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Soil water repellency influences maize yield by changing soil water availability under long-term tillage management

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Abstract

Drought is increasingly common due to frequent occurrences of extreme weather events, which further increases soil water repellency (SWR) and influences grain yield. Conservation agriculture is playing a vital role in attaining high food security and it could also increase SWR. However, the relationship between SWR and grain yield under conservation agriculture is still not fully understood. We studied the impact of SWR in 0–5 cm, 5–10 cm, and 10–20 cm layers during three growth periods on grain yield from a soil water availability perspective using a long-term field experiment. In particular, we assessed the effect of SWR on soil water content under two rainfall events with different rainfall intensities. Three treatments were conducted: conventional tillage (CT), reduced tillage (RT), and no-tillage (NT). The results showed that the water repellency index (RI) of NT and RT treatments in 0–20 cm layers was increased by 12.9%–39.9% and 5.7%–18.2% compared to CT treatment during the three growth periods, respectively. The effect of the RI on soil water content became more obvious with the decrease in soil moisture following rainfall, which was also influenced by rainfall intensity. The RI played a prominent role in increasing soil water storage during the three growth periods compared to the soil total porosity, penetration resistance, mean weight diameter, and organic carbon content. Furthermore, although the increment in the RI under NT treatment increased the soil water storage, grain yield was not influenced by RI ($p > 0.05$) because the grain yield under NT treatment was mainly driven by penetration resistance and least limiting water range (LLWR). The higher water sorptivity increased LLWR and water use efficiency, which further

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increased the grain yield under RT treatment. Overall, SWR, which was characterized by water sorptivity and RI, had the potential to influence grain yield by changing soil water availability (e.g. LLWR and soil water storage) and RT treatment was the most effective tillage management compared to CT and NT treatments in improving grain yield.

Keywords:

Conservation agriculture; rainfall; soil physical properties; maize; water use efficiency

1. Introduction

Soil water repellency (SWR) is an intrinsic physiochemical property in coarse- to fine-textured soils under different climates and land uses (Blanco-Canqui and Lal, 2009; Daniel et al., 2019; Diehl et al., 2010). The increase of drought stress in the global climate aggravates the SWR (Deurer et al., 2011; Goebel et al., 2011). It can limit soil water absorption rate and reduce water infiltration capacity (Daniel et al., 2019; Zheng et al., 2016), thus affecting some soil processes (e.g. carbon sequestration, aggregate stability, and soil erosion) and plant growth (Blanco-Canqui, 2011; Li et al., 2019; Liu et al., 2012; Moody et al., 2009).

Several studies have revealed the impact of SWR on the soil ecosystem in forests and fire-affected soils (DeBano, 2000; Plaza-Álvarez et al., 2018; Weninger et al., 2019). However, because the SWR in tilled farmland soils is smaller than in the aforementioned ones (Lucas-Borja et al., 2019; Stavi et al., 2016), there is a lack of research on SWR in farmlands, and especially its link to crop yield. The small degree of SWR, known as subcritical water repellency that occurs when the rate of wetting is

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decreased by water repellency induced by hydrophobic substances covering the surfaces of soil particles (Tillman et al., 1989), can also have a considerable effect on soil structure and hydraulic properties (Hunter et al., 2011; Tadayonnejad et al., 2017), which further affects plant growth and crop production. In addition, it is widely believed that conservation tillage practices have beneficial effects on the soil ecosystem and crop production (Blanco-Canqui and Ruis, 2018; Pittelkow et al., 2015). However, continuous no-tillage and the addition of straw can also increase SWR (Miller et al., 2019a), which is unfavorable for plant growth (Blanco-Canqui, 2011; Müller et al., 2016). Hence, studying the mechanism of how tillage practices affect crop yield by changing SWR is critically important for understanding the sustainability of conservation tillage practices.

Reduced tillage or no-tillage could reduce soil disturbance and increase soil organic carbon (Afzalinia and Zabihi, 2014; Hermansen et al., 2019; Miller et al., 2019b), both of which can increase SWR (Behrends et al., 2019; Li et al., 2021). Besides the limited knowledge about the relationship between SWR and crop production under conservation tillage practices, the results of the effect of SWR on crop production are inconsistent when conditions differ. Hassan et al. (2014) found that an increase in SWR led to higher dry mass production of alfalfa under natural climatic conditions with fluctuating temperature, whereas it had no significant effect at a constant temperature. Its poor relationship was also found in a 4-year field experiment (Roper et al., 2013). However, Li et al. (2019) added a hydrophobic substance to a sandy loam soil to increase SWR and found that it decreased summer maize yield. These inconsistent

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results show that growth conditions influence how SWR affects crop yield, making further study necessary under conservation tillage practices. Another reason for the inconsistency is that SWR characterizes soil water behavior (e.g. infiltration and absorption; Daniel et al., 2019), and if soil water status is not taken into account at the same time, the real impact of SWR on crop yield is hard to assess.

Soil water storage and availability can reflect the ease of absorbing soil water for crops and thereby influence crop yield (Filho et al., 2013; Li et al., 2020). Plant available water (PAW) and least limiting water range (LLWR) are two common ways to measure the soil water availability for plants from different angles (Asgarzadeh et al., 2014). The LLWR integrates three main plant growth-limiting factors (soil water potential, penetration resistance, and air porosity), whereas PAW is based only on soil water potential (Tormena et al., 2017). Most studies propose that SWR can reduce evaporative moisture loss by creating deep preferential flow paths (Goebel et al., 2011) and changing capillary rise (Bachmann et al., 2001), which can increase soil water storage. To the best of our knowledge, however, few studies have investigated how SWR influences PAW and LLWR. Previous studies have shown that SWR can affect water distribution in the pores and thus the relation between soil water content and potential (Hassan et al., 2014; Liu et al., 2012). Therefore, it is possible that SWR has great potential to influence PAW and LLWR because both are closely related to soil water potential. These studies further suggest that it is essential to consider soil water availability when investigating the effect of SWR on crop yield.

Plant growth and crop production are the results of the interaction of multiple soil

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properties, which makes it hard to analyze the effect of a single soil property on crop yield (Ernst et al., 2018; Liu et al., 2016; Roper et al., 2013). Previous studies have shown that soil organic matter (Denardin et al., 2019), soil aggregate stability (Nouri et al., 2019), soil penetration resistance (Guaman et al., 2016), and soil available water (Wu et al., 2019) have significant effects on crop yield. Hence, a comparative analysis of these soil properties and SWR will lead to an improved understanding of how SWR influences crop yield.

Additionally, our previous study had studied the factors governing SWR under conservation tillage and further pointed out that it was essential to study the impact of SWR on grain yield in the future because SWR could influence soil water status (Li et al., 2021). In this study, a long-term field experiment (2003–2018) with continuous spring maize was conducted to fill the knowledge gap that, to the best of our knowledge, few studies have (i) revealed the relationship between SWR and soil water availability and (ii) assessed the effect of SWR on grain yield via changes in soil water availability under conservation tillage practices. We hypothesized that SWR could reduce maize yield by changing soil water storage, PAW, and LLWR. The objectives were to (i) evaluate the effect of SWR on soil water availability, and (ii) reveal how SWR affects grain yield through a comparative analysis.

