99 ± 0.18[a]	2.01 ± 0.22[a]	1.73 ± 0.11[a]	2.11 ± 0.21[a]
September 2002	Maize	9.05 ± 0.17[a]	9.27 ± 0.42[a]	9.40 ± 0.24[a]	9.25 ± 0.29[a]
June 2003	Wheat	3.36 ± 0.17[a]	2.90 ± 0.25[a]	3.33 ± 0.26[a]	3.07 ± 0.48[a]
October 2003	Soy	1.01 ± 0.08[ab]	1.24 ± 0.14[a]	0.78 ± 0.09[b]	1.18 ± 0.10[a]
September 2004	Maize	7.47 ± 0.25[ab]	8.67 ± 0.40[a]	6.66 ± 0.21[b]	7.73 ± 0.30[ab]
July 2005	Wheat	3.55 ± 0.15[a]	3.91 ± 0.26[a]	3.23 ± 0.21[a]	3.64 ± 0.36[a]
October 2005	Soy	1.17 ± 0.08[b]	2.07 ± 0.10[a]	1.25 ± 0.08[b]	1.50 ± 0.07[b]
September 2006	Maize	3.92 ± 0.24[a]	4.41 ± 0.28[a]	3.51 ± 0.26[a]	3.97 ± 0.21[a]
June 2007	Wheat	3.86 ± 0.28[a]	4.09 ± 0.19[a]	2.91 ± 0.28[b]	3.73 ± 028[a]
October 2007	Soy	0.97 ± 0.06[c]	1.40 ± 0.05[ab]	1.07 ± 0.04[bc]	1.79 ± 0.09[a]

[a] Treatment includes: T = conventional tillage; TS = conventional tillage followed by straw mulching; NT = no-till; NTS = no-till followed by straw mulching.

($P < 0.05$) greater than those under NT, T and NTS treatments, respectively (data derived from Table 1). Yield under NTS treatment was 11% and 4% greater than those under NT and T treatments, respectively. Grain yield under NT treatment was the lowest, which was 7% ($P < 0.05$) lower than that under T treatment. The effects of tillage practices on grain yield depended on crop species (treatment × species, $P = 0.096$) and year (treatment × year, $P = 0.165$). Therefore, yield was further analysed by year and species (Table 1). The first-round yield of all three crops (October 2001 to June 2003) showed no significant differences among treatments. Soybean yields under TS and NTS treatments were greater than NT treatment in 2003. In 2005, TS treatment provided greater soybean yield compared with all other treatments. Interestingly, greatest soybean yield was observed under NTS treatment in 2007, whose value was similar to TS treatment but significantly greater than NT and T. Additionally, TS treatment increased soybean yield compared to T in the same year. In 2004, maize yield under TS treatment was 30% greater than that under NT treatment. A consistent decrease in maize yield was observed across all treatments over the years. No treatment effects were found in wheat yield until 2007. The NT treatment provided lower wheat grain yield compared to all other treatments and the average grain yield was 3.46 Mg ha^{-1}, which was similar to other winter wheat studies conducted in the North China Plain (Zhang et al., 2016b).

3.3. Soil moisture and WUE

Inter-annual variation of soil moisture at different depths depended greatly on precipitation, managerial practice, and crop water uptake (Fig. 4). For maize, with a common sowing season in mid-April, soil moisture at the deep profile will not be accessed during the early growing season. However, little recharge due to no precipitation between January and April of 2006 resulted in a lower soil moisture level than previous years. Soil moisture level at the 0–90 cm depth was almost exhausted in 2002, and relatively greater in the topsoil (0–20 cm) of 2004 and in the 0–90 cm layer of 2006 (Fig. 4). During the winter wheat harvesting stage, inter-annual variation of soil moisture was relatively large. Particularly in 2003, the soil moisture level within the 0–200-cm soil profile was mostly depleted. In 2005, soil moisture below the 90–200 cm layer also approximated the permanent wilting point. In both 2001 and 2007, soil moisture levels across all soil layers appeared to be sufficient (Fig. 4). During the soybean harvesting stage, soil moisture was relatively abundant, and its values at all levels in most of the years were high, with slightly lower numbers in 2005 and 2007, compared with other harvesting seasons. There were no significant differences in average water storage during the growing seasons among different treatments (Fig. 5). Averaged across all species, soil water storage under T, TS, NT, and NTS treatments was 432, 445, 434, and 435 mm, respectively.

Crop WUE depended greatly on species ($P < 0.05$), years ($P < 0.05$), and species-year interactions ($P < 0.05$). Therefore, WUE results were presented by year and species. In both 2004 and 2006, maize under TS treatment indicated greater WUE compared with NT (Fig. 6). Water use efficiency of wheat under NT treatment was greater than TS in 2003. Interestingly, both NT and NTS treatments resulted in lower WUE than TS treatment in 2005. In 2007, lowest wheat WUE was observed from NT treatment compared to other treatments. For soybean, TS treatment increased WUE than NT in 2003. NTS treatment resulted in greater WUE than T, and TS treatment provided greater

Table 2
A seven-year average cost breakdown of maize-winter wheat-soybean production under different tillage treatments during 2001–2007 at Xifeng, Gansu, China.

