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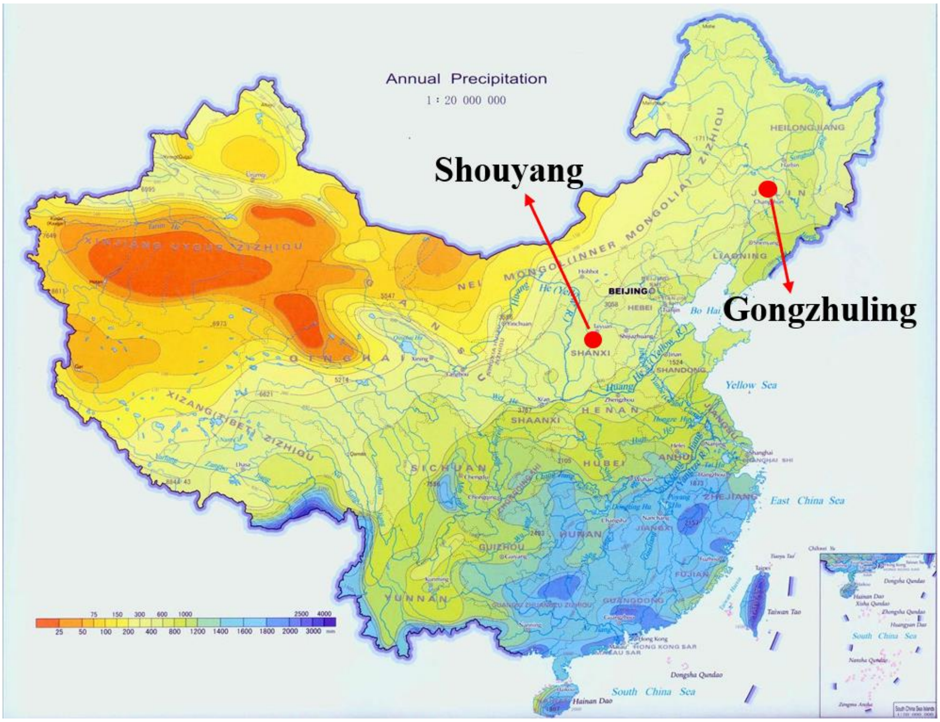
Reduced tillage increases grain yield through improving soil properties and water use efficiency



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Reduced tillage increases grain yield through improving soil properties and water use efficiency

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Dissertation originale présentée en vue de l'obtention du grade de docteur en sciences agronomiques et ingénierie biologique

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Résumé

Un des principaux défis de notre époque est d'atteindre une sécurité alimentaire élevée pour une population mondiale croissante avec des investissements réduits et en assurant la durabilité environnementale. Les pratiques de labour de conservation ont fait l'objet d'une grande attention internationale pour relever ce défi en raison de leur effet sur les propriétés physiques des sols et le rendement des céréales. Cependant, on manque de connaissances sur les relations entre les propriétés physiques du sol et le rendement en grains, notamment en ce qui concerne l'hydrophobie du sol. La dynamique des propriétés physiques du sol pendant la période de croissance est rarement prise en compte pour comprendre l'environnement physique du sol adapté à la croissance des plantes. En outre, bien qu'il soit bien connu que les pratiques de travail du sol de conservation pourraient affecter la déperlance du sol par le biais de substances hydrophobes et de la structure des pores, la plupart des études se sont uniquement concentrées sur les substances hydrophobes en raison de la complexité de la mesure ou de la quantification de la structure des pores du sol. Il en résulte une connaissance limitée de la relation entre la structure des pores du sol et son hydrophobicité.Dans cette étude, nous avons utilisé une expérience de terrain de longue durée située à la station expérimentale d'agriculture en zone sèche de Shouyang, dans la province de Shanxi, au nord de la Chine, pour étudier les changements saisonniers des propriétés physiques du sol (par exemple, la densité apparente, la résistance à la pénétration, la porosité, le diamètre moyen du poids, la gamme d'eau la moins limitante et l'eau disponible pour les plantes). Nous avons également évalué la manière dont ces propriétés physiques du sol influencent le rendement en grains, et avons notamment révélé le mécanisme par lequel la résistance à l'eau du sol affecte le rendement en grains du point de vue de la disponibilité en eau du sol. Afin de mieux comprendre les effets des substances hydrophobes et de la structure des pores sur la résistance à l'eau du sol, un autre site expérimental de long terme a été mené à Gongzhuling, dans la province de Jinlin, au nord-est de la Chine. Les traitements étaient les suivants : travail du sol conventionnel avec exportation des résidus (CT), travail du sol réduit avec incorporation des résidus (RT), et travail du sol sans labour avec mulching des résidus (NT) dans les deux champs. Les principaux résultats de cette thèse sont les suivants :

(1) Les propriétés physiques du sol (par exemple la densité apparente, la résistance à la pénétration, la distribution de la taille des pores, le diamètre moyen pondéral, LLWR et l'eau disponible pour les plantes) ont été influencées de manière significative par la gestion du travail du sol, la profondeur du sol et la période de croissance ($P < 0,05$). Dans la couche 0-5 cm, le NT était le plus élevé en densité apparente du sol le 27 avril, mais il n'y avait pas de différence significative entre les trois modes de gestion du travail du sol le 7 juillet, et le NT était inférieur au RT et au CT le 10 septembre. De plus, la densité apparente, la porosité, l'indice S et le diamètre moyen pondéral ont montré des relations irrégulières et différentes avec le rendement en grains pendant la période de croissance, en particulier il n'y avait

pas de relations significatives entre ces propriétés physiques du sol et le rendement en grains (P > 0,05). Ces résultats suggèrent que ces propriétés physiques du sol sont des indicateurs inefficaces du rendement en grains. En outre, la LLWR était plus faible que l'eau disponible pour les plantes pendant la période de croissance et plus sensible pour évaluer la disponibilité de l'eau du sol dans le cadre des trois traitements. Le NT a considérablement augmenté la limite inférieure de la LLWR, ce qui a rendu plus difficile l'absorption de l'eau par les racines. Par conséquent, le RT a présenté un rendement de maïs plus élevé que le NT, même si la teneur en eau est restée plus faible. L'analyse de redondance a en outre indiqué que le rendement du maïs était principalement dû à une limite inférieure de LLWR et à la résistance à la pénétration.

(2) Le carbone organique du sol et le carbone de la biomasse microbienne, qui sont tous deux des substances hydrophobes, étaient plus élevés dans les traitements par RT et NT que dans le traitement par CT. Le carbone de la biomasse microbienne avait une relation plus étroite avec l'indice de déperdition d'eau que le carbone organique du sol et expliquait plus complètement l'impact du travail du sol sur la déperdition d'eau. Les traitements par RT et NT ont augmenté la porosité pour les pores qui avaient un diamètre de 55 à 165 μm et ont eu une relation positive avec la sorption de l'éthanol et l'indice de déperlance, respectivement. Cependant, il n'y a pas eu de lien significatif avec les propriétés hydrophobes du sol lorsque les pores avaient un diamètre supérieur à 165 μm. Les traitements RT et NT ont augmenté la sorptivité en améliorant la porosité et la connectivité, et ont diminué la sorptivité de l'eau en augmentant la surface du sol, ce qui s'est produit parce que la surface et la possibilité de contact entre les substances hydrophobes et l'eau du sol ont augmenté.

(3) Tant la sorptivité de l’eau que l’indice de répulsivité de l’eau ont eu des effets sur la disponibilité en eau du sol (par exemple l’eau disponible des plantes, la gamme d’eau la moins limitante et le stockage de l’eau du sol) qui pourraient affecter la croissance des plantes.L’effet de la répulsivité de l’eau du sol sur la teneur en eau du sol est devenu plus évident avec la diminution de l’humidité du sol à la suite des précipitations, qui a également été influencée par l’intensité des précipitations. Bien que l’indice d’imperméabilité à l’eau et la sorptivité à l’eau puissent refléter la nature de l’imperméabilité à l’eau du sol, la sorptivité à l’eau du sol a eu une influence significative sur le rendement en grains, alors que l’indice d’imperméabilité à l’eau n’a eu aucun effet direct sur le rendement en grains.En outre, la sorptivité de l’eau a été la plus favorable à l’amélioration du rendement en grains par rapport au carbone organique du sol, au diamètre moyen du poids, à la résistance à la pénétration et à la porosité totale.

En conclusion, la thèse révèle le mécanisme de la façon dont la gestion du travail du sol affecte le rendement des céréales en modifiant les propriétés physiques du sol. Nous avons constaté que le rendement en grain était principalement déterminé par une limite inférieure de la plage d'eau la moins limitante et de la résistance à la pénétration. Le LLWR était un indicateur agrégatif comprenant non seulement la résistance à la pénétration du sol, mais également la porosité de l'air et le potentiel

hydrique du sol, ce qui peut mieux expliquer le changement du rendement en grain dans le cadre de la gestion du travail du sol à long terme dans la région semi-aride. En outre, l'effet du travail de conservation du sol sur le SWR est le résultat des interactions entre la structure des pores et les substances hydrophobes. Il est nécessaire de prendre en compte à la fois la structure des pores et les substances hydrophobes lors de l'étude des impacts du SWR sur les processus du sol. Le SWR avait également une influence potentielle sur le rendement en céréales en changeant la disponibilité de l'eau du sol et l'effet du SWR sur le rendement des cultures méritait une étude plus approfondie dans le cadre des pratiques de conservation du sol. Le rendement en grains sous traitement RT a été le plus élevé en augmentant la sorptivité de l’eau, LLWR, WUE.A partir de là, nous concluons que le traitement RT est la méthode de travail la plus efficace par rapport aux traitements CT et NT du point de vue du rendement en grain.

Mots clés: agriculture de conservation; propriétés physiques du sol; le rendement en grains; hydrofugation du sol; la disponibilité de l'eau du sol; structure des pores du sol

Abstract

A primary challenge of our time is to attain high food security for a growing world population with reduced investment and ensuring environmental sustainability. Conservation tillage practices have received wide international attention to address this challenge because of their effect on soil physical properties and grain yield. However, there is a lack of knowledge about the relationships between soil physical properties and grain yield, especially for soil water repellency. The dynamic of soil physical properties during the growth period is also seldom taken into account to understand a suitable soil physical environment for plant growth. Moreover, although it is well known that conservation tillage practices could affect soil water repellency through hydrophobic substances and pore structure, most of the studies have only focused on hydrophobic substances due to the complexity of soil pore structure measurement and quantification. This results in limited knowledge about the relationship between soil pore structure and soil water repellency.

In this study, we used a long-term field experiment located at the Dryland Farming Experimental Station in Shouyang, Shanxi Province, in northern China to study the seasonal changes of soil physical properties (e.g. bulk density, penetration resistance, porosity, mean weight diameter, least limiting water range, and plant available water). We also assessed how these soil physical properties influence grain yield, especially reveal the mechanism of how soil water repellency affects grain yield from the perspective of soil water availability. To better understand the effects of hydrophobic substances and pore structure on soil water repellency, another long-term experimental location was conducted in Gongzhuling, Jinlin Province, northeast China. The treatments were conventional tillage with residue removal (CT), reduced tillage with residue incorporation (RT), and no-tillage with residue mulching (NT) in both of the fields. The main results of this thesis are as follows:

(1) Soil physical properties (e.g. bulk density, penetration resistance, pore size distribution, mean weight diameter, least limiting water range, and plant available water) were significantly influenced by tillage management, soil depth, and growth period ($P < 0.05$). At 0-5 cm layer, NT was the highest in soil bulk density on April 27th, but there was no significant difference among the three tillage management on July 7th, and NT was lower than RT and CT on September 10th. In addition, bulk density, porosity, S index, and mean weight diameter showed irregular and different relationships with grain yield during the growth period, especially there were no significant relationships between these soil physical properties and grain yield ($P > 0.05$). These results suggested that these soil physical properties were ineffective indicators for grain yield. Besides, the range of least limiting water range was narrower than plant available water during the growth period and more sensitive to assess soil water availability under the three treatments. NT significantly increased the lower limit of LLWR, which made it more difficult for root water uptake. Hence, RT presented higher corn yield compared to NT, even if the water content remained lower. Redundancy analysis further

indicated that maize yield was mainly driven by a lower limit of LLWR and penetration resistance.

(2) Soil organic carbon and microbial biomass carbon, both of which are hydrophobic substances, were higher in RT and NT treatments than in CT treatment. Microbial biomass carbon had a closer relationship with the water repellency index than soil organic carbon and more fully explained the impact of tillage on soil water repellency. The RT and NT treatments increased the porosity of pores that were 55-165 μm in diameter and it had a positive relationship with ethanol sorptivity and the water repellency index, respectively. However, there was no significant link with soil water repellency properties when the pores were greater than165 μm in diameter. The RT and NT treatments increased sorptivity by enhancing porosity and connectivity, and decreased water sorptivity by increasing soil surface area, which occurred because the area and possibility of contact between hydrophobic substances and soil water increased.

(3) Both water sorptivity and water repellency index had effects on soil water availability (e.g. plant available water, least limiting water range, and soil water storage) that could affect plant growth. The effect of soil water repellency on soil water content became more obvious with the decrease in soil moisture following rainfall, which was also influenced by rainfall intensity. Although both water repellency index and water sorptivity can reflect the nature of soil water repellency, soil water sorptivity had a significant influence on grain yield, whereas water repellency index had no direct effect on grain yield. In addition, water sorptivity was the most favorable for grain yield improvement compared with soil organic carbon, mean weight diameter, penetration resistance, and total porosity.

In conclusion, the thesis reveals the mechanism of how soil tillage management affects grain yield by changing soil physical properties. We found that grain yield was mainly driven by a lower limit of least limiting water range and penetration resistance. LLWR was an aggregative indicator including not only soil penetration resistance but also air porosity and soil water potential, which can better explain the change of grain yield under the long-term tillage management in the semi-arid region. Furthermore, the effect of conservation tillage on SWR is a result of the interactions between pore structure and hydrophobic substances. It is necessary to take into account both pore structure and hydrophobic substances when studying the impacts of SWR on soil processes. SWR also had the potential influence on grain yield by changing soil water availability and the effect of SWR on crop yield was worthy of further study under conservation tillage practices. The grain yield under RT treatment was highest by increasing water sorptivity, LLWR, and WUE. From this, we conclude that RT treatment is the most effective tillage practice compared to CT and NT treatments from the perspective of grain yield.

Keywords: Conservation agriculture; soil physical properties; grain yield; soil water repellency; soil water availability; soil pore structure

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Shengping Li
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Chapter I

General introduction

Chapter I General Introduction

Abstract

Tillage management is a key factor driving changes in soil physical properties (e.g. bulk density, penetration resistance, porosity, pore connectivity, mean weight diameter, and hydraulic properties) and crop yield around the world. However, knowledge about how tillage management affects crop growth still remains unclear. The chapter provides an overview of the thesis frame structure with a brief description of the effect of soil tillage management on soil physical properties, crop yield, and water use efficiency. Furthermore, we also showed the relationship between crop yield and SPP under conservation agriculture. Soil physical properties, which are changed by conservation tillage, have considerable effects on the availability and uptake of soil water for plant growth. Overall, it is essential to quantify SPP under conservation tillage management for recognizing the factors that control crop growth.

Keywords:

Conservation tillage; Soil physical properties; Yield; Water use efficiency

1. Background

One of the primary challenges of our time is to attain high food security for a growing world population with reduced investment and ensuring environmental sustainability (Charles et al., 2014; Connor and Mínguez, 2012; Falcon et al., 2008). Conservation agriculture (CA), which mainly represents three crop management manners (Hobbs et al., 2008), has received wide international attention to address this challenge because of its effects on crop production and soil ecosystem. The three manners are direct crops planting with minimum soil disturbance (reduce tillage or no-tillage), soil cover by crop residues, and crop rotation (Pittelkow et al., 2015a).

CA has exponentially increased since the 1960s around the world (Friedrich et al., 2017), which is shown in Figure 1-1. In recent decades, the areas of reduced tillage and no-tillage practices have over 120 million hectares, which is equivalent to 9% of global cultivable land (Blanco-canqui and Ruis, 2018; Friedrich et al., 2017). However, the adoption rate of tillage practices is regional. The area percentage under CA by continent is shown in figure 1-2. America has about 76.5% of the total global area of CA, whereas Asia only has 6.59% (Blanco-canqui and Ruis, 2018). The CA has been practiced in China since the 1990s (Lal, 2018) and it has been developing rapidly in recent years. However, the CA area (6.7 Mha) in China in 2013 is still very lower compared to the USA (35.6 Mha), Brazil (31.8 Mha), Argentina (29.2 Mha), Canada (18.3 Mha), and Australia (17.7 Mha) in 2013 (Friedrich et al., 2017). In addition, although Chinese authorities encourage CA development, the application and promotion of CA have been slow in recent years and the CA area in 2016 is about 8 Mha (Lal, 2018). The main reason is that the effects of CA on crop productivity remain contested and the knowledge about how CA influences soil physical properties is lacking.

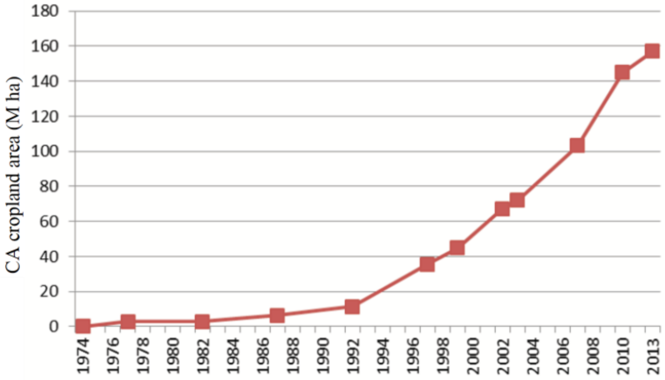

Figure 1-1 Global uptake of CA in M ha (Friedrich et al., 2017)

Changes in soil physical properties influence some soil ecosystems, such as production, soil erosion control, improvement in water and air quality, nutrient cycling, soil carbon dynamics, and biodiversity. For this reason, the effects of CA on soil physical properties have been widely investigated, but contradictory results have been found (Alvarez and Steinbach, 2009; Tuzzin de Moraes et al., 2016). CA effects on soil physical quality are supposed to be time- and space-dependent (Derpsch et al., 2014; Li et al., 2020).

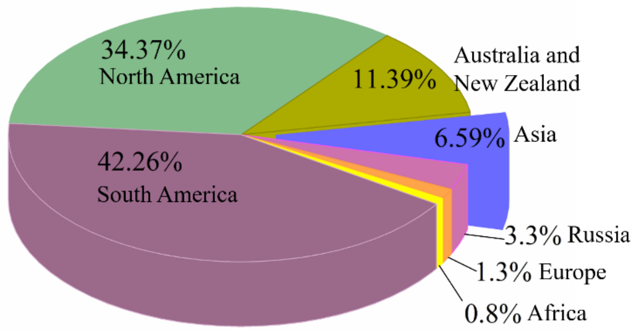

Figure 1-2 Percentage of the area under CA by continent around the world (Blanco-canqui and Ruis, 2018)

1.1 The effect of tillage management on soil compaction

Soil compaction, which is usually characterized by soil bulk density and penetration resistance, is one of the important soil physical properties. It modifies the soil pore architecture and has been known to decrease soil porosity, aeration, water infiltration, and hydraulic conductivity, which has a limitation on root growth and soil water absorption by root (Chen et al., 2014; Silva et al., 2014). Furthermore, these changes could decrease crop yield and increase risks of soil water and nutrient losses, greenhouse gas emissions, and pollution of water resources (Lipiec et al., 2003; Tuzzin de Moraes et al., 2016). There are some conflicting results about the effect of CA on soil compaction. Some studies show that reduced tillage and no-tillage increase soil compaction (bulk density and penetration resistance) compared to the conventional tillage (Afzalinia and Zabihi, 2014; Taser and Metinoglu, 2005), whereas the results that there is no significant effect of CA on soil compaction are found (Li et al., 2020; Salem et al., 2015).

1.2 The effect of tillage management on soil water availability

Soil water availability is one of the important factors controlling crop growth (Huxman et al., 2004), especially for the rain-fed crops in semi-arid and arid areas where water shortage is the main limitation of crop growth. There are different methods to determine the available soil water. The common approach is plant available water and it has been applied for many years to describe the soil water between field capacity and permanent wilting point (Asgarzadeh et al., 2011). However, the simple plant available water approach is only involved in soil water potential and does not consider other soil physical properties that influence soil water uptaken by crop roots. Furthermore, as complex interactions among roots, soil, and water determine crop growth, individual soil physical properties may not substantially explain suitable soil physical environment and provide an easy understanding of the soil-crop relationship. The least limiting water range (LLWR) has been proposed as an indicator of soil water availability associated to plant growth and productivity (Benjamin et al., 2003), because it integrates three main plant growth-limiting factors (soil resistance, air porosity, and soil water potential) into a single parameter (de Lima et al., 2012). The LLWR is defined as a range of soil moisture within which plant growth is least limited by water potential, soil penetration resistance, and aeration (Cássio A. et al., 2017). Therefore, it is essential to further study the effect of CA on LLWR for a better understanding of the relationship between soil water availability and crop growth. In addition, the soil water retention curve needs to be used to calculate both approaches (plant available water and LLWR). Among various methods, the centrifuge water extraction method stands as an appropriate technique to measure soil water retention because it has similar results with the pressure plate method and costs much less time (Reatto, 2008), and has a wider range of matric potential than pressure plate method. The details about the centrifuge machine and soil samples, which were used to measure the soil water retention curve, are shown in figure 1-3.

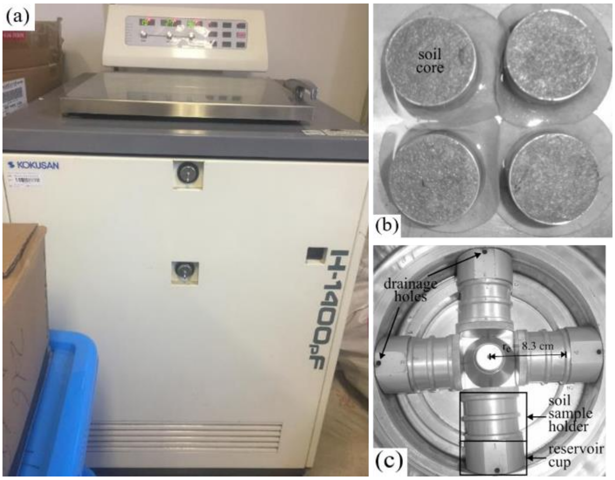

Figure 1-3. The centrifuge machine and soil samples for the centrifuge water extraction method to measure the soil water retention curve.

Some previous studies have used LLWR to explain soil physical environments (Asgarzadeh et al., 2010; Wilson et al., 2013). However, knowledge about the relationship between LLWR and crop yield is still limited. Cecagno et al. (2016) found that LLWR showed no direct correlation with soybean yield, and was an inadequate indicator in integrated soybean-beef cattle system under no-tillage management. The contrary results were also found LLWR was a useful index for plant growth under long-term tillage and cropping systems in the semi-arid region with annual precipitation of 580 mm. In addition, Benjamin et al. (2003) studied that there was no relationship between LLWR and corn yield under different soil tillage management, whereas using the Water Stress Day indicator, which considered LLWR and soil moisture at the same time, had a significant relationship with corn yield. Therefore, the relationship between LLWR and yield still needs further study from the perspective of soil available water.

1.3 The effect of tillage management on soil water repellency

Soil water repellency (SWR) is a common phenomenon in coarse- to fine-textured soils across all climatic zones under different climates and land use (Daniel et al., 2019). SWR is considered to be created by hydrophobic organic compounds covering the surfaces of soil particles (Doerr et al., 2000). These compounds originate from plant roots and leaves and mainly include resins, waxes, fatty acids, and cutins (Fontaine et al., 2003; Hallett, 2008), which are also controlled by soil microbes (Seaton et al., 2019). SWR is an important physical property with significant consequences for hydrological precesses by changing soil water infiltration, soil water storage, evaporation, and soil erosion (Chau et al., 2014; Doerr et al., 2000; Kim et al., 2015).

There are different methods used for measuring SWR. The water drop penetrating time (WDPT) can access the persistence of SWR and the ethanol droplet (MED) method can calculate the ninety-degree surface tension (Senani et al., 2016). However, the two methods and other direct methods for measuring the wetting angle need a flat surface that is problematic because soil surface is usually rough (Czachor et al., 2010). Furthermore, the time that a sessile drop infiltration cost is short, which makes it difficult to measure the degree of SWR accurately because many soils are wettable, especially for farmland soil. The MED method only works for hydrophobic soils with contact angles greater than 90° (Carrillo et al., 1999). However, SWR could influence soil hydrological processes and a slight change in water contact angle can have a considerable effect on soil hydraulic properties (Leelamanie and Karube, 2013; Tadayonnejad et al., 2017). The sorptivity method is widely adopted to calculate the degree of SWR, even if the range of water contact angle is between zero to nighty degree. In addition, the sorptivity method is more effective to explain the effect of SWR on soil hydrological processes because the method is related to the infiltration process. A self-made device is usually used in the method according to Hallett and Young (1999). The detailed information about the device is shown in figure 1-4.

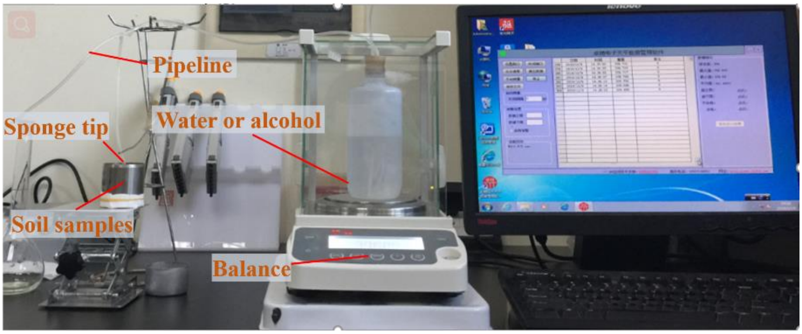

Figure 1-4. The device of the sorptivity method for measuring soil water

repellency

Some studies have shown that CA increases SWR after the addition of residues (Blanco-Canqui and Lal, 2009; Cosentino et al., 2010; Roper et al., 2013) because it increases the organic matter and microbial activity. The secondary produced from decomposing organic matter could increase SWR rapidly (Feeney et al., 2004). However, the addition of residues also increase soil porosity and connectivity and then increase soil wettability. Behrends et al. (2019) used the WDPT method to establish that the time needed for a single water drop to infiltrate a soil sample, which shows the degree of SWR, was controlled by pore structure as well as hydrophobic substances. Hence, it is essential to investigate both the pore structure and hydrophobic substances at the same time when studying SWR. In addition, SWR can decrease the capillary rise and limit the water sorptivity by plant root, which leads to negative effects on germination rate and crop yields (Gupta et al., 2015; Müller et al., 2014). Previous studies have shown difference result that soil moisture and crop growth are poorly related to soil water repellency under no-tillage management (Roper et al., 2013). Therefore, the knowledge about the relationship between SWR and crop yield is still unclear and it deserves further study.