2. Materials and methods

2.1 Study site and experimental design

The long-term tillage experiment is set up in 2003 at the Shouyang test station (112-113 °E, 37-38 °N; 1100 m a.s.l.) located in Loess Plateau of northern China. Table 1

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shows some of the soil chemical and physical properties initially. The soil texture is sandy loam and the mean annual precipitation is 483 mm (Wang et al., 2019). One of the main limiting factors for plant growth at the site is spring drought (Wang et al., 2011). The mean annual air temperature is 7.4℃ and the annual frost-free period is approximately 130 days (Li et al., 2020).

The experiment was performed using a randomized complete block design with three replications. Rain-fed continuous spring maize was planted and the fallow period was from November to the following March. There were three treatments: (a) CT, conventional tillage with maize stalk removed and using a moldboard plow twice to about 30 cm depth after harvesting in October and before seeding in April every year; (b) RT, reduced tillage with fertilizers and maize straw integrated after harvesting every year, and ploughing once to about 25 cm depth; and (c) NT, no-tillage covered with the maize straw after harvesting, then fertilizing and seeding with a no-till seed drill in April every year. Calcium superphosphate and urea fertilizers were used for each plot at 105 kg P_2O_5 ha^{-1} and 105 kg N ha^{-1}, respectively. The plant spacings and row were 30 and 60 cm, respectively.

2.2 Soil sampling

The long-term tillage experiment was subjected to the three tillage practices from 2003 to 2018, and then all samples for this study were taken in 2018. To study the changes in soil water content after two rainfall events, soil samples were collected seven times (the 1st, 2nd, 3rd, 4th, 6th, 8th, and 10th day after each rainfall event) at the depths of 0–5, 5–10, and 10–20 cm. Each treatment was repeated three times in each rainfall

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event. The first rainfall event occurred on June 26, 2018 and its precipitation was 11 mm. The second rainfall event occurred on July 22, 2018 and the precipitation was 30 mm. We collected undisturbed core samples from the depths of 0–5 cm, 5–10 cm, and 10–20 cm using a steel ring (diameter: 4.9 cm and height: 5.0 cm) to determine soil bulk density, water retention curve, penetration resistance, and soil water repellency on April 27, July 7, and September 10, 2018 that were corresponded to the establishment, tasseling, and maturity stages, respectively. In addition, undisturbed core samples were taken at the same three dates with a hand auger (5 cm diameter) to determine mean weight diameter and soil organic carbon content. Three replications were adopted for all the variables.

2.3 Soil analysis

2.3.1 The characteristics of soil water repellency

Undisturbed soil samples were air-dried for 2 weeks to a constant weight (approximately 2.3% moisture) and then a micro infiltration device was applied for measuring SWR (Hallett and Young, 1999). Detailed information about the device can be found in Li et al. (2021). One end of a tube in the infiltration device was linked with a liquid reservoir and the other end with a 4 mm diameter was a sponge-covered tip in contact with the soil sample. We used an automatic electronic balance (0.001 g) to weigh the change of the liquid every 10 s. Two liquids, distilled water and ethanol (95% v/v), were used in the study. A detailed description of the method is found in previous studies (Hallett et al., 2003; Leeds-Harrison et al., 1994; Tillman et al., 1989). The pressure heads (-2 cm) at the soil surface were the same for the two liquids and were

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negative pressures to avoid a saturated flow (Hallett and Young, 1999). The following equation was applied to calculate the pressure head (Tillman et al., 1989):

$$P = \frac{\rho g\, h}{\sigma}$$

where P is the pressure head (cm), h is the altitude intercept between the tip contacted with a soil sample and the liquid level in the reservoir, σ and ρ are surface tension (kg s^{-2}) and the density (kg m^{-3}), respectively, of the liquid. The g is the gravitational acceleration (m s^{-2}). The densities of water and ethanol are 0.998 g cm^{-3} and 0.789 g cm^{-3} and the surface tensions are 0.073 N m^{-1} and 0.023 N m^{-1}, respectively (Lamparter et al., 2010).

Cumulative infiltration was recorded and the slope of the linear part in the curve (cumulative infiltration *vs.* time) was used to calculate the flow rate Q (mm^3 s^{-1}). The linear part was obtained within a range of 300-500 s in this study. The ethanol and water sorptivity (S_e and S_w, respectively) were calculated using the following equation:

$$S = \sqrt{\frac{Qf}{4br}}$$

where f is air-filled porosity (mm^3 mm^{-3}), b is a constant that depends on the soil-water diffusivity and its value is 0.55 (Leeds-Harrison et al., 1994), and r is the tip radius of the micro infiltration device.

The S_w can be affected by hydrophobic substances and soil pore structure, whereas Se is only influenced by soil structure because ethanol is a nonpolar liquid (Tadayonnejad et al., 2017). The following equation was used to calculate the water repellency index (Tillman et al., 1989):

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$$RI = 1.95 \frac{S_e}{S_w}$$

where S_e means the sorptivity of ethanol (mm $s^{-1/2}$) and S_w means the sorptivity of water (mm $s^{-1/2}$). S_w represents the ability of soil water absorption and water repellency index (RI) shows the degree of SWR (Tadayonnejad et al., 2017). In addition, the soils with RI = 1, 1 < RI ≤ 1.95, and RI > 1.95 are considered as no water repellency, slight water repellency (wettable), and subcritical water repellency, respectively (Hallett et al., 2001; Tillman et al., 1989). The contact angle under subcritical water-repellent soil is less than 90° (Lamparter et al., 2009).

2.3.2 Soil penetration resistance, total porosity, SOC, and mean weight diameter

We used pressure plate equipment to control the different soil water content of undisturbed soil samples in corresponding to matric suction of 2, 10, 60, 100, 500, and 1000 kPa. Then, the soil penetration resistance (PR) and soil moisture were measured under each matric suction to calculate the curve of PR *vs.* soil water content. We used a micro penetrometer (Omega LC703, USA) with a cone diameter of 2 mm and an angle of 15° to measure PR. More information about calculating the functional relationship between soil water content and PR has been reported elsewhere (Li et al., 2020; Ruiz et al., 2016). We used the mean value of PR under different soil water content in this study.

Particle density and bulk density were measured to calculate total porosity (Klute and Page, 1986). An elemental analyzer (Vario Macro C/N, Elementar, Germany) with the dry combustion method was used to measure SOC. We used the wet sieving method to determine aggregate stability with sieves of 2000, 250, and 53μm sizes. Mean weight

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diameter (MWD) was calculated from the following equation :

$$MWD = \sum_{i=1}^{n} x_i w_i$$

where x_i is the mean diameter (mm) of the particle for each size range, w_i is the relative amount of particles in each range and n is the number of aggregate size classes.

2.3.3 Soil water content and storage

We used the oven-drying method to measure soil water content for studying the change in soil water content. A rain gauge at the site was applied to measure precipitation. Soil water storage (SWS) was determined by the following equation:

$$SWS = \theta \rho_b h$$

where θ is the soil gravimetric water content (%), ρ_b is soil bulk density (g cm^{-3}), and h is soil depth (mm).