Costs (USD/ha)	Maize				Wheat				Soybean			
	T[a]	TS	NT	NTS	T	TS	NT	NTS	T	TS	NT	NTS
Seeds	143				56				73			
Herbicides	37				12				18			
Fertilizers	178				79				94			
Planting[b]	38				28				27			
Labor[c]	46	58	46	58	37	45	37	45	43	50	43	50
Tillage[d]	134	134	0	0	67	67	0	0	72	72	0	0
Straw residues[e]	0	10	0	10	0	25	0	25	0	18	0	18
Total	576	598	442	464	279	312	212	245	327	352	255	280

[a] Treatment includes: T = conventional tillage; TS = conventional tillage followed by straw mulching; NT = no-till; NTS = no-till followed by straw mulching.
[b] Planting cost includes rental charge of planter, driver's wage, and fuel costs.
[c] Labor cost includes manual labor inputs for fertilization, harvesting, and application of herbicides and plant residues.
[d] Tillage cost includes rental charge of tractors and tillage equipment, driver's wage and fuel costs.
[e] No purchase was made for straw residue because sufficient quantity was obtained after each harvest. However, as a production input, its value was still calculated according to the current market value and included in the standard economic analysis.

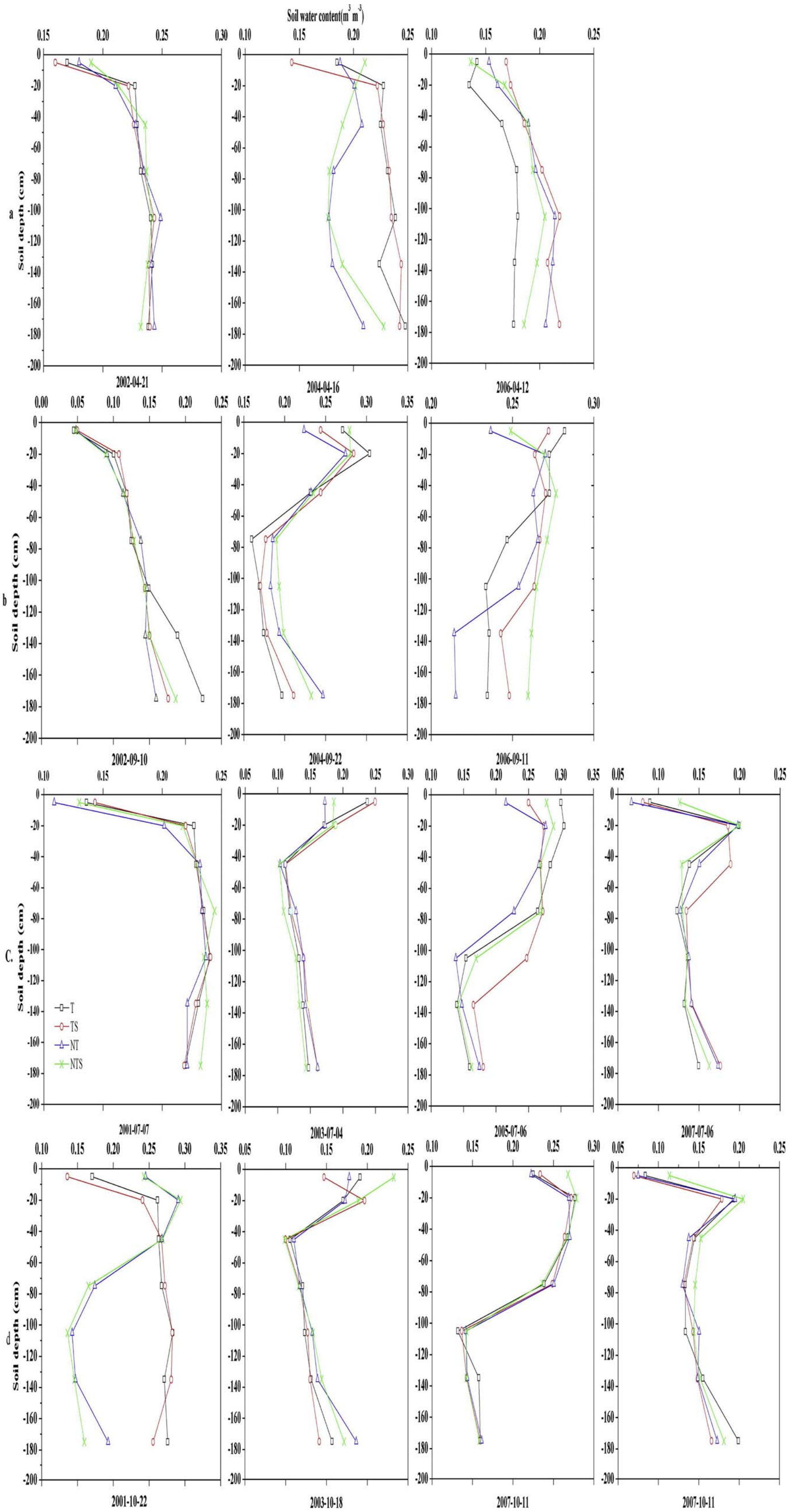

Fig. 4. soil water content of a maize-winter wheat −soybean rotation system under different tillage and crop residue retention treatments (T = conventional tillage; TS = conventional tillage followed by straw mulching; NT = no-till; NTS = no-till followed by straw mulching.) during 2001–2007 at Xifeng, Gansu, China. Soil was sampled at: a). maize sowing date, b). maize harvest time (winter wheat sowing time), c) winter wheat harvest time (soybean sowing time), and d. soybean harvest time.

WUE than both NT and T treatments in 2005. In 2007, NTS treatment had greater WUE than either T or NT treatment. No statistical differences were found in 2001.

3.4. Soil organic carbon

Soil organic carbon concentration depended greatly on treatment, year, and soil depth ($P < 0.001$). Two-way interactions

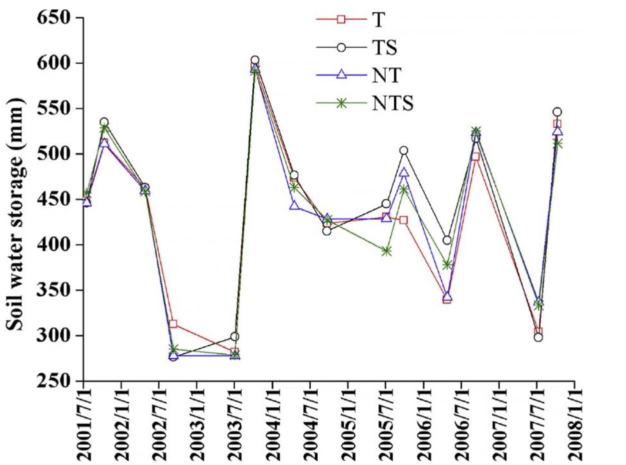

Fig. 5. Soil water storage of 0–200 cm under a maize-winter wheat −soybean rotation system affected by different tillage and crop residue retention treatments (T = conventional tillage; TS = conventional tillage followed by straw mulching; NT = no-till; NTS = no-till followed by straw mulching) during 2001–2007 at Xifeng, Gansu, China.

