PHILIPP AGRIC SCIENTIST
Vol. 103 No. 1, 38-46
March 2020

ISSN 0031-7454

Effect of Tillage Systems on Soil Properties and Yield of Wheat and Rice in Rotation

Shumin Liang[1], Ruizhi Xie[2], Zhu Zheng[3], Muhammad Abdul Rehman Rashid[4], Yonglu Tang[5], Yuee Liu[2], JinzhongYang[6], Chaosu Li[5], Bing Chen[7] and Shaokun Li[2,*]

[1]Industrial Crops Research Institute/Potato Engineering Technology Research Center of Yunnan Province, Yunnan Province Academy of Agricultural Sciences, Kunming Yunnan, China, 650205
[2]Key Laboratory of Crop Physiology and Production, Ministry of Agriculture/Institute of Crop Science, Chinese Academy of Agricultural Sciences, Beijing, China, 100081
[3]Yunnan Vocational and Technical College of Agriculture, Kunming, Yunnan, China, 650220
[4]University of Agriculture Faisalabad, Subcampus Burewala, Pakistan 61010
[5]Institute of Crop Science, Sichuan Academy of Agricultural Sciences, Chengdu, Sichuan, China, 610066
[6]College of Agronomy and Plant Protection, Qingdao Agricultural University, Qingdao, Shandong, China, 266109
[7]Xinjiang Academy Agricultural and Reclamation Science/Northwest Inland Region Key Laboratory of Cotton Biology and Genetic Breeding, Ministry of Agriculture/Shihezi, Xinjiang, China, 832000

[*]Author for correspondence; e-mail: lishaokun@caas.cn

Effect of four tillage systems (1) winter wheat and rice rotary tillage (WRRT) (CK), (2) winter wheat and rice no-tillage system (WRNT), (3) winter wheat no-tillage and rice rotary tillage (WNRR), and lastly, (4) winter wheat and rice no-tillage in a raised bed (WRNB) on soil properties and crop yields was investigated in a field experiment in 2004–2010 in a wheat-rice crop rotation on the Chengdu Plain, China. The WRNT system significantly increased the saturated hydraulic conductivity and water infiltration relative to the WNRR and the WRRT (CK) systems. The soil cone penetration resistance was greater in certain soil layers beneath the three systems, compared to the CK system ($P < 0.05$). The three tillage systems also significantly increased soil erodibility K ($P < 0.05$) and soil organic matter (SOM) ($P < 0.05$) in certain soil layers but had no significant differences in the soil bulk density, total porosity, and specific gravity among the four tillage systems. Additionally, WNRR improved the wheat yield by 4.0% and rice yield by 8.8% relative to CK.

Key Words: conservation tillage, crop yield, soil degradation, soil properties, wheat-rice crop rotation

Abbreviations: SOM – soil organic matter, WNRR – winter wheat no-tillage and rice rotary tillage, WRNB – winter wheat and rice no-tillage in a raised bed, WRNT – winter wheat and rice no-tillage system, WRRT (CK) – winter wheat and rice rotary tillage

INTRODUCTION

The wheat-rice rotation system is the dominant cropping system used on the Chengdu Plain, China. However, many years of conventional tillage, based on "high input (inorganic chemical fertilizer, pesticide, water resources) consumption and high pollution," had a harmful effect on this region's environment (Wang 2006). The continued use of tillage cultivation and straw burning is known to increase erosion, desertification and salinization of soils in the region (Yang et al. 2004). Hence, a significant focus has been placed on efforts to facilitate a transition from traditional cultivation methods to those that are more sustainable.

The use of alternative tillage systems has been reported to change the structural characteristics of the soil (Liang 2010). For example, a no-tillage system combined with the return of straw residue reduces soil erosion and improves overall soil quality (Liu et al. 2010). Such practices also have a positive effect on the soil organic matter (SOM), surface roughness, moisture content, total porosity, aeration porosity, and soil strength limitations for root growth (Letey 1985; Benjamin et al. 2003), and reduce the soil bulk density and soil specific gravity relative to conventional tillage (Villamil et al. 2006). No-tillage systems also play a key role in the soil hydrophysical properties (Feng et al. 2011). For example, no-tillage enhances water infiltration (Chang and

Lindwall 1989; Dao 1993; Shaver et al. 2002; Hobbs 2007) and saturated hydraulic conductivity (Hill 1990). Use of no-tillage, in combination with straw mulching and direct seeding, reduces labour inputs and potentially harmful emissions resulting from the straw burning. Additionally, numerous studies have confirmed that soil physical and biological factors are major regulators of overall crop growth (Kirkegaard et al. 1994; Ferreras et al. 2000). The combination of the effects of no-tillage systems on these factors increases crop productivity as no-tillage increases the soil's water-holding capacity and aeration (Letey 1985; Benjamin et al. 2003).