Conservation tillage practices could increase SWR compared with conventional tillage (Blanco-Canqui, 2011). RT and NT managements reduce soil disturbance and increase soil organic carbon (Afzalinia and Zabihi, 2014; Hermansen et al., 2019), both of which can increase SWR (Behrends et al., 2019; Li et al., 2020a). González-Peñaloza et al. (2012) found that No-tillage was significantly higher in SWR than conventional tillage after two years and the SWR increased with an increase in years of continuous cropping. However, some studies also found tillage practices have no significant effect on SWR (Bottinelli et al., 2010; Eynard et al., 2004). The main reason is that SWR could be affected by soil texture, climate, and duration of tillage management (Doerr et al., 2006; Goebel et al., 2011). Previous studies had found that drought could increase SWR (Chen et al., 2018; Deurer et al., 2011; Hewelke et al., 2018). This underscores the need for increased focus on studies of the impact of tillage management on SWR under rainfed agriculture because climate extremes and drought severity increase as global warming intensifies (Ahmed et al., 2018; Mohsenipour et al., 2018; Trenberth et al., 2014). Furthermore, soil depth also had a significant effect on SWR under tillage management (Bottinelli et al., 2010) and SWR in the 0-5 cm depth was higher than in the 5-10 cm depth under no-tillage management (Roper et al., 2013).

1.4 The effect of tillage management on soil pore structure

The soil pore structure is defined as “the combination of different types of pores” across the size range from nanometres to centimeters (Pagliai and Vignozzi, 2002). It is an important factor influencing some soil processes, such as aggregate stability (Bronick and Lal, 2005), soil carbon stabilization (Pituello et al., 2016), water holding capacity (Naveed et al., 2014), infiltration (Müller et al., 2018), and soil respiration (Monga et al., 2008). There are some indirect and direct methods to measure soil pore structure. The mercury porosimetry, water retention curve, and gas adsorption are the main indirect methods. These methods are used to measure pore size distribution, volume, and pore-solid surface area (Rabot et al., 2018). However, indirect methods can not distinguish spatial distribution and characterize the morphology and topology of the pore structure because the soil pore structure is extremely complex.

X-ray computed tomography (μCT) has been successfully used to obtain a non-destructive and detailed 3D characterization of the soil porous system (Beckers et al., 2014; Young et al., 2001), which is considered as a useful and promising direct method for measuring soil pore structure. In contrast to the indirect methods to calculate pore size distribution, volume, and surface, the direct method has two obvious advantages. One is that the direct method is a non-destructive technique and it minimizes the damage to soil samples. Another is that these variables can be obtained directly without any assumptions on the pore shape that are used in indirect methods (Rabot et al., 2018). Furthermore, some other variables can be calculated by the direct method, such as pore connectivity (Paradelo et al., 2016), tortuosity (Müller et al., 2018), and percolation threshold (Amoakwah et al., 2017).

The soil pore structure is an indicator of the soil quality and it can be changed by CA. Blanco-Canqui and Ruis (2018) reviewed 14 studies to assess the effects of tillage management on the pore size distribution and found no-tillage increased the porosity of macropores in four of 14 studies, reduced in six, and no influence in four studies compared with conventional tillage, which showed that the effect of tillage management on pore size distribution are mixed. No-tillage or the addition of residues could improve soil pore connectivity (Borges et al., 2019; Galdos et al., 2019) and consequently increase soil water and nutrient availability (Pittelkow et al., 2015b). Although the effects of tillage management on soil pore structure have been widely studied, the research about how the soil pore structure affects soil functions is still inadequate.

1.5 The effect of tillage management on crop yield and water use efficiency

Water use efficiency (WUE) is the ratio of crop yield and evapotranspiration (ET). Hence, the effects of tillage management on WUE can be studied from two perspectives: yield and changes in soil moisture. Pittelkow et al. (2015a) carried out a global meta-analysis from 610 studies to compare no-tillage with conventional tillage and found that no-tillage reduced yield. However, this response was variable when no-tillage was combined with crop residues or cover crops. One more meta-analysis was carried out to reveal the effects of no-tillage on yield and WUE in China (Wang et al., 2018). The results showed that no-tillage increase the maize WUE by 5.9%, whereas it had no significant influence on the wheat WUE, ET, and yield of maize and wheat.

Another perspective is the effect of tillage management on ET. No-tillage with crop residues could improve soil water storage capacity (Li et al., 2020; Wang et al., 2018) because the crop residues reduce soil evaporation (Zhang et al., 2015) and increase organic matter that is helpful for soil water storage (Herencia et al., 2011; Li et al., 2018). The ET values under no-tillage were lower than conventional tillage from the sowing to the flowering stage, but significantly higher at ripening stage (Guan et al., 2015). It also changes with precipitation. No-tillage could not affect ET compared with conventional tillage in the regions with ≤400 mm of precipitation, whereas reduced ET in the regions with ≥600 mm (Wang et al., 2018). Therefore, the corresponding relationship between tillage management and, yield and WUE changes with some conditions (e.g. crop species, climate, and soil texture). In addition, tillage management has a far greater influence on soil physical properties, which have direct and indirect effects on soil water movement and crop growth (Palese et al., 2014; Tuzzin de Moraes et al., 2016). It needs further study on how the soil physical properties affect crop yield and WUE under tillage management, which can provide a better understanding of the soil-crop relationship.

2. Objective

In this study, two experiment fields (northern China and northeast China) were conducted to study the effect of tillage management on soil physical properties, maize yield, and water use efficiency. The research technology roadmap of our study is shown in figure 1-5. Tillage management can change hydrophobic substances and soil pore structure. Both have effects on soil water repellency (SWR) and soil water availability, which is mainly explained by the least limiting water range (LLWR) in our study. The first part is to explain how the hydrophobic substances and soil pore structure affect SWR (blue dashed box). Then, the second part is to reveal the effect of SWR on yield and WUE through changing soil water storage (orange dashed box). The last part is to assess the effects of other soil physical properties on yield and WUE (brown dashed box). Finally, based on the above research, this thesis aims to reveal the effect of tillage management on yield and WUE of maize through changing soil physical properties.

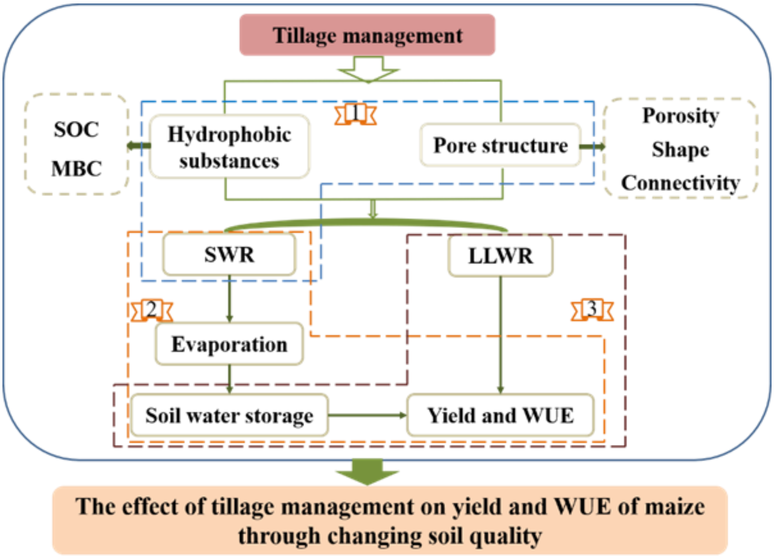

Figure 1-5 The technology roadmap of this thesis

To expound the above main objective, the following specific aims of this thesis are as follows:

(1) To quantify the magnitude of soil physical properties (i.e. bulk density, penetration resistance, porosity, mean weight diameter, LLWR, and plant available water) temporal changes.

(2) To determine the effect of conservation tillage on SWR, soil pore structure, soil organic carbon, and microbial carbon.

(3) To understand how soil pore structure and hydrophobic substances change SWR.

(4) To explain how SWR affects yield by changing soil water availability under tillage management.

(5) To assess the effects of these soil physical properties on corn yield and WUE for a better understanding of the soil-crop relationship.

3. Outline

This dissertation is structured into the following 5 chapters.

Chapter I General introduction.

In this chapter, the global description of the thesis was shown. The main contents were the development of CA around the world, especially for China, and further the effect of CA on soil compaction, soil water availability, SWR, pore structure, crop yield, and WUE. The problems and knowledge gaps were described in the part.

Chapter II Is least limiting water range a useful indicator of the impact of tillage management on maize yield?

The objective of this chapter was to explain how dynamic soil physical properties affected grain yield during the growth period. A long-term field experiment was established from 2003 in northern China, with continuous spring maize, on sandy loam soil. Seasonal changes of soil physical properties (e.g. bulk density, penetration resistance, porosity, mean weight diameter, LLWR, and plant available water) were determined under conventional tillage with residue removal (CT), reduced tillage with residue incorporated (RT), and no-tillage with residue mulch (NT).

Chapter III Factors governing soil water repellency under tillage management: the role of pore structure and hydrophobic substances

In this chapter, X-ray computed tomography was used to calculate the shape, porosity, and connectivity of the pore network and reveal the impact of hydrophobic substances and pore structure on soil water repellency (SWR). All the samples were collected from two long-term experimental fields with three tillage management (CT, RT, and NT). The intrinsic sorptivity method was used to determine the water repellency index. The results showed that the RT and NT treatments increased the water repellency index, which was a result of the interactions between pore structure and hydrophobic substances. Furthermore, the results showed that it is essential to investigate both pore structure and hydrophobic substances at the same time when studying the mechanisms underlying conservation tillage impacts on SWR.

Chapter IV Does soil water repellency reduce corn yield by changing soil water availability under long-term tillage management?

The objective of this chapter was to reveal how SWR influences grain yield from soil water availability point of view. Here we used a long-term field experiment that was established in 2003 with continuous spring maize. Three treatments were conducted: CT, RT, and NT. We found that 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. SWR, which was characterized by water sorptivity and RI, had the potential to influence grain yield by changing soil water availability and RT treatment was the most effective tillage management compared to CT and NT treatments in improving grain yield.

Chapter V General discussion and conclusions

In this chapter, the meaning, importance, and relevance of general results were delved into. We stated the answers to the main research question, made recommendations for future research on the topic, and showed what new knowledge we have contributed.

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Chapter II

Is least limiting water range a useful indicator of the impact of tillage management on maize yield?

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Chapter II Is least limiting water range a useful indicator of the impact of tillage management on maize yield?

Abstract

Tillage management is a key factor driving changes in soil physical properties (SPP) and crop yield around the world. However, there is a lack of knowledge about the relationships between SPP and crop yield. The dynamic of SPP during the growth period is also seldom taken into account to understand suitable soil physical environment for crop growth. Moreover, the crop growth process cannot be explained by an individual SPP substantially. The least limiting water range (LLWR), which integrates soil penetration resistance, air porosity, and soil water potential, may provide a better understanding of soil-crop relationship, especially in regions with limited precipitation. Our objective was to explain how dynamic SPP affected grain yield during the growth period. A long-term field experiment was established in 2003, with continuous spring maize, on sandy loam soil. Seasonal changes of SPP (i.e. bulk density, penetration resistance, porosity, mean weight diameter, LLWR, and plant available water) were determined under reduced tillage with residue incorporated (RT), conventional tillage with residue removal (CT), and no-tillage with residue mulch (NT). The results showed that these SPP were affected by both tillage management and growth stage. Bulk density, porosity, S index, and mean weight diameter were not effective indicators to explain the changes of grain yield under the three tillage managements. The range of LLWR was narrower than plant available water (PAW) during the growth period and more sensitive to assess soil water availability under RT, CT, and NT. NT significantly increased the lower limit of LLWR, which made it more difficult for root water uptake. Hence, RT presented higher corn yield compared to NT-RM, even if the water content remained lower. Redundancy analysis further indicated that maize yield was mainly driven by lower limit of LLWR and penetration resistance. Overall, LLWR was an aggregative indicator including not only soil penetration resistance but also air porosity and soil water potential, which can better explain the change of grain yield under the long-term tillage management in semi-arid region.

Keywords:

Conservation tillage; Soil physical properties; Yield; Least limiting water range; Soil water availability

1. Introduction

A primary challenge of our time is to attain high food security for a growing world population with reduced investment and ensuring environmental sustainability (Connor and Mínguez, 2012; Godfray and Garnett, 2014). Conservation agriculture has received wide international attention to address this challenge because of its effect on soil physical properties (SPP) (Biazin et al., 2011; Gao et al., 2019) and agricultural crops (Hobbs et al., 2007). SPP, which are variable with planting time (Afzalinia and Zabihi, 2014; Valle et al., 2018), have direct and indirect effects on the availability and uptake of water, nutrients, and air for plant growth (Tran Ba et al., 2016). Thus, it is essential to quantify SPP during the growth period for recognizing the factors that control crop growth.

Understanding the relationship between SPP and crop is particularly crucial in regions with limited precipitation. The effect of conservation tillage on SPP has been widely investigated, but how SPP affects crop growth is poorly understood (Filho et al., 2013). The reason why it is difficult to establish soil-crop relationship is that the results of SPP are highly variable, because of a different time, space, and management (Tuzzin de Moraes et al., 2016). Blanco-Canqui and Ruis (2018) summarized 62 studies on soil bulk density under conventional tillage and no-tillage for the past 10 years. No-tillage had no effect on bulk density in 26 of the 62 studies, increased bulk density in 24 of 62 studies, and reduced it in 12 of 62 studies in the 0-10 cm soil depth. Reduced tillage and no-tillage increased the penetration resistance compared with the conventional tillage (Afzalinia and Zabihi, 2014). However, no significant effect of the tillage system on penetration resistance was found in corn-soybean rotation (Logsdon et al., 2004). Some SPP (i.e. soil bulk density, penetration resistance, pore structure, and plant available water capacity) change with the growth period (Afzalinia and Zabihi, 2014; Moreira et al., 2016; Valle et al., 2018), which could influence the soil-crop relationship but it is overlooked in most studies. Further, as complex interactions among roots, soil, and water determine crop growth, an individual SPP may not substantially explain suitable soil physical environment and provide an easy understanding of soil-crop relationship.

The least limiting water range (LLWR) has been proposed as an indicator of soil physical quality associated to plant growth and productivity (Benjamin et al., 2003), because it integrates three main plant growth-limiting factors (soil resistance, air porosity, and soil water potential) into a single parameter (de Lima et al., 2012). The LLWR is defined as a range of soil moisture within which plant growth is least limited by water potential, soil penetration resistance, and aeration (Tormena et al., 2017).

Many studies have measured LLWR to assess soil physical environment (Asgarzadeh et al., 2010; Wilson et al., 2013). However, soil physical environment assessment by LLWR has been challenged because there is a lack of relationship between LLWR and crop yield (Guedes Filho et al., 2014), which causes LLWR to be a useless agronomic indicator for tillage practices. Cecagno et al. (2016)

concluded that LLWR was an inadequate indicator of soil physical environment due to no direct correlation with soybean yield in humid regions (average annual rainfall of 1,850 mm). However, these studies neglected the time variation of LLWR, which may cause that LLWR cannot explain the relationship with yield accurately. Precipitation also can affect the relationship between LLWR and yield. LLWR was a useful index for plant growth under annual precipitation of 580 mm (Filho et al., 2013). The reason why LLWR can influence yield is still unknown. Moreover, a simple correlation between LLWR and yields cannot reveal how soil water availability influences yield effectively. Benjamin et al. (2003) studied that there was no relationship between LLWR and corn yield under different soil tillage managements, while using Water Stress Day indicator, which considered LLWR and soil moisture at the same time, had a significant relationship with corn yield. Therefore, the relationship between LLWR and yield still needs further study from the perspective of soil available water.

The objective of this study was to: i) quantify the magnitude of SPP (i.e. bulk density, penetration resistance, porosity, mean weight diameter, LLWR, and plant available water) temporal changes, and ii) assess the effects of these SPP on corn yield to provide a better understanding of soil-crop relationship.

2. Materials and methods

2.1. Study site

The continuous field experiment was conducted in 2003 at the Dryland Farming Experimental Station in Shouyang (112-113°E, 37-38°N; 1100 m a.s.l.), Shanxi Province, in northern China. The site has a continental monsoon climate with an average annual precipitation of 483 mm from 2003 to 2018, and mean annual potential evaporation is 1700-1800 mm (Wang et al., 2019). The detailed rainfall and mean daily temperature are shown in Figure 2-1. The annual frost-free period is about 130 days. Spring drought is often a limiting factor for plant growth (Wang et al., 2011). The experimental site has a sandy loam cinnamon soil, classified as Calcaric-Fluvic Cambisols (IUSS et al., 2015). Table 2-1 shows the soil primary chemical and physical properties in 2003.

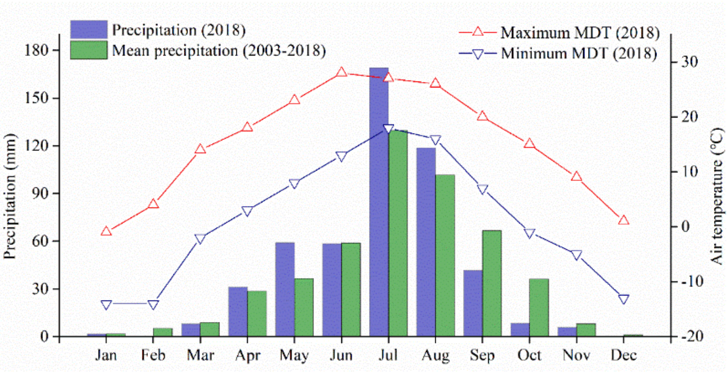

Figure 2-1. Evolution of monthly precipitation (vertical bars) for 2003-2018 period and mean daily temperature (MDT) for 2018.

Table 2-1 Soil physical and chemical properties in 0-30 cm layer in 2003

Soil layer (cm)	Soil particle size distribution (%)			Available soil nutrient (mg kg^{-1})			SOC (g kg^{-1})	Bulk density (g cm^{-3})
	>0.020 mm	0.002-0.020 mm	<0.002 mm	N	P	K		
0-10	58.5	35.7	5.8	58	8.3	96	22.7	1.06
10-20	59.6	34.6	5.8	52	6.9	93	19.8	1.20
20-30	60.6	33.7	5.7	53	3.1	87	15.1	1.36

2.2 Experimental design

The long-term tillage and residue retention experiment was arranged using a randomized complete block design with three replicates. Each plot was 5 m by 5 m in size. The crop was continuous spring maize. There was a fallow period from November to next March. Three treatments were applied: a) RT: reduced tillage with maize straw and fertilizers incorporated after harvesting (in October), plowing once to about 25 cm depth with moldboard plow; b) CT: conventional tillage with maize stalk removed after harvesting, plowed twice to about 25 cm depth with moldboard plow after harvesting and before seeding (in April); and c) NT: no-tillage with the maize stalk mulched after harvesting, then seeding and fertilizing with a no-till planter in next April. Each plot was applied 105 kg N ha^{-1} and 105 kg P_2O_5 ha^{-1}, through urea and calcium superphosphate, respectively. The row and plant spacings were 60 and 30 cm, respectively.

2.3 Soil sampling

For the rainfed long-term experiment, precipitation was measured using a rain gauge at the experimental site from 2003 to 2018. Soil samples for soil water content were collected two times (at seeding and harvesting) at 0-10, 10-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140, 140-160, 160-180, and 180-200 cm depth every year to calculate water use efficiency (WUE), which was determined from the ratio of grain yield to the cumulative evapotranspiration of the complete growing period. All details of these calculations can be found in Wang et al. (2011). Four sampling dates (May, July, August, and September) were carried out at 0-10 and 10-20 cm depth every year to study the annual change of soil moisture during the growth period (Figure. 2-2c). The four sampling dates corresponded to four phenological stages (FAO), establishment, vegetative, tasseling, and maturity stage, respectively. Maize grain yield was determined by harvesting plants from 10 continuous plants of each plot at harvesting in the 16 years. In addition, all soil water content was measured by the oven-drying method (Klute, 1986).

In order to study the temporal variations of soil physical properties in 2018, 3 sampling dates were carried out: April 27th, July 7th, and September 10th, which corresponded to the establishment, tasseling, and maturity stage, respectively. Samples were collected at three soil depths: 0-5, 5-10, and 10-20 cm each time. Nine undisturbed core samples (internal diameter of 4.9 cm and height of 5.0 cm) for measuring soil bulk density, water retention curve, and penetration resistance were taken from each plot. 81 undisturbed core samples (3 treatments × 3 layers × 3 indicators × 3 replications) in total were taken every sampling time. 27 disturbing samples (3 treatments × 3 layers × 3 replications) in total were taken every sampling time using a hand auger with 5 cm internal diameter to measure soil aggregate stability. To better study the seasonal variation of soil water content during growth period in 2018, 10 sampling dates were carried out during growth period at 0-5, 5-10, and 10-20 cm depth (Figure 2-6).

2.4 Soil analysis

2.4.1 Bulk density, total porosity, and mean water diameter

Soil bulk density was measured from the ratio of the oven-dried weight of undisturbed samples to core volume. Total porosity was calculated from bulk density and particle density which was measured by the pycnometer method (Klute, 1986). The aggregate stability was determined by a wet sieving method (Cambardella and Elliott, 1993) using the sieves of 2000, 250, and 53 μm sizes. Air-dried soil samples were sieved at 6 mm by manually crumbling along natural fracture lines to minimize aggregate size. All details were found in Wang et al. (2019). Mean weight diameter (MWD), as an indicator of aggregate stability, 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 range of each size fraction, w_i is the proportion of each aggregate fraction in whole soil and n is the number of aggregate size classes.

2.4.2 Soil water retention curve (SWRC), S index, and pore size distribution

SWRC was measured by a centrifuge water extraction method, which is an appropriate method to measure SWRC because it has similar results with pressure plate method, costs much less time (Reatto et al., 2008), and has a wider range of matric potential than pressure plate method (Lal and Shukla, 2004). Undisturbed core samples were measured by a Kohusan H-1400pF centrifuge (Kokusan Corp., Tokyo). Eleven speed levels were set: 0, 300, 500, 800, 1300, 1800, 2400, 3300, 5400, 7700, and 10000 rpm, corresponding to different matric potentials from 0-1600 kPa. Two running times (every speed within 300-2400 rpm cost 60 min and 3300-10000 rpm cost 90 min) were set. The weight and height of sample were recorded after every speed level and return to go on higher rotation speed.

The following equation was used to calculate matric potential, h (kPa):

$$h = \frac{k}{6}\frac{\omega^2 L}{g}[L - 3(r_e - h_i)]$$

where k is a constant value equal to 0.098 kPa cm^{-1}, ω is angular velocity (rad s^{-1}), L is the soil sample height (cm), g is the acceleration of gravity (981 cm s^{-2}), r_e is the outer radius of centrifuge (8.3 cm) and h_i is the descent height at each speed level.

The relationship between soil volumetric water content and soil matric potential (SWRC) was determined by the following model (Van Genuchten, 1980):

$$\theta = (\theta_{sat} - \theta_{res})[1 + (\alpha h)^n]^{-m} + \theta_{res}$$

$$m = 1 - \frac{1}{n}$$

Where θ_{sat} is saturated volumetric water content (cm^3 cm^{-3}), θ_{res} is residual volumetric water content (cm^3 cm^{-3}) and a, n, and m are curve-fitting parameters.

The SWRC slope at the inflection point (S index) was calculated as proposed by Dexter (2004):

$$S = -n(\theta_{sat} - \theta_{res})(\frac{2n-1}{n-1})^{(\frac{1}{n}-2)}$$

Equivalent pore diameter (μm) was calculated by the following equation:

$$d_e = \frac{4v\cos\omega}{\rho g h}$$

Where d_e is the equivalent pore diameter (μm), v is the water surface tension within the pores(72.8 g s^{-2}), ρ is the water density (0.998 g cm^{-3}), g is the gravitational acceleration (980 cm s^{-2}), and ω is the water contact angle with the soil sores ($\omega \approx 0$).

Three pore size classes were defined as Destain et al. (2016): Microporosity ($r < 0.2$ μm), which consisted of residual pores for chemical interactions; Mesoporosity ($0.2 \leq r < 9$ μm), which consisted of water storage pores; Macroposity ($r \geq 9$ μm), in which water flows under gravity.

2.4.3 Penetration resistance (PR), plant water available (PAW) and least limiting water range (LLWR)

To measure the soil PR curve, undisturbed soil samples from each plot were placed on a pressure plate apparatus and matric suctions of 2, 10, 60, 100, 500, and 1000 kPa, respectively. When the weights of these samples were constant, PR and soil water content were measured under these matric suctions. A micro penetrometer (Omega LC703, USA) was used to measure PR and had a cone diameter of 2 mm and angle of 15°. The cone was inserted into soil at a speed of 10 mm min^{-1}. More detail of cone penetration measurements can be found in Ruiz et al. (2016). The functional relationship between PR and θ was established for each treatment using the model proposed by Mielke et al. (1994), described in the following equation:

$$PR = a\theta^{b}$$

Where, *PR* is penetration resistance (MPa), θ is the volumetric water content and a and b are model-fitting parameters.

Plant available water (PAW) was defined as the following equation:

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

Where θ_{FC} is soil water content at -33 kPa (cm^3 cm^{-3}) and θ_{PWP} is permanent wilting point at -1500 kPa (cm^3 cm^{-3}).

When measuring LLWR, it is essential to calculate the upper and lower limits. The upper limitation of LLWR was the water content at -33 kPa (field capacity) or at air-filled porosity of 10%, whichever was the smaller. The lower limitation of LLWR was the water content at -1500 kPa (permanent wilting point) or at PR of 2 MPa, whichever was the higher. Root growth could be limited if PR was higher than 2 MPa (Bengough and Mullins, 1990). The water content at air-filled porosity of 10% was calculated the following equation:

$$\theta_{AFP} = \left(1 - \frac{BD}{PD}\right) - 0.1$$

Where BD is bulk density (g cm^{-3}) and PD is the particle density (g cm^{-3})

Wd-LLWR and Wd-PAW were used to express the degree of soil water available, which were determined from the ratio of soil water content to lower limit of LLWR and PAW, respectively. Both values of Wd-LLWR and Wd-PAW were higher than 1, which meant that there was least limited by soil water content for plant growth.