(treatment × year, treatment × soil depth, year × soil depth) were detected ($P < 0.05$). Therefore, data were presented by year and sampling depth (Table 3). The overall treatment effect became more apparent over the years (Table 3). Interestingly, SOC concentration at different depths indicated slightly different responses to treatments. No statistical differences were detected across all depths until 2004. For the top soil layer (0–5 cm depth), NTS treatment increased SOC concentration compared with T in 2004. In 2005, soil under NTS treatment had greater SOC concentration than both NT and T treatments. Additionally, TS treatment increased SOC concentration than T. In both 2006 and 2007, NTS treatment produced the greatest SOC concentration. Both TS and NT treatments resulted in greater SOC concentration than T. For the 5–10-cm soil layer, TS treatment increased SOC concentration compared with T in 2004 and 2006. No treatment effect was detected in 2005. In 2007, SOC concentration under TS treatment was greater than NT and T treatments. Additionally, both NT and NTS treatments indicated greater SOC concentration than T.

3.5. Modeling and economic analysis

The $R^2_{(j)}$ value of ecological factor "biomass" was the largest across all treatments in determining the average WUE (Fig. 7). The $R^2_{(j)}$ value of "net radiation" (R) was the lowest (but with the largest absolute value) across all treatments, years, and species; indicating that net radiation is the most confined factor in determining

On a system basis, total output values of different tillage practices ranged from 1982 USD ha^{-1} in NT treatment to 2376 USD ha^{-1} in TS treatment (Table 4). These values resembled the grain yield data. The TS treatment provided the greatest average output revenues compared to others and the NT treatment provided the lowest regardless of crop species. The total input value for TS treatment was greater than others. The NTS treatment provided the second highest yield and required second lowest inputs, leading to higher economic profit (expressed as an output/input ratio and benefit difference) than other treatments. The NTS treatment increased economic benefit by 350, 185 and 226 USD ha^{-1} compared with T, TS and NT treatments; respectively.