2.3.4 Least limiting water range, plant available water, grain yield, and water use efficiency

The least limiting water range (LLWR) was determined by measuring the upper and lower limits of water content for normal plant growth. The upper limit corresponds either to soil water content at an air-filled porosity of 10% or at field capacity (-33 kPa), which is the smaller water content. Plant growth can be limited when PR exceeds 2 MPa (Bengough and Mullins, 1990), hence, the lower limit of the LLWR is either the soil water content at PR of 2 MPa or at the permanent wilting point (-1500 kPa), which is the higher water content. The field capacity and permanent wilting point were calculated from the soil water retention curve. The soil moisture at air-filled porosity of 10% (θ_{AFP}) was obtained from the following equation (Asgarzadeh et al., 2011):

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$$\theta_{AFP} = \left(1 - \frac{\rho_b}{Pd}\right) - 0.1$$

Where P_d is the particle density (g cm^{-3}) and ρ_b is bulk density (g cm^{-3}). Detailed information about calculating LLWR is shown in Li et al. (2020).

The plant available water (PAW) was calculated by the following equation:

$$PAW = \theta_{FC} - \theta_{PWP}$$

Where θ_{FC} is the field capacity (cm^3 cm^{-3}) and θ_{PWP} is the permanent wilting coefficient (cm^3 cm^{-3}).

We used 10 plants from each plot to measure grain yield at the harvesting stage. The ratio of grain yield to cumulative evapotranspiration of the whole growing period was used to calculate water use efficiency (WUE). Detailed information is given in Wang et al. (2011).

2.4 Statistical analysis

The experimental data about the three tillage treatments (CT, RT, and NT) were analyzed, along with three soil depths (0–5, 5–10, and 10–20 cm), during three growth periods. The effects of tillage treatment, soil depth, and growth stage on S_w, RI, PR, total porosity, MWD, SOC, SWS, LLWR, and PAW were calculated using the analysis of variance (ANOVA) with the least significant difference test (LSD) in SAS 9.4 software (SAS Institute Inc., Cary, North Carolina, USA). A Spearman rank-order correlation was also performed with the PROC CORR procedure in the software to assess the relationship between grain yield and these soil properties. We carried out redundancy analysis (RDA) to further understand how SWR affects grain yield compared to other soil properties in CANOCO version 5.01 software. The response

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variables were SWS, LLWR, PAW, grain yield, and WUE. The explanatory variables were S_e, S_w, RI, PR, total porosity, MWD, and SOC. In the RDA, only uncorrelated explanatory variables were considered. We used Pearson's correlations for analyzing the relationships among these explanatory variables to avoid omitting the main indexes. Only one of the variables was selected in the RDA when a significant correlation ($p < 0.001$) between two variables was found (Matamala et al., 2017).

3. Results

3.1 Ethanol sorptivity (S_e), water sorptivity (S_w), and water repellency index (RI)

The S_e, S_w, and RI in 0–5 cm, 5–10 cm, and 10–20 cm soil layers during three growth periods were presented in Fig. 1. The RT treatment had higher S_e compared to NT treatment and significantly increased it in 0–5 cm and 5–10 cm compared to CT treatment on both July 7 and September 10. Furthermore, S_e and S_w under CT and RT treatments decreased with an increase in the growth period. The NT treatment decreased S_w in the 0–20 cm layer compared with CT treatment during the three growth periods, whereas there was no significant difference between RT and CT treatment. In addition, NT treatment had RI > 1.95 in all three depths during the three growth periods, which showed the soil under NT was considered as subcritical water repellency. The RI of RT treatment was also greater than 1.95 except for RI (1.92) in 10–20 cm on July 7. The CT treatment had RI < 1.95 in the three layers on both July 7 and September 10 and the soil was wettable. However, the RI of CT treatment on April 27 was greater than 1.95, because the increment of S_e induced by tillage practice resulted in the higher RI under CT treatment on April 27. The RI of NT treatment in the 0–20 cm layer was 15.1%–

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24.5%, 18.1%–39.9%, 12.9%–31.1% higher than CT treatment on April 27, July 7, and September 10, respectively. Compared to CT treatment, the RI under RT treatment was increased by 11.8%–14.1%, 6.5%–18.2%, and 5.7%–16.5% at the three growth stages, respectively. We also found that S_w did not decrease with an increase in RI in the 0–20 cm layer. These results suggested that it was necessary to use the two variables (S_w and RI) at the same time when studying the effect of soil water repellency.

3.2 Penetration resistance (PR), total porosity, mean weight diameter (MWD), SOC, and soil water storage (SWS)

Tillage management showed a significant impact on PR, total porosity, MWD, SOC, and SWS (Table 2). The NT treatment significantly increased PR in the 0–5 cm, 5–10 cm, and 10–20 cm layers compared to CT and RT treatments during the three growth periods. The PR under the three treatments increased with an increase in soil depth. The PR under CT and RT treatments also increased with an increase of planting time at each soil depth, whereas there was no significant difference in PR under NT treatment among the three growth periods ($p > 0.05$). The effect of tillage management on total porosity was various in different growth stages. The CT and RT treatments had higher TP in the three soil layers compared to the NT treatment on April 27. However, tillage management had no significant influence on TP in the 0–5 cm and 5–10 cm layers on July 7 and NT treatment increased TP in the 0–5 cm layer compared to CT and RT treatments on September 10. Furthermore, both MWD and SOC of NT treatment were higher than CT treatment in the three soil layers during the three growth periods. RT treatment also had higher SOC than CT treatment. Nevertheless, for MWD in the 0–5

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cm and 5–10 cm layers on July 7 and September 10, there were no significant differences between RT and CT treatments. Compared to CT treatment, the NT treatment increased SWS in the three soil layers and RT treatment increased it in 10–20 cm layer during the growth period, whereas RT treatment had no influence on SWS in the 0–5 cm and 5–10 cm layers.

3.3 The changes in soil water content after two rainfall events

The changes in soil moisture after two rainfall events, with precipitation of 11 mm and 30 mm, respectively, are shown in Fig. 2. Tillage management had no significant effect on soil moisture in the 0–5 cm layer from 0 to 4 days after both the first and second rainfall events. We further found that the effect of tillage management on soil water content was different under the two rainfall events. There were no significant effects in 5–10 cm and 10–20 cm layers among the three treatments on the first day after the first rainfall event. However, the NT treatment had higher soil moisture in the 5–10 cm and 10–20 cm layers than the CT treatment after the second rainfall event. Furthermore, NT treatment showed higher soil moisture compared with CT treatment on the tenth day after both rainfalls.

3.4 Least limiting water range (LLWR), plant available water (PAW), grain yield, and WUE

The LLWR was more susceptible to tillage management compared with PAW during the growth period (Fig. 3). Tillage management had a significant influence on LLWR in all three soil depths and its significant effects on PAW were only found in part of soil depths. Compared to CT, NT treatment decreased LLWR on April 27 and increased it in the 0–5 cm and 5–10 cm layers on September 10. The LLWR of RT treatment was greater than the CT and NT treatments in the three layers on July 7. Soil depth also significantly affected LLWR and the LLWR under the three tillage managements could decrease with an increase in soil depth. The average value of PAW under NT treatment in the three layers was higher than under CT on both July 7 and September 10, whereas there was no significant difference in the PAW between CT and RT treatments during the two growth periods.

The impact of tillage management on grain yield and WUE are the same and tillage management had significant effects on both grain yield and WUE (Fig. 4). These effects could change with growing season mainly due to the variability of climate. Hence, we showed them during 2003–2018 to check the data in 2008 that was consistent with the overall trend. The results found that RT treatment significantly increased grain yield and WUE compared with CT and NT treatments, but the grain yield and WUE under NT treatment had no significant difference with CT treatment.