2.5 Statistical analysis

Experimental data were analyzed under three tillage systems (RT, CT, and NT), along with repeated measures of seasons (April 27th, July 7th, and September 7th) and three soil depths (0-5, 5-10, and 10-20 cm). Differences among treatments, soil depth, and growth stages for grain yield, WUE, soil water content, bulk density, PR, porosity, MWD, S index, PAW, and LLWR were analyzed using the GLM analyses of variance (ANOVA) in SAS 9.4 software. PROC CORR procedure was used to determine initial relationships between grain yield and SPP. Moreover, redundancy analysis (RDA) was used to determine which soil physical properties were the main influence factors of soil water content, yield, and WUE using CANOCO version 5.01 software. Only uncorrelated soil physical properties were included in the RDA. Person's correlations among the physical properties were calculated with the SAS 9.4 software package to avoid omitting the main indexes. If there was strongly significant ($p < 0.001$) between soil properties, only one of the index was used as a variable in the RDA (Matamala et al., 2017).

3. Results

3.1 Grain yield, WUE, and soil water content

Grain yield, WUE, and soil water content for 2003-2018 period are shown in figure 2-2. Tillage management had a significant impact on grain yield every year except for 2010 (Figure 2-2a) because of the lowest precipitation in 2010 (Figure 2-2c). Grain yield of RT was higher than CT and NT, and there was no significant difference in grain yield between CT and NT in most years. Mean grain yield over the 16 years under RT-RI was 17.6% and 22.7% higher than CT and NT, respectively (Figure 2-2a).

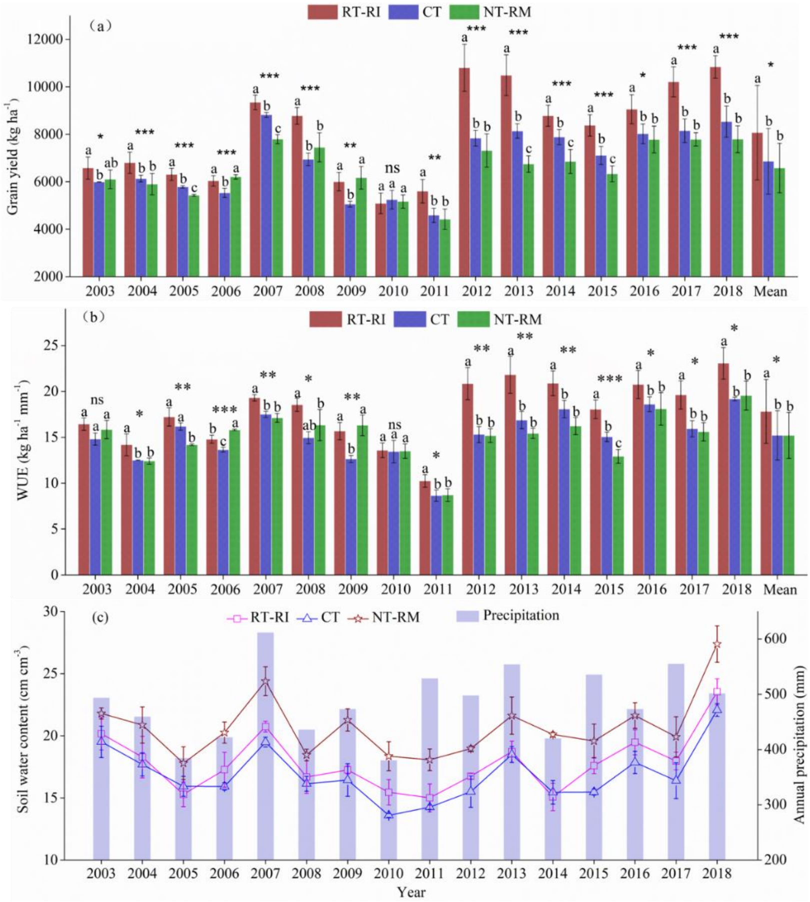

Figure 2-2. Corn grain yield (a), water use efficiency (b), and soil water content in 0-20 cm layer (c) changes for 2003-2018 period under 3 tillage managements (RT, CT, and NT). Values in the same year followed by the same letters are not

significantly different ($p < 0.05$) according to LSD test. ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; ns: not significant.

WUE was significantly influenced by tillage management except for 2003 and 2010 (Figure 2-2b). Mean WUE over the 16 years of RT was 17.1% and 17.2% higher than CT and NT, respectively. However, there was no significant difference in WUE between CT and NT in most years.

Annual changes of mean soil water content over the 16 years are shown in Figure 2-2c. NT showed the highest value every year. Mean soil water content over the 16 years of NT was 15.8% and 22.3% higher than RT and CT, respectively.

3.2 Soil bulk density and total porosity

Tillage management, time (growth stage), soil depth, and the interactions of the three factors had significant effects on soil bulk density and total porosity (Table 2-2). At 0-5 cm layer, NT was the highest in soil bulk density on April 27th, but there was no significant difference among the three tillage managements on July 7th, and NT was lower than RT and CT on September 10th (Table 2-3). At 5-10 cm layer, NT was the highest on April 27th, and there was no significant difference on July 7th and September 10th. At 10-20 cm layer, NT was the highest at the three periods. Soil bulk density under RT and CT increased overtime at 0-5 and 5-10 cm depth especially from April 27th to July 7th. However, soil bulk density under NT was stable over time in the three depths. Total porosity under RT and CT were higher than NT in the three depths on April 27th. There were no significant differences among RT, CT, and NT at 0-5 and 5-10 cm layer on July 7th and September 10th.

3.3 Soil water retention curve (SWRC) and soil pore size distribution

The van Genuchten model was used to fit the experimental data of SWRC for the three tillage managements at three soil layers (Fig. 3). The soil water content of RT and CT was higher than NT at the three soil layers under the same lower matric potential (< 10 kPa) on April 27th. NT was higher than RT and CT in moisture at 0-5 and 5-10 cm layer under the same matric potential on July 7th and September 10th.

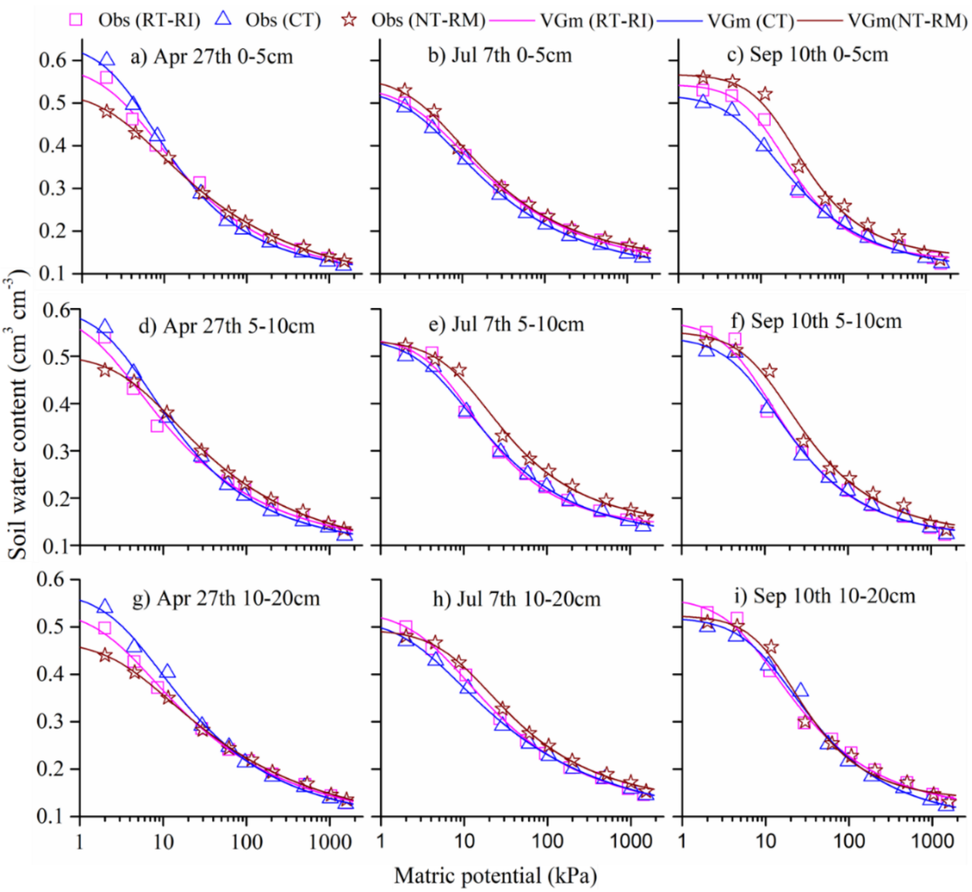

Figure 2-3. Soil water retention curve measured (Obs) with centrifuge method and fitted with van Genuchten model (VGm) for RT, CT, and NT in the 0-5 cm, 5-10 cm, and 10-20 cm layer during growth period.

Tillage management, time (growth stage), and soil depth showed significant impact on Macroporosity ($r > 9$ µm) and Mesoporosity ($r = 0.2$-9 µm) (Table 2-2). A significant impact of tillage management on Microporosity ($r < 0.2$ µm) was found, while time and soil depth had no significant influence. The soil pore size distribution calculated from SWRC is shown in Figure 2-4. At 0-5 cm layer, CT was the highest in Macroporosity at the three growth periods. NT was higher than RT and CT in Mesoporosity on September 10th. Tillage had no significant influence on Mesoporosity on April 27th and July 7th. At 5-10 cm layer, NT-RM was the lowest in Macroporosity, while Mesoporosity and Microporosity of NT were higher than RT and CT at the three growth periods. At 10-20 cm layer, NT was lowest in Macroporosity at the three growth periods.

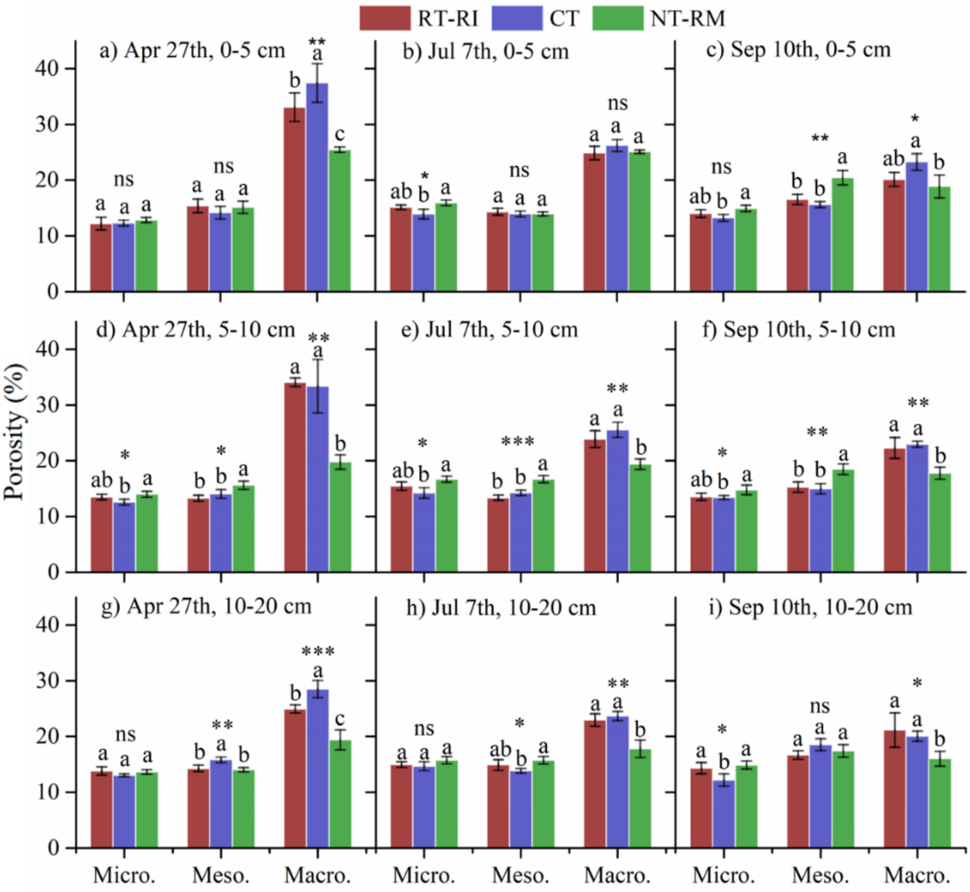

Figure 2-4. Soil pore size distribution (Microporosity: r < 0.2 μm; Mesoporosity: r = 0.2-9 μm; Macroporosity: r > 9 μm) in the 0-5 cm, 5-10 cm, and 10-20 cm layer during growth period. Micro.: Microporosity; Meso.: Mesoporosity; Macro.: Macroporosity. Values, which were influenced by tillage, followed by the same letters are not significantly different ($p < 0.05$) according to LSD test. ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; ns: not significant.

Table 2-2 ANOVA results (F and p values) for soil properties as influenced by tillage (T), growth stage (G), and depth (D).

Index	T	G	D	T*G	T*D	G*D	T*G*D
Soil moisture	77.5***	219.0***	136.5***	19.5***	2.1 ns	20.1***	1.3 ns
Bulk density	27.8***	62.5***	28.3***	29.8***	3.1*	5.8***	2.8**
PR	187.2***	60.6***	295.2***	42.1***	2.5 ns	0.4 ns	1.2 ns
Total porosity	38.6***	57.1***	33.9***	27.3***	3.3**	5.3***	2.6**
Microporosity	5.3**	0.2 ns	0.1 ns	0.7 ns	0.3 ns	0.1 ns	0.7 ns
Mesoporosity	28.4***	86.5***	3.7*	5.3**	10.7***	3.8**	5.4***
Macroporosity	110.2***	147.0***	43.6***	14.1***	4.4**	7.9***	2.6*
MWD	397.7***	67.7***	22.3***	1.2 ns	8.0***	11.0***	7.1***
S index	17.7***	37.4***	47.3***	36.9***	1.6 ns	7.3***	2.9*
LLWRup	14.5***	18.9***	0.6 ns	1.1 ns	2.3 ns	1.4 ns	0.9 ns
LLWRdown	99.7***	69.1***	97.6***	11.1***	0.9 ns	0.6 ns	0.9 ns
LLWR	98.73***	42.05***	260.4***	62.14**	16.9***	6.91***	3.33**
PAWup	14.5***	18.9***	0.6 ns	1.1 ns	2.3 ns	1.4 ns	0.9 ns
PAWdown	15.6**	34.7**	0.5 ns	0.8 ns	0.1 ns	1.0 ns	0.5ns
PAW	15.7***	51.72***	2.02 ns	2 ns	7.58***	2.93*	4.11***
Wd-LLWR	33.1***	30.9***	3.4*	2.6*	0.1 ns	7.9***	1.8 ns
Wd-PAW	4.6*	101.1***	56.3***	17.0***	0.5 ns	5.5***	1.0 ns
WUE	9.95*	-	-	-	-	-	-
yield	45. 4***	-	-	-	-	-	-

Note: PR: soil penetration resistance; MWD: mean weight diameter; LLWR: least limiting water range; LLWRup: upper limit value of LLWR; LLWRdown: lower limit value of LLWR; PAW: plant available water; PAWup: upper limit value of PAW; PAWdown: lower limit value of PAW; Wd-LLWR: water deficit degree calculated by LLWR; Wd-PAW: water deficit degree calculated by PAW; WUE: water use efficiency. ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; ns: not significant.

Table 2-3 Bulk density and total porosity in the 0-5 cm, 5-10 cm, and 10-20 cm layer on April 27th, July 7th, and September 10th.

Layer	Treatment	Bulk density (g cm^{-3})			Total Porosity (cm cm^{-3})		
(cm)		Apr 27th	Jul 7th	Sep 10th	Apr 27th	Jul 7th	Sep 10th
0-5	RT-RI	1.04de	1.21ed	1.31ab	0.61ab	0.54ab	0.51b
	CT	1.00e	1.25bc	1.30bc	0.63a	0.54ab	0.52b
	NT-RM	1.24bc	1.20e	1.21d	0.53cd	0.55a	0.54a
5-10	RT-RI	1.03de	1.24cbd	1.28bc	0.61ab	0.53bc	0.51bc
	CT	1.07de	1.23cde	1.30bc	0.60ab	0.54ab	0.51bc
	NT-RM	1.33ab	1.24bcd	1.29bc	0.49de	0.53bc	0.51bc
10-20	RT-RI	1.25bc	1.25bc	1.27c	0.53cd	0.53bc	0.52b
	CT	1.13cd	1.27b	1.31abc	0.57bc	0.52c	0.51bc
	NT-RM	1.38a	1.32a	1.35a	0.47e	0.49d	0.48d

Note: Values within a column in the same soil depth followed by the same letters are not significantly different ($p < 0.05$)

3.4 Soil penetration resistance

Tillage management, time (growth stage), and soil depth had a significant effect on soil penetration resistance (PR) (Table 2-2). The change of soil PR with soil water content is shown in Figure 2-5. Mean PR for the three depths under treatment NT was 35.5% and 34.2% higher than RT and CT on April 27th, and was 23.9% and 5.2% higher than RT and CT on July 7th, respectively.

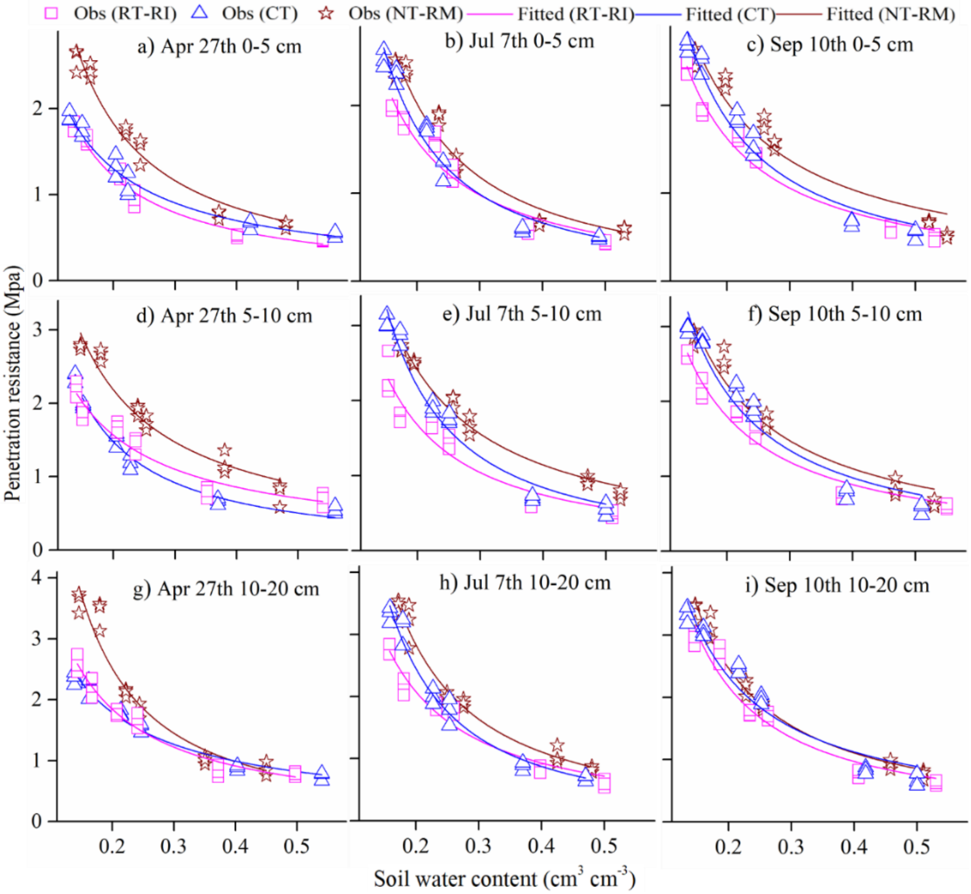

Figure 2-5. Soil penetration resistance measured (Obs) and fitted (Fitted) for RT, CT, and NT in the 0-5 cm, 5-10 cm, and 10-20 cm layer during growth period.

3.5 The seasonal changes of LLWR, PAW, and soil water content

Tillage management and time (growth stage) showed significant impacts on LLWR, upper limit of LLWR (LLWRup), lower limit of LLWR (LLWRdown), PAW, upper limit of PAW (PAWup), and lower limit of PAW (PAWdown) (Table 2-2). Depth had no significant influence on PAW and PAWdown, but it had a significant impact on LLWR and LLWRdown.

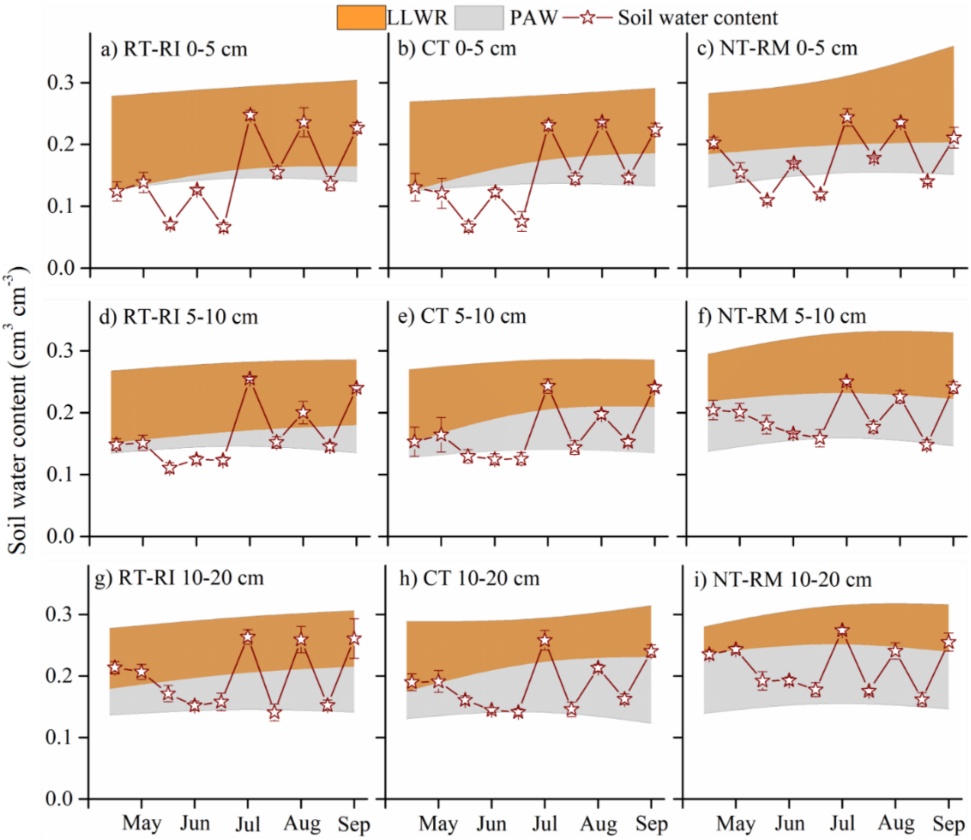

Figure 2-6. Seasonal changes of LLWR (orange area), PAW (gray + orange area), and soil water content for RT, CT, and NT in the 0-5 cm, 5-10 cm, and 10-20 cm layer during growth period. Limiting water range (LLWR) and plant available water (PAW) had the same upper boundary.

The changes of LLWR, PAW, and soil water content with growth period are shown in Figure 2-6. PAW (orange + gray) had a wider range than LLWR (orange) in the three soil depths under the three treatments. RT was wider than CT and NT in LLWR under the same depth and growth stage. Soil water content was mostly in the range of PAW, but out the range of LLWR. NT was higher in LLWRdown than RT and CT. Mean soil moisture during growth period for the three layer depths under treatment NT was 13.4% and 16.5% higher than RT and CT, respectively.

3.6 S index and mean weight diameter (MWD)

Tillage management, time (growth stage), and soil depth had significant impacts on S index, which is the slope of soil water retention curve at its inflection point, and mean weight diameter (MWD) (Table 2-2). S index and MWD are shown in

Figure 2-7. RT and CT were higher than NT in S index at the three depths on April 27th. MWD of NT was higher than RT and CT at the three depths during growth period.

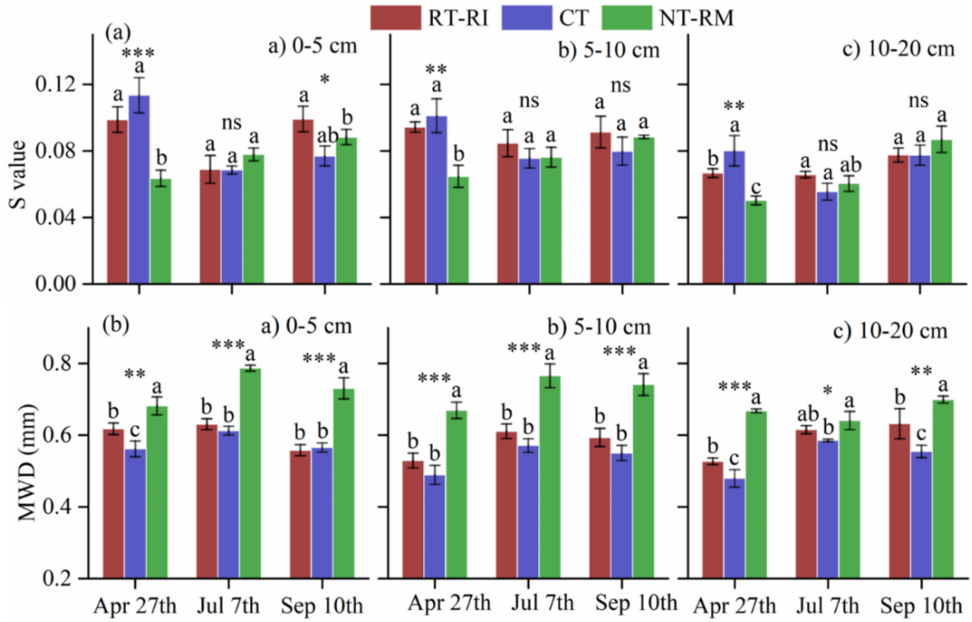

Figure 2-7. S index and mean weight diameter (MWD) in the 0-5 cm, 5-10 cm, and 10-20 cm layer during growth period. Values, , which were influenced by tillage, followed by the same letters are not significantly different ($p < 0.05$) according to LSD test. ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; ns: not significant.

