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Long-term conservation tillage influences nutrient status in a rice-wheat cropping system

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ABSTRACT

In order to better understand the effects on crop response and soil properties between zero tillage (ZT) and conventional tillage (CT), a long-term field experiment was performed in Southwest China to evaluate how crop production, soil nutrient status and plant nutrient uptake varied under four tillage practices: CT for wheat and rice, CT for rice following, ZT for wheat with residue mulching, CT for rice with half the wheat residue incorporated following, ZT for wheat with residue mulching, ZT for both crops with residue mulching, and ZT plus residue mulching on raised beds. The results obtained show that wheat under ZT had higher yield than CT, whereas the opposite was true for rice. The differences of soil nutrient mainly occurred in topsoil and sub-topsoil between treatments. ZT/residue retention improved soil organic carbon, as well as nitrogen in surface soil, but decreased potassium in topsoil. It was also found that wheat under CT absorbed fewer nutrients than other treatments. While rice under ZT had less nutrient uptake than CT. Partial N balance was negative for all wheat treatments, but positive for rice. N surplus varied (22-82 kg ha^{-1} year^{-1}) across all treatments. More than 30 kg ha^{-1} year^{-1} P was remaining in the soil because of low absorption. Moreover, residue retention also caused positive K balance. The study indicated that ZT for wheat combined with CT for rice appears optimal for sustainable production.

INTRODUCTION

Rice-wheat (RW) sequential cropping is a dominant system in China and South Asia, occupying 24 million ha of cultivated land (Ladha et al., 2003). The productivity of such systems has increased dramatically due to the adoption of high-yield varieties, irrigation and fertilizer availability, along with improved crop management. However, an analysis of 33 RW cultivation experiments in South Asia concluded that crop yield was stagnant or even declining over the long term (Ladha et al., 2003). Since then, the sustainability of RW rotation has been questioned (Ladha et al., 2007; Bhatt et al., 2016), and various contributors to unsatisfactory RW performance have been identified. These include nutrient depletion, soil deterioration, coarse tilth, planting delays, and environmental pollution (Ladha et al., 2003; Erenstein and Laxmi, 2008).

Improved soil fertility and structure are the basis of agroecosystem sustainability (Choudhary et al., 2018). Besides the influence of environmental factors, farming practices play an important role in influencing soil fertility (Obour et al., 2017; Yadav et al., 2017). For rotational RW systems, careful soil management is particularly important because environments suitable for rice and wheat oppose each other: the former crop needs flooded conditions, whereas the latter requires well-aerated, aggregated soil (Naresh et al., 2014). Unfortunately, long-term intensive RW cropping appears to have deteriorated

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Table 1. Design for long-term experiments examining five tillage and residue management practices in a wheat-rice system of southwest China.

Treatment	Wheat season		Rice season	
	Tillage practice	**Rice residue management**	**Tillage practice**	**Wheat residue management**
CTW-CTR	Rotary till	Removal	Rotary till	Removal
ZTW-CTR	Zero till	Mulching retention	Rotary till	Removal
ZTW-CTRs	Zero till	Mulching retention	Rotary till	Half residue incorporation
ZTW-ZTR	Zero till	Mulching retention	Zero till	Mulching retention
ZTW-ZTR/B	Zero till under raised bed	Mulching retention	Zero till under raised bed	Mulching retention

soil fertility in many regions (Bhandari et al., 2002; Ladha et al., 2003; Sharma et al., 2004; Nawaz et al., 2017), depleting major nutrients (tjat is, N, P, K and S) and generating a nutrient imbalance (Bhandari et al., 2002; Alam et al., 2013; Hossain et al., 2016). In addition, farmers aiming to increase yield tend to overuse chemical N/P fertilizers, inducing nutrient loss through ammonia volatilization, denitrification, and leaching (Cameron et al., 2013). Over time, these factors combine to cause nutrient escape from the soil-plant system in both paddy and rotational farming methods (Kundu and Ladha, 1999; Xu et al., 2015). Soil organic carbon (SOC) plays a critical role in the physical, chemical and biological function of cultivated soils. Continuous tillage breaks large soil aggregates and enhances SOC composition (Álvaro-Fuentesa et al., 2008; Boogar et al., 2014). Although straw is a natural resource that can enhance SOC and soil fertility, most regions usually remove straw from the field for other purposes.

Conservation tillage (zero tilling plus residue retention) has received wide attention as a management system that can improve both soil quality and crop productivity (Nagumo et al., 2006; Bhushanet al., 2007; Erenstein and Laxmi, 2008; Nawaz et al., 2017). This method minimizes carbon losses, preserves soil fertility and maintains soil moisture, while saving on labor and fuel (Erenstein and Laxmi, 2008). Conservation tillage is widely used in RW systems, especially for wheat cultivation (Tang et al., 2002; Erenstein and Laxmi, 2008; Erenstein et al., 2008). Although existing data are promising with regard to the positive effects of conservation tillage, the plant-soil system is extremely complex, subjecting to environmental fluctuation. Furthermore, the impact of tillage practices on soil properties may take a long time to manifest.