4. Discussion

4.1. Effects of conservation tillage on crop yield

The effects of no tillage on soybean or maize yield were not as obvious as straw mulching. For example, when comparing the yield differences between T vs. NT and TS vs. NTS, only soybean yield in 2005 and wheat yield in 2007 indicated statistical differences. However, when comparisons were conducted between T versus TS and NT versus NTS, wheat yield in 2007 and soybean yield in 2003, 2005, and 2007 indicated statistical differences. Throughout the experimental period, adoption of straw mulching practices (TS and NTS) consistently provided greater or similar grain yield than both T and NT treatments regardless of crop species primarily due to the superior infiltration capacity and reduced evaporation on the residue-covered soil surface. Additionally, it was well documented that conservation tillage combined with straw mulching can provide enhanced soil moisture retaining effect, thus, ensuring stable crop yield even in dry climate conditions (Mrabet et al., 2012; Zhang et al., 2014). Similar results were also observed in other studies. Huang et al. (2006) stated that the significant increase in crop yield under NTS treatment was mainly caused by reduced soil evaporation and accelerated accumulation of organic matter during the growing season. Su et al. (2007) showed that NTS treatment could improve soil moisture and WUE during the sowing stage and increase crop production. A similar study conducted by Huang et al. (2006) indicated that mere no-till practice did not improve crop yield; however, the combination of no-tillage and straw mulching achieved good economic and ecological benefits under the semiarid weather condition in the Loess Plateau area. Likewise, Shao et al. (2016) indicated that NTS conservation tillage combined with straw mulching increased maize and wheat yield by 17 and 10%, respectively.

The below-average precipitation during the 2007 soybean growing season resulted in lower yield across all treatments except for NTS, which provided even greater yield than the previous year. Winter wheat appeared to be less responsive to treatments compared to soybean and maize. No significant wheat yield differences were detected until the last rotation cycle in 2007. In general, experimental effects became more obvious across all three crops over the years, indicating a lag time in the response of yield to various tillage and straw mulching methods under local climate conditions. This emphasizes the importance of conducting long-term rotation cropping system study in the semiarid Loess Plateau region.

In our study, slight yield advantages under T treatments than NT were observed during soybean production in 2005 and wheat production in 2007. Additionally, compared with T treatment, average wheat yield under NT treatment decreased by 7%, particularly in the last year (24% yield reduction). This is mainly caused by the increased soil compaction under no-till conditions, which leads to compromised soil structure and reduced fertilizer use efficiency. Similar trends were found in maize but not as obvious as winter wheat indicating winter wheat might be more susceptible to soil compaction under the local climate conditions.

4.2. Soil moisture and water use efficiency under different tillage treatments

Soil moisture content was not significantly affected by treatments largely because this is a dryland-based study. Crops were growing in a water-deficit condition, therefore, utilizing soil moisture in the shallow profile rapidly. Additionally, limited precipitation significantly limited infiltration and soil moisture percolation, leading to very little recharging during the experimental period. We expected more obvious treatment effect on soil moisture status if water supply (precipitation) was sufficient. For example, in an irrigated study, Hu et al. (2016) found that conservation tillage with improved crop residue management practices successfully increased pre-sowing soil moisture by 7% and 10% during the growing season within a maize-wheat rotation system in the eastern part of the Hexi Corridor of China. Interestingly, in another dryland winter wheat monoculture study on the Loess Plateau, Su et al. (2007) observed significant improved in-season/post-season soil water conservation under similar NTS treatment than T in addition to yield responses. We thought the lack of response on soil moisture storage in our study was primarily because of the increased