Although no-tillage affects the soil properties, no consensus has been reached on the overall effects on crop yield (Wu et al. 2012). The effects have been demonstrated in wheat-rice rotation regimes in which wheat yield significantly increases under no-tillage (Zhuang et al. 1999; Tang et al. 2005; Liu et al. 2010). However, the effect of no-tillage on rice yield remains unclear (Saharawat et al. 2011). In fact, Shao et al. (2007) demonstrated that the rice grain yield and tiller number actually decreased under no-tillage. This trend was likely a result of water stress and increased soil infiltration rates that restrict water capture efficiency (Shaver et al. 2002). Previous studies have primarily focused on the effects of no-tillage on dry season crops (e.g., Shaver et al. 2002; Liu et al. 2010). The widely distributed wheat-rice crop coverage in China provided an opportunity to study crop yield and soil property responses to no-tillage in different cropping systems. The objectives of this study were to evaluate the cumulative effects of conventional systems (no crop residue coverage) and no-tillage (with crop straw coverage) systems by measuring the chemical and physical indicators of soil quality to evaluate soil quality in a long-term wheat-rice rotation, and to characterize the soil physical properties related to reduced rice growth and yield under long-term wheat-rice and no-tillage rotation system (WRNT).

MATERIALS AND METHODS

This long-term tillage field study was initiated in 2004 at the Lianshan Experimental Station, located in Jinhua Village (30°59′N, 104°24′E), Chengdu Plain, China. The soil was clay loam (alluvial loam) with the topsoil (pH 7.59) containing 39.9 g kg^{-1} SOM, 2.24 g kg^{-1} total nitrogen (N), 1.06 g kg^{-1} total phosphorus (P), 20.41 g kg^{-1} total potassium (K), 162.48 mg kg^{-1} alkali-hydrolyzable N, 19.67 mg kg^{-1} available P, and 116.37 mg kg^{-1} available K. Prior to the beginning of the study, the experiment site had been under conventional cultivation (wheat and rice with annual tilling) for over 100 yr.

The climate of the region is classified as "subtropical humid monsoon," with a mean annual temperature of 16.4 °C and rainfall of 910 mm (1954–2008), with 80% of the rainfall occurring between April and October. The monthly mean temperature and precipitation during the rice and wheat cycle during 2004–2009 and the long-term average (1954–2008) are presented in Tables 1 and 2.

Table 1. The description of experiment treatments.

Treatment	Description
WRNT	Wheat and rice both no-tillage with rice/wheat straw coverage and wheat seeded by a 2BJ-2 planter, and rice transplanted by hand.
WNRR	Wheat no-tillage with rice straw coverage and rice rotary tillage without wheat straw coverage, wheat seeded by a 2BJ-2 planter, and rice transplanted by hand.
WRRT (CK)	Wheat and rice both rotary tillage without rice/wheat straw coverage and wheat seeded by a 2BJ-2 planter, and rice transplanted by hand.
WRNB	Wheat and rice both ridge tillage (no-tillage, raised-bed planting) with rice/wheat straw coverage, wheat seeded by hand in prying holes, and rice transplanted by hand.

Table 2. Monthly mean temperature and precipitation during the rice cycle during 2004–2009 and long-term average (1954–2009)[a].

Month	Monthly Mean Temperature (ºC)		Mean Precipitation (mm)	
	2004-2009	1954-2009	2004-2009	1954-2009
May	22.3 ± 0.4	21.6 ± 0.1	85.9 ± 32.6	76.9 ± 7.4
June	24.8 ± 0.4	24.3 ± 0.1	74.8 ± 12.8	118.1 ± 16.5
July	26.6 ± 0.4	26.0 ± 0.1	228.6 ± 36.8	222.8 ± 14.4
August	25.8 ± 0.6	25.5 ± 0.1	126.3 ± 22.5	199.1 ± 12.9
September	22.5 ± 0.3	21.7 ± 0.1	143.4 ± 34.0	141.0 ± 12.8

[a]Source: http://cdc.cma.gov.cn/home.do

The experiment employed a randomized complete block design of four treatments with three replications (Table 4). The area of each treatment plot was 8.5 m × 10.5 m.

Initially, winter wheat cultivar 'Chuanmai42' was seeded by a 2BJ-2 planter on 30 October 2004 with an

Table 3. Monthly mean temperature and precipitation during the wheat cycle during 2004–2009 and long-term average (1954–2009)[a].

Month	Average Temperature (ºC)		Average Precipitation (mm)	
	2004-2009	1954-2009	2004-2009	1954-2009
October	17.5 ± 0.6	17.1 ± 0.1	47.4 ± 11.1	40.8 ± 2.9
November	12.7 ± 0.4	12.0 ± 0.1	11.7 ± 2.4	15.6 ± 1.8
December	7.5 ± 0.3	6.9 ± 0.1	5.1 ± 2.3	5.0 ± 0.6
January	5.7 ± 0.3	5.4 ± 0.1	10.2 ± 2.0	7.6 ± 0.8
February	8.8 ± 1.1	7.7 ± 0.2	7.7 ± 2.4	10.6 ± 1.1
March	13.1 ± 0.3	12.0 ± 0.2	20.1 ± 4.7	20.0 ± 1.4
April	18.4 ± 0.3	17.2 ± 0.2	50.9 ± 14.0	50.3 ± 4.6

[a]Source: http://cdc.cma.gov.cn/home.do

average seed rate of 150 kg ha^{-1}. For rice, the WRNB plot was planted with 30 × 42 rows of bundle seedlings and the WRNT, WNRR, and WRRT (CK) plots with 39 × 42 rows of bundle seedlings.