To address better monitor crop response and soil properties under various tillage practices, long-term experiments in multiple regions are necessary. Several informative RW trials are underway, primarily in the Indo-Gangetic Plain (IGP) (Ladha et al., 2003; Gupta and Hobbs, 2003; Ghimire et al., 2017). Similar experiments–especially those focusing on soil fertility–are scarce in the Yangtze River region in which has different environmental and climatic conditions from IGP. In addition, the productivity of RW system in this region has been more than 12 t grian yield ha^{-1} (Bai et al., 2017), which implies higher requirements for soil quality. Thus, in 2004, the Sichuan Academy of Agricultural Science established a long-term RW experiment that continues to this day. Soil samples were collected for nutrient analysis during the tenth year, and plant nutrient uptake was estimated in the eleventh year. The present study analyzed those data to compare the effects of long-term, continuous conventional versus zero tillage practices.

MATERIALS AND METHODS

Experimental site

The field experiment was established in October 2004 on a clayey loamy soil (40–43% clay, 28–29% silt, and 27–31% sand for 0–15 cm soil layer) at the Research Station of Sichuan Academy of Agriculture Science, Guanghan, Sichuan Province, China (31°0′22.09″ N, 104º23′54.61″ E; altitude 476 m). Before establishment, composite topsoil (0–15 cm) samples were collected for chemical analysis, yielding the following characteristics: pH, 7.33; soil organic matter, 43.6 g kg^{-1}; total N, 2.79 g kg^{-1}; available N, 226.0 mg kg^{-1}; available P, 26.0 mg kg^{-1}; available K, 130.6 mg kg^{-1}; and average bulk density, 1.20 mg cm^{-3}. The region experiences a warm temperate climate, with monthly mean temperature being lowest (5.6°C) in January and highest (25.5°C) in August. Mean annual precipitation is about 800 mm, 85% of which falls from May to September.

Experimental design

The experiment was a randomized complete block design comparing wheat-rice systems with five tillage and residue-management treatments (Table 1). Plot size was 8.5 m × 10.5 m each surrounded by a soil dike of 0.5 m in width and 0.3 m in height. Each treatment had three replicates. The first treatment was conventional rotary tillage for both crops and full residue removal (CTW-CTR). The second was ZT wheat and surface rice-residue retention in rotation with conventional rice tillage (ZTW-CTR); the third was identical, except half of wheat residue was incorporated (ZTW-CTRs). Fourth, ZT and residue retention were employed for both crops (ZTW-ZTR). The last system was the same as the fourth, but on permanent raised beds (ZTW-ZTR/B). Beds were manually formed after plots were cultivated with a rotary tiller (before sowing of the first wheat crop); top width was 0.7 m, whereas furrow width and depth were 0.3 m and 0.2 m, respectively.

Prior to soil preparation, all crop residues were removed from the plots, leaving only a 3–5 cm layer of stubble on the soil surface. For CTW, soil (20 cm depth) was tilled using hoes in the first three years. Subsequently, two passes were made with a 6.3 kW mini-tiller to a soil depth of 15 cm. Soil was treated in the same way for CTR, except that irrigation occurred before rotary tilling.

Wheat ‘Chuanmai 42’ was planted at the end of October or early November. Flat plots were sown using a simple manpower hill seeder with two vertical-plate precise seedmeters and two openers (2BJ-2) (Tang et al., 2000). Seeding rate was 150 kg ha^{-1} with rows separated by 20 cm. Seeds were placed on the soil surface for ZTW, whereas sowing depth was ~2 cm for CTW. Hand drills were used for sowing of raised beds, each with 4 rows separated by 20 cm. After seeding, ZT soil was mulched with rice residue. Post-sowing, N-P-K synthetic fertilizer (15-15-15) was applied at a dose of 600 kg ha^{-1}. At stem elongation, 98 kg ha^{-1} urea was top-dressed.

Rice ‘Fuyou 63’ was used in the first four years, then replaced with ‘Chuanxiang 9838’ owing to its higher disease resistance. Nursery beds for rice seedlings were prepared in late March, and the dry-nursery method was used to sow seeds during April 6 to 8. At 50–55 d, seedlings were manually transplanted in flat, 27 cm × 20 cm soil sections during late May or early June (after wheat harvesting). Three rows of rice were planted on beds with 20 cm distance from hill to hill. Basal fertilizer application was the same as for wheat, followed by 163 kg ha^{-1} urea 10 d after transplanting. Weeds, diseases, and insect pests were all controlled for both crops.

Monitoring crop yield and soil nutrients

All plots were fully harvested to determine grain weight and water content using a PM-8188 grain moisture analyzer. Yield per plot was recorded at 13% moisture.

After 10 complete rotations (ending on rice harvest), soil samples per plot were collected from each corner, all located 2 m from the nearest border. Four soil depths (0–7.5, 7.5–15, 15–30 and 30–45 cm) per corner were sampled with an auger (5 cm i.d.).

Samples from the same layer per plot were composited, air-dried for 2 months at room temperature (11.4°C on average), and passed through a 1 mm sieve before determining nutrient profile. SOC, total nitrogen (TN), total phosphorus (TP) and total potassium (TK) were measured with the dichromate oxidation, Kjeldahl, molybdenum, and flame photometer methods, respectively (Liu, 1996). Available N (AN) was analyzed using alkali diffusion. Available P (AP) was first extracted with 0.5 mol L^{-1} $NaHCO_3$ (pH = 8.5) before being subjected to the molybdenum method (Liu, 1996). Available K (AK) was extracted with 1 N ammonium acetate and measured with a flame photometer (Liu, 1996; Lu, 2000).