3.5 The relationships among soil properties, grain yield, and WUE

A Spearman rank-order correlation analysis was used to analyze the relationships among soil water availability, grain yield, and soil properties (Fig. 5). We found S_e had a positive correlation with grain yield in the 0–5 cm, 5–10 cm, and 10–20 cm layers during the three growth periods and higher S_e could also increase LLWR. In addition, higher S_w significantly increased LLWR in the10–20 cm layer during the three growth periods. There was a negative correlation between S_w and PAW in the 0–5 cm and 5–10 cm layers. Although RI had no significant relationship with grain yield, it had the

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potential to increase soil water storage and PAW. The RI had a positive relationship with SWS in the three soil layers during the three growth periods and increased PAW in the 0–5 cm and 5–10 cm layers on April 27 and September 10. The PR showed a negative relationship with LLWR, grain yield, and WUE. Soil total porosity, MWD, and SOC showed no direct relationship with grain yield, but they could affect SWS, PAW, or LLWR, for example, MWD had a positive relationship with SWS.

In addition, RDA was carried out to reveal how SWR affects corn yield through a comparative analysis with PR, TP, MWD, and SOC (Fig. 6). Our results showed that S_e and S_w had a closer positive relationship with grain yield than TP, MWD, and SOC during the three growth periods. Moreover, S_w was also the most significant factor for reducing soil water storage and increasing LLWR compared with PR, MWD, and SOC. Notably, the RI and MWD were not included in the RDA at the same time to eliminate collinearity issues, because there is a significant linear correlation between the two variables during the three periods ($p < 0.001$). The SOC , like MWD, had a positive relationship with RI during the three growth periods. Although RI, PR, MWD, and SOC during the three growth periods were increased by NT treatment, PR was the most detrimental factor for grain yield and WUE. The PR was also the most important factor to reduce LLWR compared with other soil properties. Furthermore, RI played a prominent role in increasing soil water storage compared with the other variables in the three growth periods.

4. Discussion

The S_w is affected by both soil pore structure and hydrophobic substances (Hallett et

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al., 2001; Li et al., 2021). We found that NT treatment decreased S_w at the 0–5 cm, 5–10 cm, and 10–20 cm depths compared to CT treatment during the three growth periods (Fig. 1) due to increment of hydrophobic substances under no-tillage system (González-Peñaloza et al., 2012; Urbanek et al., 2007). We also found that S_e was higher for the RT treatment than for the CT treatment (Fig. 1) because ethanol is a nonpolar liquid and S_e is only affected by soil pore structure (Tadayonnejad et al., 2017; Tillman et al., 1989). In addition, we used X-ray computed tomography under two long-term experimental fields and found that RT treatment increased the soil porosity of 55–165 μm and pore connectivity compared to NT treatment in our previous study (Li et al., 2021). Therefore, RT treatment increased S_e and S_w compared to NT treatment (Fig. 1) because of the improvement of soil pore structure. These results also indicated that reduced or occasional tillage increased soil disturbance compared to no-tillage, which could increase the ability of soil water absorption (Blanco-Canqui and Wortmann, 2020). We further found the S_e and S_w under CT treatment decreased with an increase in planting time because the improvement of soil porosity induced by tillage practice could weaken over time (Li et al., 2020). Furthermore, the NT treatment significantly increased RI at 0–5 cm, 5–10 cm, and 10–20 cm depths compared to CT treatment during the growth period (Fig. 1). A similar result was discovered by Blanco-Canqui (2011) who found that the degree of SWR under a no-tillage system was 1.5 to 40 times higher than conventional tillage. The main reason is that no-tillage can increase SOC and reduce soil disturbance, both of which favor the production of hydrophobic substances and increase the degree of SWR (Šimon et al., 2009). This study also showed

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that NT treatment was higher than CT treatment in SOC (Table 2) that could represent hydrophobic substances (Jimenez-Morillo et al., 2016; Lozano et al., 2013). It should be noted that there was no significant difference in S_w between RT and CT treatments on July 7 ($p > 0.05$), whereas the RI of RT treatment was higher than that of CT treatment (Fig. 1). This suggested that the ability of soil water absorption was not only affected by the degree of soil water repellency as indicated by RI. The main reason is that RT treatment improved soil pore structure and water transmission (Gao et al., 2019; Li et al., 2021; Sauwa et al., 2013), which attenuated the effect of the increase in RI on soil water absorption.

Soil compaction is normally evaluated by measuring soil PR and total porosity (Afzalinia and Zabihi, 2014; Lipiec and Hatano, 2003; Salem et al., 2015). We found that the RT treatment reduced PR at the 0–5 cm, 5–10 cm, and 10–20 cm depth compared to CT and NT treatments during the growth period (Table 2). Some similar results have also been found that the increase in soil organic matter under RT treatment reduced soil compaction compared to CT treatment (Jemai et al., 2013; Shi et al., 2012). However, although NT treatment had higher soil organic matter compared to CT treatment, NT had higher PR on April 27 and there was no significant difference in PR between the two treatments on September 10 (Table 2). The main reason is that soil compaction under NT treatment can be produced by reducing soil disturbance (Blanco-Canqui and Ruis, 2018; Sun et al., 2018). We further found that NT treatment decreased soil total porosity in the 0–5 cm on April 27, had no influence on July 7, and increased it on September 10 compared to CT treatment (Table 2), because soil total porosity

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under CT treatment decreased with an increase in time after tillage practice (Li et al., 2020). In addition, MWD is commonly used to indicate soil aggregate stability, which is an important indicator of soil structural features and soil functionality (Chen et al., 2017; Nouwakpo et al., 2018). The MWD of NT treatment was higher than that of CT treatment at the 0–5 cm, 5–10 cm, and 10–20 cm depths during the three growth periods (Table 2). As found in other studies (Sun et al., 2020; Wang et al., 2019), reducing soil disturbance under NT treatment was beneficial to soil aggregate stability.

Although tillage management had a significant effect on SWR (Fig. 1), it did not affect the soil water content on the first day after the first rainfall when precipitation was 11 mm (Figs. 2a–c). This could be supported by the results that there was no relationship between SWR and soil water content under a no-tillage system because crop roots provided pathways for water movement (Roper et al., 2013). However, the opposite results were found in our study. With the higher precipitation of the second rainfall (30 mm), the NT treatment had a higher soil water content at the 5-10 and 10-20 cm depths than the CT treatment (Figs. 2f and g). This is a similar finding to previous studies because SWR can cause preferential flow and then increase the soil water content in a deeper depth (Lozano et al., 2013; Rye and Smettem, 2017). One of the reasons for the inconsistent results was that the soil water content under the two rainfall events was different, resulting in a different degree and behavior of SWR (Chau et al., 2014). The crop straw mulching under no-tillage could influence soil water content (Wang et al., 2020) and may also alter the effect of rainfall events on S_w and S_e. Another reason was that the higher rainfall intensity under the second rain event was more likely

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to cause preferential flow compared with the first rainfall. Therefore, we propose that it is essential to consider rainfall intensity when studying the impact of SWR on soil water movement under conservation tillage practices. Moreover, the effect of SWR on soil water content became more obvious with the soil moisture decreasing after the two rainfall events (Fig. 2) because the degree of SWR generally increases with the decrease in soil moisture (Hermansen et al., 2019; Vogelmann et al., 2017). The NT treatment showed a higher soil moisture content compared to CT treatment on the eighth day after both rainfall events (Fig. 2). Hence, we believe that SWR has the ability to increase soil water content under conservation tillage practices, especially in arid regions. This further provided new insights into the conditions of the effect of SWR on soil water movement and confirms the previous studies that reported conservation agriculture has more benefits on increasing crop yield in arid regions (Pittelkow et al., 2015; Sun et al., 2020).