The average ratio of N:P:K was 135.0:37.2:32.0 kg ha^{-1} for wheat and 165.5:25.2:35.3 kg ha^{-1} for rice. In all plots, before sowing the wheat or transplanting the rice, the existing weeds were killed using pre-emergence herbicides (40% pretilachlor + bensulfuron-methyl, 750 g ha^{-1}). Weeds that emerged following wheat emergence were controlled via use of post-emergence herbicides (10% tribenuron-methyl, 150 g ha^{-1}) or were removed by hand in the rice fields.

At the end of the growing season for winter wheat in May 2009, three soil samples were collected from each plot at 0–10 and 10–20 cm intervals for determination of soil pH and SOM content. The soil samples were air-dried and sieved through a 2-mm sieve in the laboratory. The soil physical properties were determined using the cylinder method (Wei 1990). Three samples of intact soil cores from each plot were collected in 100-cm^3 stainless steel rings at depths of 0–10 and 10–20 cm and the soil bulk density, total soil porosity, capillary porosity, and non-capillary porosity were measured.

The saturated hydraulic conductivity was determined using the constant head technique (Dai 2008). Three undisturbed soil core samples were extracted from each plot from depths of 0–10 cm and 10–20 cm using stainless steel tubing (50.4 mm diameter × 50 mm length). The tubing was inserted into the soil until the upper edge of the tube was level with the soil surface, and extracted by hand (Feng et al. 2011).

The penetration resistance was determined with a SC-900 penetration resistance meter (Cone index; Spectrum Technologies, Inc., Plainfield, IL, USA) between rows at 5 cm increments from the soil surface to a depth of 45 cm. Five measurements were made at each position for each (18 May and 6 October) harvest of winter wheat.

The soil erodibility (*K* factor) was determined by placing 50 air-dried and weighed soil clods (5–7 mm diameter) on a 5-mm aperture sieve and subsequently immersing in water (Yu 2010). The number of cracked clods was counted at 1-min intervals for 10 min and the remaining soil was weighed after drying. *K* was determined from the equation:

$$K = 2.303/t^{*}\log X/X - x$$

where X is the weight of the 50 air-dried soil clods, x is the weight of the 50 soil clods after immersion in water, and t is the time (Chandra and De 1978).

The soil water infiltration rate was measured using a calibration method. The first water level was recorded shortly after an irrigation event and the second water level was measured 2 h later. This measurement was repeated every 10 d and the soil water infiltration rate was calculated as follows:

Soil water infiltration rate = (first level – second level)/120 min

The soil pH was determined using a potentiometer immersed in a 1:2.5 soil:water mixture (the soil was sieved through a 2-mm sieve). The SOM content was determined using the potassium dichromate volumetric method (Bao 2000), and analyzed in composite samples that had been previously air-dried and sieved through a 2-mm sieve.

At harvest, all plants within each treatment plot were harvested by hand to determine the wheat and rice yields. During the rice transplanting period, the rice tiller number within a zone of area 1 m multiplied by the width of one row (>1 m from the boundary line) was counted with three repeats in each plot. The tiller number within this same zone was then counted every 7 d. These data were subsequently used to calculate the mean rice tiller number per square meter.

The soil physical and chemical properties were analyzed using analysis of variance (ANOVA). The data model was as follows:

$$y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij}$$

where μ is the population mean, τi represents tillage system effects (fixed effects), βj indicates block effects (random effects), and εij is error (in the random effects). The least significant difference (LSD) was used to separate the means if the effect was considered significant ($P < 0.05$). All statistical analyses were performed using the Statistical Analysis System (version 8.0; SAS Institute, Cary, NC, USA).

RESULTS

No statistically significant differences in the soil bulk density, total porosity and soil specific gravity were observed among the tillage treatments ($P > 0.05$; Table 3). The soil bulk density at 0–10 cm depth was significantly lower (8.4%) than that observed at 10–20 cm for all treatments ($P < 0.05$). However, the no-tillage systems reduced the soil non-capillary porosity by 23% except for WRNB at 10–20 cm depth.

After harvest in the wheat fields, the soil penetration resistance under no-tillage was significantly higher (35.5%) than that measured under conventional tillage at 32.5 cm depth, and 9.9% higher at 40 cm depth ($P < 0.05$; Fig. 1). After harvest in the rice fields, the soil penetration resistance under no-tillage was 22% lower ($P < 0.05$) than that measured under conventional tillage at 22.5 cm depth and 17% ($P < 0.05$) lower at 25 cm depth (Fig. 1). No difference in the water content was observed between the tillage systems over the sampling period.