Plant nutrient uptake

During the eleventh rotation, rice and wheat samples were collected at the following stages: active tillering (45 and 20 d after wheat sowing and rice transplanting, respectively), stem elongation (80 and 40 d post-sowing and transplanting), anthesis, and maturity. Wheat was obtained from three representative 0.2 m^2 quadrats, and rice was collected from six holes per plot. After root removal, above ground parts were oven-dried at 75°C to determine biomass. Dried samples were crushed and mixed thoroughly for macronutrient (N, P, K) measurements using the same methods as above. Grains of mature samples were threshed and analyzed separately. Nutrient accumulation was the product of biomass and nutrient concentration at each stage.

Partial balance of nutrient

Partial nutrient balances in the eleventh year were calculated as the difference between fertilizer input and removal by plants (Zhang et al., 2010). Nutrient-removal measurements in residue retention treatments focused only on grains, excluding vegetative parts. Additionally, nutrient input from seeds, irrigation, atmospheric sedimentation, and other means were not considered.

Statistical analysis

All data are represented as the means of three replicates. Statistical analysis was performed in SPSS 20.0. The effect of treatment was determined with an analysis of variance (ANOVA) using the general linear model, followed by means separation with Duncan's tests at $p < 0.05$.

Table 2. Maximum, minimum, and mean yield for wheat and rice in a long-term tillage experiment from southwest China (t ha^{-1}).

	CTW-CTR	**ZTW-CTR**	**ZTW-CTRs**	**ZTW-ZTR**	**ZTW-ZTR/B**
Wheat					
Max.	7.81	8.08	8.43	8.10	8.04
Min.	6.32	6.45	6.59	6.58	6.40
Mean	7.11	7.45	7.57	7.40	7.38
C.V.%	6.78	7.46	7.64	6.98	6.62
Rice					
Max	9.76	9.60	9.52	9.52	9.74
Min	6.24	7.48	6.09	5.73	5.31
Mean	8.35	8.79	8.57	7.47	7.13
C.V.%	14.91	8.82	11.54	16.89	18.81
Annual production					
Max	17.33	17.63	17.84	17.02	17.17
Min	13.25	14.65	13.54	12.79	12.38
Mean	15.46	16.24	16.14	14.88	14.51
C.V.%	9.25	6.82	7.67	9.37	10.22

CTW-CTR, Conventional tillage for wheat and rice; **CTW-ZTR,** conventional tillage rice following zero-tillage wheat with residue mulching; **CTW-ZTRs,** like CTW-ZTR, but with the wheat residue incorporated; **ZTW-ZTR,** zero tillage for both crops with residue mulching; **ZTW-ZTR/B,** zero-tillage plus residue mulching on raised beds.

Table 3. Grain yield and biomass for wheat and rice in the eleventh growing season of the long-term tillage experiment (t ha^{-1}).

	CTW-CTR	**ZTW-CTR**	**ZTW-CTRs**	**ZTW-ZTR**	**ZTW-ZTR/B**
Wheat					
Grain yield	7.09 b	7.84 a	8.12 a	7.99 a	7.80 a
Biomass	11.70 b	13.50 a	13.87 a	13.60 a	13.40 a
Rice					
Grain yield	9.76 a	9.60 a	9.35 a	7.32 b	7.02 b
Biomass	15.30 a	15.26 a	14.59 a	11.34 b	10.94 b

Values are means across three replicates. Values in the same row with different letters are significantly different (n = 3, $P < 0.05$). **CTW-CTR,** Conventional tillage for wheat and rice; **CTW-ZTR,** conventional tillage rice following zero-tillage wheat with residue mulching; **CTW-ZTRs,** like CTW-ZTR, but with the wheat residue incorporated; **ZTW-ZTR,** zero tillage for both crops with residue mulching; **ZTW-ZTR/B,** zero-tillage plus residue mulching on raised beds.

RESULTS

Crop yield

Average wheat yield over the last 10 years ranged from 7.11 to 7.57 t ha^{-1} (Table 2). The highest production occurred under ZTW-CTRs, followed by ZTW-CTR, ZTW-ZTR, ZTW-ZTR/B, and CTW-CTR. Maximum yield for CTW-CTR was only 7.81 t ha^{-1}, whereas all other treatments yielded > 8 t ha^{-1}. Overall, CT had a negative effect on wheat production.

In contrast, puddled tillage led to much higher rice yield than ZT, regardless of straw retention. Average yield of double ZT was below 7.5 t ha^{-1}, when compared with > 8.0 t ha^{-1} for all other treatments. Thus, double ZT had a negative effect on rice growth.

In the eleventh year (Table 3), wheat yield and biomass under CTW-CTR were significantly lower than other treatments. Additionally, rice yield and biomass in CTW-CTR, ZTW-CTR, and ZTW-CTRs were significantly higher than in ZTW-ZTR and ZTW-ZTR/B. These results were similar to the performance averaged across 10 years.