Soil water storage (SWS), LLWR, and PAW are three common indicators of soil water availability, that represent the ease of absorbing soil water for crops (de Lima et al., 2020; Silva et al., 2019; Sun et al., 2018). The SWS was higher for NT than CT and RT treatments in the three soil depths and RT also increased SWS in the 10–20 cm layer compared with CT treatment during the growth period (Table 2). We further found that both S_w and RI had a significant influence on SWS (Figs. 5 and 6) because increasing the degree of SWR could cause preferential flow, resulting in decreasing soil evaporation and increasing the soil water content in deeper soil depth (Rye and Smettem, 2017). Additionally, increasing the degree of SWR can reduce the capacity to transport

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soil water to upper layers by capillary rise, which also increases SWS (Bachmann et al., 2001). Tillage management had a significant influence on LLWR in all three soil depths during the growth period, whereas its significant effects for PAW were only found in part of soil depths and the effects were various during the different growth periods (Fig. 3). Hence, the LLWR was more susceptible to tillage management compared with PAW during the growth period. The main reason is that LLWR can be affected not only by soil matric potential but also by penetration resistance (Asgarzadeh et al., 2010; Silva et al., 2019). Furthermore, correlation analysis illustrated that S_w and RI were capable of impacting LLWR and PAW (Fig. 5). Previous studies also have found that SWR can strongly influence the soil water retention curve (Hassan et al., 2014; Liu et al., 2012; Naasz et al., 2008). Therefore, these results further supported our hypothesis that SWR can change soil water availability (e.g. SWS, LLWR, and PAW).

Tillage management had significant effects on both grain yield and WUE (Fig. 4). We found that significantly higher grain yield and WUE for the RT than the CT and NT treatments ($p < 0.05$), but the grain yield and WUE under NT treatment were not significantly different from CT treatment ($p > 0.05$). Similar results were obtained in other studies (Nunes et al., 2018; Wang et al., 2011). We found that S_e and S_w had influences on grain yield, unlike RI (Fig. 5), which cannot support the hypothesis that an increase in RI reduces grain yield. One reason is that although tillage management had a significant effect on RI (Fig. 1), the differences were not as large in our study as in a previous study in which SWR was 1.5 to 40 times higher in the NT than CT treatment (Blanco-Canqui, 2011). Hence, the effect of the degree of SWR on crop yield

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should be further considered in soils with a high degree of SWR. Another reason is that S_w is controlled by hydrophobic substances as well as pore structure and it represents the real ability of soil water absorption (Behrends et al., 2019; Vogelmann et al., 2017). This suggested that although RI can reflect the degree of SWR, S_w had a closer relationship with grain yield than RI and more fully explained the effect of SWR on grain yield under conservation tillage practices. In addition, our previous studies showed that soil water availability strongly influences grain yield under conservation agriculture (Li et al., 2020), and we further found that soil water availability was also affected by RI and S_w in the present study (Fig. 5). Therefore, we believe that there is an indirect relationship between RI and grain yield. We cannot yet quantify this indirect effect, but we did demonstrate its existence and pointed out that it is worth investigating further. This result challenges the traditional proposition that crop growth is poorly related to SWR under a no-tillage system when using a simple correlation (Roper et al., 2013).

Soil water availability and crop production are the results of a combination of multiple soil properties (e.g. porosity, PR, MWD, and LLWR) and therefore their effects can be better understood through a comparative analysis (Ernst et al., 2018; Scarpare et al., 2019; Zhang et al., 2018). The RI played a prominent role in increasing SWS compared to the other soil properties at the three soil depths (Fig. 6) because a higher RI can reduce evaporation loss (Rye and Smettem, 2017). Although a higher RI is advantageous to SWS, it still restricts plant growth because it increases the difficulty for crops to absorb soil water (Li et al., 2019; Madsen et al., 2012). Li et al. (2020)

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also found that although the soil water content under RT treatment was lower than under NT treatment, the RT treatment resulted in higher grain yield because it increased soil water availability. Notably, previous studies had shown that SWR can affect water distribution in the pores, which may further influence soil water availability (Hassan et al., 2014; Liu et al., 2012). It suggested that investigating the effect of SWR on grain yield through a comparative analysis with other soil properties was highly warranted. In this study, we found that although RI, PR, MWD, and SOC in the three depths were increased by NT treatment (Fig. 6), PR was the most detrimental factor for grain yield and WUE (Figs. 5 and 6). Kadžienž et al. (2011) also had a similar result of PR being the most limiting factor for crop growth under a no-tillage system. Moreover, compared to other soil properties, increased S_e and S_w was the most effective way of increasing grain yield in this study (Figs. 5 and 6). The relationship between S_w and RI is often inverse and increasing S_w can reduce RI (Behrends et al., 2019; Vogelmann et al., 2017). These results indicate that crop yield could be improved by reducing RI and increasing S_w under conservation tillage practices. The conclusion that increasing the degree of SWR has the potential to reduce crop yield was further confirmed. It should be noted that the effect of tillage management on SWR and yield could change with growing season mainly due to the variability of climate and this study is only based on one growing year. The relationship between SWR and yield under different climate conditions should be further studied. However, we also found that its effect on yield in 2018 was consistent with the overall trend (Fig. 4b), which indicates that these conclusions in this study could be applicable to most situations in semi-arid regions.

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Moreover, previous studies have shown that SWR can influence other soil properties, such as improving soil aggregate stability and carbon sequestration (Blanco-Canqui, 2011; Lamparter et al., 2009; Sepehrnia et al., 2017). In our study, we also found that RI had a significantly positive correlation with MWD and SOC, respectively. Hence, a focused effort to study the effect of SWR on plant growth and soil properties will improve our understanding of the role of conservation tillage practices in the sustainable development of agriculture in the future.

5. Conclusions

The NT treatment decreased S_w compared to CT and RT treatments and the S_e was the highest for RT treatment. We further found that NT treatment increased RI compared to CT treatment probably due to increasing hydrophobic substances and reducing soil disturbance. Both S_w and RI had the potential to influence soil water availability. The effect of SWR on soil water content became more obvious with the decrease in soil moisture following rainfall, which was also influenced by rainfall intensity. Moreover, the SWS was higher for the NT than that for CT treatment and there was a positive correlation between RI and SWS. Nevertheless, although RI could reflect the degree of SWR, S_w and S_e had a closer relationship with grain yield than RI and more fully explained the effect of SWR on grain yield under conservation tillage practices. In addition, S_w and S_e was a more important factor for increasing grain yield than MWD, SOC, TP, and RI. This further confirmed that grain yield could be improved by increasing S_w. The grain yield under RT treatment was highest by increasing S_w, S_e, LLWR, and WUE. From this, we conclude that RT treatment is the most effective tillage

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practice compared to CT and NT treatments from the perspective of grain yield.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

Author contributions. SL and XW designed this study. Sampling was carried out by SL, AA, and JL. Data analysis were carried by SL, GL, and XL. All co-authors revised the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1 Soil physical and chemical properties of the tested soils (0–30 cm) in 2003.