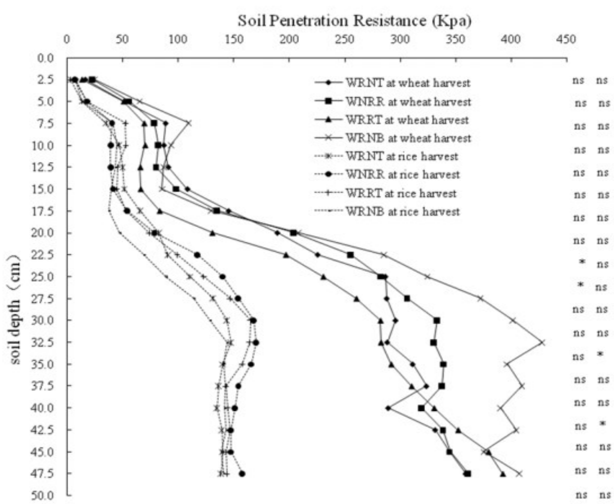

Fig. 1. Variation in soil penetration resistance with depth at wheat harvest (May 2009) and at rice harvest (October 2009) averaged for measurements at five different sampling points for four different treatments. Among two columns on right side of the figure, left column (*) indicates significance at the 0.05 level of probability and (ns) indicates no significant difference at rice harvest. The right column (*) indicates significance at the 0.05 level of probability and (ns) denotes no significant difference at wheat harvest. Note: WRNT, wheat and rice no-tillage; WNRR, wheat no-tillage and rice rotary-tillage; WRRT, wheat and rice rotary tillage (CK); WRNB, wheat and rice no-tillage in a raised bed.

No significant differences in the saturated hydraulic conductivity existed among the four tillage systems (WRNT, WRRT, WNRR, WRNB) at a depth of 0–10 cm but significant differences were noted at 10–20 cm (Fig. 2). The saturated hydraulic conductivity (mm min^{-1}) of WRNT at 10–20 cm was greater (57.8%) than that at 0–10 cm. The saturated hydraulic conductivity and water infiltration under no-tillage were on average 2.1 times greater than under the WNRR and WRRT systems. The soil water infiltration rate at a depth of 0–20 cm was identical under the four tillage systems (Fig. 3). The infiltration rate was greater under WRNT than under WNRR and CK especially during the rice transplanting period after which it gradually fell.

The soil pH was lower at a depth of 0–10 cm in the WRNT and WRNB systems compared with WRRT (CK)

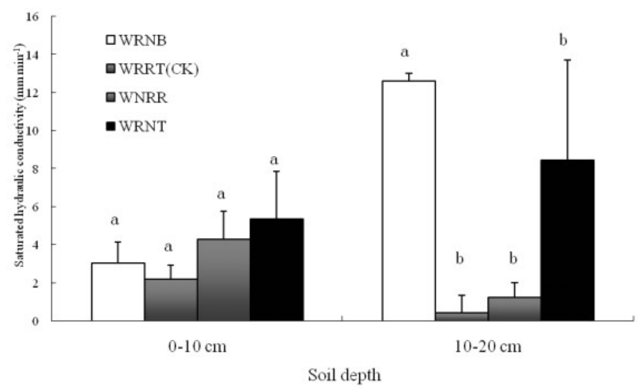

Fig. 2. Soil-saturated hydraulic conductivity following wheat harvest at a depth of 0–20 cm under different treatments. Note 1: Bars of the same color and the same letter are not significantly different according to a least-significant difference (LSD) test at $P \leq 0.05$. Note 2: WRNT, wheat and rice no-tillage; WNRR, wheat no-tillage and rice rotary tillage; WRRT, wheat and rice rotary tillage (CK); WRNB, wheat and rice no-tillage in a raised bed.

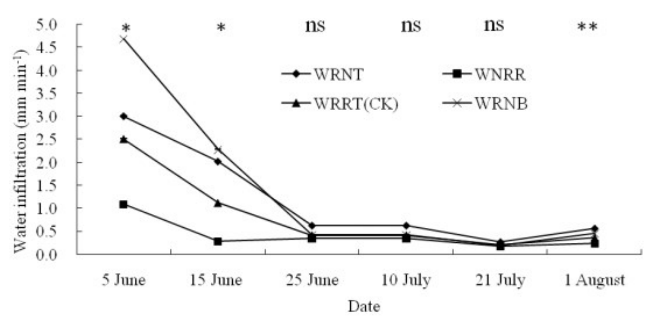

Fig. 3. Soil water infiltration under different treatments in rice fields. Parallel to the x-axis and at the top of the figure, (*) indicates significance at the 0.05 level of probability, (ns) indicates no significant difference, and (**) indicates significance at the 0.01 level of probability. Note: WRNT, wheat and rice no-tillage; WNRR, wheat no-tillage and rice rotary tillage; WRRT, wheat and rice rotary tillage (CK); WRNB, wheat and rice no-tillage in a raised bed.

(P < 0.05) but was almost neutral under the WRNT and WRNB systems. The soil pH of all treatments at a depth of 0–10 cm was lower (4.1%) than that at 10–20 cm. No-tillage increased soil pH (0.9%) at a depth of 10–20 cm compared with WRRT with the exception of WRNB (P < 0.05; Table 4).