Soil nutrient status

The differences of soil nutrient parameters mainly

Table 4. Soil nutrient content after 10-year continuous tillage and residue management in a rice-wheat cropping system.

Treatment	SOC	TN	TP	TK	AN	AP	AK	C/N
	(g kg^{-1})				(mg kg^{-1})			
0-7.5 cm								
CTW-CTR	23.0 b	2.29 b	1.11 a	17.4 a	143.7 c	40.0 b	199.3 a	10.0 a
ZTW-CTR	34.7 a	2.59 ab	1.07 a	14.1 ab	139.4 c	44.6 ab	194.3 a	13.4 a
ZTW-CTR$_S$	40.7 a	2.78 ab	1.12 a	11.7 b	171.3 b	51.5 ab	202.8 a	14.6 a
ZTW-ZTR	35.0 a	2.66 ab	1.27 a	12.6 b	192.1 a	50.5 ab	148.8 b	13.2 a
ZTW-ZTR/B	41.9 a	3.05 a	1.27 a	13.8 ab	198.0 a	58.1 a	145.7 b	13.7 a
7.5-15 cm								
CTW-CTR	22.5 b	2.23 bc	1.02 a	16.8 a	136.5 b	38.3 ab	186.8 a	10.1 a
ZTW-CTR	32.9 a	2.37 ab	1.03 a	14.4 ab	136.9 b	34.5 ab	185.8 a	13.9 a
ZTW-CTR$_S$	35.9 a	2.54 a	1.13 a	11.8 b	161.3 a	47.0 a	194.3 a	14.2 a
ZTW-ZTR	26.7 a	2.12 c	1.13 a	13.0 ab	133.4 b	33.2 ab	142.0 b	12.6 a
ZTW-ZTR/B	32.2 a	2.17 bc	1.13 a	14.2 ab	134.0 b	29.7 b	140.1 b	14.8 a
15-30 cm								
CTW-CTR	15.0 b	1.45 a	0.77 a	17.0 a	76.6 a	15.9 ab	190.9 a	10.4 a
ZTW-CTR	22.2 ab	1.60 a	0.77 a	14.3 ab	91.0 a	17.4 ab	183.6 a	13.9 a
ZTW-CTRS	21.3 ab	1.58 a	0.77 a	12.9 b	88.4 a	20.8 a	199.2 a	13.5 a
ZTW-ZTR	18.2 ab	1.70 a	0.86 a	13.0 b	80.8 a	14.8 b	147.0 b	10.7 a
ZTW-ZTR/B	28.7 a	1.52 a	0.88 a	14.4 ab	86.3 a	15.5 ab	143.7 b	18.9 a
30-45 cm								
CTW-CTR	9.4 a	0.91 a	0.61 a	16.9 a	39.6 a	9.3 ab	186.5 a	10.3 ab
ZTW-CTR	18.2 a	0.92 a	0.52 a	12.7 b	38.1 a	8.2 ab	173.5 ab	19.7 a
ZTW-CTRS	17.2 a	0.95 a	0.52 a	12.8 b	46.3 a	9.9 a	171.1 ab	18.1 ab
ZTW-ZTR	10.6 a	0.90 a	0.59 a	13.1 b	43.0 a	8.2 ab	149.6 bc	11.8 ab
ZTW-ZTR/B	9.6 a	0.99 a	0.60 a	14.6 ab	53.4 a	6.3 b	134.6 c	9.7 b

Values are means across three replicates. Values in the same column with different letters in the same soil layer are significantly different (n = 3, $P < 0.05$). **SOC,** Soil organic carbon; **TN,** total nitrogen; **TP,** total phosphorus; **TK,** total potassium; **AN,** available nitrogen; **AP,** available phosphorus; **AK,** available potassium; **C/N,** the ratio of soil organic carbon and total nitrogen; **CTW-CTR,** conventional tillage for wheat and rice; **CTW-ZTR,** conventional tillage rice following zero-tillage wheat with residue mulching; **CTW-ZTRs,** like CTW-ZTR, but with the wheat residue incorporated; **ZTW-ZTR,** zero tillage for both crops with residue mulching; **ZTW-ZTR/B,** zero-tillage plus residue mulching on raised beds.

occurred in the topsoil and sub-topsoil between treatments (Table 4). Straw retention was effective in improving SOC. In depths of 0–7.5 cm and 7.5–15 cm, residue-addition plots had significantly higher SOC than CTW-CTR plots.

Tillage and residue managements had only limited effects on TN and AN in the topsoil. At 0–7.5 cm depth, TN was highest in ZTW-ZTR/B and lowest in CTW-CTR. At 7.5–15 cm, TN was highest in ZTW-CTRs, then in ZTW-CTR and CTW-CTR, and finally in ZTW-ZTR. Thus, in surface soil, double ZT significantly increased AN, ZTW-CTRs led to moderate AN, whereas CTW-CTR and ZTW-CTR had the lowest AN. In subsoil, ZTW-CTRs resulted in significantly higher AN than all other treatments.