Depth	Soil particle size distribution (%)				Available nutrient (mg kg^{-1})			SOC	Bulk density
(cm)	> 200μm	20-200 μm	2-20 μm	< 2μm	N	P	K	(g kg^{-1})	(g cm^{-3})
0-10	5.7	52.8	35.7	5.8	58	8.3	96	22.7	1.06
10-20	7.9	51.7	34.6	5.8	52	6.9	93	19.8	1.20
20-30	4.8	55.8	33.7	5.7	53	3.1	87	15.1	1.36

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Table 2 Soil penetration resistance (PR), total porosity (TP), mean weight diameter (MWD), soil organic carbon (SOC), and soil water storage (SWS) in the 0–5, 5–10, and 10–20 cm layers under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) treatments during three growth periods.

Date	Layer (cm)	Treatment	PR (Mpa)	TP (%)	WMD (mm)	SOC (g kg^{-1})	SWS (mm)
Apr 27	0-5	CT	1.21±0.08b	63.2±5.4a	0.56±0.02c	18.2±1.1b	6.5±0.7b
		RT	1.09±0.05b	60.6±2.5a	0.62±0.02b	27.1±1.7a	7.4±0.6b
		NT	1.62±0.09a	53.4±0.8b	0.68±0.04a	28.4±0.8a	10.1±0.4a
	5-10	CT	1.39±0.06b	60.0±4.4a	0.49±0.03c	18.4±0.3c	6.8±0.6b
		RT	1.38±0.11b	60.8±0.8a	0.53±0.02b	34.2±2.9a	7.4±0.5b
		NT	1.84±0.09a	49.4±1.4b	0.67±0.04a	29.2±1.7b	10.2±0.8a
	10-20	CT	1.59±0.07b	57.4±1.3a	0.48±0.03c	20.2±1.1b	18.9±1.4c
		RT	1.59±0.05b	53.0±0.6b	0.53±0.01b	31.1±3.0a	21.4±1.0b
		NT	2.14±0.13a	47.1±1.0c	0.67±0.01a	22.9±0.8b	23.5±0.7a
Jul 7	0-5	CT	1.49±0.02a	54.1±1.8a	0.61±0.02b	17.4±0.9c	10.2±0.8ab
		RT	1.27±0.05b	54.3±0.6a	0.63±0.03b	27.1±2.0a	11.4±0.4b
		NT	1.55±0.04a	54.9±1.4a	0.79±0.01a	23.3±2.1b	12.1±1.0a
	5-10	CT	1.70±0.13ab	54.0±0.8a	0.57±0.02b	16.3±1.5b	9.8±0.8ab
		RT	1.39±0.03b	52.7±1.0a	0.61±0.04b	24.0±1.7a	11.4±0.6b
		NT	1.86±0.02a	52.7±0.9a	0.77±0.01a	21.6±1.9a	12.4±1.3a
	10-20	CT	1.86±0.12ab	52.2±1.2a	0.59±0.03b	15.1±1.6b	22.4±1.1ab
		RT	1.66±0.02b	52.8±0.7a	0.62±0.02ab	20.4±1.1a	23.7±1.6b
		NT	2.06±0.11a	49.3±1.1b	0.64±0.04a	20.3±1.8a	25.9±0.5a
Sep10	0-5	CT	1.56±0.08a	52.1±1.3b	0.57±0.01b	21.2±1.8c	6.8±0.3b
		RT	1.41±0.01b	50.1±0.6c	0.56±0.02b	33.5±2.2a	7.5±0.7b
		NT	1.63±0.05a	54.2±0.9a	0.73±0.03a	26.0±1.4b	9.7±1.8a
	5-10	CT	1.75±0.05a	51.3±1.6a	0.55±0.02b	20.3±1.5b	8.3±1.0b
		RT	1.59±0.07b	51.1±1.3a	0.59±0.03b	30.8±2.6a	8.9±0.9b
		NT	1.86±0.12a	50.9±0.8a	0.74±0.05a	30.3±2.8a	12.1±0.7a
	10-20	CT	1.95±0.17a	50.8±1.2a	0.55±0.02c	20.8±1.6b	21.5±0.5c
		RT	1.74±0.03b	52.1±0.7a	0.63±0.04b	28.9±1.5a	24.0±1.8b
		NT	2.10±0.11a	48.3±1.5b	0.70±0.01a	27.4±1.8a	28.1±1.1a

Note: The same letters within a column in the same soil depth indicate no significant differences between tillage managements ($p < 0.05$) according to the LSD test.

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Figures:

Fig. 1. The effect of conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) on soil ethanol sorptivity(S_e), water sorptivity (S_w), and water repellency index (RI) in the 0–5 cm, 5–10 cm, and 10–20 cm depths on April 27, July 7, and September 10. The same letter means that there is no significant difference ($p > 0.05$) between tillage managements according to the LSD test. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

Fig. 2. The changes in soil volumetric water content for conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) treatments in the 0–5, 5–10, and 10–20 cm depths after two rainfall events. The ANOVA was used to measure the effect of tillage management on soil moisture on different days. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

Fig. 3. Least limiting water range (LLWR) and plant available water content (PAW) in the 0–5 cm, 5–10 cm, and 10–20 cm depths on April 27, July 7, and September 10 under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) treatments. The same letter means that there is no significant difference ($p > 0.05$) between tillage management according to the LSD test. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant.

Fig. 4. Grain yield and water use efficiency (WUE) under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) treatments in 2018 (a) and during 2003-2018 (b). The same letter means that there is no significant difference ($p > 0.05$) between tillage management according to the LSD test. *: $p < 0.05$; ***: $p < 0.001$. Boundaries of the box indicate 25th quantile, mean value, and 75th quantile. The top and bottom whiskers represent the minimum and maximum values, respectively.

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Fig. 5. Spearman correlation analysis on the relationships among soil water availability, yield, and soil properties in the 0–5 cm, 5–10 cm, and 10–20 cm depths. Blue and red represent negative and positive correlations, respectively, and a darker color represents a higher correlation. S_e: soil ethanol sorptivity; Sw: water sorptivity; RI: water repellency index; PR: soil penetration resistance; TP: total porosity; MWD: mean weight diameter; SOC: soil organic carbon; SWS: average soil water storage of two rainfall; WUE: water use efficiency; LLWR: least limiting water range; PAW: plant available water. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

Fig. 6. Redundancy analysis of the relationships among soil water availability, yield, and soil properties during the three growth periods. The response variables are yield, WUE, LLWR, PAW, and SWS. The explanatory variables are S_e, S_w, RI, PR, TP, MWD, and SOC. S_e: soil ethanol sorptivity; Sw: water sorptivity; RI: water repellency index; PR: soil penetration resistance; TP: total porosity; MWD: mean weight diameter; SOC: soil organic carbon; SWS: average soil water storage of two rainfall; WUE: water use efficiency; LLWR: least limiting water range; PAW: plant available water.