SOM content at 0–10 cm depth was 18.2% and 24.4% higher, and at 10–20 cm, it was 0.3% and 22.8% higher, under the WRNT and WRNB systems, respectively, than under WRRT. The SOM content was higher under the WRNB system relative to all other treatments at depths of 0–10 and 10–20 cm, and was significantly higher relative to WRRT (CK). This increase in SOM content under the WRNT and WRNB systems also resulted an increase in the soil erodibility K by 23%, 3.3%, 12%, and 32% at 0–10 cm depth (P < 0.05) and 10–20 cm (P > 0.05), respectively (Table 4).

For identical irrigation levels, the tiller number decreased under the WRNT and WRNB systems relative to the WRRT system. For WRRT, the rice reached the maximum tillering stage of 21 d after transplanting, but in the WRNT and WRNB systems, the maximum tillering stage did not occur until 42 d after transplanting (Fig. 4). The entire rice growth cycle (i.e., flowering, producing a head, and reaching maturity) was delayed by 1 wk under the WRNT and WRNB systems relative to the WRRT system (Table 4).

The trend of mean wheat grain yields from 2005 to 2010 under different tillage treatments was as follows: WNRR (6974.9 kg ha^{-1}) > WRNB (6948.5 kg ha^{-1}) > WRNT (6900.8 kg ha^{-1}) > CK (6703.8 kg ha^{-1}) (P > 0.05). With the exception of 2006 and 2007, no significant differences in the wheat grain yield were found among the tillage systems. The trends under different tillage treatments from 2005 to 2010 were not completely identical (Fig. 5). The trend of mean rice grain yields from 2005 to 2010 under different tillage treatments was: WNRR (8209.8 kg ha^{-1}) > CK (7546.9 kg ha^{-1}) > WRNT (6880.1 kg ha^{-1}) > WRNB (6352.0 kg ha^{-1}) (P < 0.05); hence, significant differences occurred in the rice grain yield among the tillage systems (Fig. 6).

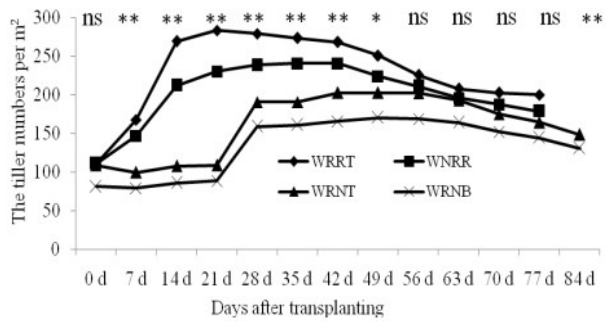

Fig. 4. Rice tillering growth of a 1 m^2 dynamic graph under four different treatments after transplanting. Parallel to the x-axis and at the top of the figure, (*) indicates significance at the 0.05 level of probability, (ns) indicates no significant difference, and (**) indicates significance at the 0.01 level of probability. Note: WRNT, wheat and rice no-tillage; WNRR, wheat no-tillage and rice rotary tillage; WRRT, wheat and rice rotary tillage (CK); WRNB, wheat and rice no-tillage in a raised bed.

DISCUSSION

The results showed that for rice-wheat cropping system, the soil bulk density was not significantly different

Table 4. Effects of different treatments on soil properties

Soil Property Depth	WRNT		WRNB		WRRT (CK)		WNRR	
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
Soil bulk density (Mg·m^{-3})	1.20^a	1.37^a	1.22^a	1.25^a	1.27^a	1.33^a	1.20^a	1.35^a
Total porosity (%)	54.59^a	48.92^a	52.33^a	52.61^a	51.15^a	48.21^a	52.78^a	48.96^a
Capillary porosity (%)	51.35^a	46.92^a	49.23^a	47.54^a	48.78^a	45.53^a	49.13^a	46.86^a
Non-capillary porosity (%)	3.24^a	2.00^b	3.09^a	5.06^a	2.37^a	2.68^b	3.66^a	2.10^b
Soil erodibility K	0.37^a	0.28^a	0.31^b	0.33^a	0.30^c	0.25^a	0.37^a	0.28^a
Soil specific gravity (g·cm^{-3})	2.55$_a$	2.57^a	2.52^a	2.58^a	2.55^a	2.58^a	2.50^a	2.57^a
pH	7.08^b	7.55^a	6.94^c	7.32^b	7.44^a	7.50^a	7.27^a	7.58^a
Soil organic matter (g·kg^{-1})	44.55^a	29.53^b	46.9^a	36.16^a	37.70^b	29.45^b	41.83^{ab}	30.45^b

Means for soil properties under a wheat-rice cropping system within different tillage systems followed by the same lower case letters (a, b, and c) are not significantly different at the 5% level.
WRNT, wheat and rice no-tillage; WNRR, wheat no-tillage and rice rotary tillage; WRRT, wheat and rice rotary tillage (CK); WRNB, wheat and rice no-tillage in a raised bed

