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Effect of rotational tillage regimes on water-use efficiency and yield of wheat under corn–wheat cropping system (Case Study: North China Plain)

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Abstract

Tillage practices have been widely acknowledged to play a critical role in optimizing water use efficiency (WUE) for winter wheat production in the Northern China Plain (NCP) where drought is a critical limiting factor. Therefore, the WUE of wheat as influenced by annual rotational tillage under the corn–wheat cropping system during 2016–2018 has determined. The tillage regimes in the corn season were either N: no–tillage or SR: sub–soiling with rotary tillage). One of three regimes, sTR: strip rotary tillage; R: rotary tillage; and SR: sub–soiling with rotary tillage) were the tillage practices in the wheat seasons. Thus, making a total of 6 treatments. N–SR markedly decreased the penetration resistance, while the soil water storage was enhanced in the 60-100 cm layer during the wheat season, over both years. On the other hand, the use of SR during the wheat-growing season increased evapotranspiration. Compared with other tillage practices, the photosynthesis rate enhanced under the N–SR. As a result, the highest yield and WUE of wheat were recorded in the N–SR regime. Our findings suggest that no–tillage in the corn season and sub–soiling with rotary tillage in the succeeding wheat season can improve wheat yield by promoting deep soil water, enhancing the leaves photosynthesis rate and increasing WUE.

Introduction

The North China Plain occupies nearly 20% of China's total cropland and produces about a quarter of all grain output (Zhao et al., 2013). It contributes massively to China's food security and is a key area for winter wheat production (Wang and Li, 2018). However, the annual precipitation of 90 mm to 300 mm is insufficient to meet the water needs of the crop (Wu et al., 2006). The high water demand of wheat cropping systems and the inadequate rainfall put enormous pressure on the irrigation system making the cultivation of wheat in the NCP even more challenging (Zhang et al., 2017).

In the NCP, winter wheat production is threatened by drought. One important management practice for ameliorating the impact of drought on wheat production is tillage practices (Shi et al., 2016). Because tillage practices have profound impacts on the soil properties, it has strong implication for the conservation of soil water and productivity of crops, particularly in drought-prone regions (Garcia-Franco et al., 2015; Latifmanesh et al., 2016; Shi et al., 2016). Generally, no-tillage and reduced tillage practices are commonly suggested for the protection of the soil structure and enhancement of soil fertility (Su et al., 2007; Sun et al., 2016; Wang et al., 2006). Meanwhile, sub-soiling tillage can boost soil properties, water and fertility statuses of croplands, compared with conventional tillage practices (Su et al., 2007). Under arid conditions, Li et al. (2006) and Zheng et al. (2014) recommended no-tillage and sub-soiling tillage for water conservation, improving the chlorophyll contents of flag leaves, net photosynthetic rates and consequently higher crop yield. By reducing the seasonal evapotranspiration, no–tillage and reduced tillage and mulching can improve WUE (Jemai et al., 2013; Sainju et al., 2011; Verhulst et al., 2011) while as much as 90% of rainfall can be retained in soil following by deep tillage (Wang et al., 2002).

In the NCP, several studies have reported the impacts of tillage on soil characteristics, crop productivity and resource use efficiency. Soil sub-soiling and ridge tillage were found to have improved soil moisture, facilitate root development and photosynthesis, enhance resilience of maize to extreme temperature, and increase grain output (Tao et al., 2013). Following plow tillage in the corn season, root parameters and water use efficiency improved while penetration resistance and soil bulk density were reduced (Guan et al., 2015). However, these reports have focused mainly on single cropping systems or one of multiple cropping cycles (Guan et al., 2015; Tao et al., 2013). Less has been documented on the additive impact of corn and wheat season tillage regimes on the productivity of the wheat in the succeeding season. Considering that the NCP contributes about 50% to China's total wheat production (Fang et al., 2010a), it is beneficial to understand how the choices of tillage practices in corn and wheat season impact wheat yield. Accordingly, the objective of this study is to determine the effects of corn season tillage practices on: (i) soil penetration resistance, (ii) soil water storage, (iii) evapotranspiration, (iv) photosynthetic rate, (v) WUE, and (vi) yield of wheat.

Materials and Methods

Site Description

The experiment was carried out at the Institute of Agricultural Science of Dongping County near the Dongping Lake, Dongping (35°54′30″N 116°18′00″E, 35.937°N 116.470°E) (fig. 1), stands 377 meters above sea level, in the southwestern part of Tai'an, in the west of Shandong Province, China. Here, the traditional cropping pattern is corn- wheat cropping with no–tillage and rotary tillage regimes in the corn season and wheat seasons, respectively. The precipitation amounts to 609.2mm annually and the wettest months are between April and August. Meanwhile, the average annual temperature is about 14.4 °C. During the 2016–2017 and 2017–2018 growing cycle of wheat, the total precipitation was 156.9 and 104.9 mm, respectively. The soil is categorized as cumulated irrigated fluvo–aquic soil according to the classification system of the United States Department of Agriculture (USDA) (Soil Survey Staff 1999). At initial total N, available N, soil organic matter, available potassium and available phosphorus of the soil at the depth of 0–20 cm were 1.2 g kg−1, 104.9 mg kg−1,18.6 g kg−1, 108.7 mg kg−1 and 40.5 mg kg−1, respectively.