3.7 The relationship among soil physical properties, grain yield, and WUE

Correlative coefficients between grain yield and soil properties are shown in Table 2-4. Further, RDA was carried out to reveal relationships among soil water content, grain yield, WUE, and soil physical properties (Figure 2-8). A negative relationship between LLWRdown and grain yield at all three soil depths on July 7th and 0-5 cm and 5-10 cm on September 10th was found (Table 2-4). PR showed a negative correlation with grain yield at all soil depths during the whole growth period. LLWR and Wd-LLWR had a positive correlation with grain yield and WUE (Figure 2-8 and Table 2-4). However, PAW and PAWdown had no correlation with grain yield during the growth period. LLWR was the most effective indicator to increase grain yield, while PR and LLWRdown were the main restrict factors for grain yield (Figure 2-8). RT was higher than NT and CT in WUE and Wd-LLWR, both of which represent the degree of soil water available. WUE was mainly controlled by Wd-LLWR. In addition, we also found microporosity, PAWup, and PAWdown always had no significant correlation with grain yield in the three soil depths during the growth period ($p > 0.05$).

Table 2-4 Correlative coefficients between grain yield and soil physical properties for RT, CT, and NT at the 0-5 cm, 5-10 cm and 10-20 cm layer during the growth period.

Index	April 27th			July 7th			September 10th		
	0-5 cm	5-10 cm	10-20 cm	0-5 cm	5-10 cm	10-20 cm	0-5 cm	5-10 cm	10-20 cm
Soil moisture	-0.60	-0.70*	-0.46	-0.49	-0.51	-0.47	0.23	-0.58	0.27
Bulk density	-0.45	-0.70*	-0.31	-0.62	0.05	-0.17	0.69	-0.18	-0.79*
PR	-0.81**	-0.70*	-0.70*	-0.91***	-0.95***	-0.87**	-0.69*	-0.70*	-0.91***
Total porosity	0.40	0.66	0.35	0.64	-0.35	-0.08	-0.92**	-0.05	0.78*
Microporosity	-0.15	-0.21	0.17	-0.31	-0.13	-0.25	-0.34	-0.59	-0.07
Mesoporosity	0.07	-0.82**	-0.17	-0.26	0.49	-0.86**	-0.59	-0.65	-0.53
Macroporosity	0.31	0.69*	0.40	0.56	-0.34	0.53	0.09	0.62	0.76*
MWD	-0.27	-0.55	-0.50	-0.26	-0.65	-0.57	-0.73*	-0.55	-0.26
Wd-LLWR	0.13	-0.12	0.32	0.74*	0.36	0.72*	0.69*	0.57	0.42
Wd-PAW	-0.68*	-0.86**	0.07	-0.24	-0.68*	-0.18	0.13	-0.07	0.02
LLWRup	0.25	-0.24	0.16	-0.23	0.12	-0.55	-0.38	-0.41	-0.01
LLWRdown	-0.59	-0.59	-0.51	-0.75*	-0.68*	-0.83**	-0.70*	-0.71*	-0.42
LLWR	0.90**	-0.59	-0.50	0.93***	0.59*	0.98***	0.01	0.26	0.84*
PAWup	0.25	-0.24	0.16	-0.23	0.12	-0.55	-0.38	-0.41	-0.01
PAWdown	0.11	0.21	0.21	-0.31	-0.02	-0.27	-0.11	-0.19	0.16
PAW	0.33	-0.55	0.05	0.31	-0.72*	-0.16	-0.49	-0.51	-0.14

Note: See Table 2-3 for abbreviations of some soil physical properties. ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$.

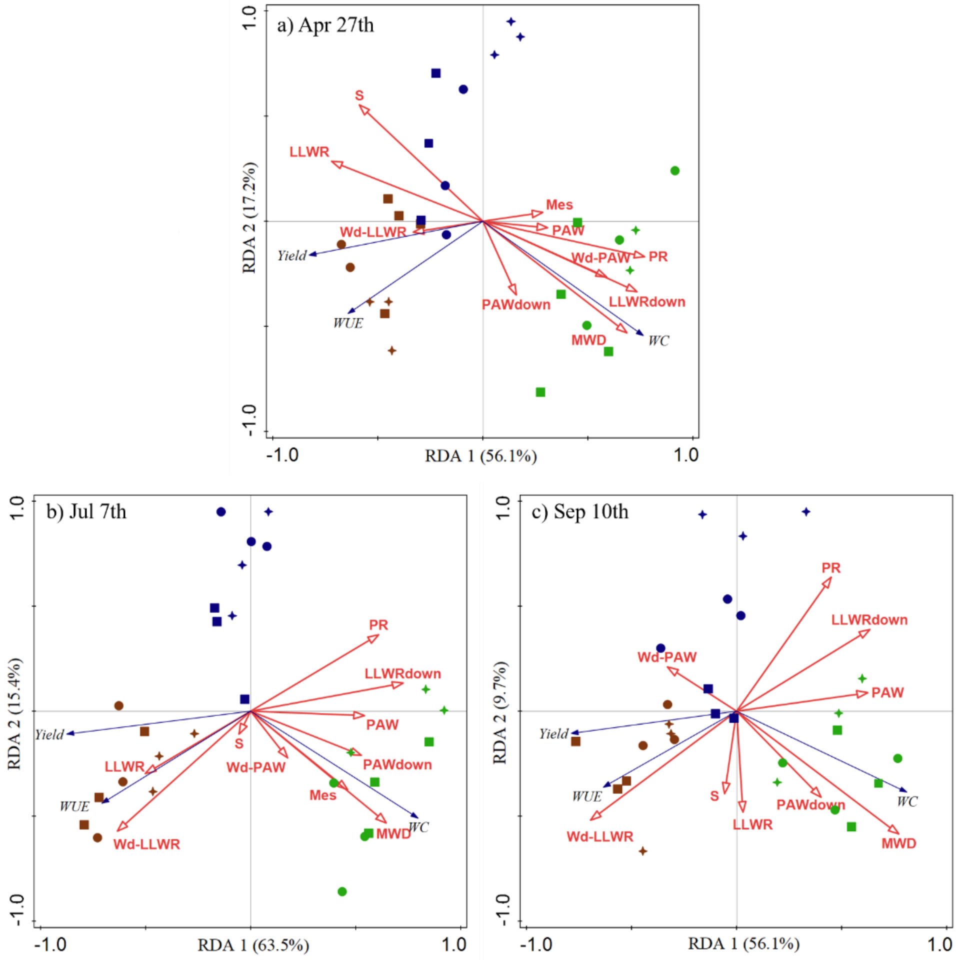

Figure 2-8. Redundancy analysis of the effects of soil physical properties on yield, WUE and soil water content (WC). The response variables are yield, WUE, and WC. The explanatory variables are PR, MWD, LLWR, LLWRup, LLWRdown, PAW, PAWup, PAWdown, Wd-LLWR, Wd-PAW, S index (S), and bulk density (BD). See Table 2 for abbreviations of some soil physical properties. Brown, blue, and green represent RT, CT, and NT treatment, respectively. Square, circle, and star represent 0-5 cm, 5-10 cm, and 10-20 cm layer, respectively.

4. Discussion

Conservation agriculture is highly debated, because of its different effects on crop yields (Giller et al., 2009; Brouder et al., 2014). Gao et al. (2019) found that there were no significant differences in grain yield among no-tillage, CT, and sub-soiling after 16 years in the Loess Plateau of China, while grain yield under reduced tillage was found to be higher compared with CT and no-tillage in sandy loam cinnamon soil (Wang et al., 2019). Pittelkow et al. (2015) carried out a global meta-analysis from 610 studies to compare no-tillage with conventional tillage and found that no-tillage reduced yield. However, this response was variable when no-tillage was combined with crop residues or cover crops. A grain yield benefit with no-tillage in combination with residue retention was probably because of greater soil moisture conservation (Serraj and Siddique, 2012) and increasing soil organic carbon (Büchi et al., 2018). In our study, NT significantly increased (2 years), decreased (5 years), and had no significant effect (9 years) on grain yield compared with CT (Figure 2-2a). Mean grain yield over the 16 years under NT-RM treatment was not significantly different from CT. The effect of no-tillage and CT on grain yield could be controlled by precipitation (Wang et al., 2007), soil water content (Hobbs et al., 2007), and water deficit level (Lampurlanés et al., 2016). Further, in our result, RT was always higher in grain yield than NT (Figure 2-2a). The soil water content under RT was lower than NT (Figure 2-2c). Su et al. (2007) also found that soil moisture under no-tillage was higher than reduced tillage in rained region. Crop residue mulching under NT could reduce potential soil evaporation effectively (Alliaume et al., 2017). In addition, NT was higher in Mesoporosity (Figure 2-4) and MWD (Figure 2-7b) compared with RT, both of which also could enhance soil water storage capacity (Fig. 8).

Soil physical properties (SPP) such as air-filled porosity, penetration resistance(PR), and water holding capacity directly affect plant growth, while others including bulk density, MWD, and the pore size distribution can have indirect effects (Letey, 1985; Filho et al., 2013). Therefore, the multiple and complex effects of SPP on plant growth make it difficult to establish soil-crop relationship. In addition, seasonal changes in SPP during growth period increase the difficulty. It’s another worth noting that the number of sample replicates should be considered in the future study because SPP shows high variability. The growth stage had significant impacts on bulk density, PR, porosity, MWD, LLWR, and PAW (Table 2-3). In particular, NT increased, reduced, and had no significant impact on bulk density on April 27th, September 10th, and July 7th, respectively, compared with RT and CT at 0-5 cm depth. Salem et al. (2015) also found that bulk density increased with time under CT and kept stable under no-tillage management during growth period at 0-15 cm soil depth. Contradictory results of the effect of tillage management on other SPP were found in previous studies (Jabro et al., 2016; Blanco-Canqui and Ruis, 2018). For example, Alam et al. (2017) reported that no-tillage increased plant available water, while Reynolds et al. (2007) observed no significant difference between no-tillage and CT. These inconsistent results about the impact of tillage management on SPP are partly due to the temporal variation of SPP (Afzalinia and Zabihi, 2014; Valle et al., 2018). Therefore, seasonal changes in SPP need to be considered, which is essential to better understand how SPP affects plant growth under tillage management practices.

SPP at different growth stages had diverse effects on grain yield (Table 2-4). Soil bulk density was commonly used as an indicator of air porosity, penetration, and capacity to store water (Reynolds et al., 2008), and grain yield decreased when bulk density was greater than 1.3 g cm^{-3} (Drewry et al., 2001). In our experiment, bulk density was less than 1.3 g cm^{-3} during the growth period, except for NT at 10-20 cm (Table 2-3). Macroporosity indicated the soil capacity to drain excess water and facilitate root growth, which was greater than 0.1 m^{3} m^{-3} as optimal (Drewry and Paton, 2005). S index, an indicator of soil physical quality, was greater than 0.035 as "good physical quality" (Dexter, 2004; Tormena et al., 2008). Macroporosity (Figure 2-4) and S index (Figure 2-7a) were in the optimum range. MWD, an index of aggregate stability, was unstable (0.4 mm <MWD< 0.8 mm) and very unstable (MWD < 0.4 mm) soils (Paradelo et al., 2016). MWD was in an unstable range (Figure 2-7b). Bulk density, porosity, S index, and MWD had irregular and different relationships with yield during the growth period, particularly in most cases there was no significant correlation between these physical properties and yield (Table 2-4). Therefore, Bulk density, porosity, S index, and MWD were not effective indexes to explain the changes in grain yield under different tillage management in our study. One of the reasons was that these SPP were almost in their optimal range, which had no restriction on plant growth. Another reason was that these properties had indirect effects on grain yield (Letey, 1985; Filho et al., 2013).

Soil compaction and water availability were the two principal factors limiting plant growth (Lapen et al., 2004; Yan et al., 2017). The soil available water for plants was usually defined by plant available water (PAW) and least limiting water range (LLWR) (Asgarzadeh et al., 2014). The range of LLWR was narrower than PAW during the growth period (Figure 2-6). As a result, soil moisture was mostly in the range of PAW, but out of the range of LLWR (Figure 2-6). PAW, PAWup, and PAWdown did not show significant correlations with grain yield, while LLWR and LLWRdown had significant correlations with yield (Table 2-4 and Figure 2-8). Hence, LLWR was more sensitive than PAW to assess soil water availability under RT, CT, and NT. LLWR was more efficient indicator to influence grain yield than PAW. The PAW is only based on the potential (energy) of soil moisture and ignore other limiting soil physical properties for plant growth. However, LLWR integrates soil compaction, soil aeration, and soil water potential into a single parameter (de Lima et al., 2012). The soil moisture at air-filled porosity (AFP) was always above field capacity on the LLWR, which led to the same upper boundary of LLWR and PAW (Figure 2-6). Therefore, soil aeration was not a limiting factor for plant growth under RT, CT, and NT. A similar result was discovered by Lapen et al. (2004) in loam soil under NT and CT. Tormena et al. (2017) found that aeration controlled the upper limit of LLWR only at BD > 1.45 and BD > 1.55 g cm^{-3} for CT and NT, respectively. PR was always a negative correlation with grain yield at 0-5, 5-10 and 10-20 cm depths during growth period (Table 2-4). In addition, PR under NT was higher than CT and RT (Figure 2-8). PR was the main impact to restrict plant growth under NT. Our results are also supported by those of Kadžienė et al. (2011), who reported that soil PR was the most limiting factor for plant growth at 10-20 cm depth under NT. Wd-LLWR, which was the main indicator affecting WUE, was higher under RT compared with NT (Figure 2-8). Hence, although RT-RI was lower in soil water content compared with NT, it had a lower LLWRdown and higher Wd-LLWR (Figure 2-8), which can increase soil water available.

LLWR can explain the reason why RT was higher in grain yield despite lower soil moisture from the perspective of soil available water. However, the opposite conclusion was reported by Cecagno et al. (2016) who found that LLWR showed no direct correlation with soybean yield, and was an inadequate indicator in integrated soybean-beef cattle system under a mean annual rainfall of 1850 mm. The mean annual precipitation at our study site is 483 mm over the last 16 years. Higher soil water content like the one observed by Cecagno et al. (2016) may be almost in the range of LLWR, which decrease the ability of LLWR to assess soil water availability. Filho et al. (2013) also found LLWR was a useful index for plant growth under long-term tillage and cropping systems in semi-arid region with annual precipitation of 580 mm. Therefore, mean annual precipitation should be considered when exploring the relationship between LLWR and grain yield. In addition, using LLWR without considering soil water content, which cannot represent soil water availability well, may not strongly enough to explain the changes of grain yield. Wd-LLWR, the ratio of soil water content to lower limit of LLWR, was used to express degree of soil water availability. RT was higher than NT-RM in Wd-LLWR, which was the main factor to increase WUE and thereby raise grain yield (Figure 2-8). Hence, considering LLWR and soil moisture at the same time is helpful to better comprehend the relationship between LLWR and yield. Finally, grain yield would be most closely correlated with soil water content and SPP in critical yield formation period (Nielsen et al., 2009). Nielsen et al. (2010) found the response of corn yield in dryland to precipitation and soil moisture were sensitivity from July 16th to August 26th (92 to 132 days after sowing) than other growth stages. Wd-LLWR and LLWRdown had no significant correlations with grain yield on April 27th, while significant relationships were found on July 7th (70 days after sowing) (Table 2-4). Grain yield would be sensitive to soil available water around 70 days after sowing. Therefore, overlooking the impact of different growth stages may result in an inadequate conclusion of soil-crop relationship under different tillage practices.

5. Conclusions

Soil physical properties (i.e. bulk density, PR, pore size distribution, MWD, LLWR, and PAW) were significantly affected by tillage management and soil depth. Furthermore, they change significantly during the growing season. We considered seasonal variations in soil physical properties under RT, CT, and NT, which was helpful to better understand how soil physical properties affect plant growth. Bulk density, porosity, S index, and MWD showed irregular and different relationships with grain yield during the growth period, and were ineffective indicators for grain yield. The range of LLWR was narrower than PAW during the growth period and more sensitive than PAW to assess soil water availability under RT, CT, and NT.

LLWR was a more efficient indicator to influence grain yield than PAW. NT showed higher LLWRdown compared to RT and CT. It strongly impacted plant growth under NT. The RT treatment had a lower LLWRdown and higher Wd-LLWR, which increased soil water availability. Hence, RT presented higher corn yield compared to NT, even if the water content remained lower. It is necessary to determine both LLWR and soil water content for a better understanding of soil-crop relationship from the view of soil water availability. Overall, our results suggest that LLWR could be considered as an effective indicator of soil physical properties to elucidate the soil-crop relationship under tillage management in semi-arid region.

6. Acknowledgments

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Chapter III

Factors governing soil water repellency under tillage management: the role of pore structure and hydrophobic substances

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Chapter III Factors governing soil water repellency under tillage management: the role of pore structure and hydrophobic substances

Abstract

Soil water repellency (SWR) has significant effects on the soil ecosystem (e.g. carbon sequestration, aggregate stability, and soil erosion). Understanding the influence factors of SWR under conservation agriculture are playing a vital role in the sustainable development for improving soil quality. However, how soil pore structure influence on SWR remains unclear. In this study, X-ray computed tomography was used to calculate the shape, porosity, and connectivity of the pore network and reveal the impact of hydrophobic substances and pore structure on SWR. All the samples were collected from two long-term experimental fields. The treatments were conventional tillage with residue removal (CT), reduced tillage with residue incorporation (RT), and no-tillage with residue mulching (NT) in both of the fields. The intrinsic sorptivity method was used to determine the water repellency index. The results showed that soil organic carbon (SOC) and microbial biomass carbon (MBC), both of which are hydrophobic substances, were higher in RT and NT treatments than in CT. MBC had significant influences on soil water sorptivity (Sw) and water repellency index (RI) ($P < 0.001$), whereas SOC had no influence on Sw ($P > 0.05$). MBC also showed a closer relationship with SWR than SOC in redundancy analysis. The RT and NT treatments increased sorptivity of 55–165 μm that had a positive relationship with ethanol sorptivity and RI ($P < 0.05$). Ethanol sorptivity increased with an increase in soil pore porosity and connectivity under RT and NT treatments. However, increasing the pore surface area could decrease Sw due to enhance contact area between hydrophobic substances and soil water. Overall, the RT and NT treatments increased the water repellency index, which was a result of the interactions between pore structure and hydrophobic substances. The results showed that it is essential to investigate both pore structure and hydrophobic substances at the same time when studying the mechanisms underlying conservation tillage impacts on SWR.

Keywords:

Conservation tillage; soil water repellency; X-ray computed tomography; soil pore structure; soil carbon

1. Introduction

Soil water repellency (SWR) is a common phenomenon in coarse- to fine-textured soils across all climatic zones (Daniel et al., 2019). SWR can limit the soil water absorption rate and capacity (Dekker and Jungerius, 1990; Li et al., 2019), which has important impacts on the soil ecosystem and crop growth (González-Peñaloza et al., 2012; Martínez-García et al., 2018). A lot of research has already been conducted to reveal the impact of SWR on the soil ecosystem under forest and fire-affected soils (Debano, 2000; Plaza-Álvarez et al., 2018; Weninger et al., 2019). However, because the degree of SWR in farmland tillage soil is smaller than the forest and fire-affected soils (Lucas-Borja et al., 2019; Stavi et al., 2016), there is a lack of research on the SWR in farmland, especially for the study on how conservation agriculture affect SWR. The small degree of SWR, known as subcritical water repellency (Hallett et al., 2001), can also have a considerable effect on soil structure and hydraulic properties (Hunter et al., 2011; Tadayonnejad et al., 2017). Therefore, understanding the factors that affect SWR is critically important when studying to improve soil quality.

SWR is considered to be created by hydrophobic organic compounds covering the surfaces of soil particles (Doerr et al., 2000). These organic materials are produced by plant roots, leaves, and microorganisms (Fontaine et al., 2003; Seaton et al., 2019), which are the main sources of SOC (Schmidt et al., 2011; Stockmann et al., 2013). Some researchers have used SOC, as hydrophobic substances, to build relationships with SWR. However, the results are contradictory. There have been reports of positive (Jimenez-Morillo et al., 2016; Zavala et al., 2009), negative (Mataix-Solera et al., 2014), and no (Woche et al., 2005) relationships between SWR and SOC. These inconsistent results indicate that not all organic materials induce SWR. Research should focus on specific groups of compounds (Atanassova and Doerr, 2011; Daniel et al., 2019). Microbial biomass carbon (MBC) can have a more useful and sensitive response to soil processes than the SOC (Sparling, 1992). It has been previously shown that there is a positive correlation between SWR and soluble carbohydrates linked to biological activity in soil (Behrends et al., 2019; Wander, 2004). Seaton et al. (2019) also found that soil microbial community composition strongly influenced SWR that could be induced by microbes in a shorter time. Therefore, studies should focus on identifying an accessible and reliable indicator for hydrophobic substances that more closely reflects SWR in order to overcome the inconsistent effects of SOC on SWR.

Another possible reason for the inconsistency between SWR and SOC is that SWR is affected by factors other than hydrophobic substances. Soil water repellency is described as soil water behavior on the soil surface that limits the rate and capacity for soil water absorption (Daniel et al., 2019). The factors that influence the SWR effects on soil function and crop growth, such as water infiltration (Madsen et al., 2011; Rye and Smettem, 2017), plant available water (González-Peñaloza et al., 2012; Ritsema et al., 2008), and aggregate stability (Girona-garcía et al., 2018), are affected by soil water movement that usually occurs as unsaturated flow in a farmland environment (Han and Zhou, 2018). Furthermore, the soil pore structure has been shown to be the main controlling soil water movement (Katuwal et al., 2015; Pagliai et al., 2004; Pituello et al., 2016), and therefore, SWR behavior could also be influenced by pore structure. For example, an increase in soil porosity or pore surface area could increase the possibility of contact between soil water and hydrophobic substances, which would increase SWR because it is controlled by hydrophobic substances on the surfaces of aggregates (Urbanek et al., 2007). In addition, the porosity of same sized pores has different impacts on hydraulic conductivity under different degrees of SWR (Nyman et al., 2010), which suggests that SWR behavior can be influenced by pore size distribution. Behrends et al. (2019) used the water drop penetration time (WDPT) method to establish that the time needed for a single water drop to infiltrate a soil sample, which shows the degree of SWR, was controlled by pore structure as well as hydrophobic substances.

Although soil pore structure is critical to understanding SWR, few studies, as far as we can ascertain, investigated how the pore network influences SWR using direct measurements. In addition to the limited theoretical knowledge about the relationship between pore structure and SWR, the main reason why there have been few studies on the pore network influences on SWR is that the soil pore structure is complicated and difficult to measure. In recent years, X-ray computed tomography (μCT) has been successfully used to obtain a non-destructive and detailed 3D characterization of the soil porous system (Beckers et al., 2014; Young et al., 2001). Morphological variables, such as pore size, volume, shape, connectivity, and critical pore diameter can be obtained using μCT (Koestel and Schlüter, 2019; Lu et al., 2019). Percolation theory, which states that flow takes place through a percolating pore network composed of multiple connected pathways (Renard and Allard, 2013; Skaggs, 2006), is usually used to calculate some of these variables. In addition, critical path analysis, which is based on the theory, can be used to show that flow is limited in porous media by the smallest or bottleneck pore sizes. Initially, the theory was successfully used to calculate the permeability of rocks and artificial porous materials (Arns et al., 2005; Ghanbarian et al., 2016; Nokken and Hooton, 2008). Jarvis et al. (2017) further used X-ray computed tomography to show that percolation theory could describe the connectivity of pore structure in tilled soil. The critical pore diameter was the dominant factor controlling saturated hydraulic conductivity according to percolation theory and critical path analysis results (Koestel et al., 2018).

Furthermore, most land-use types have a significant effect on soil pore structure (Fang et al., 2019; Palm et al., 2014; Rabot et al., 2018). The addition of crop residues combined with tillage management, which is one of the main conservation tillage methods, has been widely promoted and developed around the world as a way of sustainably increasing productivity by improving soil pore structure (Blanco-Canqui and Ruis, 2018; Gao et al., 2019a; Pittelkow et al., 2015). The addition of crop residues has two opposite impacts on SWR. It increases SWR because crop residues produce hydrophobic substances, but it reduces SWR by enhancing soil porosity and connectivity (Cosentino et al., 2010). Most researchers studied the effect of hydrophobic substances on SWR and they found the degree of SWR could increase with an increase in hydrophobic substances under conservation tillage practices (Blanco-Canqui, 2011; Miller et al., 2019; Roper et al., 2013), whereas only a few researchers used indirect methods to measure soil pore structure and thereby assess the impact of pore structure on SWR. Some researchers studied the effects of hydrophobic substances and pore structure on SWR at the same time. Hallett et al. (2001) and Cosentino et al. (2010) found that SWR was mainly controlled by hydrophobic compounds rather than pore structure when they used ethanol sorptivity as an indirect indicator of pore structure. However, other researchers have reported that SWR, when measured by the water drop penetration time method, was more affected by pore structure than hydrophobicity (Behrends et al., 2019). However, these conclusions were not based on the direct measurement of pore structure and their results were only obtained from indirect indicators associated with pore structure. Although many researchers have noted the importance of pore structure, the real relationship between pore structure and SWR cannot be evaluated clearly.

In our study, two long-term experimental fields were used to fill the knowledge gap that few studies assessed the effect of soil pore structure on SWR using a direct method. We hypothesize that conservation tillage practices can reduce the degree of SWR by improving soil pore structure. The objectives were to (i) determine the effect of conservation tillage on SWR, soil pore structure, SOC, and MBC; and (ii) understand how soil pore structure and hydrophobic substances change SWR. It is essential for better understand the role of conservation tillage practices on soil quality studying the effect of conservation tillage on SWR when both hydrophobic substances and pore structure were taken into account at the same time.

2. Materials and methods

2.1. Study site

The study involved two long-term experimental locations at two Dryland Farming Experimental Stations to increase the credibility of our findings and provide a better understanding of how soil pore structure and hydrophobic substances affect SWR under conservation tillage practices. One experiment was located at Shouyang, Shanxi Province, northern China (S) and the other was at Gongzhuling, Jilin Province, northeast China (G). Table 3-1 shows some of the physical and chemical properties of the two soils at the beginning of the experiments.

Table 3-1 Soil physical and chemical properties of the 0–10 cm layer for Shouyang station (S) in 2003 and for Gongzhuling station (G) in 2015.