None of the treatments significantly affected TP. Annual ZT promoted AP accumulation in surface soil, but caused the opposite response in deeper layers. Conventional tillage (CTW-CTR) increased TK across all soil depth, but other treatments had no effect. Similarly, AK was highest in CTW-CTR, although values did not significantly differ from ZTW-CTR and ZTW-CTRs. However, AK in CTW-CTR was clearly higher than in ZTW-ZTR and ZTW-ZTR/B. Finally, CTW-CTR had lower SOC and TN, whereas C/N ratio did not differ across treatments.

Wheat nutrient uptake

Before anthesis and even at maturity, CTW-CTR always had lower wheat K concentration than other treatments (Table 5). Wheat N concentration at jointing and anthesis did not differ significantly across treatments. At maturity, however, wheat N (of both grains and vegetative parts) was higher in ZTW-ZTR. This treatment also resulted in increased soil P absorption, which was as an advantage maintained to maturity.

Table 5. N, P, K concentration in wheat at different sampling stages in the eleventh growing season of the long-term tillage experiment (%).

Sampling time	Nutrient	CTW-CTR	ZTW-CTR	ZTW-CTRs	ZTW-ZTR	ZTW-ZTR/B
Active tillering	N	4.50 ab	4.34 ab	4.46 ab	4.55 a	4.25 b
	P	0.48 a	0.46 a	0.45 a	0.47 a	0.46 a
	K	2.11 b	2.92 a	3.17 a	3.18 a	3.25 a
Stem elongation	N	4.91 a	4.98 a	4.58 a	4.60 a	4.76 a
	P	0.50 b	0.50 b	0.50 b	0.58 a	0.56 a
	K	2.07 c	3.38 ab	3.87 ab	4.51 a	4.29 ab
Anthesis	N	1.64 a	1.71 a	1.71 a	1.67 a	1.71 a
	P	0.22 a	0.26 a	0.26 a	0.23 a	0.24 a
	K	1.14 b	1.63 a	1.89 a	1.80 a	1.90 a
Maturity/straw	N	0.46 b	0.55 ab	0.52 ab	0.58 a	0.62 a
	P	0.03 b	0.04 a	0.04 ab	0.05 a	0.04 ab
	K	1.23 b	1.52 ab	1.54 ab	1.60 a	1.80 a
Maturity/grain	N	1.95 ab	1.83 b	1.95 ab	1.97 ab	2.07 a
	P	0.30 b	0.32 ab	0.32 ab	0.35 a	0.29 b
	K	0.37 b	0.40 ab	0.39 ab	0.40 a	0.37 b

Values are means across three replicates. Values in the same row with different letters are significantly different (n = 3, $P < 0.05$). **CTW-CTR,** Conventional tillage for wheat and rice; **CTW-ZTR,** conventional tillage rice following zero-tillage wheat with residue mulching; **CTW-ZTRs,** like CTW-ZTR, but with the wheat residue incorporated; **ZTW-ZTR,** zero tillage for both crops with residue mulching; **ZTW-ZTR/B,** zero-tillage plus residue mulching on raised beds.

Wheat under CTW-CTR tended to have less N, P, and K uptake due to poor growth (Figure 1). None of the other treatments differed in nutrient accumulation, which generally occurred before anthesis. However, K accumulation declined post-anthesis, with K content being significantly lower at maturity than at the flowering stage.

Rice nutrient uptake

The effects of tillage on macronutrient concentrations in rice mainly manifested during early growth (Table 6). Compared to ZT, the CT rice had significantly higher N and P concentration at active tillering stage. After anthesis, the The difference for macronutrient concentrations between treatments decreased.

Macronutrient accumulation was directly proportional to the amount of dry matter (Figure 1), especially during early stages. CT practices that resulted in rapid post-transplantation growth (CTW-CTR, ZTW-CTR, and ZTW-CTRs) also had higher nutrient accumulation than ZT practices. As in wheat, N and P accumulated in rice constantly from transplanting to maturity, with the majority occurring before anthesis. At the reproductive stage, N uptake stalled in rice under CTW-CTR was only 1.7 kg ha^{-1}, but higher in other treatments (11.8–28.9 kg ha^{-1}). Likewise, K accumulation declined post-anthesis.

Partial balance of Nutrients

For all treatments, partial N balance was negative during wheat season and positive during rice season. After wheat harvest, N deficit ranged from 4.5 kg ha^{-1} year^{-1} (ZTW-ZTR) to 30.1 kg ha^{-1} year^{-1} (ZTW-CTR). In contrast, N surplus was highest in ZTW-ZTR (90.3 kg ha^{-1} year^{-1}) and lowest in CTW-CTR (36.7 kg ha^{-1}year^{-1}) after rice harvest. N surplus varied across the two seasons among all treatments, and ZTW-ZTR had the lowest vaule due to a relatively lower rice yield (Table 7).

Wheat and rice P uptake were both very low (< 30 kg ha^{-1} year^{-1}). However, P fertilizer input was 39.2 kg ha^{-1} for both crops, following local recommendations. As a result, unused P in the soil profile reached as high as 30 kg ha^{-1} year^{-1}.

Unlike N and P, K was predominantly stored in straw rather than in grains. Thus, K balance was positive in all treatments with residue retention. Across the two crop seasons, ZTW-ZTR and ZTW-ZTR/B produced a K surplus of > 104 kg ha^{-1} year^{-1}, while CTW-CTR resulted in a K deficiency of 78.0 kg ha^{-1} year^{-1}.