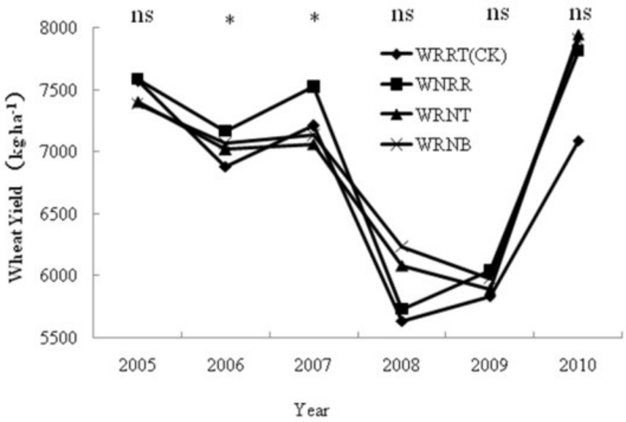

Fig. 5. Wheat yields from 2005 to 2010 under four different treatments. Note: WRNT, wheat and rice no-tillage; WNRR, wheat no-tillage and rice rotary tillage; WRRT, wheat and rice rotary tillage (CK); WRNB, wheat and rice no-tillage in a raised bed. Along the x-axis, (*) indicates significance at the 0.05 level of probability, and (ns) indicates no significant difference.

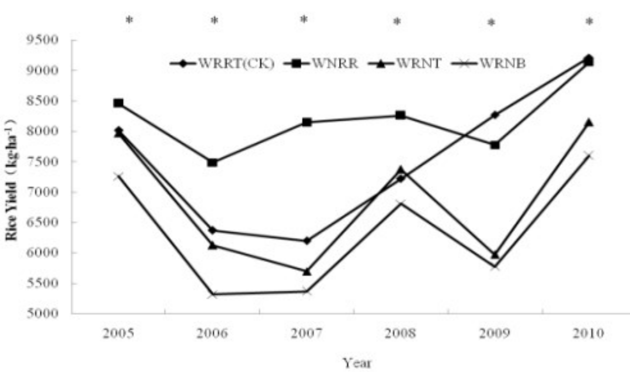

Fig. 6. Rice yields from 2005 to 2010 under four different treatments. Note: WRNT, wheat and rice no-tillage; WNRR, wheat no-tillage and rice rotary tillage; WRRT, wheat and rice rotary tillage (CK); WRNB, wheat and rice no-tillage in a raised bed. Along the x-axis, (*) indicates significance at the 0.05 level of probability.

among tillage treatments. This is not consistent with Shaver et al. (2002) who demonstrated that if no-tillage decreased bulk density, it must also increase total porosity, and as residue increased, so would total porosity. Villamil et al. (2006) also showed that no-tillage (with a winter cover crop) decreased bulk density and significantly increased total porosity. But in this study, no significant differences were observed in total porosity and soil capillary porosity between the tillage treatments; however, the WRNB systems did significantly increase the non-capillary porosity at a depth of 0–10 cm, which was beneficial for improving the soil pore structure. It means tillage systems may have a significant effect on the soil bulk density required for longer term: the effect did not yet reach statistical significance in 6 yr tillage system experiment.

At wheat harvest and rice harvest, the soil cone penetration resistance was significantly different among the tillage treatments at 22.5 and 25 cm soil layers (Fig. 1). The soil cone penetration resistance (Kpa) is known to be highly correlated with soil physical properties, such as soil moisture content, soil texture and structure (Celik et al. 2010; Vaz et al. 2011), which is also known as an indicator of the quality of the soil structure (Singh and Kaur 2012) and soil productivity (Chung et al. 1995). Because a plough pan was under the WRRT (CK) and WNRR systems at 22.5 and 25 cm depths, the soil cone penetration resistance was greater under WRRT (CK) and WNRR at top soil, which had the beneficial effect of preventing water in the topsoil from leaking into the subsoil. Meanwhile, they had a small effect on deeper soil under tillage systems but there still was a general trend for an increase in influence on deeper soil under 6 yr tillage system experiment, which was due to the water moisture that reduced the effect of tillage systems. Relative to post-harvest of rice, the post wheat-harvest soil penetration resistance increased, whereas the WNRR, WRNT and WRNB systems increased the soil penetration resistance relative to the WRRT (CK) system. The soil penetration resistance was >400 Kpa under WRNB below 30 cm depth, which had a detrimental effect on the soil production system. The increases in the soil cone penetration resistance ultimately affected the root system distribution, plant growth and final yield when the soil penetration resistance is too high. It should be reduced by irrigation (http://www.ac.ntu.edu.tw/DYLee/acrobat/wen.pdf), which is in agreement with the results of our research; compared with the WRRT (CK) system, the WRNT and WRNB regimes can increase the need for irrigation post wheat-harvest.

The soil water storage is usually characterized by the

Table 5. Effect of tillage systems on the growth stages of rice.