Experimental Design and Management

The field experiment was first set up in the 2012–2013 cropping season. In the wheat season of 2012, three tillage practices i.e. strip rotary tillage (sTR), rotary tillage (R), and sub–soiling with rotary tillage (SR), were designed. Meanwhile, two additional tillage regimes, i.e. no–tillage (N) and sub–soiling with rotary tillage (SR), were established in the succeeding corn season in the next year. In all, our treatments were: N–sTR; N–R; N–SR; SR–sTR; SR–R; and SR–SR for the entire corn-wheat cropping. Each of the plots, including the three replications of each treatment, had a dimension of 55 m × 5.2 m, and was arranged in a completely randomized design.

Each year, the straw obtained after the harvest of wheat and corn were returned into the soil as described (Table 1). Jimai 22 was the wheat cultivar of choice for this experiment. The planting dates of the wheat was October 10th, 2016 and 2017, harvesting dates was June 15th, 2017 and 2018. We applied 60% of the nitrogen fertilizer (135 kg N ha−1) as basal fertilizer while the rest (90 kg N ha−1) was applied as top dressing at the jointing stage. In the case of the potassium and the phosphorus fertilizers all the allocated quantities, 77 kg K2O ha−1 and 130 kg P2O5 ha−1, respectively, were applied at once as basal fertilizer.

Fig. 1- Digital elevation model (DEM) of Dongping County

Table 1- Operational procedure of different tillage treatments during corn and wheat seasons

	Corn planting tillage practices		Wheat planting tillage practices	Treatments
N	Returning wheat straw to the field, base fertilizer spread and seeding with common seeder without any soil disturbance.	sTR	Returning corn straw to the field, the strip rotary tillage only on wheat sowing row (15 cm in depth) and base fertilizer spread simultaneously one time.	N-sTR
		R	Returning corn straw to the field, base fertilizer spreading, completely rotary tillage two times for wheat season (15 cm in depth), seeding with common seeder.	N-R
		SR	Returning corn straw to the field, base fertilizer spreading, sub-soiling once (35 cm in depth) followed completely rotary tillage two times (15 cm in depth), seeding with common seeder.	N-SR
SR	Returning wheat straw to the field, base fertilizer spreading, sub-soiling once (35 cm in depth) followed completely rotary tillage two times (15 cm in depth), seeding with common seeder	sTR	Returning corn straw to the field, the strip rotary tillage only on wheat sowing row (15 cm in depth) and base fertilizer spread simultaneously one time.	SR-sTR
		R	Returning corn straw to the field, base fertilizer spreading, completely rotary tillage two times for wheat season (15 cm in depth), seeding with common seeder.	SR-R
		SR	Returning corn straw to the field, base fertilizer spreading, sub-soiling once (35 cm in depth) followed completely rotary tillage two times (15 cm in depth), seeding with common seeder.	SR-SR

Fig. 2- SC-900 Field Scout Digital Soil Compaction Meter (Digital Penetrometer)

Soil penetration resistance

The soil penetration resistance (PR, MPa) was determined in the second year of the experiment. We used a digital handheld cone–tipped penetrometer (Field Scout, SC 900 Soil Compaction Meter; Spectrum Technologies, Inc., Plainfield, IL, USA) (Fig. 2) of 6.4 mm radius to measure the PR at six different points in each plot from 0–45 cm at 2.5 cm interval (Mu et al., 2016).

Soil sampling for water content

We estimated the soil water content (%) at different stages of wheat growth at a depth of 140 cm and an interval of 20 cm. Firstly, a sampling tube was used in collecting six cores (diameter: 5 cm). Then, the oven–drying approach was employed in determining the soil water content by instantaneously weighing a portion of the fresh soil, and reweighing after it attained a constant weigh following oven-drying at 105 ◦C for 48 h. We estimated the changes in the stored soil water (ΔS) by finding the difference in stored soil water in the upper 140 cm soil layers at the sowing and maturity stages. We calculated the soil water storage (SWS, mm) based on the formula given by Xu et al. (2016).

$$SWS = MWC \times \gamma \times H \quad (1)$$

where MWC represents the mass water content (g g–1), γ (g cm–3) stands for the soil bulk density, and the thickness of the soil layer is given as H (mm).

SET was calculated using the water balance equation (Wang et al., 2009) as follows:

$$SET = (RG + I + SG) - D - ROFF - \Delta S \quad (2)$$

Where:
RG is the growing seasonal rainfall (mm)
I is the irrigation amount (mm)
SG is the groundwater contribution to the plant's available water (mm)
D is the downward drainage out of the root-zone (mm)
ROFF is the surface runoff (mm), and
ΔS (mm) is the change in stored soil water in the upper 140 cm of the soil between the sowing and maturity phases.
Noteworthy, SG, D and ROFF were all negligible or insignificant because the depth of groundwater in the experiment was about 10 m below the surface, and the experimental plots were designed in such a way any entry of runoff was blocked.

Photosynthetic characteristics

The flag leaf, which is known to contribute immensely to photosynthesis was tested for the net photosynthetic rate (Pn) by using the LI-COR 6400 portable photosynthesis system (LI-COR, Inc., Lincoln, Nebraska, USA). To prevent errors caused by variation in sunlight intensity on different days, we conducted all the measurements on sunny days between 8:00 am and 11:00 am. The CO2 concentration in the leaf chamber and the light intensity of red blue light emitting diode (LED) of LI-6400 were set at 400 μmol

mol−1 and 1500 photons µmol m−2 s−1, respectively.