Location	Soil particle size distribution (%)			Available soil nutrient (mg kg^{-1})			SOC (g kg^{-1})	Bulk density (g cm^{-3})
	20–200 μm	2–20 μm	< 2 μm	N	P	K		
S	55.3	37.9	6.8	55	7.6	95	25.7	1.13
G	40.0	23.9	36.1	67	12.4	97	22.6	1.24

The Shouyang experiment was set up in 2003 and the site has a continental monsoon climate with an average annual precipitation of 483 mm (Wang et al., 2019). The annual frost-free period is approximately 130 days, the experimental site has a sandy loam soil, and the annual average temperature is 7.4°C.

The Gongzhuling experiment was established in 2015 and it has a continental monsoon climate. The annual frost-free period is 144 days. The experimental site has a clay loam soil and the average temperature is 5.6°C. The average annual precipitation is 595 mm and 70% of the rainfall occurs between June and August (Zhang et al., 2016).

2.2. Experimental design

The two long-term tillage experiments had a randomized complete block design. Each plot at Shouyang and Gongzhuling was 5 m × 5 m and 12 m × 30 m in size, respectively. The crop in the two experiments was rain-fed continuous spring maize. The fallow periods were from November to the following March in Shouyang and November to the following April in Gongzhuling. There were three treatments at both sites: a) CT: conventional tillage with maize stalk removed after harvesting, plowing twice to about 30 cm depth with a moldboard plow after harvesting and before seeding (in April and May for Shouyang and Gongzhuling, respectively); b) RT: reduced tillage with maize straw and fertilizers incorporated after harvesting (in October), plowing once to about 25 cm depth with a moldboard plow; and c) NT: no-tillage with the maize stalk mulched after harvesting, then seeding and fertilizing with a no-till planter in the following April in Shouyang and May in Gongzhuling. Urea and calcium superphosphate fertilizer were applied to each plot in Shouyang at 105 kg N ha^{-1} and 105 kg P_2O_5 ha^{-1}, respectively. Each plot in Gongzhuling, received 80 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 45 kg K ha^{-1} as urea, calcium superphosphate, and potassium sulfate, respectively.

2.3. Soil sampling

Samples from Shouyang and Gongzhuling were taken on September 10th and August 20th, 2018, respectively. The soil sampling methods for the two sites were identical. Undisturbed core samples from the 0–10 cm layer were taken using steel rings (internal diameter: 4.9 cm and height: 5.0 cm). The samples were used to determine soil water repellency. Another set of undisturbed core samples were also taken using PVC tubes (internal diameter: 4.0 cm and height: 5.0 cm) from the 0–10 cm layer to determine soil pore structure using X-ray computed tomography. All the undisturbed core samples were stored at 4°C in order to avoid damaging the soil pore structure and to minimize microbial development. Disturbed samples were collected using a hand auger with a 5 cm internal diameter and were used to measure soil organic carbon and microbial biomass carbon. A total of 48 undisturbed core samples (2 fields × 2 variables × 3 treatments × 4 replications) and 48 disturbed samples (2 fields × 2 variables × 3 treatments × 4 replications) were taken.

2.4. Soil analysis

2.4.1. Soil water repellency characteristics

The undisturbed soil core samples were air-dried for two weeks and then a tension micro infiltrometer was used to measure SWR according to the intrinsic sorptivity method (Hallett and Young, 1999). The infiltrometer equipment consisted of a tube with one end connected to the liquid reservoir and the other end (with a 2 mm radius) was covered with a sponge. Detailed information about the equipment can be obtained from Hallett and Young (1999). The liquid reservoir was placed on an automatic counting electronic balance (0.001 g) which recorded the weight every 10 s. Two liquids were used in our study: distilled water and ethanol (95% v/v). Detailed descriptions of the test methods can be found in Tadayonnejad et al. (2017). The pressure heads of the two liquids were the same in the tip covered with the sponge, which was touching the soil core sample surface. The pressure head was negative pressure to avoid saturated flow. The pressure head (P) was calculated using the following equation (Tillman et al., 1989):

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

where P is the pressure head (m^{-1}), h is the height difference between the tip covered with the sponge and the liquid level, ρ and σ are the density (kg m^{-3}) and surface tension (kg s^{-2}) of the liquid, respectively, and g is the acceleration due to gravity (m s^{-2}). This equation indicates that different h values should be applied to different liquids in order to get the same pressure head. In our study, the h values for water and ethanol were 2 cm and 2.5 cm, respectively.

Cumulative infiltration was recorded by the electronic balance between 0 and 600 s. The flow rate, Q (mm^3 s^{-1}), was obtained from the slope of the linear parts of the curves (cumulative infiltration *vs.* time). In our study, the steady-state flow was observed within the 300–500 s range. The water and ethanol sorptivity (S) were obtained from the following equation:

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

where f is the air-filled porosity ($mm^3\ mm^{-3}$), b is a constant that depends on the soil-water diffusivity function and had a value of 0.55 (Leeds-Harrison et al., 1994), and r is the infiltrometer tip radius. The sorptivity change with time trend was recorded over 0–600 s. The values for water sorptivity (S_w) and ethanol sorptivity (S_e) were calculated from the steady-state flow rate (300–500 s) (Blanco-Canqui and Lal, 2009; Fischer et al., 2010).

Water sorptivity is affected by soil pore structure and water repellency, whereas ethanol sorptivity is only affected by pore structure because ethanol is a non-polar liquid (Tadayonnejad et al., 2017; Tillman et al., 1989). The water repellency index (RI) was calculated using the following equation (Tillman et al., 1989):

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

where S_e is the sorptivity of ethanol ($mm\ s^{-1/2}$) and S_w is the sorptivity of water ($mm\ s^{-1/2}$). Detailed information about how to calculate the coefficient can be found in Tadayonnejad et al. (2017). Tillman et al. (1989) defined soil with RI > 1.95 as subcritical water repellency.

The soil water contact angle (β) was obtained using the RI as follows:

$$\beta = \arccos\left(\frac{1}{RI}\right)$$

2.4.2. Computerized tomography (CT) scanning, image processing, and morphological analyses

The core samples were dried in an oven for ten days at 30°C before scanning to obtain a better contrast between the solid and porous phases (Parvin et al., 2017). The tomographic acquisition was then performed on a high-resolution desktop micro-computed tomography (Skyscan-1172, Skyscan, Kontich, Belgium) at the Chemistry Engineering Laboratory of the University of Liege. The X-ray source was set at 100 kV and 100 µA, and an aluminum-copper filter was used to reduce beam hardening (Beckers et al., 2014; Smet et al., 2018). The rotation step for each soil sample was 0.3° over 180°. Then a 3D reconstruction of these images was created using NRecon software. During this process, a 0.7 ring artifact correction was used and no beam hardening correction was applied. The reconstructed images had a voxel resolution of $27.27 \times 27.27 \times 27.27\ \mu m^3$ and the16-bit TIFF-format 3D images were saved for further processing.

Image preprocessing, segmentation, and quantification were undertaken using FIJI software and a 3D Gaussian filter with a radius of 2 pixels was used to reduce noise. An unsharp mask with a standard deviation of one voxel (weight of 0.6) was then applied to emphasize edges (Jarvis et al., 2017). The images had a pixel size of 55 µm, which also was the minimum size of the recognizable pores. A region of interest that was $1000 \times 1000 \times 1000$ voxel^3 in size was selected from the central part of the image. An "opening " operation was used to remove pores that were smaller than the size of the structural mask (Hu et al., 2017). The Otsu global threshold method (Otsu, 1979) was used to obtain acceptable segmentation results in our study.

We calculated the indexes that describe the porosity, shape, surface area, and connectivity of the pore network from the final binary images. The pore size distribution was calculated using the pore thickness measure, which was defined as the diameter of the largest sphere that fitted into the pore. The calculation was carried out using BoneJ (Doube et al., 2010). There are no uniform standards for the classification of pore size (Lu et al., 2019; Sandin et al., 2017). In our study, three pore size classes (55–165, 165–385, and >385 μm) were chosen based on the variation trends of pore size distributions among the three treatments, which is beneficial to reveal the relationship between pore size distribution and SWR. The degree of anisotropy was also calculated by the BoneJ plugin. The critical pore diameter, connection probability (Γ), and special surface area were calculated by SoilJ (Koestel, 2018). The critical pore diameter is defined as the diameter of the largest sphere (bottleneck) that can pass through the pore network from top to bottom and Γ, a global connectivity measure, is defined as the probability that two voxels belong to the same pore cluster. The Γ value is 1 when all the voxels in a sample are connected. However, the Γ value decreases as the pore space gets fragmented (Koestel and Schlüter, 2019). The following equation was used to calculate Γ:

$$\Gamma = \frac{\sum_{i=1}^{N} n_i^2}{\left(\sum_{i=1}^{N} n_i\right)^2}$$

Where N is the number of connected pore clusters, and n_i is the number of pore voxel in cluster i.

2.4.3. Soil organic carbon (SOC) and microbial biomass carbon (MBC)

The samples were acidified with 1.0 M HCl to decompose the carbonate and then dried at 60°C before the SOC was measured. After drying, the samples were ground (< 0.149 mm) with a mortar and pestle and the SOC was measured by dry combustion method using an elemental analyzer (Vario Macro C/N, Elementar, Germany)

An incubation experiment was carried out before the MBC was measured. Soil samples at 30% field capacity were kept at a constant temperature (20°C) environment for two weeks to ensure maximum microbial activity. The fumigation extraction method (Vance et al., 1987) was used to calculate MBC. Both fumigated and non-fumigated soil samples were extracted using 0.5 M K_2SO_4 for 1 hour. The carbon content was measured using a TOC analyzer (Vario TOC, Elementar, Germany).

2.5. Statistical analysis

The experimental data for three tillage systems (RT, CT, and NT) in the two experimental fields (Shouyang (S) and Gongzhuling (G)) were analyzed. The sorptivity of water and ethanol, water repellency index, water contact angle, porosity, critical pore diameter, connection probability, special surface area, degree of anisotropy, soil organic carbon, and microbial biomass carbon differences among the treatments were analyzed by a GLM analysis of variance (ANOVA) using SAS 9.4 software. The PROC CORR procedure was used to determine the initial relationships among the soil properties. Then redundancy analysis (RDA) was used to further understand these relationships and the effect of conservation tillage on SWR using CANOCO version 5.01 software. Sorptivity, infiltration, water repellency index, and water contact angle were the response variables and the other variables were explanatory variables. Only the uncorrelated explanatory variables were included in the RDA. Pearson's correlations among the physical properties were calculated by SAS 9.4 to avoid omitting the main indexes. If there was a strong correlation ($p < 0.001$) between two explanatory variables, then only one of the variables was chosen in the RDA (Matamala et al., 2017).

3. Results

3.1. Sorptivity, infiltration, water repellency index, and water contact angle

The trend for sorptivity change with time, calculated from the infiltration rate over 0–600 s, is shown in Figure 3-1. Both water and ethanol sorptivity increased rapidly under the three tillage treatments (CT, RT, and NT) at the beginning of the infiltration in the S and G field experiments. Time had no significant influence on sorptivity during 300–500 s in the two experiments ($P > 0.05$), which suggests that the infiltration was stable during this period. The reduction in water sorptivity was greater than the ethanol sorptivity reduction for all samples. The mean water sorptivity values for CT, RT, and NT, which were calculated using the steady-state flow rate (300–500 s), were 0.64, 0.61, and 0.50 mm $s^{-1/2}$, respectively, and the mean ethanol sorptivity values for CT, RT, and NT were 0.58, 0.71, and 0.67 mm $s^{-1/2}$, respectively. The NT treatment had a lower water sorptivity value than RT and CT, whereas CT had the lowest ethanol sorptivity value in the two field experiments. The cumulative ethanol infiltration value of RT treatment was highest and NT treatment had the lowest water infiltration value in the two experiments (Figure 3-1c and f).

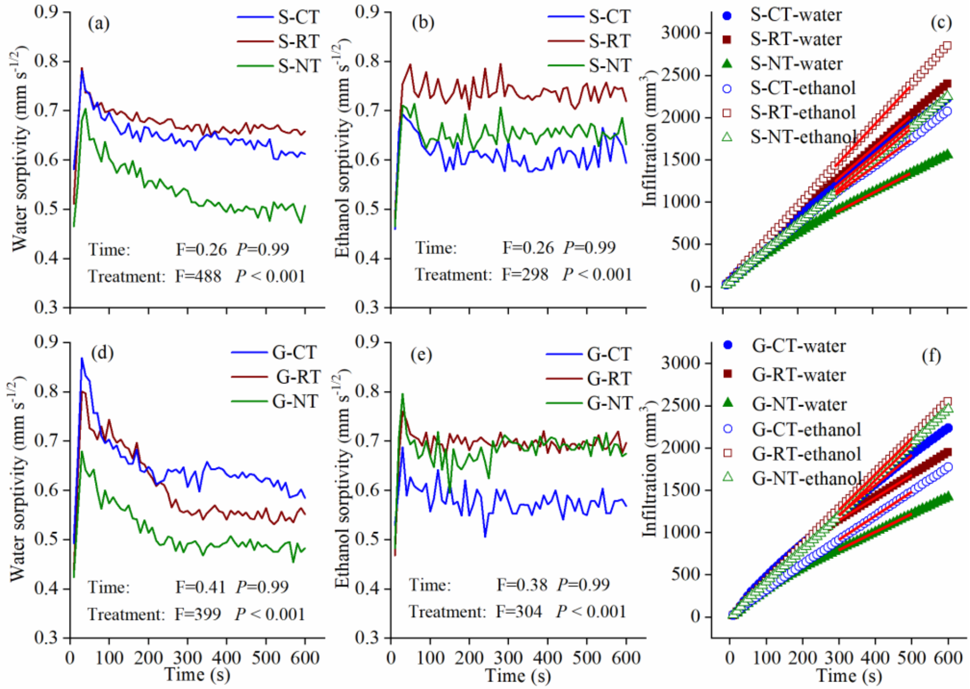


Figure 3-1. Water sorptivity, ethanol sorptivity, and cumulative infiltration of water and ethanol measured with an intrinsic sorptivity method for the three tillage managements (CT, RT, and NT) in Shouyang (S) and Gongzhuling (G) field experiments. The red lines in (c) and (f) represent the stable infiltration range 300-500 s.

Water repellency index (RI) and water contact angle (β) are shown in Figure 3-2. They were calculated according to the water and ethanol sorptivity during the stable infiltration phase (300–500 s). The RI of NT treatment was 34.7% and 56.9% higher than the CT treatment in S and G fields, respectively. The RT treatment was 15.7% and 37.7 % higher in RI than the CT treatment in the S and G fields, respectively. The β and RI followed the same trends and the RT and NT treatments increased RI and β compared to the CT treatment in the two fields. In addition, the β values for all the samples were less than 90 degrees.

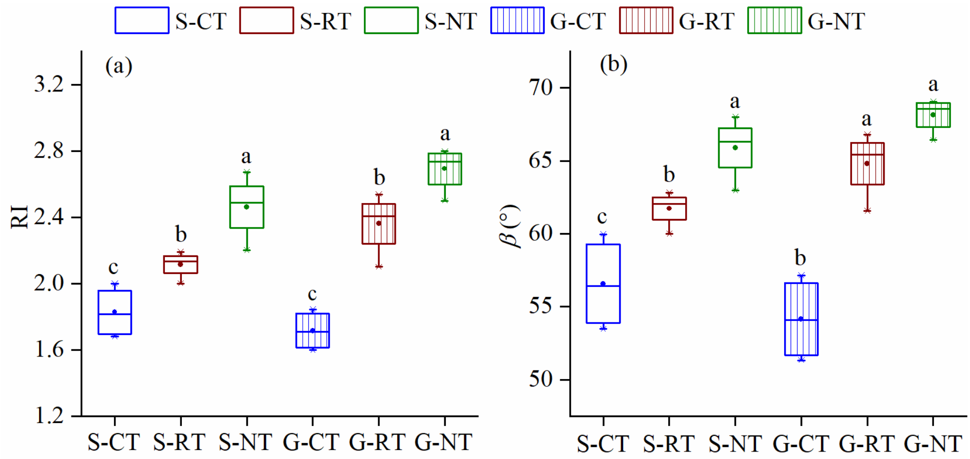


Figure 3-2. Comparisons of (a) water repellency index (RI) and (b) water contact angle (β) among the three tillage managements (RT, CT, and NT). S and G mean that samples were taken from Shouyang and Gongzhuling field experiments, respectively. Boundaries of the box indicate 25th quantile, median, and 75th quantiles. The top and bottom whiskers represent the minimum and maximum values, respectively. Dots denote mean values. Values, which were influenced by tillage management, followed by the same letters are not significantly different ($p < 0.05$) according to LSD test.

3.2. Soil organic carbon (SOC) and microbial biomass carbon (MBC)

The SOC (Figure 3-3a) and MBC (Figure 3-3b) were significantly improved after the addition of crop residues under the conservation tillage treatments (RT and NT) in the two field experiments. SOC and MBC are both hydrophobic substances, but they showed different change trends under the three treatments. There was no significant SOC difference between the RT and NT treatments in the two experiments. However, the MBC of the NT treatment was significantly higher than the RT treatment in both experiments ($P < 0.05$).

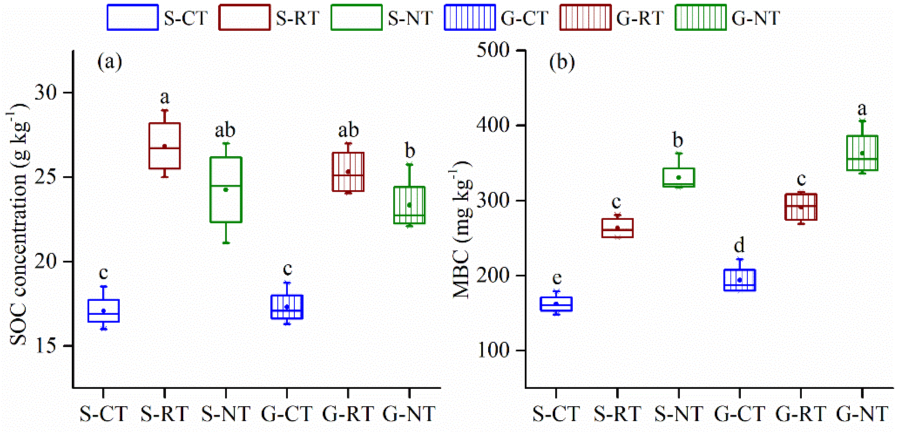


Figure 3-3. Comparisons of (a) soil organic carbon (SOC) and (b) microbial biomass carbon (MBC) among the three tillage managements (RT, CT, and NT). Boundaries of the box indicate 25th quantile, median, and 75th quantiles. The top and bottom whiskers represent the minimum and maximum values, respectively. Dots denote mean values. Values, which were influenced by tillage management, followed by the same letters are not significantly different ($p < 0.05$) according to LSD.

3.3. Characteristics of pore structure

Tillage management had significant impacts on the pore size distribution in both field experiments (Figure 3-4). The RT and NT treatments increased the porosity of the 55–165 μm diameter pores compared to the CT treatment, which is shown in the representative two-dimensional images of the three tillage management treatments (Figure 3-5a–c). The porosity of different pores sizes of RT treatment was the highest compare with CT and NT treatments in the Shouyang site (Fig. 4a), whereas the regular changed in the Gongzhuling site (Fig. 4b). The total porosity (> 55 μm) in the G field was higher than in S field. The total porosity in G-CT was higher than in the G-RT and G-NT treatments, and there was a larger porosity of pores > 165 μm in diameter under the G-CT treatment than under the G-RT and G-NT (Figure 3-5 d–f). Compared with NT treatment, RT treatment significantly increased the porosity of different pore sizes in both sits ($P < 0.05$).

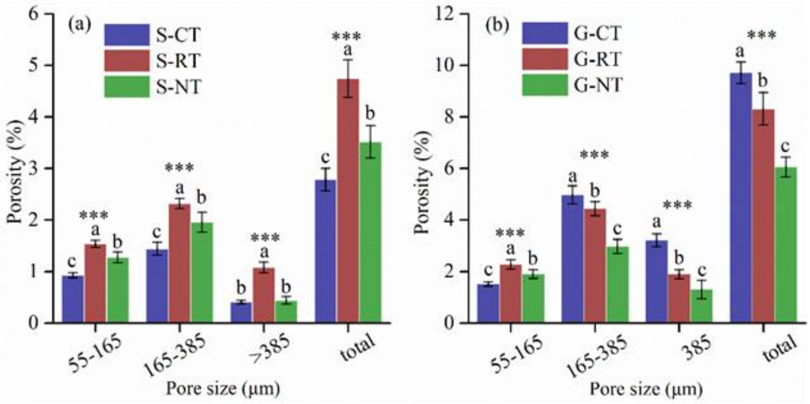


Figure 3-4. Comparison of pore size distribution among the three tillage managements (RT, CT, and NT) in Shouyang (a) and Gongzhuling (b) field experiments, respectively. Values, which were influenced by tillage management, followed by the same letters are not significantly different ($p < 0.05$) according to LSD test. ***: $p < 0.001$.

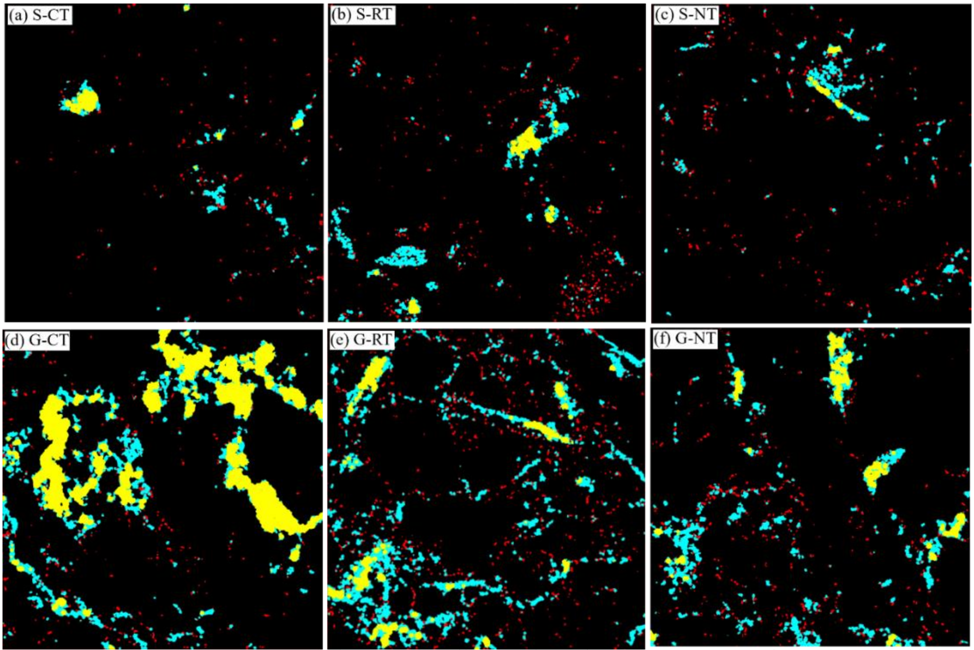


Figure 3-5. Representative two-dimensional images of the three tillage managements (CT, RT, and NT) in Shouyang (S) and Gongzhuling (G) field experiments, respectively. The red area represents pores of 55-165 μm; the cyan area represents pores of 165-385 μm; the yellow area represents pores larger than 385 μm in diameter.

Critical pore diameter (d_{crit}) had different responses to conservation tillage in the two field experiments (Figure 3-6a). The d_{crit} for S-CT was not significantly different from S-RT ($P > 0.05$), but was significantly higher than S-NT ($P < 0.05$). The d_{crit} for G-CT treatment was higher than RT and NT treatments in the G field experiment. The RT and NT treatments increased the connection probability Γ (Figure 3-6b), specific surface area (Figure 3-6c), and degree of anisotropy (Figure 3-6d) compared to CT in both field experiments. The RT treatment had a greater effect on Γ and degree of anisotropy than the NT treatment, whereas the specific surface area in NT was larger than in RT.

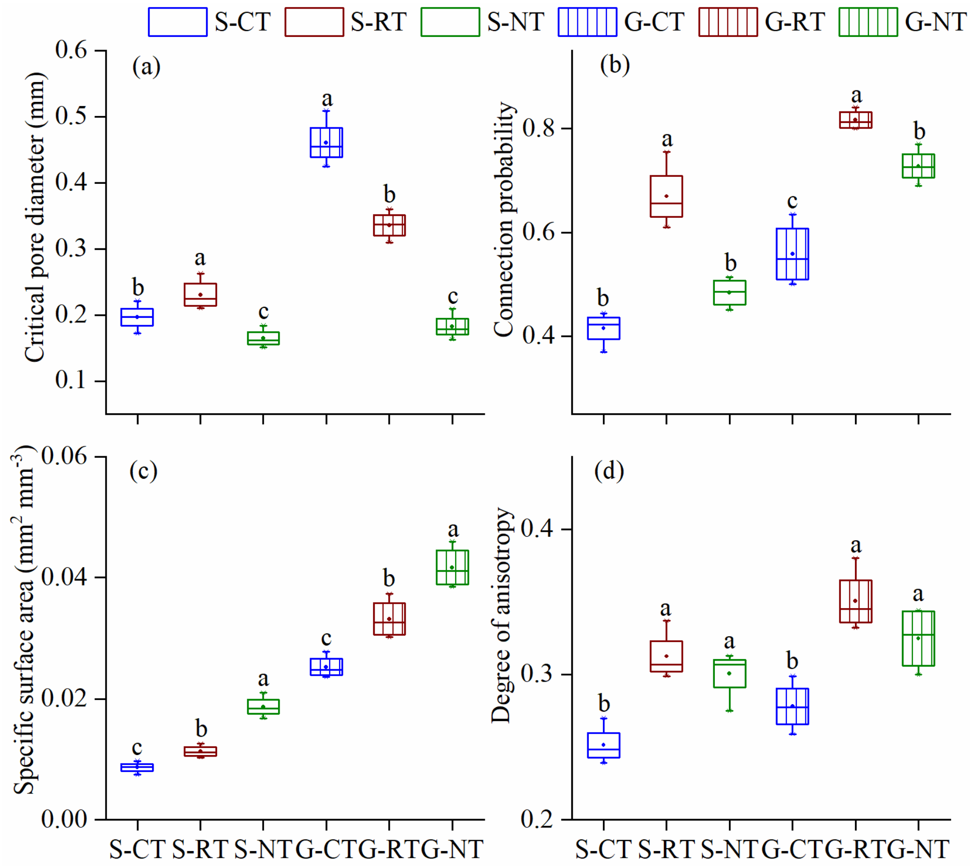
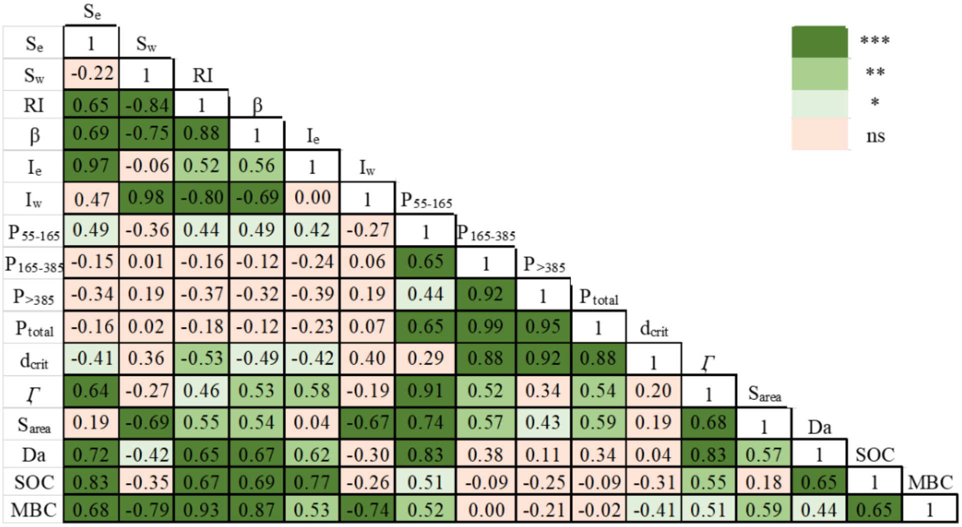


Figure 3-6. Comparisons of (a) critical pore diameter, (b) connection probability, (c) specific surface area, and (d) degree of anisotropy among the three tillage managements (RT, CT, and NT). Boundaries of the box indicate 25th quantile, median, and 75th quantiles. The top and bottom whiskers represent the minimum and maximum values, respectively. Dots denote mean values. Values, which were influenced by tillage management, followed by the same letters are not significantly different ($p < 0.05$) according to LSD test.