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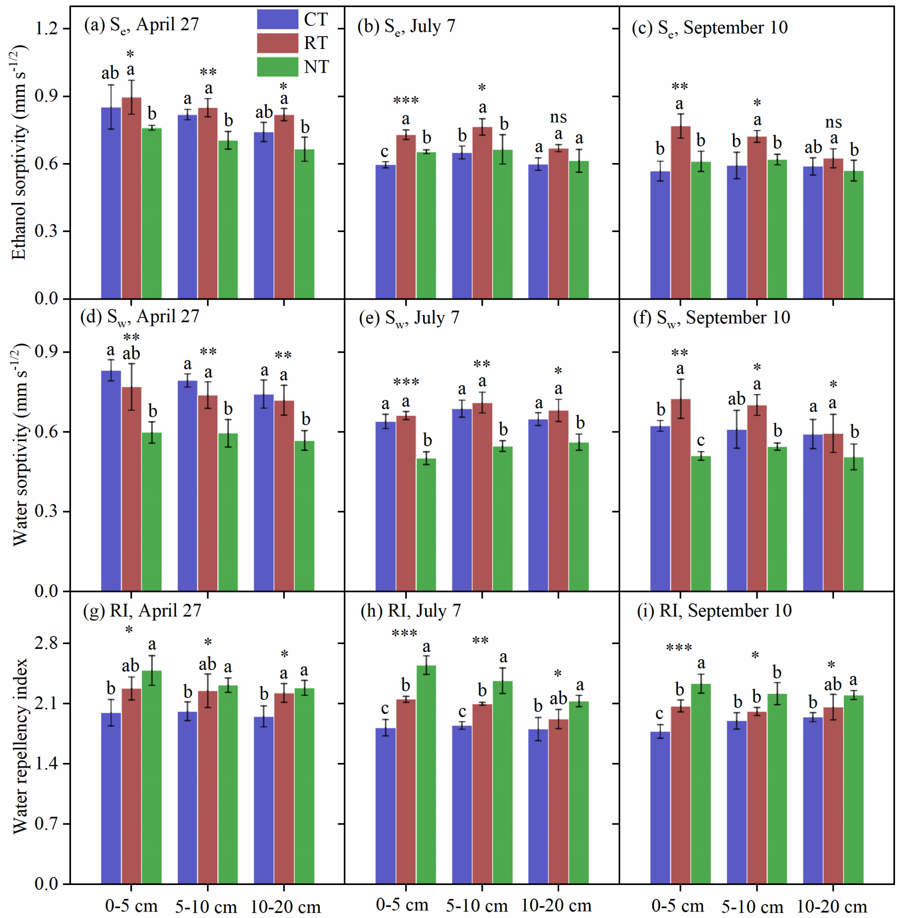

Fig. 1.

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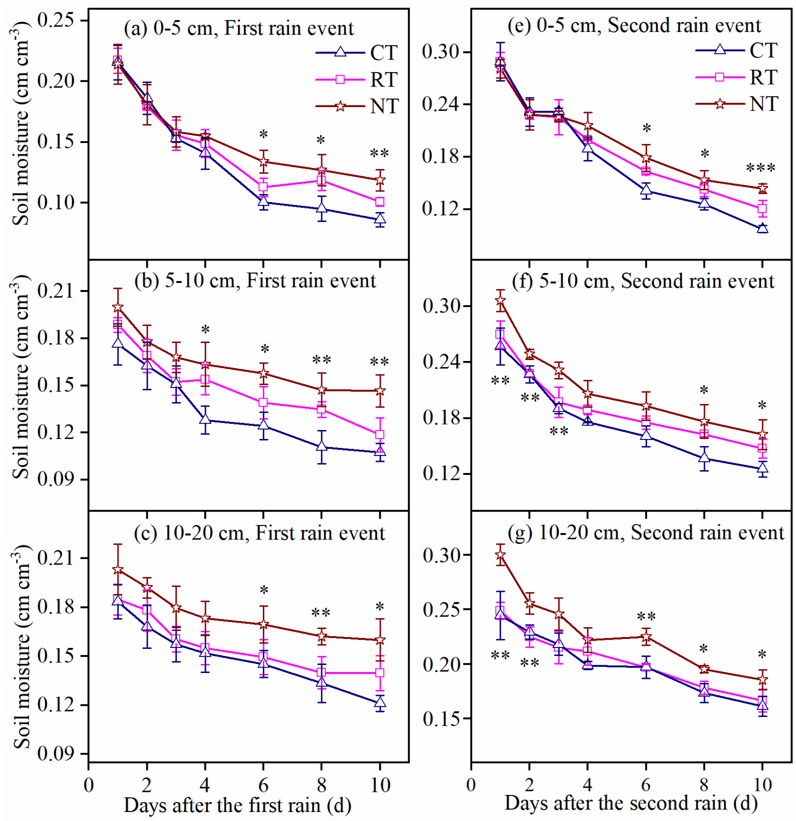

Fig. 2.

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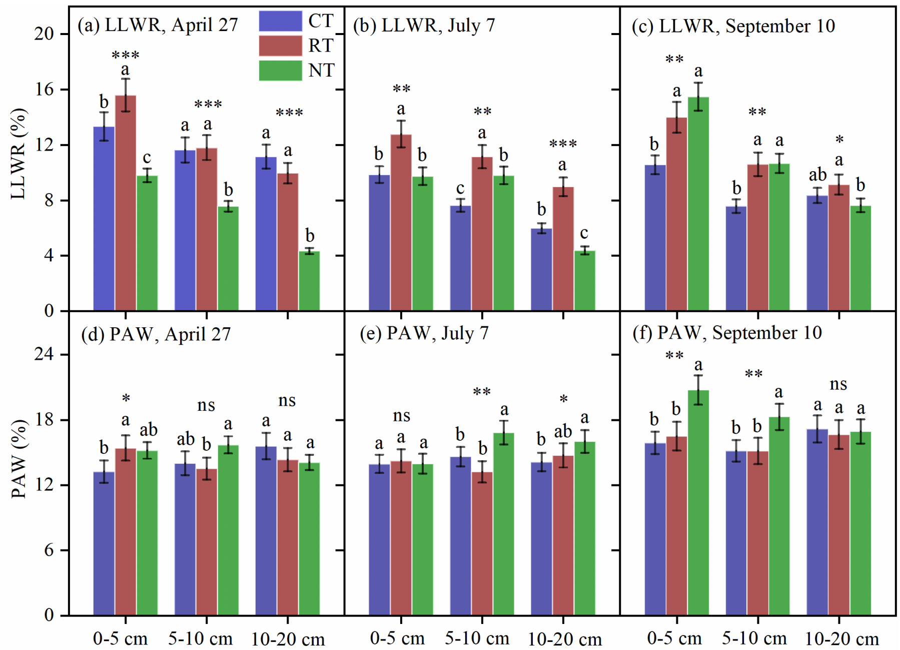

Fig. 3.