Grain yield

The grain yield was determined from a 2 m2 undisturbed subplot of each of the six replicate plots and was reported at moisture of 17%.

2.7. WUE

WUE was calculated using the following equation (Fang et al., 2010b):

$$WUE = Y/SET \quad (3)$$

where Y is the grain yield (kg ha−1).

Data analysis

SAS 9.2 statistical package (SAS institute Inc., Cary, NC, US) was used to carry out statistical analysis while Microsoft Excel 2010 (Microsoft Corporation, New Mexico, USA) and sigma plot Ver.12.5 (Systat Software Inc., Chicago, IL, USA) was used to make the figures. The statistical analysis of variance (ANOVA) was employed to test for differences among the treatments while the least significant difference (LSD) test used to compare the means of the treatments at $P < 0.05$.

Results

Soil penetration resistance (PR)

In 2017–2018, the PR in the 0–45 cm soil layer at the revival stage of winter wheat illustrated significant difference (Fig. 3). Under no-tillage in corn, the lowest and highest PR were observed in N-SR and N–sTR, respectively. Meanwhile, the PR of SR–sTR in the 0-33 cm soil depth was 77.5% and 94.6% higher when compared with SR–R and SR–SR, respectively.

No significant difference was noted between N–SR and SR–SR, while SR–R had 4.7% higher PR than N–SR at the 0-45 cm soil layer. The average PR of N–sTR soil was 11.2 % and 11.4% higher than SR–sTR treatment in the 0-33 cm and 0–45 cm soil depths, respectively (Fig. 3).

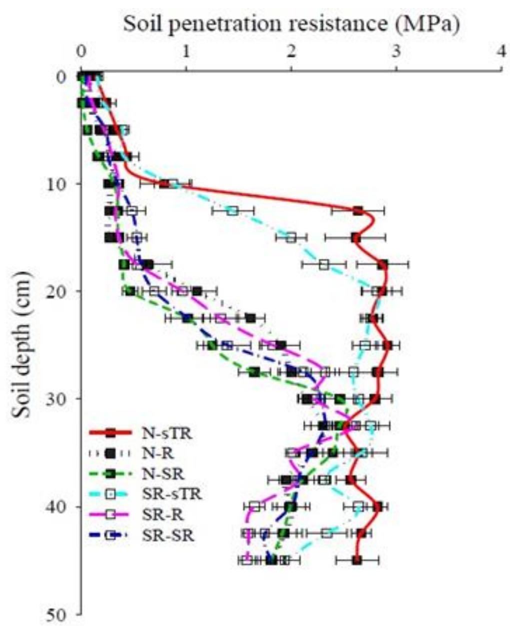

Fig. 3- Effect of different tillage practices on soil penetration resistance in 0–45 cm soil depth at revival stage of wheat season 2017–2018, N= no–tillage and SR= sub–soiling with rotary tillage, in the corn season; sTR= strip rotary tillage, R=rotary tillage and SR=sub–soiling with rotary tillage, in the wheat season.

Soil water content

In both 2016–2017 Fig. (4a) and 2017–2018 Fig. (4b) wheat growing seasons, the soil water contents was significantly different in the 0–140 cm soil layers at the different wheat growing stages. At the sowing stage of both years, the top 40 cm layers of soil had higher water content under the use of no–tillage in corn and was 6.9%, 5.4%, and 6.2% higher under N–sTR, N–R and N–SR compared with SR–sTR, SR–R, and SR–SR, respectively. On the contrary, the water content in the 40–140 cm layers at the same stage, was higher under SR–tillage in corn by 6.7%, 2.2%, and 6.3% under SR–sTR, SR–R, and SR–SR, in comparison with N–sTR, N–R, and N–SR tillage practices, respectively.

At revival stage of the first year, the water content at the 0–40 cm depth was 3.3% higher in those treatments under no–tillage in the corn season, while no difference was detected in 40–140 cm. N–sTR had 15.7% higher water content at 0–20 cm soil, compared with SR–sTR but there was no difference at 40–140 cm between these two treatments. Generally, the water content at the 0–140 cm depth of the revival stage, was higher under N–sTR, N–R, and N–SR by 3.8%, 5.7% and 3.9%, compared with SR–sTR, SR–R, and SR–SR, respectively. There was no marked difference in water content noted in the second year among N–sTR and N–SR, compared with SR–sTR and SR–SR, but N–R had 2.1% and 4.4% higher water content at 0–40 and 40–140 cm, compared with SR–R, respectively.

At jointing stage in the first year, the soil moisture content of N–sTR, N–R, and N–SR were significantly higher in the 0–40 cm soil layer by 4%, 4.8% and 11.8%, compared with SR–sTR, SR–R, and SR–SR, respectively but no marked difference was seen at the 40–140 cm depth among the treatments. In the second year, we observed an insignificant reduction in the soil water content at 0–40 cm in all treatments compared with the previous year.