3.4. The impacts of pore structure, SOC, and MBC on SWR under the three tillage managements

A Spearman rank-order correlation analysis (Figure 3-7) was used to analyze the relationships among SWR, pore structure characteristics, SOC, and MBC. Furthermore, RDA was carried out to reveal how pore structure, SOC, and MBC affected SWR (Figure 3-8). Its first and second axes accounted for 67.1% and 21.7% of the total variations, respectively. The 55–165 μm diameter pores ($P_{55\text{–}165}$) had positive correlations with S_e, RI, and β (Figure 3-7). However, there were no significant correlations with sorptivity, infiltration, RI, and β when the pore diameter was greater than 165 µm. The results showed that the porosity of $P_{55\text{-}165}$ increased under the RT and NT treatment compared to CT (Figure 3-8) and had positive correlations with connectivity probability (Γ) and specific surface area (S_{area}), respectively (Figure 3-7). Furthermore, Γ and S_{area} had a positive correlation with RI. The results suggested that Γ increased RI by improving S_e, whereas S_{area} increased RI because there was a reduction in S_w (Figures 3-7 and 3-8). Both SOC and MBC had positive correlations with RI and β, respectively (Figure 3-7). However, MBC had a more sensitive response to the RI and β than SOC (Figure 3-8). The MBC had a negative correlation with S_w, but there was no significant correlation between SOC and S_w.



	S_e	S_w	RI	β	I_e	I_w	$P_{55\text{-}165}$	$P_{165\text{-}385}$	$P_{>385}$	P_{total}	d_{crit}	Γ	S_{area}	Da	SOC	MBC
S_e	1															
S_w	-0.22	1														
RI	0.65	-0.84	1													
β	0.69	-0.75	0.88	1												
I_e	0.97	-0.06	0.52	0.56	1											
I_w	0.47	0.98	-0.80	-0.69	0.00	1										
$P_{55\text{-}165}$	0.49	-0.36	0.44	0.49	0.42	-0.27	1									
$P_{165\text{-}385}$	-0.15	0.01	-0.16	-0.12	-0.24	0.06	0.65	1								
$P_{>385}$	-0.34	0.19	-0.37	-0.32	-0.39	0.19	0.44	0.92	1							
P_{total}	-0.16	0.02	-0.18	-0.12	-0.23	0.07	0.65	0.99	0.95	1						
d_{crit}	-0.41	0.36	-0.53	-0.49	-0.42	0.40	0.29	0.88	0.92	0.88	1					
Γ	0.64	-0.27	0.46	0.53	0.58	-0.19	0.91	0.52	0.34	0.54	0.20	1				
S_{area}	0.19	-0.69	0.55	0.54	0.04	-0.67	0.74	0.57	0.43	0.59	0.19	0.68	1			
Da	0.72	-0.42	0.65	0.67	0.62	-0.30	0.83	0.38	0.11	0.34	0.04	0.83	0.57	1		
SOC	0.83	-0.35	0.67	0.69	0.77	-0.26	0.51	-0.09	-0.25	-0.09	-0.31	0.55	0.18	0.65	1	
MBC	0.68	-0.79	0.93	0.87	0.53	-0.74	0.52	0.00	-0.21	-0.02	-0.41	0.51	0.59	0.44	0.65	1

Figure 3-7. Spearman rank-order correlation analysis for all samples. S_e: ethanol sorptivity; S_w: water sorptivity; RI: water repellency index; β: water contact angle; I_e: ethanol accumulative infiltration; I_w: water accumulative infiltration; $P_{55\text{-}165}$: pores of 55-165 µm in diameter; $P_{165\text{-}385}$: pores of 165-385 µm in diameter; $P_{>385}$: pores greater than 385 µm in diameter; P_{total}: total porosity; d_{crit}: critical pore diameter; Γ: connection probability; S_{area}: special surface area; D_a: degree of anisotropy; SOC: soil organic carbon; MBC: microbial biomass carbon. ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; ns: not significant.

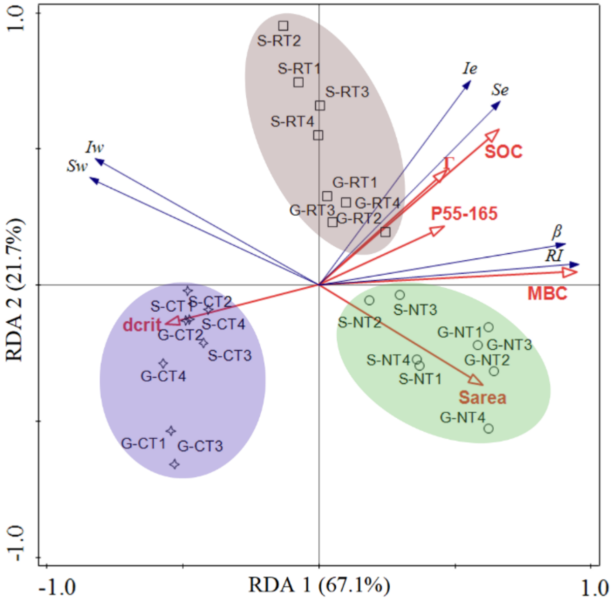


Figure 3-8. Redundancy analysis of the effects of pore structure, SOC, and MBC on SWR. The response variables are S_e, S_w, I_e, I_w, RI, and β. The explanatory variables are $P_{55\text{-}165}$, d_{crit}, Γ, S_{area}, SOC, and MBC. See Figure 3-7 for abbreviations of these variables.

4. Discussion

Our study showed that conservation tillage had a significant influence on SWR, and RT and NT treatments increased the repellency index (RI) and soil water contact angle (β), which confirmed previous results (Behrends et al., 2019; Blanco-Canqui, 2011; González-Peñaloza et al., 2012). It has been stated that soil is hydrophobic if the β is greater than 90° (Carrillo et al., 1999; Gordon et al., 2018; Xiong et al., 2012). This is true for cylindrical pores. However, it does not really apply to wavy pores in the soil and where the hydrophobicity begins to emerge when the critical water angle is much smaller than 90° (Czachor et al., 2010). In our study, the contact angle values under the three treatments ranged from 54° to 68° in the two field experiments. Similar results were reported by Behrends et al. (2019). In addition, a slight change in β can have a considerable effect on soil hydraulic properties (Leelamanie and Karube, 2013; Tadayonnejad et al., 2017). Therefore, it is important to determine the impact of conservation tillage on SWR, even if the water contact angle is less than 90°.

Hydrophobic substances, which are generally derived from roots (Seaton et al., 2019), microbial residues (Goebel et al., 2011), and fungi (Bedini et al., 2009; Rillig, 2005), are one of the factors that control SWR. Most previous studies used SOC to represent hydrophobic substances when attempting to determine their effects on

SWR (Jimenez-Morillo et al., 2016; Zavala et al., 2009). In this study, the RI showed a positive correlation with SOC, but there was no relationship between water sorptivity (S_w) and SOC (Figure 3-7). Hallett et al. (2001) also reported similar results for plowing and no-tillage systems. In addition, the microbial biomass carbon (MBC), rather than the total SOC, showed more useful and sensitive responses to soil processes (Sparling, 1992). Soil microbial community composition strongly influenced SWR (Behrends et al., 2019; Seaton et al., 2019). The MBC had a negative correlation with S_w and a positive correlation with the RI (Figure 3-7). This is because that the microbial biomass carbon (MBC), rather than the total SOC, showed more useful and sensitive responses to soil processes (Sparling, 1992). Previous researchers also found that soil microbial community composition strongly influenced SWR (Behrends et al., 2019; Seaton et al., 2019). Furthermore, the MBC had a negative correlation with Sw and a positive correlation with the RI (Figure 3-7). This can be supported by the result that there was a positive relationship between MBC and the RI when a straw amendment was applied (Zhang et al., 2007). Therefore, although most of the previous studies used SOC to explain SWR (Jimenez-Morillo et al., 2016; Zavala et al., 2009), our results suggested that MBC produced more useful information about the effects of different factors on SWR than SOC.

X-ray computed tomography was used in this study to obtain a detailed 3D characterization of the soil porous system (e.g. the shape, porosity, and connectivity of the pore network). The RT and NT treatments increased the porosity of pores in the 55–165 μm diameter range compared to CT treatment (Figure 3-4). Borges et al. (2019) used the soil water retention curve method to show that NT treatment had a greater effect on the porosity of the 30–70 μm diameter pores than CT treatment. Only the pores in the 55–165 μm diameter range had a positive correlation with S_e, RI, and β, whereas the porosity of the pores with a diameter >165 μm had no significant influence on SWR (Figure 3-7). The reason is that the infiltration method used to measure SWR requires unsaturated flow conditions, which is mainly controlled by small pores compared to the saturated flow (Haverkamp et al., 2016). Moreover, the infiltration method is a reasonable and practical way of measuring SWR because soil water movement is usually an unsaturated flow in rainfed agriculture and the method can provide more information about the SWR effects on soil ecosystems than the contact angle method that is commonly used in soil hydraulic modeling (Papierowska et al., 2018). We were unable to analyze the pores that were less than 55 μm in diameter, which are the pores that are more likely to affect SWR. Resolution limitations are a common problem when using X-ray computed tomography to study soil pore structure (Gao et al., 2019b; Hu et al., 2017). Therefore, further research should investigate ways of improving the resolution so that more detailed information about small pores can be obtained, which would improve our understanding of the relationship between pore structure and SWR. However, this study has shown that SWR, measured by the intrinsic sorptivity method, was controlled by smaller pores (55–165 μm) rather than large pores (>165 μm).

Percolation theory concepts can be used to quantify the pore system connectivity (Jarvis et al., 2017; Schlüter and Vogel, 2011) and connectivity probability (Γ) could influence hydraulic conductivity (Sandin et al., 2017). In our study, Γ increased in the RT and NT treatments compared to CT treatment (Figs. 4 and 8) and it had a positive correlation with RI and S_e, but there was no significant correlation between Γ and S_w (Fig. 7). This showed that although the RT and NT treatments increased soil pore connectivity, water sorptivity was not promoted because the increase in hydrophobic substances under RT and NT probably reduced water sorptivity. This challenges the traditional view that increasing soil pore connectivity could improve soil hydraulic conductivity (Borges et al., 2019; Schlüter et al., 2020). The main reason may be that the increase in hydrophobic substances under RT and NT treatments could reduce water sorptivity (Hallett et al., 2001; Liu et al., 2018). Furthermore, an increase in the critical pore diameter (d_{crit}) usually enhances saturated hydraulic conductivity and water infiltration (Koestel et al., 2018; Koestel and Schlüter, 2019). However, in our study, d_{crit} had a negative correlation with S_e, I_e, and RI (Figure 3-7). The reason was that d_{crit} was mostly controlled by mechanical disturbance in the CT treatment rather than the addition of maize residues, as was the case in the RT and NT treatments (Figure 3-8). In addition, the d_{crit} value was greater than 165 μm in the three treatments (Figure 3-6), but the larger pores (>165 μm) had no significant influence on SWR properties (Figure 3-7). Therefore, d_{crit} did not affect SWR properties under the tillage management.

The RT and NT treatments improved the porosity (55–165 μm) and connectivity to increase S_e (Figure 3-8) and the capacity of soil water absorption. However, the increase of S_{area} in the RT and NT treatments also increased the possibility and area of contact between soil water and hydrophobic compounds, which intensified the capacity limitation of soil water absorption and then led to an increase in the RI. In addition, S_{area} had no significant correlation with S_e (Figure 3-7) because ethanol is a non-polar liquid that is not affected by hydrophobic compounds (Tadayonnejad et al., 2017; Tillman et al., 1989). More importantly, the results indicated that the addition of crop residues under the RT and NT treatments not only increased sorptivity by enhancing porosity and connectivity but also decreased water sorptivity by increasing S_{area} due to the increase in the potential contacts between hydrophobic substances and soil water. These results challenge the traditional view that the addition of crop residues increases sorptivity and reduces water repellency by improving pore structure (Cosentino et al., 2010).

Previous studies were not based on the direct measurements of pore structure and their results were obtained using other indirect methods associated with pore structure. There are obvious limitations in using indirect variables (e.g. ethanol sorptivity) to explain the effect of pore structure on SWR. Our results came from two experimental fields with different soil types, climate, and length of time that the tillage systems were used. These factors could also affect pore structure, SOC, MBC, and SWR. However, the impact of pore structure and hydrophobic substances on SWR could still be determined for each field. This reinforces our conclusions. The results from this study, calculated by X-ray computed tomography, have improved our understanding of pore structure characteristics, and have indicated the real relationship between pore structure and SWR. In addition, the water drop penetration time (WDPT) method, which is often used to measure SWR, defines the time needed for a single water drop to infiltrate a soil sample (Hallin et al., 2013), but the infiltration time is controlled by two factors, which are hydrophobic substances and pore structure (Behrends et al., 2019). This also suggests that it is essential to take both pore structure and hydrophobic substances into account when studying the factors governing SWR. In our study, although ethanol sorptivity increased under RT and NT treatments because porosity and connectivity improved, water sorptivity decreased due to the increase in hydrophobic substances and S_{area} (Figures 3-7 and 8). Therefore, the degree of SWR is controlled by the interactions between pore structure and hydrophobic substances under conservation tillage management.

5. Conclusions

X-ray computed tomography made it possible to better understand the impacts of pore structure and hydrophobic substances on SWR. Although SWR is induced by hydrophobic substances, pore structure can also affect its degree and behavior. The RT and NT treatments improved porosity and connectivity, which enhanced ethanol sorptivity, whereas the increase in pore surface area (S_{area}) under the two treatments led to a decrease in water sorptivity because the rise in S_{area} increased the possibility of contact between the soil water and hydrophobic substances. In addition, the RT and NT treatments increased water repellency index (RI) by improving MBC and SOC. However, MBC had a closer relationship with RI than SOC and more fully explained the impact of tillage on SWR. Although porosity and connectivity improved sorptivity, the degree of SWR for the two conservation tillage managements (RT and NT) still increased, which was due to the increase in MBC, SOC, and S_{area}. The change in pore structure after the addition of maize residues increased sorptivity by improving porosity and connectivity, but decreased water sorptivity by increasing S_{area} due to the hydrophobicity. Therefore, the effect of conservation tillage on SWR is a result of the interactions between pore structure and hydrophobic substances. Future studies should take into account both pore structure and hydrophobic substances when studying the impacts of SWR on soil processes.

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Chapter VI

Does soil water repellency reduce corn yield by changing soil water availability under long-term tillage management?

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Chapter VI Does soil water repellency reduce corn yield by changing soil water availability under long-term tillage management?

Abstract

Drought is increasingly common due to frequent occurrences of extreme weather events, which further increases soil water repellency (SWR) and influence grain yield. Conservation tillage practices are playing a vital role in the sustainable development of agriculture in attaining high food security and it also can increase SWR. However, the relationships between SWR and grain yield under conservation agriculture are still not fully understood. We studied the influence of SWR on grain yield from a soil water availability point of view and used a long-term field experiment established in 2003 with continuous spring maize. 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 with residue removal (CT), reduced tillage with residue incorporated (RT), and no-tillage with residue mulch (NT). The results showed that NT treatment increased the water repellency index (WRI) compared to the CT and RT treatments. 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 WRI played a prominent role in increasing soil water storage compared to the soil total porosity, penetration resistance, mean weight diameter, and organic carbon content. Furthermore, although the increment in the WRI under NT treatment increased the soil water storage and plant available water, grain yield was not influenced by WRI ($p > 0.05$) because the grain yield under NT treatment was mainly driven by penetration resistance and least limiting water range (LLWR). The higher water sorptivity increased water use efficiency and LLWR, which further increased the grain yield under RT treatment. Overall, SWR, which was characterized by water sorptivity and WRI, 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 pproperties; soil water availability; water used efficiency

1. Introduction

Soil water repellency (SWR) is an intrinsic physical property in coarse- to fine-textured soils under different climates and land uses (Blanco-Canqui and Lal, 2009a; Daniel et al., 2019; Goebel et al., 2011). The increase of drought stress in the global climate aggravates the SWR. The SWR is described as soil water behavior on the soil surface that limits the rate and capacity for soil water absorption (Daniel et al., 2019; Zheng et al., 2016). Therefore, SWR has important impacts on some soil processes (e.g. carbon sequestration, aggregate stability, and soil erosion) and crop growth (Li et al., 2019; Liu et al., 2012; Moody et al., 2009).

Several studies reveal 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 degree of 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 impact on crop yield. The small degree of SWR, known as subcritical water repellency (Hallett et al., 2001), 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 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, which are unfavorable for plant growth (Blanco-Canqui, 2011; Müller et al., 2016). Hence, studying the mechanism of how tillage affects crop yield by changing SWR is critically important for understanding the sustainability of conservation tillage practices.

Although conservation tillage practices increase SWR compared with conventional tillage (Blanco-Canqui, 2011), the degree of SWR is still small (Lucas-Borja et al., 2019) and it is essential to adopt an effective measuring method of SWR in cultivated soils. Water drop penetrating time (WDPT), ethanol droplet (MED), and sorptivity are three common methods used to measure SWR (Behrends et al., 2019; Senani et al., 2016). The time, a water droplet infiltration into the soil, is short in subcritical water repellent soils when using the WDPT method, which makes it difficult to measure the small degree of SWR accurately (Czachor et al., 2010). The MED method only works for hydrophobic soils with contact angles greater than 90° (Carrillo et al., 1999), whereas the contact angles under conservation tillage management are generally smaller than 90° (Behrends et al., 2019). However, the sorptivity method can be adapted to calculate the degree of subcritical water repellency, even if the range of water contact angle is less than 90° (Tadayonnejad et al., 2017). In addition, it is more effective in explaining the impact of SWR on soil hydrological processes compared with WDPT and MED methods, because the method is more relevant to the water infiltration and movement in the soil (Hunter et al., 2011). Therefore, using the sorptivity method to measure SWR is acceptable in cultivated soils.

Reduced tillage or no-tillage could reduce soil disturbance and increase soil organic carbon (Afzalinia and Zabihi, 2014; Hermansen et al., 2019), both of which can increase SWR (Behrends et al., 2019; Li et al., 2020a). González-Peñaloza et al. (2012) found that no-tillage resulted in significantly higher SWR than conventional tillage after two years and the SWR increased with an increase in years of continuous cropping. However, other studies also found tillage practices have no significant effect on SWR (Bottinelli et al., 2010; Eynard et al., 2004). The main reason is that SWR can be affected by soil texture, climate, and duration of tillage management (Doerr et al., 2006; Goebel et al., 2011). Previous studies found that drought could increase SWR (Chen et al., 2018; Deurer et al., 2011; Hewelke et al., 2018). This underscores the need for increased focus on studies of the impact of tillage management on SWR under rainfed agriculture because climate extremes and drought severity will increase as global warming intensifies (Ahmed et al., 2018; Mohsenipour et al., 2018; Trenberth et al., 2014). Furthermore, soil depth also had a significant effect on SWR under tillage management (Bottinelli et al., 2010) and SWR was higher in the 0–5 cm depth than in the 5–10 cm depth under no-tillage management (Roper et al., 2013).

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 in a climate chamber with a constant temperature. It was also found that crop yield was poorly related to SWR in a 4-year field experiment (Roper et al., 2013). However, Li et al. (2019) added a hydrophobic substance (dichlorodimethylsilane) into a sandy loam soil to increase SWR and found that it decreased summer maize yield. These inconsistent results show that growth environmental 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 degree of 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 (Asgarzadeh et al., 2014). Both are defined as the ranges of soil water content and can reflect soil water availability from different angles. LLWR integrates three main plant growth-limiting factors (soil water potential, resistance, and air porosity), whereas PAW is based only on the soil 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 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 influence crop yield.

Additionally, our previous study had found that SWR was a result of the interactions between soil pore structure and hydrophobic substances 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., 2020a). In our study, a long-term experimental field 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 hypothesize that SWR can reduce corn yield by changing soil water storage, PAW, and LLWR. The objectives of this study were to (i) evaluate the effect of SWR on soil water availability; and (ii) reveal how SWR affects corn yield through a comparative analysis.

2. Materials and methods

2.1 Study site and experimental design

The long-term field experiment was set up in 2003 and located at Shouyang (112-113 °E, 37-38 °N; 1100 m a.s.l.), Shanxi Province, northern China. Table 4-1 showed some of soil physical and chemical properties at the beginning of the experiment. The site has a sandy loam soil and a continental monsoon climate with an average annual precipitation of 483 mm (Wang et al., 2019). Spring drought is often a limiting factor for plant growth at the site (Wang et al., 2011). The annual average temperature is 7.4°C and the annual frost-free period is approximately 130 days.

The long-term tillage experiment was carried out using a randomized complete block design with three replications. Each plot was 5 m × 5 m in size. The crop was rain-fed continuous spring maize and the fallow period was from November to the following March. There were three treatments: a) CT: conventional tillage with maize stalk removed after harvesting, plowing twice to about 30 cm depth with a moldboard plow after harvesting and before seeding (in April); b) RT: reduced tillage with maize straw and fertilizers incorporated after harvesting (in October), plowing once to about 25 cm depth with a moldboard plow; and c) NT: no-tillage with the maize straw mulched after harvesting, then seeding and fertilizing with a no-till planter in the following April. Urea and calcium superphosphate fertilizers were applied to each plot at 105 kg N ha^{-1} and 105 kg P_2O_5 ha^{-1}, respectively. The row and plant spacings were 60 and 30 cm, respectively.

Table 4-1 Soil physical and chemical properties in 0-30 cm layers in 2003.

Soil layer (cm)	Soil particle size distribution (%)			Available soil nutrient (mg kg^{-1})			SOC (g kg^{-1})	Bulk density (g cm^{-3})
	20-200 µm	2-20 µm	< 2µm	N	P	K		
0-10	55.3	37.9	6.8	58	8.3	96	26.4	1.06
10-20	56.4	37.3	6.3	52	6.9	93	25.0	1.20
20-30	58.5	35.5	6.0	53	3.1	87	20.9	1.36

2.2 Soil sampling

In order to study the change in soil water content and storage after two rainfall events, soil samples were collected seven times (the 1st, 2nd, 3rd, 4th, 6th, 8th, and 10th days after each rainfall event) at 0-5 cm, 5-10 cm, and 10-20 cm layers. Each treatment was repeated three times in each rainfall event. The first rainfall event occurred on June 26th, 2018 and its precipitation was 11 mm. The second rainfall event occurred on July 22nd, 2018 and the precipitation was 30 mm. Undisturbed core samples from the 0–5 cm, 5-10 cm, and 10-20 cm layers were taken on July 7th, 2018 using steel rings (internal diameter: 4.9 cm and height: 5.0 cm) to determine soil bulk density, water retention curve, and penetration resistance. The same undisturbed core samples were collected on September 10th, 2018 to measure soil water repellency. In total, 108 undisturbed core samples (4 variables × 3 treatments × 3 replications × 3 layers) were taken. A total of 54 disturbed samples (2 variables × 3 treatments × 3 replications × 3 layers) were collected on July 7th, 2018 using a hand auger with 5 cm diameter to measuring mean weight diameter and soil organic carbon.

2.3 Soil analysis

2.3.1 Soil water repellency characteristics

Soil core samples were air-dried for two weeks and then a tension micro infiltrometer was applied for measuring SWR according to the sorptivity method (Hallett and Young, 1999). The infiltrometer equipment consisted of a tube with one end connected to the liquid reservoir and the other end (with a 2 mm radius) was covered with a sponge. Detailed information about the equipment can be found in Hallett and Young (1999). The liquid reservoir was placed on an automatic counting electronic balance (0.001 g) which recorded the weight every 10 s. We used two liquids: distilled water and ethanol (95% v/v). Detailed descriptions of the method can be obtained from Tadayonnejad et al. (2017). The pressure heads of the two liquids were the same in the tip covered with the sponge that was touching the soil core sample surface. The pressure head was negative pressure to avoid saturated flow. The pressure head (P) was calculated using the following equation (Tillman et al., 1989):

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

where P is the pressure head (m^{-1}), h is the height difference between the tip covered with the sponge and the liquid level, ρ and σ are the density ($kg\ m^{-3}$) and surface tension ($kg\ s^{-2}$) of the liquid, respectively, and g is the acceleration due to gravity ($m\ s^{-2}$). This equation indicates that different h values should be applied to different liquids in order to get the same pressure head. 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 by the electronic balance between 0 and 600 s. The flow rate, Q ($mm^3\ s^{-1}$), was obtained from the slope of the linear parts of the curves (cumulative infiltration *vs.* time). In our study, the steady-state flow was observed within the 300-500 s range. The water and ethanol sorptivity (S) were calculated using the following equation (Leeds-Harrison et al., 1994):

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

where *f* is the air-filled porosity ($mm^3\ mm^{-3}$), *b* is a constant that depends on the soil-water diffusivity function and had a value of 0.55, and *r* is the infiltrometer tip radius. The sorptivity change with time trend was recorded over 0-600 s. The values for water sorptivity (Sw) and ethanol sorptivity (Se) were calculated from the steady-state flow rate (300–500 s) (Fischer et al., 2010).