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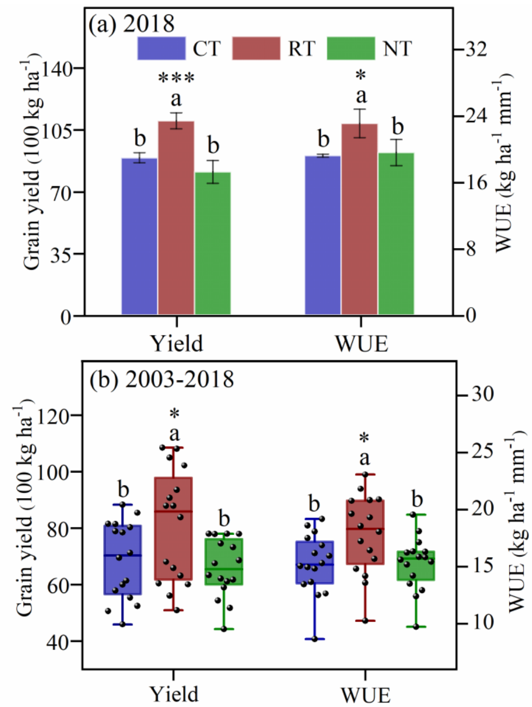

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923 **Fig. 4.**

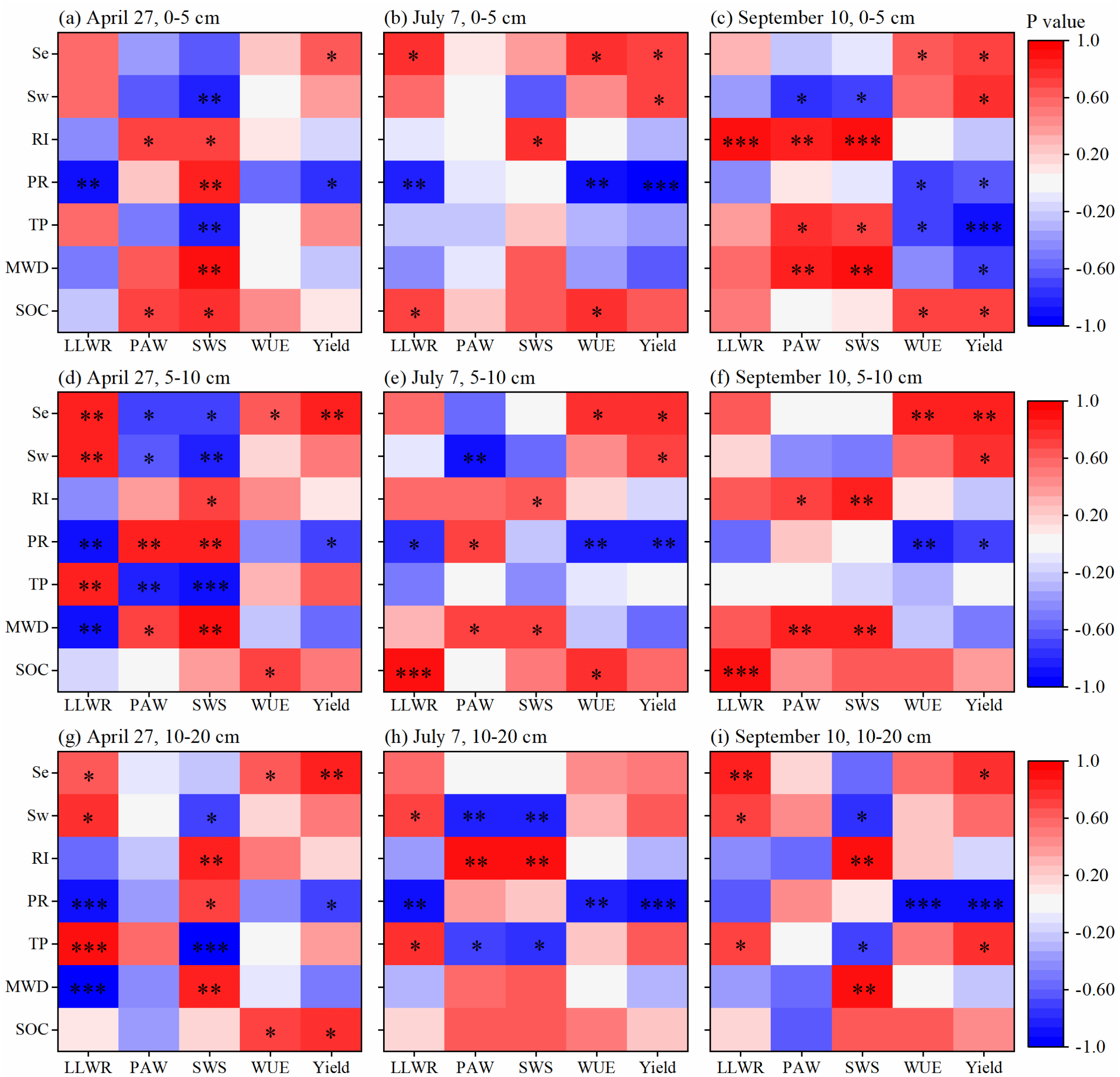
(a) April 27, 0-5 cm
(b) July 7, 0-5 cm
(c) September 10, 0-5 cm
(d) April 27, 5-10 cm
(e) July 7, 5-10 cm
(f) September 10, 5-10 cm
(g) April 27, 10-20 cm
(h) July 7, 10-20 cm
(i) September 10, 10-20 cm
Se
Sw
RI
PR
TP
MWD
SOC
LLWR
PAW
SWS
WUE
Yield
P value
1.0
0.60
0.20
-0.20
-0.60
-1.0

Fig. 5.

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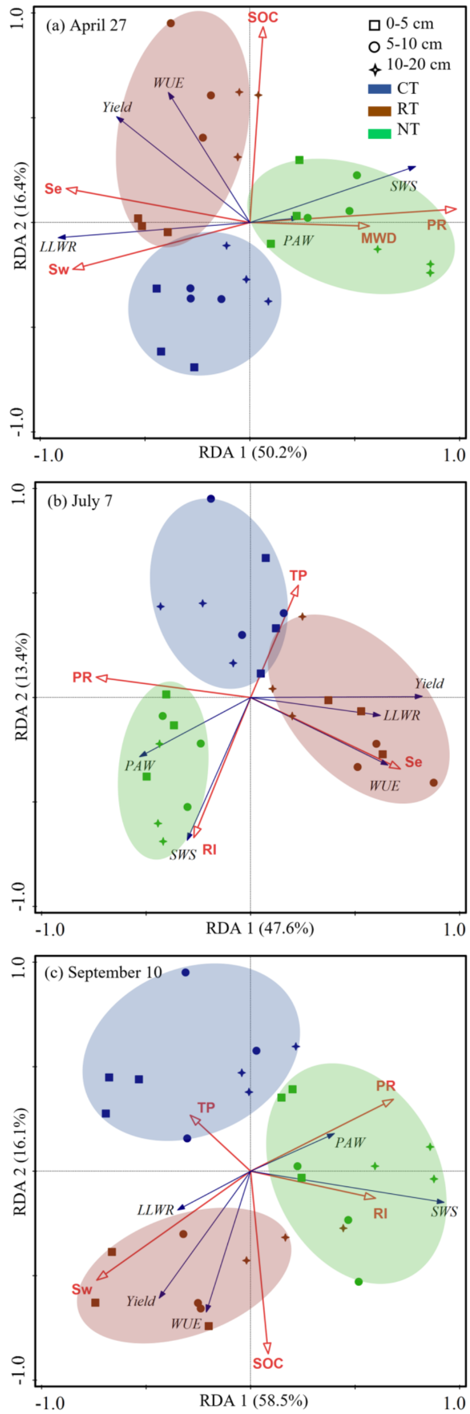

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927 **Fig. 6.**