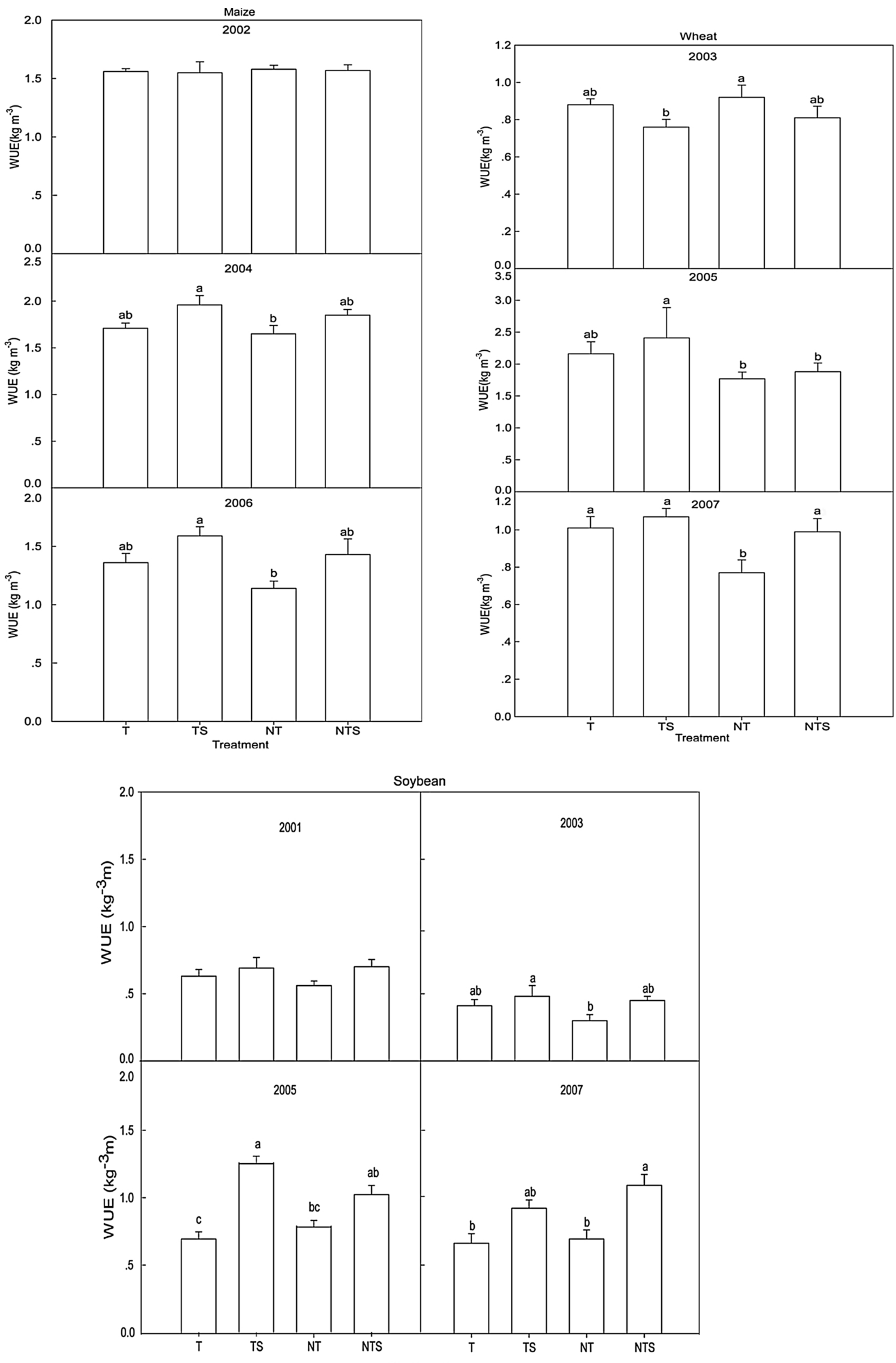

Fig. 6. Crop water use efficiency of a maize-winter wheat –soybean rotation system under different tillage and crop residue retention treatments (T = conventional tillage; TS = conventional tillage followed by straw mulching; NT = no-till; NTS = no-till followed by straw mulching) during 2001–2007 at Xifeng, Gansu, China. Letters separate means based on $P < 0.05$ level by pair-wise comparison within each harvesting season.

Table 3
Soil organic carbon (%) of 0–5, 5–10 cm under a maize-winter wheat –soybean rotation system affected by different tillage and crop residue retention treatments during 2001–2007 at Xifeng, Gansu, China. Letters separate means based on $P < 0.05$ level by pair-wise comparison within each sampling.

Soil depth	Year	Treatment[a]			
		T	TS	NT	NTS
0–5 cm	2001	0.63^{a}	0.66^{a}	0.67^{a}	0.66^{a}
	2002	0.66^{a}	0.69^{a}	0.70^{a}	0.69^{a}
	2003	0.67^{a}	0.71a	0.70a	0.76^{a}
	2004	0.69^{b}	0.82^{ab}	0.75^{ab}	0.85^{a}
	2005	0.61^{c}	0.71^{ab}	0.66^{bc}	0.77^{a}
	2006	0.64^{c}	0.76^{b}	0.76^{b}	0.91^{a}
	2007	0.68^{c}	0.81^{b}	0.86^{b}	1.05^{a}
5–10 cm	2001	0.67^{a}	0.66^{a}	0.68^{a}	0.66^{a}
	2002	0.66^{a}	0.67^{a}	0.70^{a}	0.67^{a}
	2003	0.66^{a}	0.68^{a}	0.68^{a}	0.68^{a}
	2004	0.70^{b}	0.80^{a}	0.75^{ab}	0.75^{ab}
	2005	0.60^{a}	0.65^{a}	0.62^{a}	0.63^{a}
	2006	0.62^{b}	0.74^{a}	0.67^{ab}	0.71^{ab}
	2007	0.64^{c}	0.82^{a}	0.72^{b}	0.79^{ab}

[a] Treatment includes: T = conventional tillage; TS = conventional tillage followed by straw mulching; NT = no-till; NTS = no-till followed by straw mulching.

soil water depletion under rotational cropping in addition to limited precipitation.

Crop WUE was a broadly defined term and can be calculated using various methods (Nair et al., 2013) and its value can be greatly influenced by many crop physiological and environmental factors (Kurc and Small, 2004). In China, the majority of agronomic research interpreted crop WUE as the amount of yield or profit per unit of water usage (Huang et al., 2003a), which is very similar to what was originally proposed by Gregory (2004). A number of studies have been conducted in this region on crop WUE, including investigating the underlying mechanisms and influencing factors for improving crop WUE (Huang et al., 2002; Su et al., 2007), selecting crop varieties with high WUE (Gregory, 2004), adopting new field management practices, and using crop residual coverage and chemicals to increase crop WUE (Woodhouse and Johnson, 2001; Tong et al., 2009; Shao et al., 2016). In this research project, crop WUE indicated great responses to different tillage and residual management practices.