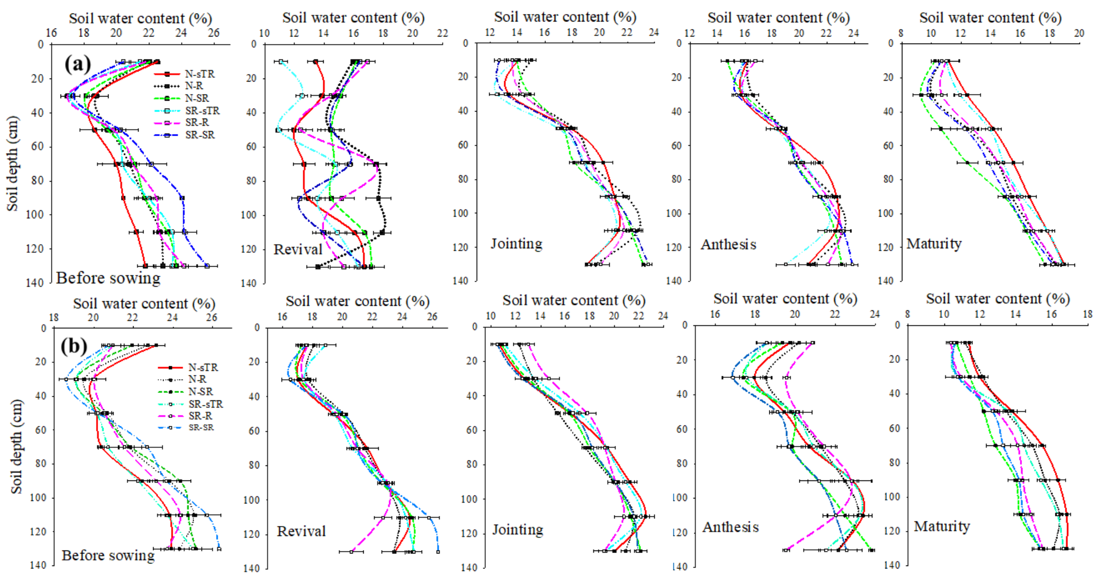

Fig. 4- Soil water content at different stage of the wheat growing season in 2016–2017 (a), and 2017–2018 (b); N= no–tillage and SR= sub–soiling with rotary tillage, in the corn season; sTR= strip rotary tillage, R=rotary tillage and SR=sub–soiling with rotary tillage, in the wheat season.

On comparing the treatment at the anthesis stage, no significant differences were found among them in both years but in the first year, N–sTR showed 4.3% lower water content in 40–140 cm while in the second year 4.2% higher water content compared with SR–sTR. Furthermore, in first year N–SR showed lower water content by 2.7% and 1.4%, but second–year water content was higher by 3.6% and 2.4% in 0–40 and 40–140 cm depths, in comparison to SR–SR respectively.

At maturity, both years exhibited a similar trend of water content across all the treatments. In the 0–140 cm soil depth, the highest and lowest water content were observed in N–sTR and N–SR, respectively. The moisture content of SR–SR and SR–R were higher by 5.0% and 4.9%, at the 0–40 cm layer, and also by 5.5% and 1.2% at the 40–140 cm soil layer, compared with N–SR and N–R, respectively. Overall, the water content in the 0–140 cm depth under N–sTR, SR–R, and SR–SR tillage at the maturity stage were 2.1%, 2.0%, and 5.4% more than those under SR–sTR, N–R, and N–SR, respectively (Fig. 4).

Apparent ΔS in different soil layers

In the wheat season, there were noticeable variations in the ΔS at the 0–140 cm soil layers among all six treatments (Fig. 5a & b). The ΔS in the 0–40 cm depth was 12.6%, 5.2% and 5.4% higher in the treatments N–sTR, N–R and N–SR, as against SR–sTR, SR–R and SR–SR, respectively. Elsewhere, reverse was the case at the soil depth of 40–140 cm where SR–sTR, SR–R and SR–SR were 12.3%, 33.0% and 0.8% higher than N–sTR, NR and N–SR, respectively. Together, N and SR in the corn-growing season combined with sub–soiling with rotary tillage in the wheat-growing, i.e. N–SR and SR–SR, promoted the use of the soil water resident in the deeper soil layers (60 – 140 cm) by winter wheat.

Evapotranspiration (ET) during the wheat season

The ET in the six treatments were between the range of 372.9 mm and 435.6 mm during both cropping years (Fig. 6). There was no marked difference between N–sTR and SR–sTR in the first and second year while SR–sTR was higher than N–sTR in both years. The highest ET was observed under the sub-soiling with rotary tillage in the wheat-growing season under both N and SR during the corn season, while sTR recorded the least ET in both years. Together, we can deduce that the sub–soiling with rotary tillage improved the water consumption of winter wheat in both years.

Water use efficiency (WUE)

The range of values for the WUE was between 20 kg ha−1mm−1 and 25.4 kg ha−1mm−1 (Fig. 7). Under both N and SR–tillage in the corn season, SR in wheat recorded the highest WUE, in comparison with other treatments. N–SR achieved the highest WUE at 24.3 and 25.4 kg ha−1mm−1 in the 2016–2017 and 2017–2018 growing seasons, respectively ($P<0.05$). Averagely, in both years N–sTR and SR–sTR had the lowest WUE compared with those practices under N–SR tillage, respectively. In this experiment, a strong positive relationship (R2=0.86– 0.90) was observed between WUE and grain yield (Fig. 8).