DISCUSSION

Crop production over time

In the present study, a clear difference between the two

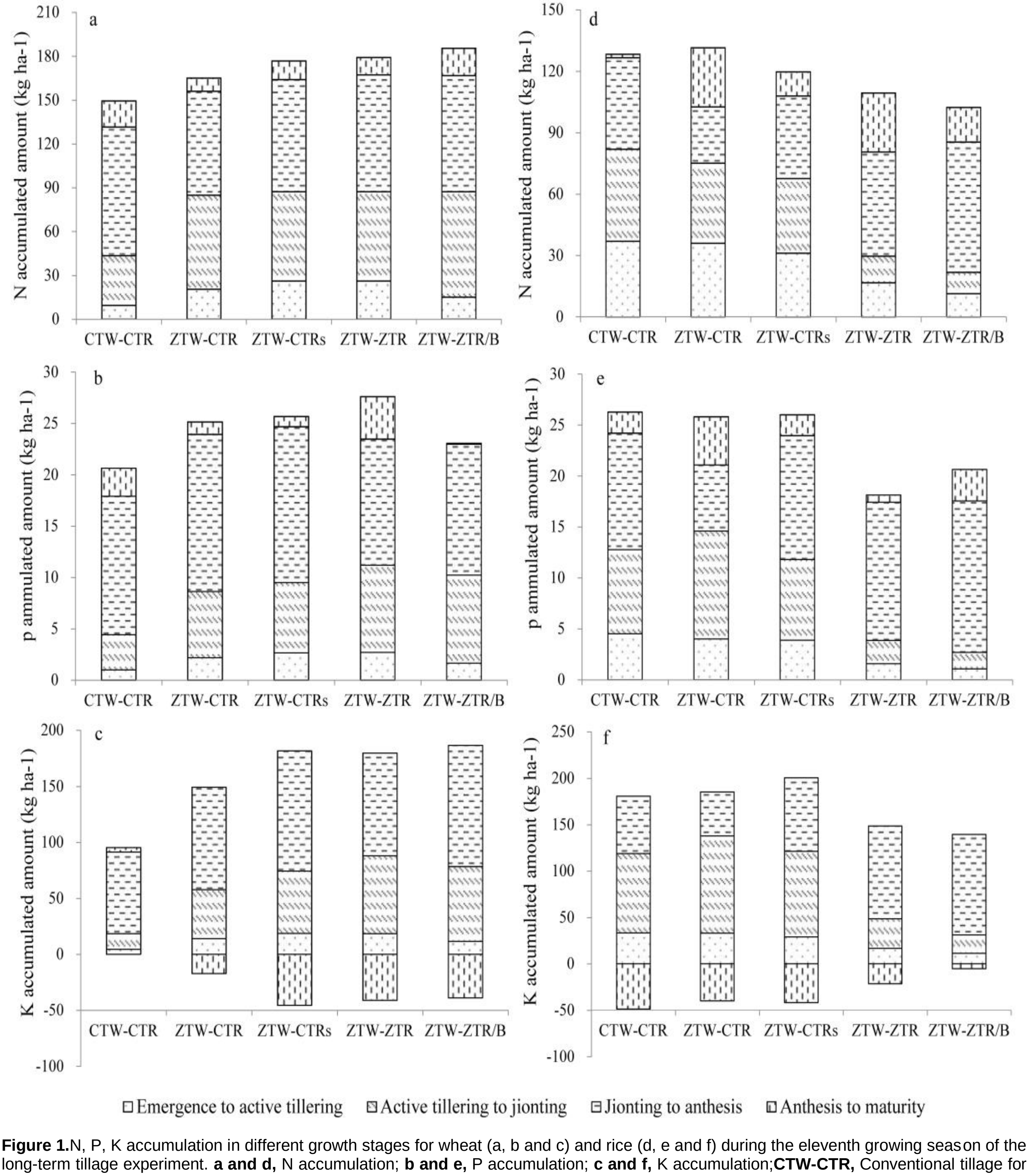

Figure 1.N, P, K accumulation in different growth stages for wheat (a, b and c) and rice (d, e and f) during the eleventh growing season of the long-term tillage experiment. **a and d,** N accumulation; **b and e,** P accumulation; **c and f,** K accumulation;**CTW-CTR,** Conventional tillage for wheat and rice; **CTW-ZTR,** conventional tillage rice following zero-tillage wheat with residue mulching; **CTW-ZTRs,** like CTW-ZTR, but with the wheat residue incorporated; **ZTW-ZTR,** zero tillage for both crops with residue mulching; **ZTW-ZTR/B,** zero-tillage plus residue mulching on raised beds.

Table 6. N, P, K concentrations in rice at different sampling stages during the eleventh growing season of the long-term tillage experiment (%).