Particularly, straw mulching (TS and NTS) effectively maintained or increased WUE in the maize-wheat-soybean rotation system regardless of crop species. Our findings were consistent with findings from numerous previous studies (Huang et al., 2003a; Gilmour et al., 2004; Zhang et al., 2014), mainly through shifting the field water consumption from physical processes (evaporation) to biological processes

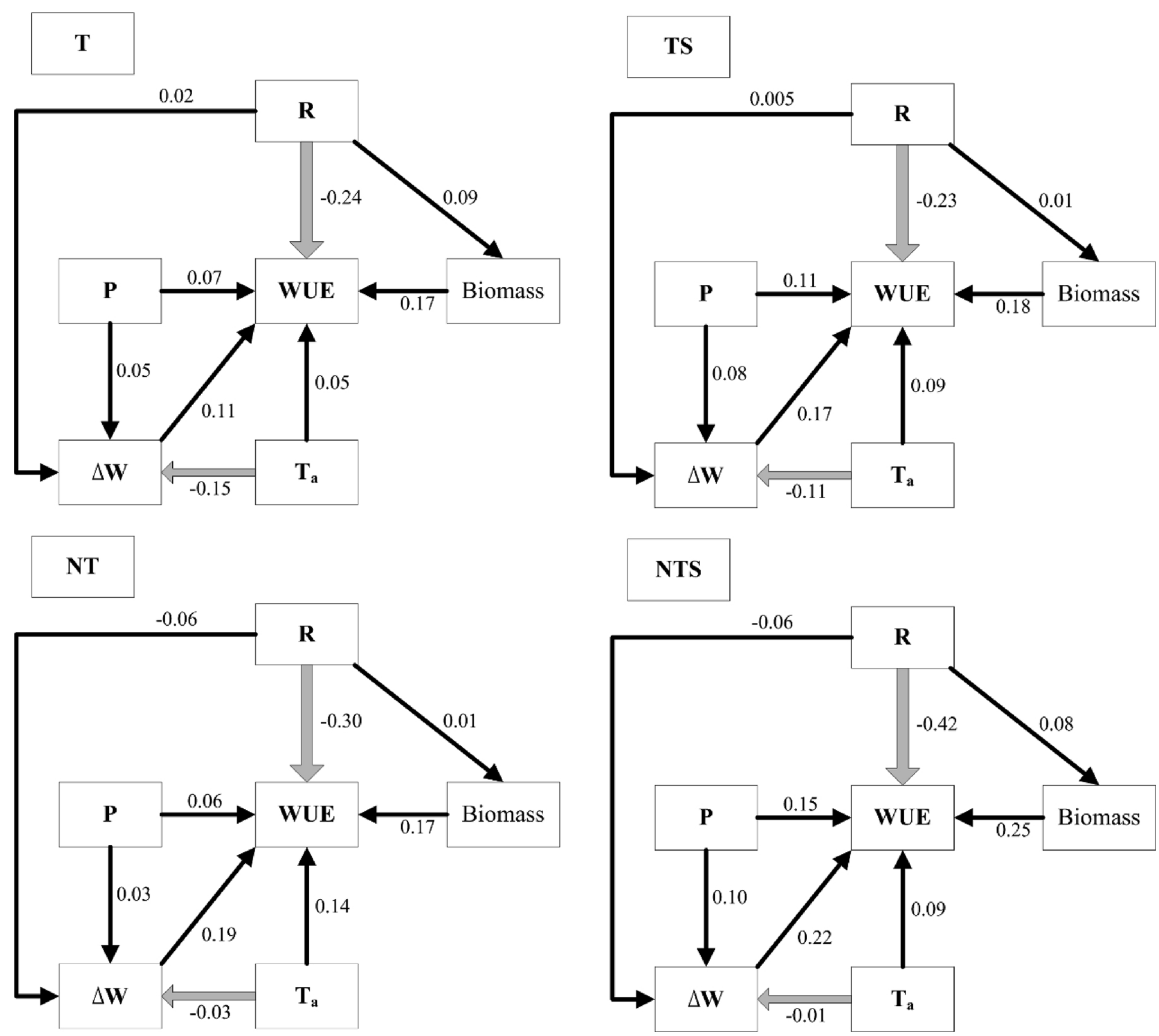

Fig. 7. Path diagrams illustrating the effects of included ecological factors on average crop water use efficiency (WUE) of a maize-winter wheat –soybean rotation system under different tillage and crop residue retention treatments (T = conventional tillage; TS = conventional tillage followed by straw mulching; NT = no-till; NTS = no-till followed by straw mulching.) during 2001–2007 at Xifeng, Gansu, China. Ecological factors include: net radiation (R), air temperature (T_a), precipitation (P), crop biomass (Biomass) and the difference of soil moisture between harvest time and sowing time. The value beside each arrow represented the path coefficient. The analysis was based on daily average values of all the environmental variables.