Fig. (9) depicts the relationship of WUE and grain yield with ΔS using regression. We found a positive correlation between grain yield and ΔS and between WUE and ΔS in the wheat-growing seasons of 2016–2017 and 2017–2018, respectively (Fig. 9).

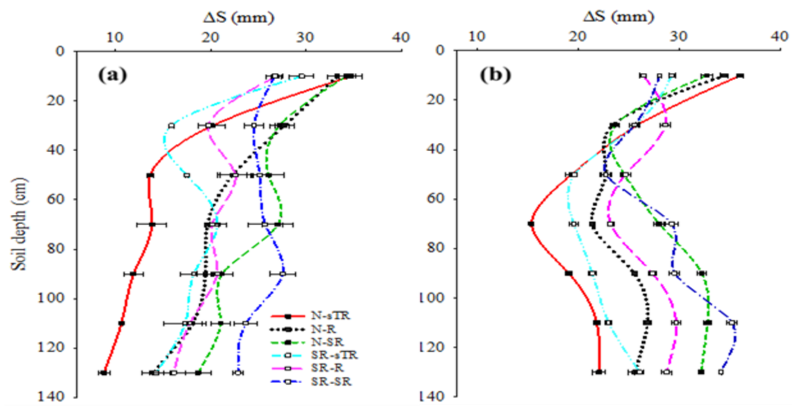

Fig. 5- Change in soil water storage (0–140 cm) under different tillage practices during wheat growing season in 2016–2017 (a) (Latifmanesh et al., 2018), and 2017–2018 (b); N= no–tillage and SR= sub–soiling with rotary tillage, in the corn season; sTR= strip rotary tillage, R=rotary tillage and SR=sub–soiling with rotary tillage, in the wheat season.

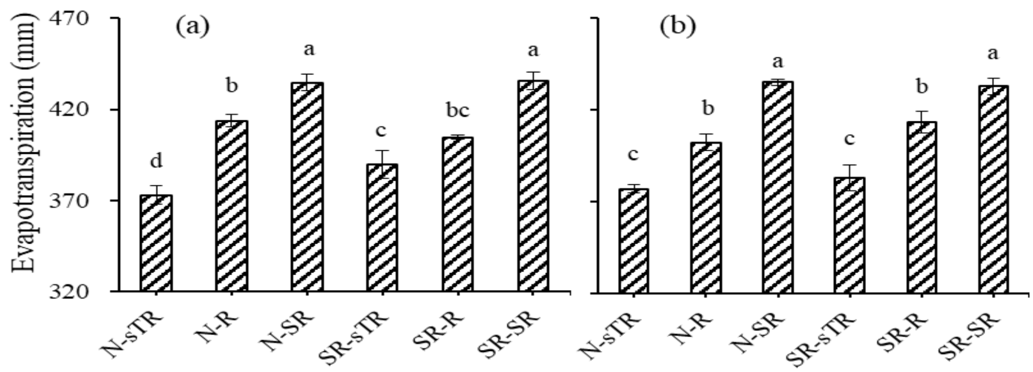

Fig. 6- Evapotranspiration during the wheat season 2016–2017 (a), and 2017–2018 (b); N= no–tillage and SR= sub–soiling with rotary tillage, in the corn season; sTR= strip rotary tillage, R=rotary tillage and SR=sub–soiling with rotary tillage, in the wheat season.

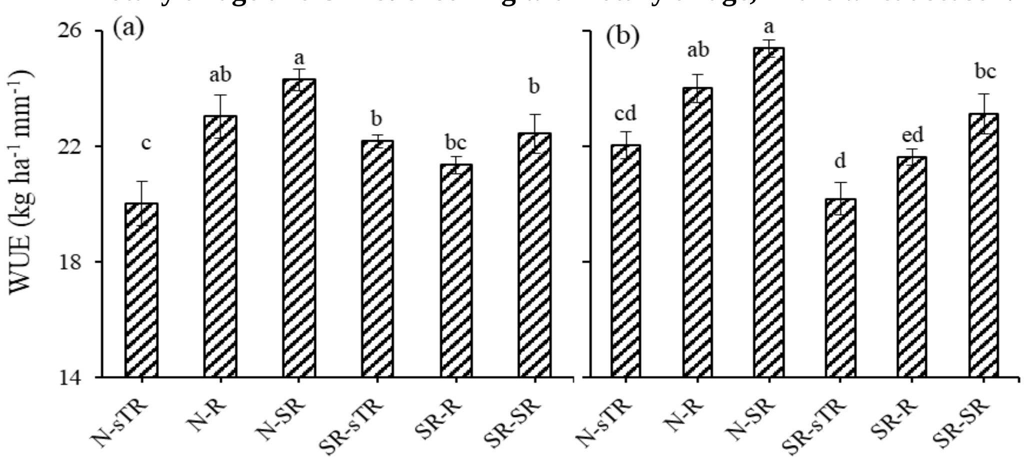

Fig. 7- Water use efficiency during the wheat season 2016–2017 (a), and 2017–2018 (b).