	Tillering (d)	Transplanting - Flowering (d)	Flowering -Harvest (d)	Entire Growth (d)
WRRT (CK)	77	84	30	114
WNRR	76	84	30	114
WRNT	84	93	29	122
WRNB	84	93	29	122

WRNT, wheat and rice no-tillage; WNRR, wheat no-tillage and rice rotary tillage; WRRT, wheat and rice rotary tillage (CK); WRNB, wheat and rice no-tillage in a raised bed saturated hydraulic conductivity and the water infiltration rate. The WRNT and WRNB systems significantly increased the saturated hydraulic conductivity and water infiltration relative to WRRT (CK) which did not disturb the soil, as the SOM was low below 20 cm soil depth. When soil dries, it shrinks and large cracks form. Additionally, long-term no-tillage broke the plough pan, which caused significant water leakage during rice transplanting, which is detrimental for the rice tiller number and rice grain yield and waste irrigation water. These results were consistent with those of Panday et al. (2008) but inconsistent with Laxmi et al. (2007) and Saharawat et al. (2010), who found that no-tillage resulted in a saving of irrigation water. Conversely, WNRR and CK, due to the rice rotary tillage, formed a dense plough pan at 20–25 cm depth. Therefore, the soil-saturated hydraulic conductivity and soil water infiltration rate were significantly lower and water leakage was slow, which was beneficial for the rice tiller number and grain yield. The soil-saturated hydraulic conductivity and soil infiltration rates were 8.47, 12.60, 1.18, and 1.40 mm min–1 under the WRNT and WRNB systems at 10–20 cm soil depth, which was beneficial for wheat yields, but not for rice yields.

Tillage systems greatly influence the soil properties (Table 5) and the performance of plant growth (e.g., tillering), which in turn affects crop production (Singh and Kaur 2012). The yield of winter wheat under the WRNT and WRNB systems was higher than that under the WRRT (CK) system, consistent with that observed by Tang et al. (2005) and Liu et al. (2010). However, the effect of WRNT and WRNB management on rice yield was less evident. Several studies have reported that WRNT results in an increased rice yield, while others reported a decrease (Zhuang et al. 1999; Li et al. 2001). The study showed that the WRNT and WRNB systems increased the saturated hydraulic conductivity and water infiltration, which caused rapid water loss, thus diminishing the tiller number. As a result, the field population of rice was insufficient, with an average increase in above-ground dry weight of <1 g m^2/day, resulting in a loss in yield. However, the WNRR regime resulted in less water loss, ultimately increasing yield (Liang et al. 2010).

The results showed the WNRR regime is better than the three other tillage systems in a wheat-rice cropping system which might be due to the generally positive effect of WNRR on the soil properties as demonstrated by the increase in resistance to soil erosion. However, the WRNT and WRNB systems resulted in a high saturated hydraulic conductivity and water infiltration rate, both of which are favourable for dry ploughing operations but were not beneficial for wet ploughing as they caused rapid water loss and increased the need for irrigation, since precipitation was lower during the rice cycle (Table 2); thus, rice tillering decreased, ultimately reducing grain yields. Findings of this study further highlight the key restrictive factors to crop growth in the region. The mechanism of the effect on the tillage systems in wheat-rice rotation for a longer-term needs more research in the future.

CONCLUSION

More than 6 yr of cropping and tillage system studies on the Chengdu Plain showed that tillage/no-tillage systems significantly altered the soil physical and chemical properties, especially soil permeability. Changes in the soil properties directly affected crop growth and production but these effects differed depending on the crop type (e.g., no-tillage was beneficial to wheat production but not beneficial to rice yield due to a lower tillering number). The highest annual yield of the four tillage treatments was found in the WNRR system. These data provide a theoretical foundation for efforts to select the most appropriate region- and crop-specific tillage methods. A more complete understanding would form the basis for tillage management for improving the soil and crop yields in wheat-rice rotation areas.

REFERENCES CITED

BAO SD (editor). 2000. Soil and Agricultural Chemistry Analysis. China Agric. Press, Beijing [in Chinese].

BENJAMIN JG, NIELSEN DC, VIGIL MF. 2003. Quantifying effects of soil conditions on plant growth and crop production. Geoderma 116: 137–148.

CELIK I, GUNAL H, BUDAK M, AKPINAR C. 2010. Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. Geoderma 160: 236–243.

CHANDRA S, DE SK. 1978. A simple laboratory apparatus to measure relative erodibility of soil. Soil Sci 125: 115–121.

CHANG C, LINDWALL CW. 1989. Effect of long-term minimum tillage practices on some physical properties of a Chernozemic clay loam. Can J Soil Sci 69: 443–449.

CHUNG CK, CHONG SK, VARSA EC. 1995. Sampling strategies for fertility on a Stoy silt loam soil. Commun Soil Sci Plant Anal 26: 741–763.

DAI HY. 2008. Evaluation and Study on the Ecological

Benefits of Main Forest Type in Daqing Mountain. [Ph.D. Dissertation]. Neimenggu Agric. Univ., Huhehaote [in Chinese, English abstract].

DAO TH. 1993. Tillage and winter wheat residue management effects of water infiltration and storage. Soil Sci Soc Am J 57: 1586–1595.

FENG G, SHARRATT B, YOUNG F. 2011. Influence of long-term tillage and crop rotations on soil hydraulic properties in the US Pacific Northwest. J Soil Water Cons 66: 233–241.

FERRERAS LA, COSTA JL, GARCIA FO, PECORARI C. 2000. Effect of no-tillage on some soil physical properties of a structural degraded petrocalcic paleudoll of the south "pampa" of Argentina. Soil Tillage Res 54: 31–39.

HILL RL. 1990. Long-term conventional and no-tillage effects on selected soil physical properties. Soil Sci Soc Am J 54: 161–166.