Sampling time	Nutrient	CTW-CTR	ZTW-CTR	ZTW-CTRs	ZTW-ZTR	ZTW-ZTR/B
Active tillering	N	3.11 a	2.95 a	3.25 a	2.30 b	2.31 b
	P	0.38 a	0.32 ab	0.40 a	0.22 b	0.22 b
	K	2.81 a	2.72 a	3.03 a	2.33 a	2.32 a
Stem elongation	N	2.14 a	1.75 b	1.83 ab	1.95 ab	2.11 ab
	P	0.33 a	0.34 a	0.32 a	0.24 b	0.26 b
	K	3.11 a	3.20 a	3.29 a	3.07 a	3.02 a
Anthesis	N	1.06 a	0.94 a	0.98 a	0.97 a	1.01 a
	P	0.20 ab	0.19 b	0.22 a	0.21 ab	0.21 ab
	K	1.53 b	1.69 ab	1.83 a	1.79 a	1.69 ab
Maturity straw	N	0.62 ab	0.56 ab	0.51 b	0.65 a	0.64 a
	P	0.07 a	0.06 a	0.06 a	0.05 a	0.07 a
	K	1.76 c	1.94 c	2.24 b	2.45 ab	2.71 a
Maturity/grain	N	0.92 c	1.00 abc	0.96 bc	1.09 a	1.07 ab
	P	0.23 ab	0.23 ab	0.24 ab	0.22 b	0.25 a
	K	0.24 ab	0.24 ab	0.27 a	0.23 b	0.26 ab

Values are means across three replicates. Values in the same row with different letters are significantly different (n = 3, $P < 0.05$). **CTW-CTR,** Conventional tillage for wheat and rice; **CTW-ZTR,** conventional tillage rice following zero-tillage wheat with residue mulching; **CTW-ZTRs,** like **CTW-ZTR,** but with the wheat residue incorporated; **ZTW-ZTR,** zero tillage for both crops with residue mulching; **ZTW-ZTR/B,** zero-tillage plus residue mulching on raised beds.

Table 7. Nutrient balance for wheat, rice, and year-round cropping under different tillage practices (kg ha^{-1}).

	Wheat			Rice			Year-round balance
	Input	Output	Difference	Input	Output	Difference	
N							
CTW-CTR	135.0	149.4	-14.4	165.0	128.3	36.7	22.3
ZTW-CTR	135.0	165.1	-30.1	165.0	96.2	68.8	38.7
ZTW-CTR$_S$	135.0	158.6	-23.6	165.0	89.4	75.6	52.0
ZTW-ZTR	135.0	139.5	-4.5	165.0	80.1	84.9	80.4
ZTW-ZTR/B	135.0	143.8	-8.8	165.0	74.7	90.3	81.6
P							
CTW-CTR	39.2	20.6	18.6	39.2	26.3	12.9	31.5
ZTW-CTR	39.2	25.1	14.1	39.2	22.1	17.1	31.2
ZTW-CTRS	39.2	24.3	14.9	39.2	22.4	16.8	31.7
ZTW-ZTR	39.2	24.5	14.7	39.2	15.7	23.5	38.2
ZTW-ZTR/B	39.2	20.4	18.8	39.2	17.7	21.5	40.3
K							
CTW-CTR	74.7	95.2	-20.5	74.7	132.2	-57.5	-78.0
ZTW-CTR	74.7	132.0	-57.3	74.7	23.3	51.4	-5.9
ZTW-CTRS	74.7	82.1	-7.4	74.7	24.8	49.9	42.5
ZTW-ZTR	74.7	28.5	46.2	74.7	16.8	57.9	104.1
ZTW-ZTR/B	74.7	25.5	49.2	74.7	18.1	56.6	105.8

CTW-CTR, Conventional tillage for wheat and rice; **CTW-ZTR,** conventional tillage rice following zero-tillage wheat with residue mulching; **CTW-ZTRs,** like CTW-ZTR, but with the wheat residue incorporated; **ZTW-ZTR,** zero tillage for both crops with residue mulching; **ZTW-ZTR/B,** zero-tillage plus residue mulching on raised beds.

crops in their yield responses to tillage practices was observed. Yield performance was higher in ZT wheat, but grain yield was higher in CT rice. After 10 years, the yield of rice under ZT achieved only 70% of CTW-CTR. These results suggest that although conservation tillage can improve production (Friedrich et al., 2012), actual performance also depends on multiple factors, including crop type, soil properties, climate, and cropping sequences (Bhushan et al., 2007; Erenstein and Laximi, 2008; Friedrich et al., 2012; Reicosky, 2015; Pittelkow et al., 2015a, 2015b; Ghimire et al., 2017; Yadav et al., 2017). The results also corroborated previous studies in demonstrating that ZT combined with residue mulching minimizes soil evaporation, improves moisture migration through soil capillary action, and promotes moisture use efficiency, beneficial to dryland crop growth (He et al., 2007; Su et al., 2007). However, long-term ZT has the potential to enhance large-aggregate formation and biopore increase (Fernández et al., 2010) causing higher seepage and thus adversely affecting irrigated water maintenance (Sharma et al., 1988). This characteristic led to severe water stress symptoms (yellow leaves, poor tillering) in rice across most growth stages. Similar results have also been reported for rice grown in Vertisol from central India (Mohanty et al., 2004).

Soil nutrient status

After 10 years, SOC (especially in topsoil) was significantly higher in the four ZT plus residue treatments than in the CT treatment. These results confirm reported positive effects of continuous residue application on soil health and nutrient use efficiency in RW systems (Singh et al., 2014). It could be demonstrate that practices without residue management would deplete soil SOC and negatively influence the stability of future agricultural production, as seen in reports of major SOC losses from intensive agriculture (Lal et al., 2007; Ghimire et al., 2017).