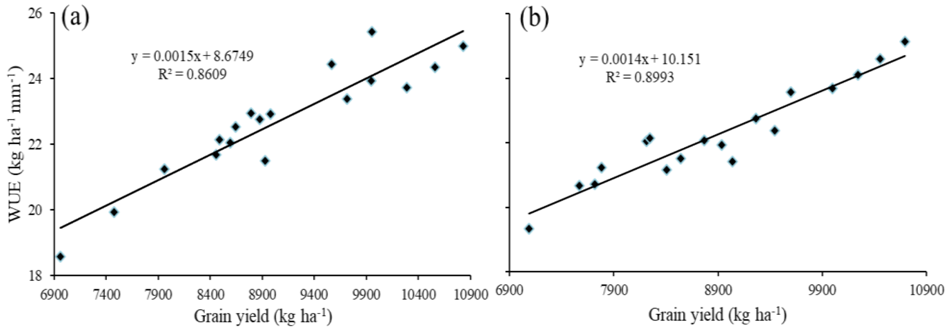

Fig. 8- Linear relationship between WUE and grain yield of wheat growing season in 2016–2017 (a), and 2017–2018 (b).

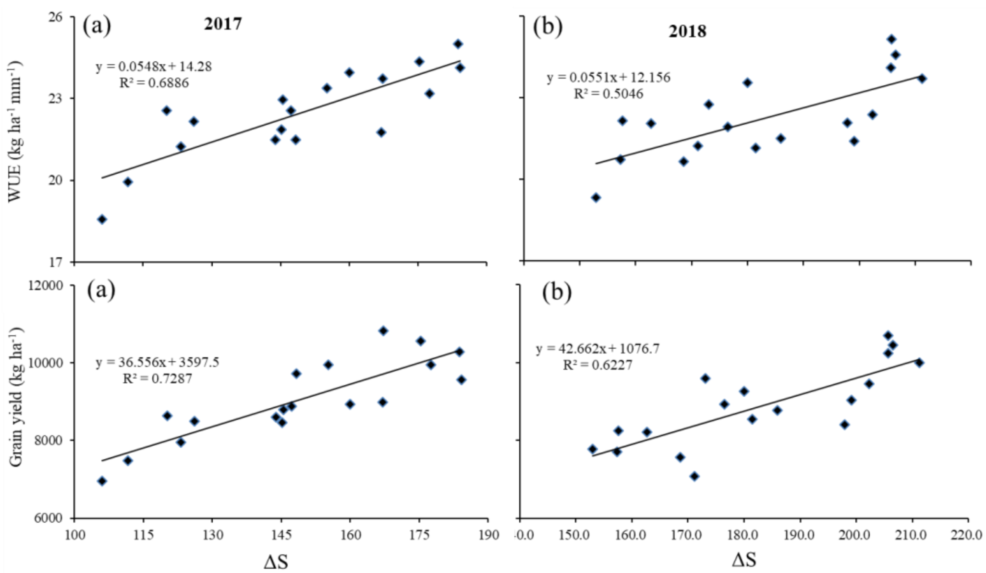

Fig. (9) Regression (polynomial) relationship between WUE and grain yield with ΔS in wheat growing season 2016–2017 (a), and 2017–2018 (b)); N= no–tillage and SR= sub–soiling with rotary tillage, in the corn season; sTR= strip rotary tillage, R=rotary tillage and SR=sub–soiling with rotary tillage, in the wheat season.

Consumption of different water resources of ET

In the 2016–2017 growing season, the irrigation supplied amounted to 102.4 mm with an RG of 156.9 mm while in 2017–2018 growing season, 101.3 mm was recorded with an RG of 104.9 mm (Table 2).

ET irrigation ratios in the N–SR and SR–SR were similar in both years and were the lowest among those treatments in N and SR in the corn season, respectively. This implies that SR in the wheat season can decline soil water consumption. On average, ΔS at the 0–140 cm soil depth was higher by 54.4% and 13.6% under the treatment N–SR in the first year and by 29.4% and 14.6% in the succeeding year, compared with N–sTR and N–R, respectively. Similarly, SR–SR had the highest ΔS which was higher than that under SR–sTR and SR–R by 35.0% and 21.2% in the first year and 24.3% and 8.4% in the second year, respectively.

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Table 2- Effects of tillage practices on different water resources consumption amount and their ratio on ET.

Year	Tillage practices	R_G		Irrigation		ΔS	
		Amount (mm)	Ratio (%)	Amount (mm)	Ratio (%)	Amount (mm)	Ratio (%)
2016 – 2017	N–sTR	156.9	42.1	102.4	27.5	113.6	30.5
	N–R	156.9	37.9	102.4	24.7	154.5	37.3
	N–SR	156.9	36.1	102.4	23.6	175.5	40.4
	SR–sTR	156.9	40.2	102.4	26.3	130.6	33.5
	SR–R	156.9	38.8	102.4	25.3	145.4	35.9
	SR–SR	156.9	36.0	102.4	23.5	176.3	40.5
2017 – 2018	N–sTR	104.9	28.7	101.3	27.7	159.2	43.6
	N–R	104.9	27.2	101.3	26.3	179.7	46.6
	N–SR	104.9	25.5	101.3	24.6	205.9	50.0
	SR–sTR	104.9	28.3	101.3	27.3	164.2	44.3
	SR–R	104.9	26.6	101.3	25.7	188.4	47.7
	SR–SR	104.9	25.6	101.3	24.7	204.2	49.8

Abbreviation: N= no–tillage and SR= sub–soiling with rotary tillage, in the corn season; sTR= strip rotary tillage, R=rotary tillage and SR=sub–soiling with rotary tillage, in the wheat season.
RG: growing season rainfall (mm); ΔS: apparent change of soil water storage (mm).