HOBBS PR. 2007. Conservation agriculture: What is it and why is it important for future sustainable food production? J Agric Sci (Cambridge) 145: 127–137.

KIRKEGAARD JA, ANGUS JF, GARDNER PA, MULLER W. 1994. Reduced growth and yield of wheat with conservation cropping I: Field studies in the first year of the cropping phase. Aust J Agric Res 45: 511–528.

LAXMI V, ERENSTEIN O, GUPTA RK. 2007. Impact of zero tillage in India's rice-wheat systems. Mexico, D.F.: CIMMYT.

LETEY J. 1985. Relationship between soil physical properties and crop production. Adv Soil Sci 1: 277–294.

LI HX, LU WS, LIU YJ, ZHANG XM, CHEN XC, LI YF, HUO JT. 2001. Effect of different tillage methods on rice growth and soil ecology. Chinese J Applied Ecol 12: 553–556 [in Chinese, English abstract].

LIANG SM. 2010. The Effects of Tillage Systems on the Soil Quality and Agro-ecosystem—A Case of Chengdu Plain. [Ph.D. Dissertation]. Shanxi Agric. Univ., Taigu [in Chinese, English abstract].

LIANG SM, XIE RZ, TANG YL, YANG JZ, LI CS, WANG LB, WU C, LI SK. 2010. Effects of tillage systems on fields in Chengdu Plain I. The effects of tillage systems on soil properties and crop yields. Scientia Agric Sinica 43: 3988–3996 [in Chinese, English abstract].

LIU EK, ZHAO BQ, MEI XR, SO HB, LI J, LI XY. 2010. Effects of no-tillage management on soil biochemical characteristics in northern China. J Agric Sci (Cambridge) 148: 217–223.

PANDAY SC, SINGH RD, SAHA S, SINGH KP, PRAKASH V, KUMAR A, KUMAR M, SRIVASTAVA AK. 2008. Effect of tillage and irrigation on yield, profitability, water productivity and soil health in rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping systems in north-west Himalayas. Indian J Agric Sci 78: 1018–1022.

SAHARAWAT YS, LADHA JK, GATHALA M, JAT ML, CHAUDHARY N. 2011. InfoRCT: productivity, income and environment simulation tool for conservation agriculture based rice-wheat rotation. In: Abstracts of the 5th World Congress on Conservation Agriculture, 26–29 September 2011. Brisbane, Australia. p. 152–153.

SAHARAWAT YS, SINGH B, MALIK RK, LADHA JK, GATHALA M, JAT ML, KUMAR V. 2010. Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in North Western IGP. Field Crops Res 116: 260–267.

SHAO XW, LIU HD, DU ZY, YANG J, MENG FX, MA JY. 2007. Effects of water disposal on growth and yield of rice. J Soil Water Cons (Chinese J.). 21: 193–196 [in Chinese, English abstract].

SHAVER TM, PETERSON GA, AHUJA LR, WESTFALL DG, SHERROD LA, DUNN G. 2002. Surface soil physical properties after twelve years of dry and no-till management. Soil Sci Soc Am J 66: 1296–1303.

SINGH A, KAUR J. 2012. Impact of conservation tillage on soil properties in rice wheat cropping system. Agric Sci Res J 2: 30–41.

TANG YL, ZHENG JG, HUANG G. 2005. Studies on permanent-bed-planting with double zero tillage for rice and wheat in Sichuan basin. Southwest China J Agric Sci 18: 25–28.

VAZ CMP, MANLERI JM, DE MARIA IC, TULLER M. 2011. Modeling and correction of soil penetration resistance for varying soil water content. Geoderma 166: 92–101.

VILLAMIL MB, BOLLERO GA, DARMODY RG, SIMMONS FW, BULLOCK DG. 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Sci Soc Am J 70: 1936–1944.

WANG F. 2006. Theoretical Analysis and Empirical Research on Recycle Agricultural Development in China's Western Regions. [Ph.D. Dissertation]

Huazhong Agric. Univ., Wuhan [in Chinese, English abstract].

WEI MR. 1990. Method for once sampling continuous determinates soil physical properties. J Liaoning Forestry Sci Technol 1: 56–57 [in Chinese].

WU J, GUO XS, ZHANG XM, WANG YQ, XU ZY, LU JW. 2012. Effects of tillage patterns on crop yields and soil physicochemical properties in wheat-rice rotation system. Transactions of the CSAE 28: 87–93 [in Chinese, English abstract].

YANG XM, ZHANG XP, FANG HJ, LIANG AZ, QI XN, WANG Y. 2004. Conservation tillage systems in North America and their significance for China. Chin J Applied Ecol 15: 335–340 [in Chinese, English abstract].

YU YH. 2010. Characteristics of soil corrosion resistance and quantitative prediction of soil erosion at small watershed - The case of Guang Qiao He Small watershed. [Ph.D. Dissertation]. Hunan Agric. Univ., Changsha [in Chinese, English abstract].

ZHUANG HY, LIU SP, SHEN XP, CHEN HQ, LU JF. 1999. Effect of long-term minimal and zero tillages on rice and wheat yields, SOM and bulk density. Scientia Agric Sinica 32: 39–44 [in Chinese, English abstract].