Table 4
Input and output values of a maize-winter wheat-soybean rotation system under different tillage and crop residue retention treatments during 2001–2007 at Xifeng, Gansu, China.

Treatment[a]	AY[‡]	OV[b]	IV	EB[c]	O/I[d]	BFD[e]
Maize						
T	6813[a]	1022[a]	576	446	1.77	0
TS	7451[a]	1118[a]	598	520	1.87	74
NT	6522[a]	978[a]	442	536	2.21	90
NTS	6986[a]	1048[a]	464	584	2.26	138
Wheat						
T	3590[a]	646[a]	279	367	2.32	0
TS	3633[a]	654[a]	312	342	2.10	−25
NT	3156[a]	568[a]	212	356	2.68	−11
NTS	3604[a]	649[a]	245	404	2.65	37
Soybean						
T	1285[ab]	463[a]	327	136	1.41	0
TS	1680[a]	605[a]	352	253	1.72	117
NT	1210[b]	436[a]	255	181	1.71	45
NTS	1642[a]	591[a]	280	311	2.11	176
Total						
T		2131	1182	949	1.80	0
TS		2376	1262	1114	1.88	166
NT		1982	909	1073	2.18	124
NTS		2288	989	1299	2.31	350

AY = 3-year yield (maize, wheat) average (kg ha^{-1}), 4-year yield (soybean) average (kg ha^{-1}); OV = output value (USD ha^{-1}); IV = input value (USD ha^{-1}); O/I = output/input; EB = economic benefit (USD ha^{-1}); BFD = benefit difference (USD ha^{-1}).
[a] Treatment includes: T = conventional tillage; TS = conventional tillage followed by straw mulching; NT = no-till; NTS = no-till followed by straw mulching.
[b] OV = output value (USD ha^{-1}), calculated based on market grain price (maize = 0.15 USD/kg, wheat = 0.18 USD/kg, soybean = 0.36 USD/kg).
[c] EB = economic benefit (USD ha^{-1}), calculated as OV– IV.
[d] O/I was calculated as OV/IV ratio.
[e] BFD was calculated as EB difference from the T treatment.
[‡] AY = average grain yield (kg ha^{-1}).

(transpiration), thus improves WUE of crops (Li et al., 2002). Particularly, Shao et al. (2016) reported that NTS treatment could increase WUE of winter wheat and maize by 24 and 15%, respectively in the North China Plain in a maize-winter wheat rotation research. Previous studies also have pointed out some negative effects of straw mulching practices on WUE, primarily caused by indirect effects such as reduced yield from soil pathogen problems (Cook and Haglund, 1991), which were not observed in this study.

4.3. Soil organic carbon affected by straw mulching

Soil organic carbon is an important indicator of soil quality and soil health. Conservation tillage reduces soil disturbance and slows mineralization of soil organic matter (Liu et al., 2014). Straw mulching can effectively return organic substrates back to the soil for supporting microbial activity and increase SOC reserve over time (Sun et al., 2011). The results from this study showed that combining both practices can effectively increase SOC content in the 0–5-cm soil layer by the end of year 6, and NTS treatment indicated the most significant effect compared with all other treatments. Our research findings were very similar to another study also conducted in the Loess Plateau region, where Chen et al. (2009) found that similar NTS treatment could increase SOC by 14% than conventional tillage without residue cover. Additionally, treatment effect on SOC in the 0–10 cm surface soil layer became significant only by the end of the fourth year, which agrees with previous studies indicating that SOC takes an extended period of time to respond to short-term managerial practices (Cui et al., 2014) and the responses typically appear in the top soil layer first (Álvaro-Fuentes et al., 2014). Additionally, NT and NTS treatments had greater SOC content at the 0–5 cm soil layer than 5–10 cm. Interestingly, TS treatment indicated lower 0–5 cm SOC content than 5–10 cm soil layer. This is mainly due to the enhanced stratification of SOC under limited or no-till practices, which make SOC accumulate and mainly concentrate in the surface layer of soil profile (Qin et al., 2006). At the deeper soil profile (5–10 cm), TS treatment tended to produce equal or more SOC than other treatments and this effect started to become significant by the end of year 4. This makes perfect sense because tillage will place crop residue in the soil profile and increase access by the microbial community.

4.4. Water use efficiency in relation to environmental factors

Environmental factors (solar radiation, ambient air temperature, precipitation, etc.) directly affect carbon, energy, and hydrological dynamics on an agroecosystem basis, therefore playing important roles in determining crop WUE (Rajan et al., 2013, 2015). Understanding the complex interplay and dynamics of different external factors in determining crop yield and WUE requires modeling-based simulation approaches. Path analysis is a statistical method that partitions the correlation between predictors and response variables into direct and indirect effects (Bernstein et al., 1988). It overcomes the limitation of the simple linear relationship assumption between two variables by adopting multivariate correlation-based analysis. It also resolves the issue that the causality effect could not be directly compared in multiple regression analysis because the units in the partial regression coefficient are usually different. Path analysis has been used extensively in agronomic studies (Huxman et al., 2004; Okuyama et al., 2004; Li et al., 2006; Saito et al., 2009; Munawar et al., 2013; Mhoswa et al., 2016). Although many studies used it to evaluate yield formation in cereals, little information exists on assessing the contributions of different environmental factors on crop WUE on the Loess Plateau of China.