Table 3- Effects of tillage practices on photosynthetic rate (*Pn*)

Year	Tillage practices	*Pn* (μmol CO_2 m^{-2} s^{-1}) DAA		
		0	10	20
2017 – 2018	N–sTR	21.9 b	19.2 d	18.2 c
	N–R	23.8 ab	21.3 bc	20.3 ab
	N–SR	25.6 a	23.4 a	21.7 a
	SR–sTR	21.7 b	19.9 cd	18.7 c
	SR–R	22.2 b	20.3 bcd	19.6 bc
	SR–SR	23.9 ab	21.6 b	20.9 ab

Means of each column followed by similar letters are not significantly different (5%).
Abbreviation: N= no–tillage and SR= sub–soiling with rotary tillage, in the corn season; sTR= strip rotary tillage, R=rotary tillage and SR=sub–soiling with rotary tillage, in the wheat season.
DAA is days after anthesis.

Leaf photosynthetic rate (Pn)

Pn values from anthesis to twenty days after anthesis (DAA), were significantly higher under N–SR and SR–SR treatments, in comparison with other tillage practices under N and SR in the corn season ($P<0.05$). The results showed that the Pn of N–SR was markedly higher at anthesis, ten DAA, and twenty DAA by 17%, 21.6% and 18.6% compared with N–sTR, respectively. Meanwhile, the Pn under SR–SR was higher by 10% at anthesis, 8.2% at ten DAA, and 11.5% at twenty DAA, compared with SR–sTR (Table 3).

The flag leaf Pn at anthesis, ten and twenty DAA were higher by 6.9%, 8.6% and 4.0% under N–SR than SR–SR, and by 7.2%, 5.0% and 3.3% under N–R as against SR–R, respectively. We found no significant difference in the flag leaf Pn between N–sTR and SR–sTR.

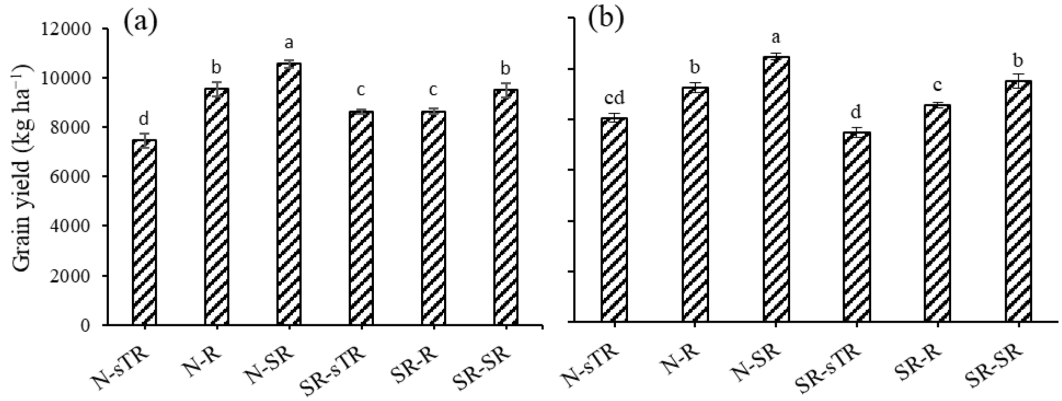

Fig. 10- Wheat grain yield 2016–2017 (a), and 2017–2018 (b)); N= no–tillage and SR= sub–soiling with rotary tillage, in the corn season; sTR= strip rotary tillage, R=rotary tillage and SR=sub–soiling with rotary tillage, in the wheat season

Tillage impacts on yield

In comparison with SR–SR and SR–R, the use of N–SR and N–R significantly increased grain yield by 10% and 9.9% in the first year and by 10.2% and 8.1% in the second year, respectively. On the contrary, there was a 6.4% decrease in grain yield under N–sTR, compared with SR–sTR tillage in the first year but increased by 7.8% in the second year (Fig. 10). On comparing the tillage practices during the wheat season under no–tillage and SR–tillage in the corn, the higher grain yield recorded under N–SR by 41.5% and 10.8% in the first year, and 29.8%, and 12.9% than N–sTR and N-R in the second year, and by 9.9% and 10% in the first year, and 27% and 10.7% in the second year under SR–SR than SR–sTR and SR–R, respectively.

Discussion

Effects of tillage practices on soil penetration resistance

Tillage practices have a notable effect on soil penetration resistance (Suci et al., 2021). In no–tillage systems, improvement in soil structure has been reported (Cavalieri et al., 2009) but long-term continuous use results in soil surface compaction leading to increase in penetration resistance (Kuhwald et al., 2020). More so, soil compaction in deeper layers restricts lateral root growth, therefore limiting the ability of plants to access the water and nutrients in the subsoil (Guan et al., 2014). In this study, the adverse impact of the no-till on penetration resistance was annulled by sub-soiling with rotary tillage in the wheat season; the effect of which could last up to 2 years before the reappearance of the plow pan (Wang et al., 2020). The better performance of sub-soiling with rotary tillage over strip rotary can be linked to its ability to impact soil properties in the deeper soil layers. Following sub-soiling with rotary tillage in the wheat season, improvement in bulk density caused the penetration resistance to decrease (He et al., 2019). Hence, the soil water supply was better regulated and the vertical distribution of nutrients was more balanced (Li et al., 2019; Pengcheng et al., 2019).