Water sorptivity is affected by soil pore structure and hydrophobic substances, whereas ethanol sorptivity is only affected by pore structure because ethanol is a non-polar liquid (Tadayonnejad et al., 2017; Tillman et al., 1989). The water repellency index (WRI) was obtained from the following equation (Tillman et al., 1989):

$$WRI = 1.95\frac{Se}{Sw}$$

where *Se* is the sorptivity of ethanol ($mm\ s^{-1/2}$) and *Sw* is the sorptivity of water ($mm\ s^{-1/2}$). Detailed information about how to calculate the coefficient can be found in Tadayonnejad et al. (2017). Tillman et al. (1989) defined soil with WRI > 1.95 as subcritical water repellency. It is noted that both Sw and WRI reflect the nature of SWR. Sw represents the ability of soil water absorption and WRI shows the degree of SWR (Tadayonnejad et al., 2017). The relationship between Sw and WRI is inverse and increasing Sw can reduce WRI (Behrends et al., 2019; Vogelmann et al., 2017).

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

To measure soil penetration resistance (PR) curve, undisturbed soil samples were placed on a pressure plate apparatus and the matric suction of 2, 10, 60, 100, 500, and 1000 kPa were set. When the weights of these samples were constant, PR and soil moisture were measured under each matric suction. We used a micro penetrometer (Omega LC703, USA) to obtain PR and the penetrometer had a cone diameter of 2 mm and an angle of 15°. The mean value of PR and the functional relationship between PR and soil water content were calculated. Detailed information has been reported previously (Li et al., 2020; Ruiz et al., 2016).

Toposity was obtained from bulk density and particle density measured by the pycnometer method (Klute and Page, 1986). Soil bulk density was measured by the ring method (Liu et al., 2009). The samples were acidified with 1.0 M HCl to decompose the carbonate and then dried at 60°C before the SOC was measured. After drying, the samples were ground (< 0.149 mm) with a mortar and pestle and the SOC was measured by dry combustion method using an elemental analyzer (Vario Macro C/N, Elementar, Germany). We used the wet sieving method (Cambardella and Elliott, 1993) to determine aggregate stability with the sieves of 2000 μm, 250 μm, and 53μm sizes. Mean weight 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 range of each size fraction, w_i is the proportion of each aggregate fraction in whole soil and n is the number of aggregate size classes.

2.3.3 Soil water content and storage after two rain

We used the oven-drying method to measure soil water content for studying the change in soil water content after two rain. The precipitations of the two rainfall events were measured using a rain gauge at the experimental site. Soil water storage (SWS) was determined by the following equation:

$$SWS = \theta BDh$$

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

2.3.4 Least limiting water range, plant available water, grain yield, and WUE

It is necessary to determine the upper and lower limits for calculating the least limiting water range (LLWR). The upper limitation of LLWR was the water moisture at filed capacity (-33 kPa) or at air-filled porosity of 10%, whichever was the smaller. Plant growth could be limited when PR was greater than 2 Mpa

(Bengough and Mullins, 1990). Hence, the lower limit of LLWR was the water soil moisture at the permanent wilting point (-1500 kPa) or at PR of 2 Mpa, whichever was the higher. The field capacity and permanent wilting point were calculated from the soil water retention curve. The soil moisture at air-filled porosity of 10% was obtained from the following equation:

$$\theta_{AFP} = \left(1 - \frac{BD}{PD}\right) - 0.1$$

Where BD is bulk density (g cm^{-3}) and PD is the particle density (g cm^{-3}). Detailed information on how to calculated LLWR can be found in Li et al. (2020).

Plant available water (PAW) was defined as the following equation:

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

Where θ_{FC} is filed capacity at -33 kPa (cm^3 cm^{-3}) and θ_{PWP} is permanent wilting point at -1500 kPa (cm^3 cm^{-3}).

Grain yield was determined by harvesting plants from 10 continuous plants of each plot at the harvesting stage. Water use efficiency was determined from the ratio of grain yield to cumulative evapotranspiration of the complete growing period. The detailed information is shown in Wang et al. (2011).

2.4 Statistical analysis

The experimental data for three tillage systems (CT, RT, and NT) were analyzed, along with three soil layers (0-5 cm, 5-10 cm, and 10-20 cm). The effects of tillage treatment and soil depth on soil water sorptivity, water repellency index, penetration resistance, total porosity, MWD, SOC, SWS, LLWR, and PAW were calculated with the GLM analyses of variance (ANOVA) by least significant difference test (LSD) in SAS 9.4 software. The Spearman rank-order correlation was performed using the PROC CORR procedure in SAS 9.4 software to determine the initial relationships among these soil properties and grain yield. The redundancy analysis (RDA) was used to further understand how SWR affects grain yield compared with other soil properties using CANOCO version 5.01 software. The response variables were SWS, LLWR, PAW, grain yield, and WUE. Soil water sorptivity, water repellency index, penetration resistance, total porosity, MWD, and SOC were explanatory variables. Only the uncorrelated explanatory variables were included in the RDA. Pearson's correlations among the physical properties were calculated by SAS 9.4 to avoid omitting the main indexes. If there was a strong correlation ($p < 0.001$) between two explanatory variables, then only one of the variables was chosen in the RDA (Matamala et al., 2017).

3. Results

3.1 Soil water sorptivity and repellency index

Soil water sorptivity (Sw), which represents the ability of soil water absorption, in the 0-5 cm, 5-10 cm, and 10-20 cm layers under CT, RT, and NT treatments is presented in Figure 4-1a. NT treatment decreased soil water sorptivity in the 0-20 cm layer compared with CT treatment, whereas there was no significant difference between RT and CT treatment. The effects of CT, RT, and NT treatments on soil water repellency index (WRI) that shows the degree of SWR are illustrated in Figure 4-1b. WRI of NT treatment was 14.2%-40.1% higher than CT treatment in the 0-20 cm layer and the difference decreased with an increase in soil depth. However, RT treatment only enhanced WRI in the 0-5 cm layer and had no significant influence (P > 0.05) on WRI in the 5-20 cm layer compared with CT treatment. In addition, soil depth had significant effects on Sw and WRI (P < 0.001) (Table 4-2). Sw and WRI diminished with increasing soil depth.

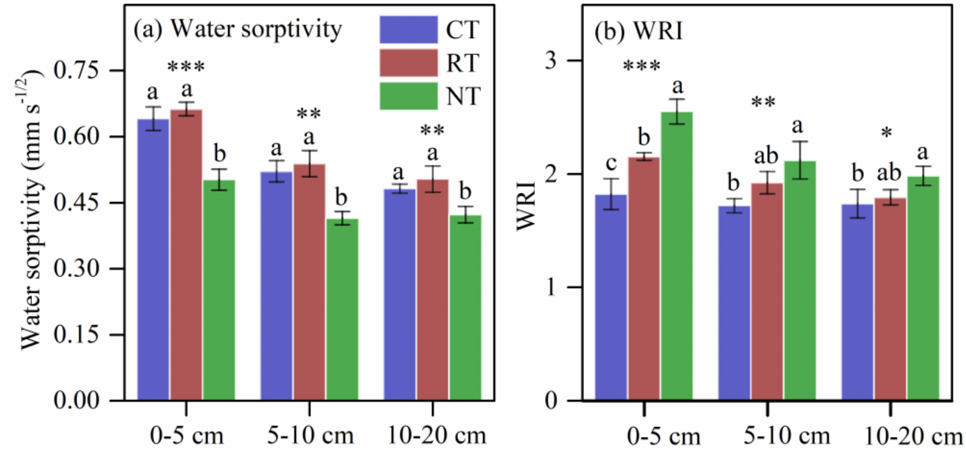


Figure 4-1. Soil water sorptivity and water repellency index in the 0-5 cm, 5-10 cm, and 10-20 cm layers under CT, RT, and NT treatments. The same letter means that there are not significantly different ($p > 0.05$) between tillage managements according to LSD test. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant.

Table 4-2 ANOVA results (F and *p* values) for soil properties as affected by tillage and depth.

Index	Source of variation		
	Tillage	Depth	Tillage*Depth
Sw	74.0***	71.9***	2.26ns
WRI	28.5***	46.7***	4.76**
PR	122.5***	86.5***	2.64ns
TP	26.4***	4.1*	6.31**
MWD	25.9***	145.2***	16.5***
SOC	13.4***	50.4***	1.5ns
SWS	533.1***	15.3***	1.4ns
LLWR	110.6***	69.8***	7.8**
PAW	2.7ns	7.7**	3.86*

Note: Sw: soil water sorptivity; WRI: 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 rain; LLWR: least limiting water range; PAW: plant available water. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant.

3.2 Soil penetration resistance, total porosity, MWD, and SOC

Table 4-3 Soil penetration resistance, total porosity, mean weight diameter, and soil organic carbon in the 0-5 cm, 5-10 cm, and 10-20 cm layers under CT, RT, and NT treatments.

Layer (cm)	Treatment	PR (Mpa)	TP (%)	MWD (mm)	SOC (g kg^{-1})
0-5	CT	1.49±0.02a	54.1±3.8a	0.61±0.02b	17.4±0.9c
	RT	1.27±0.05b	54.3±1.6a	0.63±0.03b	27.1±2.0a
	NT	1.55±0.04a	54.9±2.4a	0.79±0.01a	23.3±2.1b
5-10	CT	1.80±0.13a	54.0±0.8a	0.57±0.02b	16.3±1.5b
	RT	1.39±0.03b	52.9±1.0b	0.61±0.04b	24.0±1.7a
	NT	1.76±0.02a	52.6±2.9b	0.77±0.01a	21.6±1.9a
10-20	CT	1.96±0.12a	52.2±1.2a	0.59±0.03b	15.1±1.6b
	RT	1.66±0.02b	52.8±0.7a	0.62±0.02ab	20.4±1.1a
	NT	2.06±0.11a	49.3±1.1b	0.64±0.04a	20.3±1.8a

Note: Values within a column in the same depth, which were influenced by tillage management, followed by the same letters are not significantly different ($p < 0.05$). See Table 4-2 for these soil properties abbreviations.

Tillage management and soil depth showed a significant impact on soil penetration resistance (PR), total porosity, MWD, and SOC (Table 4-2). RT treatment reduced PR in the 0-5 cm, 5-10 cm, and 10-20 cm layer compared with CT and NT treatments, whereas NT had no significant effect on PR compared with CT treatment (Table 4-3). There was no significant impact of tillage management on total porosity in the 0-5 layer and NT treatment decreased total porosity in the 5-10 cm and 10-20 cm layers compared with CT treatment. Furthermore, NT treatment enhanced MWD and SOC in the three soil layers compared with CT treatment. SOC of RT treatment was also higher than CT treatment in the three soil layers. Nevertheless, for MWD in the three soil layers, there were no significant differences between RT and CT treatments.

3.3 The changes in soil water content and storage after two rainfall events

The changes in soil moisture after two rainfall events are shown in Figure 4-2. The precipitation of the first and second rainfall events was 11 mm and 30 mm, respectively. Tillage management had no significant effect on soil moisture in the 0-5 cm layer on the first day after both the first (Figure 4-2a) and second rainfall (Figure 4-2e). There were still no significant differences among the three tillage managements for soil moisture in 5-10 cm and 10-20 cm layers on the first day after the first rainfall (Figures 4-2b and c). Nevertheless, NT treatment had higher soil moisture in the two layers than CT treatment on the first day after the second rainfall (Figures 4-2f and g). Furthermore, NT treatment increased soil moisture compared with CT treatment on the tenth day after both the first and second rainfall, except for the 10-20 cm layer of the second rainfall.

The average soil water storages from 0-10 days after the first and second rainfall are presented in Figures 4-3a and b, respectively. As the same with soil moisture, tillage management also had no significant effects on soil water storage in the 0-5 cm layer under both rainfalls. However, NT treatment had higher soil water storage than CT and RT treatments in the 5-10 cm and 10-20 cm. RT treatment had no significant effect on soil water storage compared with CT treatment.

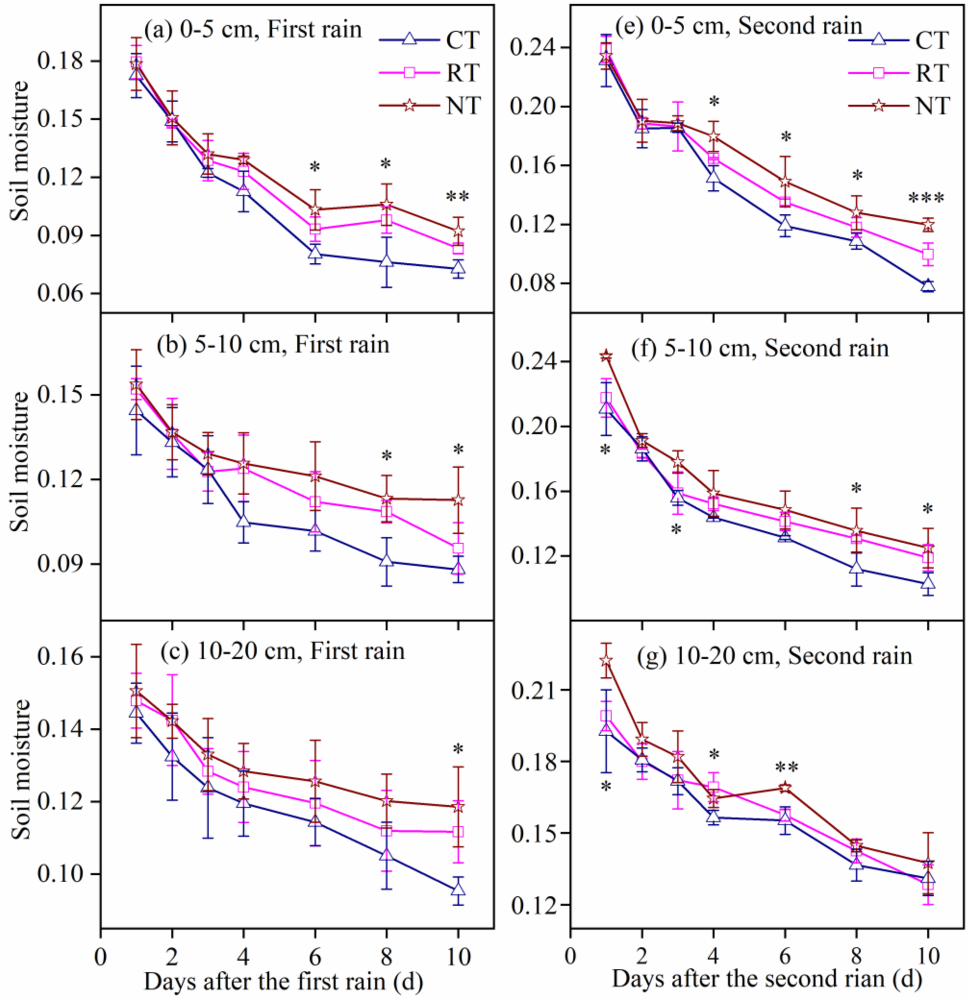


Figure 4-2. The changes in soil gravimetric water content for CT, RT, and NT treatments in the 0-5 cm, 5-10 cm, and 10-20 cm layers after two rainfall events. The ANOVA was used to measure the effect of tillage management on soil moisture under different days. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

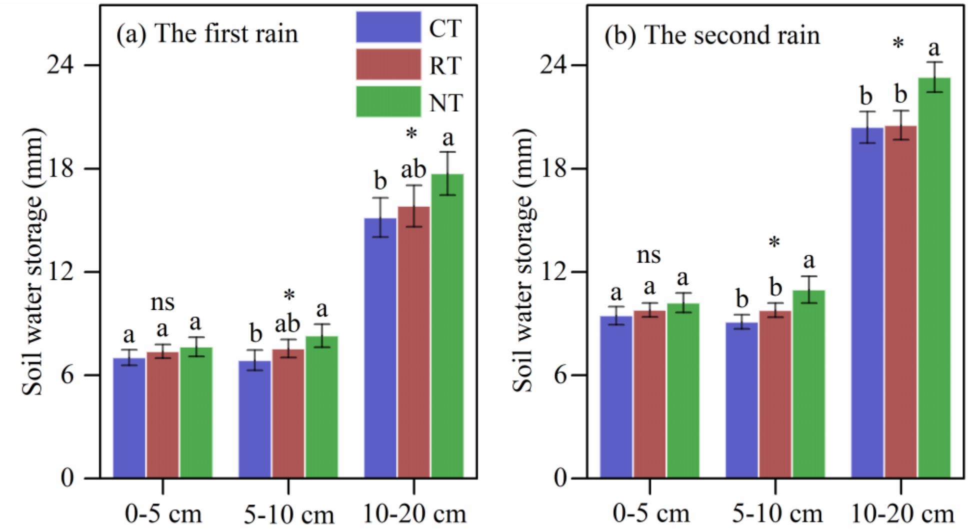


Figure 4-3. The average soil water storage in the 0-5 cm, 5-10 cm, and 10-20 cm layers after two rainfall events (0-10 d). The same letter means that there are not significantly different ($p > 0.05$) between tillage managements according to LSD test. *: $p < 0.05$; ns: not significant.

3.4 Least limiting water range, plant available water, grain yield, and WUE

The effect of tillage management on LLWR (Figure 4-4a) and PAW (Figure 4-4b) was different. Tillage management had a significant effect on LLWR in the 0-5 cm, 5-10 cm, and 10-20 cm layers ($P < 0.001$) (Table 4-2). The LLWR of RT treatment was higher than the CT and NT treatments in the three layers. Soil depth also significantly influenced LLWR (Table 4-2) and the LLWR under the three tillage managements could decrease with an increase in soil depth. However, tillage management had no significant effect on the PAW in the 0-5 cm layer ($P > 0.05$) and it only significantly influenced PAW in 5-10 cm and 10-20 cm layers ($P < 0.05$). NT treatment increased PAW in the 5-10 cm and 10-20 cm layers, whereas it had no significant effect on PAW in the 0-5 cm layer compared with CT treatment. In addition, there was no significant difference in PAW in the three soil layers between RT and CT treatments.

Grain yield and WUE under CT, RT, and NT treatments were shown in Figure 4-5. Tillage management had significant effects on both grain yield and WUE. The results showed 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.

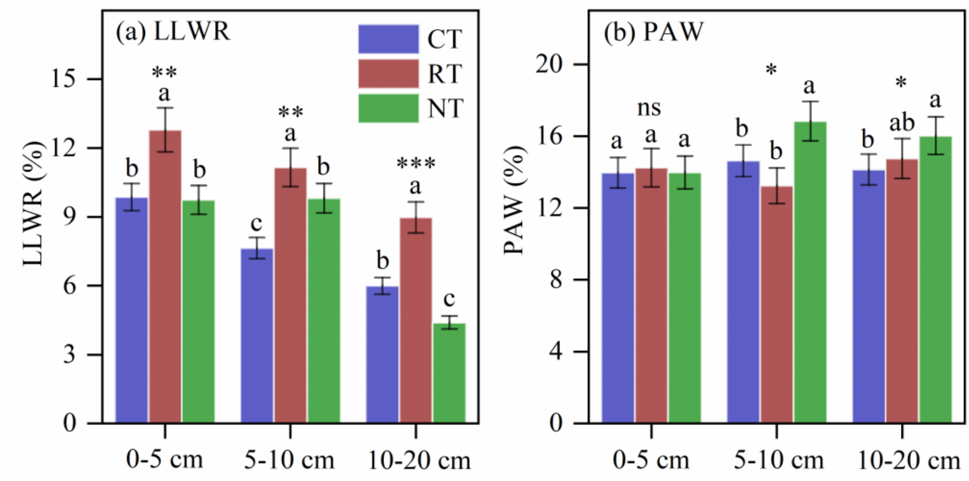


Figure 4-4. Least limiting water range and plant available water in the 0-5 cm, 5-10 cm, and 10-20 cm layers under CT, RT, and NT treatments. LLWR: least limiting water range; PAW: plant available water. The same letter means that there are not significantly different ($p > 0.05$) between tillage managements according to LSD test. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; ns: not significant.

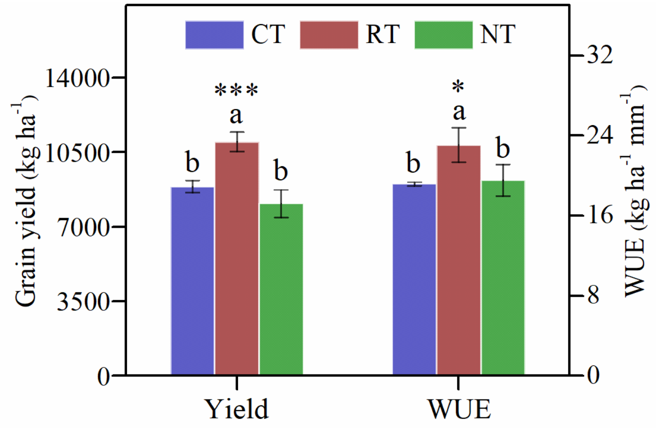
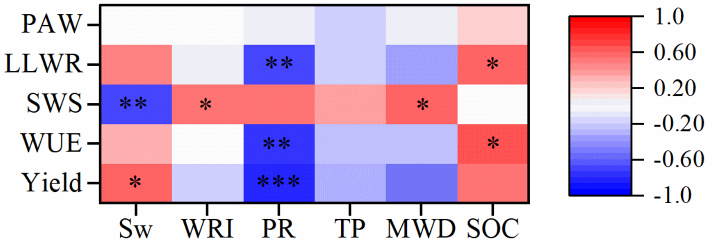


Figure 4-5. Grain yield and water use efficiency under CT, RT, and NT treatments. The same letter means that there are not significantly different ($p > 0.05$) between tillage managements according to LSD test. *: $p < 0.05$; ***: $p < 0.001$.

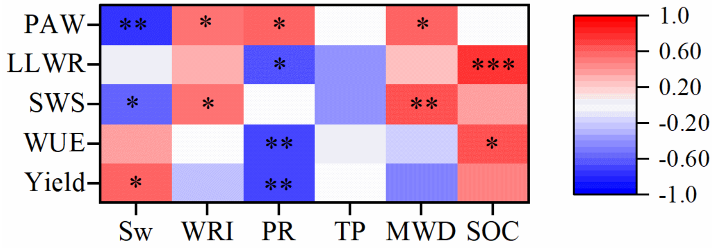
3.5 The relationship among soil properties, grain yield, and WUE

A Spearman rank-order correlation analysis was used to analyze the relationships among soil water availability, grain yield, and soil properties (Figure 4-6). Sw had a positive correlation with grain yield and soil water storage in the 0-5 cm (Figure 4-6a), 5-10 cm (Figure 4-6b), and 10-20 cm (Figure 4-6c) layers. There was a negative correlation between Sw and PAW in the 5-10 cm and 10-20 cm layers. Although WRI had no significant relationship with grain yield, it had the potential to increase soil water storage and availability. WRI had a positive relationship with soil water storage in the three soil layers and PAW in the 5-10 cm and 10-20 cm layers. Furthermore, PR in the three layers showed a negative relationship with LLWR, grain yield, and WUE. Soil total porosity, MWD, and SOC had no direct relationship with grain yield, but they could affect soil water storage, PAW, or LLWR.

(a) 0-5 cm



(b) 5-10 cm



(c) 10-20 cm

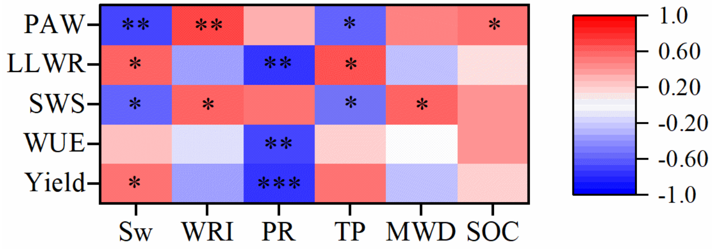
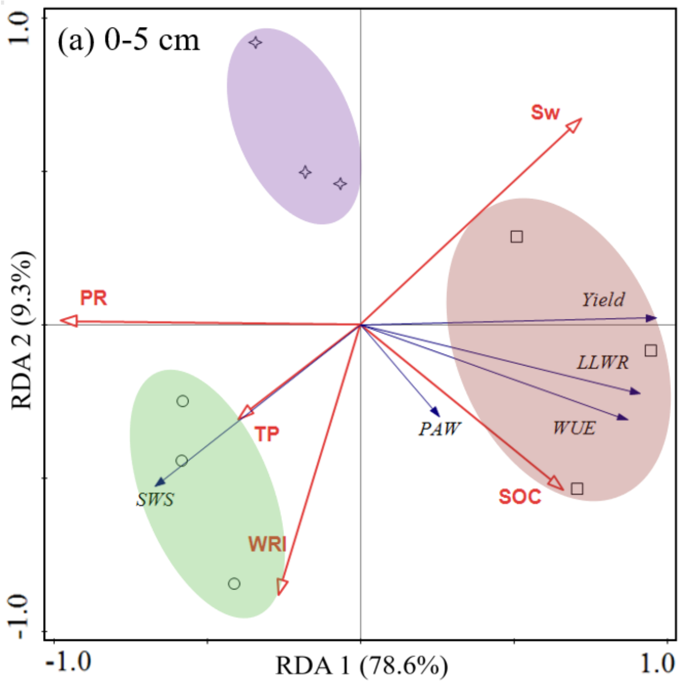


Figure 4-6. Spearman correlation analysis on the relationships among soil water availability, yield, and soil properties in the 0-5 cm (a), 5-10 cm (b), and 10-20 cm (c) layers. Bule and red represent negative and positive correlations, respectively, where darker color represents a higher correlation. See Table 2 for these soil properties abbreviations. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

In addition, RDA was carried out to further reveal how SWR affect corn yield through a comparative analysis with PR, TP, MWD, and SOC (Figure 4-7). Our results showed that Sw had a closer positive relationship with yield than TP, MWD, and SOC in the three soil layers. Moreover, Sw was also the most significant factor to reduce soil water storage compared with PR, TP, MWD, and SOC. Although WRI, PR, MWD, and SOC in the three layers were increased by NT treatment (circle symbol in Figure 4-7), PR was the most detrimental factor for grain yield and WUE. Compared with Sw and WRI, SOC was the most influential variable on LLWR in the three soil layers. The most influential variable on PAW was MWD in 5-10 cm and 10-20 cm layers. However, WRI played a prominent role in increasing soil water storage compared with the other soil properties in the three soil layers.