In this study, we employed the path analysis method to study the effects of solar radiation, soil moisture changes, air temperature, precipitation, and plant biomass on WUE in this rotation cropping system. The results indicated that "biomass" was the main factor determining crop WUE in this study. In other words, crop productivity *per se* is the most critical factor in determining WUE, which agrees with many previous studies (Osmond et al., 1980; Tanner and Sinclar, 1983). The difference in WUE among different crop species under similar environmental conditions is primarily caused by difference in photosynthetic pathway (in general, CAM > C4 > C3). Although, interspecific WUE difference was not the main focus for this study, we did observe that maize (a C4 crop) consistently provided higher WUE than soybean and wheat (both are C3). The $R2_{(j)}$ values of biomass to WUE under TS and NTS treatments were significantly larger than those under T and NT treatments (Fig. 6), indicating that the contribution of biomass on WUE was more significant under TS and NTS treatments. This also verified that straw mulching practices helped improved soil moisture condition and consequentially made soil moisture content a less limiting factor (biomass productivity more important) in determining crop WUE.

Interestingly, path analysis also indicated that net radiation (R) was the main confined factor for determining WUE in this maize-wheat-soybean rotation system, which is in agreement with the results reported by Tong et al. (2009) in a summer maize study and by Zhang et al. (2011) in another alpine shrub meadow ecosystems study. The reason for the negative correlation between R and WUE was two-fold. On one hand, lower net solar radiation with lower light intensity can actually increase scattered radiation within the canopy, making photosynthetic activity at the bottom of the canopy more effective, thus enhancing the overall radiation use efficiency (Gu et al., 2003). On the other hand, under intense solar radiation conditions of semiarid environment, as net radiation energy decreases, latent heat flux in the form of evaporation and transpiration will also decrease (Law et al., 2002), leading to conserved liquid water and higher WUE (Yield/ET) under similar crop yield. In the semiarid East Gansu area on the Loess Plateau, radiation was typically not the limiting factor for crop production due to the lack of precipitation and cloud cover throughout the growing season. However, too much radiation can lead to crop water/heat stress and intense soil evaporation. Hence, using necessary soil coverage such as straw mulching and no-till practices could reduce soil evaporation, conserve water, and improve crop WUE as indicated in this study.

4.5. Economic impact

The economic profitability of adopting conservation tillage and straw mulching practices in the semiarid region can be greatly affected by many factors, such as planting density, presence or encroachment of weeds, variety selection, weather conditions, as well as labor and other input costs (Janosky et al., 2002; Cui et al., 2014). The use of conservation tillage is generally considered profitable because of moderate yield and reduced farm inputs (Zentner et al., 2002; Lithourgidis et al., 2006). This economic benefit was also observed in our study. Particularly, the NTS treatment generated the greatest economic benefit despite of its moderate grain yield compared with T and TS treatments. This is mainly achieved through the combination of moderate total energy expenditure associated with no-till practices and satisfactory grain yield. The largest expense for all treatments were fertilizer costs (almost 30% of the total production cost across all species) largely driven by the rising fossil fuel price in recent years. Therefore, improvement on nutrient use efficiency should hold great promises for increasing the long-term economic profitability. Overall, the farm-level economic analysis provided great insights into trends and tendencies that are likely to be observed across local producers and policy makers

5. Conclusion

This long-term study evaluated the effects of four different tillage × residual straw mulching practices on the productivity, WUE, soil carbon/water, and economic return of a maize-wheat-soybean rotation system in the Loess Plateau region of China. No-tillage combined with straw mulching provided comparable or even improved yield and WUE over the years. No significant yield difference was detected between no-till and conventional tillage treatments except for winter wheat during the last growing cycle. Residual straw mulching significantly increased SOC at both shallow and deep soil profiles at the end of the experimental period. Water use efficiency was greatly affected by a variety of environmental factors. Path analysis indicated that crop yield and net solar radiation had the main impact on determining the crop WUE. Therefore, breeding and selecting cultivars with high yield potential and adopting managerial practices that can improve soil moisture retention under local climate conditions should be pivotal. Consistent economic advantages were also found though incorporation of both no tillage and straw mulching practices, thus, more extension effort was warranted to communicate research findings to local farmers, stake holders, and policy makers. The limited treatment responses from the initial years emphasize the importance of conducting long-term cropping system study in the semiarid environment. Future research work should also evaluate the full-scale carbon budget, life cycle analysis, greenhouse gas emission, and energy flow and partitioning on an agroecosystem basis.

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