Here, CTW-CTR had lower topsoil TN and AN than other treatments, likely because conventional tillage lacked the residue that contributed to soil organic matter, an important N pool (Cassman et al., 1998; Wutzler et al., 2017). Overall, tillage practices had little influence on TP, but rotary tillage increased subsoil AP, possibly because the process moved nutrients into deeper soil profiles. Similarly, a 20-year rice-rice-wheat experiment in the Indo-Gangetic plain of Nepal found that TP and AP both increased under recommended NPK fertilizer levels (Regmi et al., 2002).

Most long-term RW experiments report soil K deficiency due to insufficient K application (Ladha et al., 2003, Regmi et al., 2002). Because straw stores most of the crop's K output, several studies have found that using residue as mulch replenishes K (Ladha et al., 2013; Mandal et al., 2004; Zhao et al., 2014). However, the present findings were not consistent with those reports. Soil TK and AK in CTW-CTR remained high despite the removal of all residues. Furthermore, the condition with full residue retention (ZTW-ZTR) experienced the lowest K levels. Thus, straw residue mulching did not benefit soil K replenishment. Based on these results, it could be hypothesized that soil K status may be associated with irrigation, and high seepage in ZT plots could have heightened K leaching. However, post-anthesis K excretion for both wheat and rice was observed, possibly buffering changes in the soil K pool.

Plant nutrient uptake

The present study showed that the difference in wheat K uptake were greater than in N and P uptake between treatments. Despite having a larger soil K pool, wheat K uptake in CTW-CTR was lower, suggesting that soil K status is not the limiting factor for K uptake. In Southwest China, the rainfall during wheat growth mostly occurs post-anthesis and is < 150 mm. Thus, un-mulched soil in CTW-CTR plots likely experienced higher moisture evaporation and lower soil moisture, inhibiting root activity. Slow root growth then led to a significant reduction in K absorption per unit root length (Wang et al., 1995).

Unlike wheat, rice nutrient uptake was highly associated with growth status. After transplanting, large quantities of irrigated water escaped through seepage under ZT, which caused poor vegetative growth and nutrient leaching (Lu et al., 2006). As a result, pre-anthesis nutrient concentrations and accumulation were much lower for ZTW-ZTR and ZTW-ZTR/B than for CTW-CTR.

Partial balance of Nutrients

A positive partical balance for N, P, and K in all treatments except conventional tillage (control) was found in the present study. Additionally, tillage and residue management had less influence on P partial balance due to minimal P uptake by plants. Year-round P surplus was approximately 30 kg ha^{-1}, accounting for 40% of the applied P fertilizer.

In wheat, N deficiency occurred post-harvest, especially for ZTW-CTR and ZTW-CTRs. In contrast, rice experienced an N surplus, especially under ZTW-ZTR treatments, which tended to experience poor rice growth. Likewise, in rice/wheat/mung bean and rice/wheat/maize annual cropping sequences of South Asia, wheat and maize suffered high N deficiency, whereas rice did not (Timsina et al., 2006). Moreover, although annual N budget was above zero (2–80 kg ha^{-1}), little was accumulated in the soil profile, possibly because of irrigation- and seepage-related losses (Raun and Johnson, 1999).

Irrespective of crop species, the addition of straw resulted in a K surplus, consistent with previous findings (Mandal et al., 2004). However, as mentioned earlier, CTW-CTR actually had a higher soil K status than the other treatments, despite the lack of residue addition. Although beyond the scope of our current study, the dynamics of nutrient exchange and transfer may explain this unusual outcome. For instance, soil organic matter and crop residues both significantly decreased soil K fixation levels (Dhaliwal et al., 2006). In this study, SOC was already abundant when the experiment began, and after 10 years of continuous straw retention, SOC was higher than most other RW regions. Coupled with high seepage and possible K leaching during the rice season, soil K status may wind up unexpectedly lower under ZT. Future studies should therefore focus on potential mechanisms for the phenomena observed in this work.

Conclusion

The study demonstrates that the combination of ZT and residue recycling increases SOC, with the highest concentrations observed under double ZT with straw mulching. Additionally, nutrient uptake was related to crop growth. Thus, nutrient uptake was low for wheat under CT, whereas rice nutrient uptake was significantly lower under ZT than under CT. This pattern reflected the tillage practice that resulted in poor growth for both crops.

Annual P surplus was high because crops absorbed very little P. Additionally, under local recommended N rate (135 kg ha^{-1} for wheat and 165 kg ha^{-1} for rice), wheat N was deficient, while rice N was in excess. The highest N surplus for both crops occurred under ZTW-ZTR and ZTW-ZTR/B. The lack of straw mulching resulted in high annual K deficiency under CTW-CTR, in contrast to the surplus experienced in treatments with straw retention. However, despite K deficiency, we observed little depletion of soil K under CTW-CTR.

Based on these results, it suggests that ZTW-CTR may be the best strategy for long-term sustainable crop production in southwest China. Moreover, we recommend decreasing the P input rate as the high P surplus and low absorption by plants.

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