Effects of tillage practices on soil water and ΔS

Tillage practices affect the soil's physical properties resulting in changes in water cycling in the soil-plant-atmosphere continuum (Dalmago et al., 2004). In our study, the practice of no-tillage in the corn season increased soil moisture in the top 40 cm layer than sub-soiling with rotary tillage. This corroborates with the report of Li et al. (2020) in the Arid Loess Plateau in China and can be attributed to the role of corn straw as mulch; thereby, preventing the loss of soil water by evaporation and promoting water infiltration. Meanwhile, the reverse effect in the 40-140 cm layer was because the sub-soiling with rotary tillage fostered the accumulation of water in deeper soil layer while the benefit of water retention in no-tillage systems were restricted to the upper layer of the soil (Huang et al., 2012). Thus, sub-soiling with rotary tillage in winter wheat promoted water conservation in deeper layers much more than strip rotary tillage, which restricts the infiltration of water into this layer due to the hard pan of the subsoil (He et al., 2019). Sub-soiling with rotary tillage promoted water retention in this layer due to its capacity to improve infiltration by disintegrating the hardpan of the soil without disturbing the top soil (Chen et al., 2005; Rathinavel, 2020). The impact of the tillage practices was predominant and significant in the sowing stage, compared to other growth stages because the changes in the soil must have benefited the early growth of wheat which has high water demand (Noor et al., 2022).

Effects of tillage practices on WUE and photosynthesis

Variations in evapotranspiration and WUE as a result of tillage practices have been reported (Noor et al., 2022). In this study, we observed there was no notable difference in the evapotranspiration when strip tillage was applied in the wheat season regardless of the tillage practice in the corn season. Thus, the lack of residual effect of corn tillage practices on the wheat season under strip tillage infers that strip tillage without sub-soiling is unsuitable for winter wheat cultivation, particularly in Arid climates (He et al., 2019). However, when sub-soiling with rotary tillage was carried out in the wheat season, evapotranspiration was higher than strip rotary tillage. This can be linked to the potential of sub-soiling to reduce runoffs, ensuring that more water available for the wheat plant and consequently, increasing evapotranspiration and WUE (Jiao et al., 2017).

The no-tillage in corn season ensures that water is available in the topsoil and used by the crop during the early growth stages of the wheat season whereas sub-soiling in the wheat season promoted the availability of water in the deeper layer of the soil, and its utilization at the later growth stages of wheat rather than the moisture-depleted top soil (Zheng et al., 2014). By so doing, the combination of no-till in the corn season and sub-soiling with rotary tillage in the wheat season promoted water conservation, increased WUE and reduced irrigation water requirements. Meanwhile, strip rotary tillage causes the soil to loosen such that soil water is easily lost. It has been demonstrated that strip rotary as a tillage practice that is not suited to arid agroecosystems or water-deficient soils (He et al., 2020). Moreso, wheat performs poorly in loose soil due to poor contact with roots (He et al., 2020).

Since water is a raw material for photosynthesis, tillage indirectly influences the rate of photosynthesis. The no-tillage in corn season, which had the higher moisture content than sub-soiling in the top 40 cm layer, equally recorded the higher photosynthesis rate. Also, the no-tillage in corn season and sub-soiling with rotary tillage in the winter wheat ensured the diversification of water use, higher WUE, and higher rate of photosynthesis, as against sub-soiling in both seasons. This finding conforms with previous work that tillage practices, like no-tillage, promote leaf photosynthesis in wheat due to increased soil water availability (Buczek et al., 2021).

Effects of tillage practices on yield

The availability of water drives wheat production and yield in the North China Plain. Therefore, we observed significant positive correlation relationship between WUE and grain yield. Meanwhile, wheat performs poorly in soil under strip rotary tillage without sub-soiling owing to the high risk of erosion and water loss (He et al., 2020). In addition, a double sub-soiling with rotary tillage does not allow for diversification of water sources because only the water in the deeper layers is conserved while the top isn’t optimized. However, the combination of no-tillage in the corn season and sub-soiling in the wheat season complement each other by ensuring the conservation of soil water in the topsoil when temperature is relatively higher in the corn season, while during a period of water scarcity, sub-soiling with rotary ensure that the top soil remains unturned, the hardpan of the subsoil is loosened and water from the deeper layer of the soil is accessible for the wheat (Qin et al., 2008). Thus, the most significant yield improvement were observed in the no-tillage and sub-soiling with rotary tillage.

Conclusion

Optimal grain production in the corn-wheat system of the NCP require that tillage practices are implemented in such a way that it benefits the succeeding crop. In this study, implementing no-tillage or sub-soiling with rotary in the corn season reduced penetration resistance in the wheat season under sub-soiling with rotary but not under rotary or strip rotary. However, treatments under no-tillage in corn had more water in the 0-40 cm soil layer while those under sub-soiling saved more water in the 40-140 cm layer. Together, the combination of no-tillage in the corn season and sub-soiling with rotary in the wheat season recorded the highest WUE efficiency and leaf photosynthetic rate due to the capacity to utilize the water in the upper and deeper layers of the soil at different stages of wheat growth. Hence, the application of no-tillage in the corn season and sub-soiling in the wheat season improved wheat yield, and it is therefore recommended for sustainable wheat production in the NCP.

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