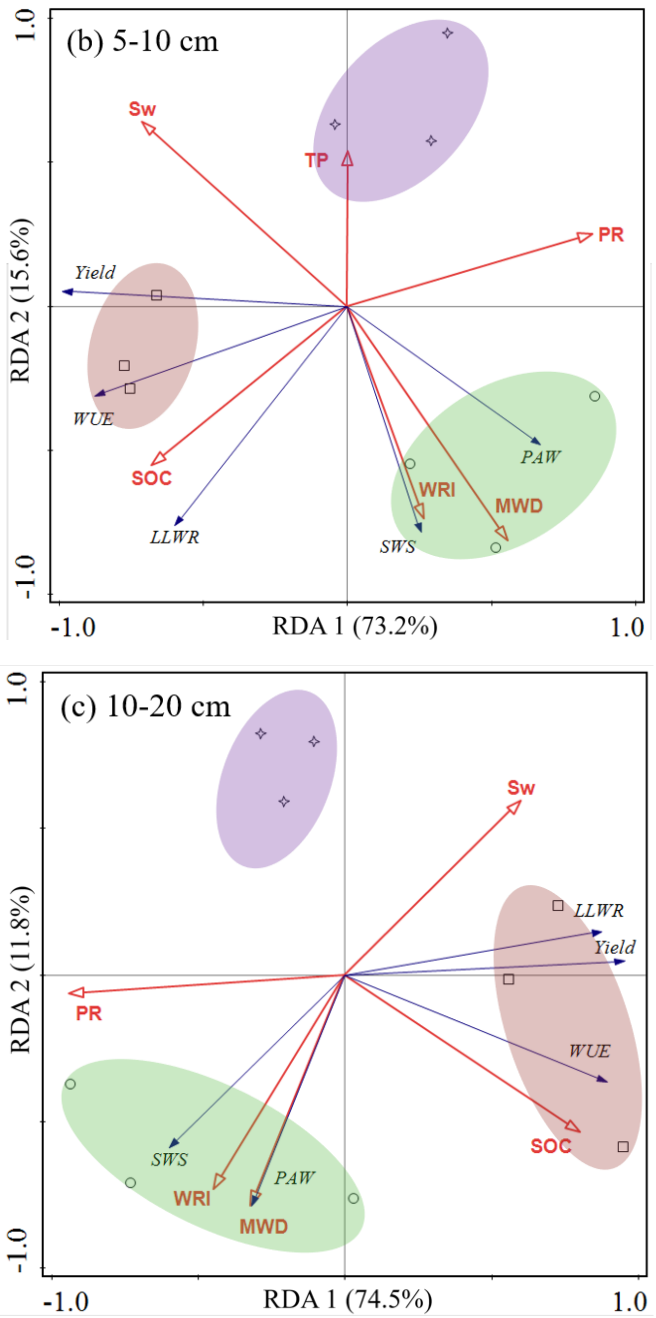


Figure 4-7. Redundancy analysis of the relationships among soil water

availability, yield, and soil properties in the 0-5 cm (a), 5-10 cm (b), and 10-20 cm (c) layers. The response variables are yield, WUE, LLWR, PAW, and soil water storage (SWS). The explanatory variables are Sw, WRI, PR, TP, MWD, and SOC. See Table 4-2 for these soil properties abbreviations. Star, square, and circle represent CT, RT, and NT treatments, respectively.

4. Discussion

Conservation tillage practices are playing a vital role in the sustainable development of agriculture in light of growing food demand and environmental change (Sun et al., 2020), but one challenge to developing the conservation tillage practices is that its effects on crop yield are still controversial (Blanco-Canqui and Lal, 2009b; Gao et al., 2019; Pittelkow et al., 2015). To address this challenge, our study reveals how SWR changes soil water availability and affects corn yield. NT treatment could significantly increase the degreed of SWR (WRI) in 0-5 cm, 5-10 cm, and 10-20 cm layers compared with CT treatment (Figure 4-1b). A similar result was discovered by Blanco-Canqui (2011) who found that the degree of SWR under 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 then increase the degree of SWR (Šimon et al., 2009). This study also showed that SOC of NT treatment was higher than CT treatment (Table 4-3). Furthermore, compared with NT treatment, RT treatment increased soil water sorptivity (Sw) that shows the ability of soil water absorption (Figure 4-1). Thess results suggest that reduced or occasional tillage increase soil disturbance compared with no-tillage, which could increase Sw and decrease the degree of SWR (Blanco-Canqui and Wortmann, 2020).

Although tillage management had a significant effect on SWR (Table 4-2), tillage management had no significant influence on the soil water content on the first day after the first rainfall when the 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 no-tillage system because crop roots provided pathways for water movement (Roper et al., 2013). However, the opposite results were found in our study. When the precipitation of the second rainfall was 30 mm, the NT treatment had higher soil water content in 5-10 cm and 10-20 cm layers than CT treatment (Figures 4-2f and g). There are many similar results because SWR can cause preferential flow and then increase the soil water content in a deeper layer (Lozano et al., 2013; Rye and Smettem, 2017). One of the reasons for the inconsistent results is 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). Another reason is that the higher rainfall intensity under the second rain was more likely to cause a preferential flow compared with the first rainfall. Therefore, we put forward that it is essential to consider rainfall intensity when studying the impact of SWR on soil movement under conservation tillage practices. In addition, the effect of SWR under NT treatment on soil water content became more obvious with the soil moisture decreasing after the two rainfall (Figure 4-2) because the degree of SWR generally increases with the decrease in soil moisture (Hermansen et al., 2019; Vogelmann et al., 2017). Hence, we believe that SWR has the ability to increase soil water content under conservation tillage practices, especially in arid regions. This further provides 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 to increasing crop yield in an arid region (Pittelkow et al., 2015; Sun et al., 2020).

Soil water storage (SWS), LLWR, and PAW are three common variables, as indicators of soil water availability, that represent the degree of ease of absorbing soil water for crops (de Lima et al., 2020; Silva et al., 2019; Sun et al., 2018). We found that both Sw and WRI had a significant influence on SWS (Figure 4-6) because increasing the degree of SWR could cause the preferential flow to reduce soil water content in the soil surface layer and decrease soil evaporation (Rye and Smettem, 2017). In addition, SWR can reduce the capacity to transport soil water to upper layers by capillary rise and then increase SWS (Bachmann et al., 2001). Our results also suggested that Sw and WRI were capable of impacting LLWR and PAW (Figure 4-6). The reason why WRI had a significant influence on PAW and no effect on LLWR in 5-10 cm and 10-20 cm layers is that LLWR can be affected by not only soil matric potential but also penetration resistance (Asgarzadeh et al., 2010; Silva et al., 2019). Previous studies have shown that the degree of SWR can strongly influence soil water retention curve that describes the relation between soil matric potential and soil moisture (Hassan et al., 2014; Liu et al., 2012; Naasz et al., 2008). These results further support our hypothesis that SWR can change soil water availability (SWS, LLWR, and PAW).

Furthermore, Sw had a significant influence on grain yield, whereas WRI had no effect on grain yield (Figure 4-6). The degree of SWR cannot reduce grain yield in our study (Figure 4-5), which does not support the previous hypothesis. One reason is that although tillage management had a statistically significant effect on WRI (Table 4-2), the differences were not large in this study compared to the previous results showing that the SWR under no-tillage system was 1.5 to 40 times higher than in conventional tillage (Blanco-Canqui, 2011). Hence, the effect of the degree of SWR on crop yield should be further considered in severely repellent soils. Another reason is that Sw 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 suggests that although both Sw and WRI can reflect the nature of SWR, Sw has a closer relationship with grain yield than WRI and more fully explained the effect of SWR on grain yield under conservation tillage practices. In addition, our previous studies have shown that soil water availability strongly influences on grain yield under conservation agriculture (Li et al., 2020). Soil water availability was also affected by the degree of SWR in this study (Figure 4-6). Therefore, we believe there is an indirect relationship between the degree of SWR and grain yield. Although the indirect effect cannot be quantified in this study, we still have pointed out the potential relationship and believed that the effect of SWR on crop yield was worthy of further study. This study challenges the traditional review that crop growth is poorly related to SWR under the no-tillage system (Roper et al., 2013).

Soil water availability and crop production are the results of a combination of multiple soil properties (Ernst et al., 2018; Scarpare et al., 2019; Zhang et al., 2018) and therefore the effects of these soil properties can be well understood through a comparative analysis. Like MWD, WRI was favorable for soil water storage compared with PR, SOC, TP, and Sw (Figure 4-7) because WRI could reduce evaporation loss (Rye and Smettem, 2017). Although WRI is advantageous to SWS, it could restrict plant growth because it also reduces the soil water availability and increases the difficulty of absorbing soil water by crops (Li et al., 2019; Madsen et al., 2012; Mcmillan et al., 2010). It should be noted that the most detrimental factor for reducing grain yield was not the degree of WRI but PR under the three tillage managements (Figures 4-6 and 7). PR had significant positive correlations with grain yield in 0-5 cm, 5-10 cm, and 10-20 cm layers in our study. A similar result that PR was the most limiting factor for crop growth in a 10-20 cm layer under the no-tillage system was also found by Kadžienž et al. (2011). Moreover, Sw was the most effective variable for increasing grain yield compared with other soil properties in the present study (Figures 4-6 and 7). This result indicates that crop yield could be improved by reducing the degree of SWR and increasing the ability of soil water absorption (Sw) under conservation tillage practices. The conclusion that increasing the degree of SWR has the potential to reduce crop yield was further confirmed. Besides, previous studies have shown that SWR can influence other soil behavior and environments, such as improving soil aggregate stability and carbon sequestration (Blanco-Canqui, 2011; Lamparter et al., 2009; Sepehrnia et al., 2017). Hence, a focused effort to study the effect of SWR on plant growth and soil behavior will improve our understanding of the role of conservation tillage practices in the sustainable development of agriculture.

5. Conclusions

The NT treatment decreased Sw compared to CT and RT treatments and the Se was the highest for RT treatment. We futher found that NT treatment increased WRI compared to CT treatment probably due to increasing hydrophobic substances and reducing soil disturbance. Both Sw and WRI were found 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. The SWS was higher for the NT than that for CT treatment and there was a positive correlation between WRI and SWS. The Sw also had a positive relationship with LLWR. Nevertheless, although WRI could reflect the degree of SWR, Sw had a closer relationship with grain yield than WRI and more fully explained the effect of SWR on grain yield under conservation tillage practices. In addition, Sw was a more important factor for increasing grain yield than MWD, PR, SOC, TP, and WRI. This further confirmed that grain yield could be improved by increasing Sw. The grain yield under RT treatment was highest by increasing Sw, LLWR, and WUE. From this, we conclud that RT treatment is the most effective tillage practice compared to CT and NT treatments from the perspective of grain yield.

6. Acknowledgements

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Chapter V

General discussion and conclusions

Chapter V General discussion and conclusions

In this chapter, the meaning, importance, and relevance of general results were delved into. We stated the answers to the main research question, made recommendations for future research on the topic, and showed what new knowledge we have contributed.

1. General discussion

Conservation tillage practices are developing very fast in the world and playing an essential role to maintain plant productivity and environmental quality (Blanco-Canqui and Wortmann, 2020; Palm et al., 2014; Somasundaram et al., 2017). However, one challenge to developing the conservation tillage practices is that its effects on crop yield and soil quality are still controversial (Blanco-Canqui and Ruis, 2018; Cusser et al., 2020; Pittelkow et al., 2015). Blanco-Canqui and Ruis, (2018) summarized 62 studies on soil bulk density under conventional tillage and no-tillage for the past 10 years. No-tillage had no effect on bulk density in 26 of the 62 studies, increased bulk density in 24 of 62 studies, and reduced it in 12 of 62 studies in the 0-10 cm soil depth. Reduced tillage and no-tillage increased the penetration resistance compared with the conventional tillage (Afzalinia and Zabihi, 2014). However, no significant effect of tillage system on penetration resistance was found in corn-soybean rotation (Logsdon and Karlen, 2004). Our study used two long-term experiments to reveal the change in soil physical properties and further assess how these soil properties affect grain yield. We found the growth stage had significant impacts on bulk density, PR, porosity, MWD, LLWR, and PAW (Table 2-2). In particular, NT increased, reduced, and had no significant impact on bulk density on April 27th, September 10th, and July 7th, respectively, compared with RT and CT at 0-5 cm depth (Table 2-3). These results suggest that the effect of tillage management on soil physical properties is not consistent at the different growth stages, which could be used to explain the reason why the impact of tillage management on soil physical properties is controversial. Salem et al. (2015) found a similar result under a loam texture soil that the bulk density of conventional and minimum tillage management increased with an increase in growth time, whereas the bulk density of no-tillage was stable during the growth period in 0-15 cm layer. The similar results also have been shown that soil penetration resistance (Moreira et al., 2016) and plant available water capacity (Valle et al., 2018) are changed with sampling date under tillage management. Therefore, seasonal changes in soil physical properties deserve further consideration, which is essential to better understand how soil physical properties affect plant growth under tillage management practices.

Crop production is the result of a combination of multiple soil properties (Ernst et al., 2018; Scarpare et al., 2019; Zhang et al., 2018) and it is necessary to analyze the optimal ranges of these soil physical properties to better understand how one soil physical properties affect on plant growth. Soil bulk density was commonly used as an indicator of air porosity, penetration, and capacity to store water (Reynolds et al., 2009). It could decrease grain yield when soil bulk density was greater than 1.3 g cm^{-3} (Drewry et al., 2001). Our results showed that bulk density was less than 1.3 g cm^{-3} during the growth period, except for NT at 10-20 cm (Table 2-3). Macroporosity indicated the soil capacity to drain excess water and facilitate root growth, which was greater than 0.1 m^3 m^{-3} as optimal (Drewry and Paton, 2005). S index, an indicator of soil physical quality, was greater than 0.035 as “good physical quality” (Dexter, 2004; Tormena et al., 2008). We found that macroporosity (Figure 2-4) and S index (Figure 2-7a) were in the optimum range. MWD, an index of aggregate stability, was unstable (0.4 mm <MWD< 0.8 mm) and very unstable (MWD < 0.4 mm) soils (Paradelo et al., 2016). MWD was in an unstable range (Figure 2-7b). Bulk density, porosity, S index, and MWD had irregular and different relationships with yield during the growth period, particularly in most cases there was no significant correlation between these physical properties and yield (Table 2-4). Therefore, Bulk density, porosity, S index, and MWD were not effective indexes to explain the changes in grain yield under different tillage management in our study. One of the reasons was that these soil physical properties were almost in their optimal range, which had no restriction on plant growth. Another reason was that these properties had indirect effects on grain yield. Previous studies have shown that soil physical properties such as air-filled porosity, penetration resistance(PR), and water holding capacity directly affect plant growth, while others including bulk density, MWD, and the pore size distribution can have indirect effects (Filho et al., 2013; Letey, 1958).

Most studies believe that soil compaction and water availability are the two principal factors limiting plant growth (Lapen et al., 2004; Yan et al., 2017). Soil penetration resistance is usually used as an indicator of soil compaction. The previous study has shown that increased PR under no-tillage decreased cassava root growth and induce the stem and planted cutting to play the role of storage organs (Figueiredo et al., 2017). A similar result was also found that deep moldboard plowing and chisel plowing reduced PR, which is beneficial to improve maize and wheat yields under tillage practices (Mu et al., 2016). In our study, we found PR in the 0-5 cm, 5-10 cm, and 10-20 cm had negative correlations with grain yield at the three growth stages (Table 2-4). Furthermore, we used redundancy analysis (RDA) and found that PR had the most important impact to restrict plant growth under NT compared with other soil physical properties (Figure 2-8). The result can be supported by the conclusion that PR was the most limiting factor for plant growth at 10-20 cm depth under no-tillage (Kadžienž et al., 2011). Plant available water (PAW) and least limiting water range (LLWR) are two common approaches to define the soil water availability for plants (Asgarzadeh et al., 2014). Both are defined as the ranges of soil water content and can reflect soil water availability from different angles. LLWR integrates three main plant growth-limiting factors (soil water potential, resistance, and air porosity), whereas PAW is based only on the soil potential (Tormena et al., 2017). The range of LLWR was narrower than PAW during the growth period (Figure 2-6). As a result, soil moisture was mostly in the range of PAW, but out of the range of LLWR (Figure 2-6). PAW, PAWup, and PAWdown did not show significant correlations with grain yield, while LLWR and LLWRdown had significant correlations with yield (Table 2-4 and Figure 2-8). Hence, LLWR was more sensitive than PAW to assess soil water availability under RT, CT, and NT treatments. LLWR was a more efficient indicator to influence grain yield than PAW. The PAW is only based on the potential (energy) of soil moisture and ignore other limiting soil physical properties for plant growth. It should be noted that Wd-LLWR, which combines LLWR and soil water content, was the main indicator affecting WUE and higher under RT treatment compared with NT treatment (Figure 2-8).

Although RT treatment was lower in soil water content than NT treatment, it had higher Wd-LLWR and lower LLWR down, both of which could increase soil water availability. This can explain the reason why RT treatment was higher in grain yield in spite of lower soil water content in our study. This further suggests that considering LLWR and soil moisture at the same time is helpful to better comprehend the relationship between LLWR and yield. However, the opposite conclusion was reported by Cecagno et al. (2016) who found that LLWR showed no direct correlation with soybean yield, and was an inadequate indicator in integrated soybean-beef cattle system under a mean annual rainfall of 1850 mm. The main reason is probably that high precipitation leads to higher soil water content, resulting in the soil moisture in the range of LLWR. It could decrease the ability of LLWR to assess soil water availability and crop production. This further confirmes that it is essential to determine both LLWR and soil water content for a better understanding of soil-crop relationship from the view of soil water availability.

Soil water repellency (SWR) is a common phenomenon in coarse- to fine-textured soils across all climatic zones (Daniel et al., 2019; Jimenez-Morillo et al., 2016; Seaton et al., 2019). A lot of research has already been conducted to reveal the impact of SWR on the soil ecosystem under forest and fire-affected soils (Debano, 2000; Plaza-Álvarez et al., 2018; Weninger et al., 2019). However, because the degree of SWR in farmland tillage soil is smaller than the forest and fire-affected soils (Lucas-Borja et al., 2019; Stavi et al., 2016), there is a lack of research on the SWR in farmland, especially for the study on how conservation agriculture affect SWR. Our study showed that conservation tillage had a significant influence on SWR, and RT and NT treatments increased the repellency index (RI) and soil water contact angle (β), which confirmed previous results (Behrends et al., 2019; Blanco-Canqui, 2011; González-Peñaloza et al., 2012). It has been stated that soil is hydrophobic if the β is greater than 90° (Carrillo et al., 1999; Gordon et al., 2018; Xiong et al., 2012). This is true for cylindrical pores. However, it does not really apply to wavy pores in the soil and where the hydrophobicity begins to emerge when the critical water angle is much smaller than 90° (Czachor et al., 2010). The small degree of SWR, known as subcritical water repellency (Hallett et al., 2001), can also have a considerable effect on soil structure and hydraulic properties (Hunter et al., 2011; Tadayonnejad et al., 2017). Therefore, it is important to determine the impact of conservation tillage on SWR, even if the water contact angle is less than 90°.

Most previous studies have used SOC to represent hydrophobic substances (Jimenez-Morillo et al., 2016; Zavala et al., 2009) and they found that the degree of SWR increased with an increase in SOC (Jimenez-Morillo et al., 2016; Zheng et al., 2016). In this study, the RI showed a positive correlation with SOC, but there was no relationship between water sorptivity (Sw) and SOC (Figure 3-7). Hallett et al. (2001) also reported similar results for plowing and no-tillage systems. In addition, we undertook a redundancy analysis and found that MBC had a closer relationship with RI than SOC (Fig. 8). This is because the microbial biomass carbon (MBC), rather than the total SOC, showed more useful and sensitive responses to soil processes (Sparling, 1992). Previous researchers also found that soil microbial community composition strongly influenced SWR (Behrends et al., 2019; Seaton et al., 2019). Furthermore, the MBC had a negative correlation with Sw and a positive correlation with the RI (Figure 3-7). This can be supported by the result that there was a positive relationship between MBC and the RI when a straw amendment was applied (Zhang et al., 2007). Therefore, although most of the previous studies used SOC to explain SWR (Jimenez-Morillo et al., 2016; Zavala et al., 2009), our results suggested that MBC produced more useful information about the effects of different factors on SWR than SOC.

However, some inconsistent results also are found by some other studies. There have been reports of positive (Jimenez-Morillo et al., 2016; Zavala et al., 2009), negative (Mataix-Solera et al., 2014), and no (Woche et al., 2005) relationships between SWR and SOC. The main reason is probably that SWR is affected by factors other than hydrophobic substances. Soil water repellency is described as soil water behavior on the soil surface that limits the rate and capacity for soil water absorption (Daniel et al., 2019; Madsen et al., 2012; Saldanha et al., 2017). Soil pore structure is the main controlling soil water movement (Katuwal et al., 2015; Pagliai et al., 2004; Pituello et al., 2016), therefore, SWR behavior could also be influenced by pore structure. For example, an increase in soil porosity or pore surface area could increase the possibility of contact between soil water and hydrophobic substances, which would increase SWR because it is controlled by hydrophobic substances on the surfaces of aggregates (Urbanek et al., 2007). Besides, the porosity of same-sized pores has different impacts on hydraulic conductivity under different degrees of SWR (Nyman et al., 2010), which suggests that SWR behavior can be influenced by pore size distribution. In addition, the water drop penetration time (WDPT) method, which is often used to measure SWR, defines the time needed for a single water drop to infiltrate a soil sample (Hallin et al., 2013), but the infiltration time is controlled by two factors, which are hydrophobic substances and pore structure (Behrends et al., 2019). This also suggests that it is essential to take both pore structure and hydrophobic substances into account when studying the factors governing SWR.

However, to our best knowledge, few previous studies used direct measurements of pore structure to reveal the effect of soil pore structure on SWR. In recent years, X-ray computed tomography (μCT) has been successfully used to obtain a non-destructive and detailed 3D characterization of the soil porous system (Beckers et al., 2014; Young et al., 2001). In our study, we used the direct measurement method to calculate soil pore structure. We found the RT and NT treatments increased the porosity of pores in the 55-165 μm diameter range compared to CT treatment (Figure 3-4). Only the pores in the 55-165 μm diameter range had a positive correlation with Se, RI, and β (Figure 3-7). The reason is that soil water first infiltrates into small pores during the infiltration process (Parvin et al., 2017) because the small pores have higher suction (Hu et al., 2017), which causes the pores in the 55-165 μm diameter range to have a closer relationship with SWR compared to the pores with a diameter > 165 μm (Figure 3-7). In addition, previous studies have shown that connectivity probability (Γ) that is measured by percolation theory concepts (Jarvis et al., 2017; Schlüter and Vogel, 2011) could influence soil hydraulic properties (Sandin et al., 2017). In our study, Γ had a positive correlation with RI and Se, but there was no significant correlation between Γ and Sw (Figure 3-7). This showed that the RT and NT treatments increased soil pore connectivity, but water sorptivity was not increased. This challenges the traditional view that increasing soil pore connectivity could improve soil hydraulic conductivity (Borges et al., 2019; Schlüter et al., 2020). The main reason may be that the increase in hydrophobic substances under RT and NT treatments could reduce water sorptivity (Hallett et al., 2001; Liu et al., 2018). The RT and NT treatments improved the porosity (55-165 μm) and connectivity to increase S_e (Figure 3-8) and the capacity of soil water absorption. However, the increase of S_{area} in the RT and NT treatments also increased the possibility and area of contact between soil water and hydrophobic compounds (Allen, 2007; Greco and Gargano, 2015), which intensified the capacity limitation of soil water absorption and then led to an increase in the RI. More importantly, the results indicated that the addition of crop residues under the RT and NT treatments not only increased sorptivity by enhancing porosity and connectivity but also decreased water sorptivity by increasing Sarea due to the increase in the potential contacts between hydrophobic substances and soil water (Allen, 2007; Greco and Gargano, 2015). Therefore, the degree of SWR is controlled by the interactions between pore structure and hydrophobic substances under conservation tillage management. It should be noted that we were unable to analyze the pores that were less than 55 μm in diameter, which are the pores that are more likely to affect SWR. Resolution limitations are a common problem when using X-ray computed tomography to study soil pore structure (Gao et al., 2019b; Hu et al., 2017). Therefore, further research should investigate ways of improving the resolution so that more detailed information about small pores can be obtained, which would improve our understanding of the relationship between pore structure and SWR.

Another limitation of the study of SWR is the mechanism of how SWR affects grain yield under conservation tillage practices. Previous studies have shown that the results of the effect of SWR on crop production are inconsistent in other production systems. Hassan et al. (2014) found that the dry mass production of alfalfa increased with an increase in SWR under natural climatic conditions with fluctuating temperature, whereas SWR had no significant effect on the dry mass production of alfalfa in a climate chamber with a constant temperature. It was also found that crop yield was poorly related to SWR in a 4-year field experiment (Roper et al., 2013). However, Li et al. (2019) added a hydrophobic substance (dichlorodimethylsilane) into a sandy loam soil to increase the degree of SWR and found that SWR decreased summer maize yield. These inconsistent results show that crop growth environment influences the mechanism of action of SWR on crop yield, which further suggests that studying the effect of SWR on grain yield under conservation tillage practices is critically important for understanding the sustainability of conservation tillage practices. We found the degree of SWR (WRI) had no significant influence on grain yield, whereas water sorptivity (Sw) that represents the capacity of soil water sorptivity. One reason is that although tillage management had a statistically significant effect on WRI (Table 4-2), the differences were not large in this study compared to the previous results showing that the SWR under the no-tillage system was 1.5 to 40 times higher than in conventional tillage (Blanco-Canqui, 2011). Hence, the effect of the degree of SWR on crop yield should be further considered in the serious SWR soils. Another reason is that Sw 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 suggests that although both Sw and WRI can reflect the nature of SWR, Sw has a closer relationship with grain yield than WRI and more fully explained the effect of SWR on grain yield under conservation tillage practices.

Furthermore, SWR can affect soil water behavior (e.g. infiltration and absorption) (Daniel et al., 2019). Previous studies have shown that SWR can affect water distribution in the pores and thereby influence soil water retention curve that is a relation curve 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. If soil water status is not taken into account at the same time, the real impact of SWR on crop yield is hard to be assessed. In our study, we found that although WRI had no direct effect on grain yield in our study, it had the potential to influence grain yield by changing soil water availability (Figure 4-6). Soil water storage (SWS), LLWR, and PAW are three common variables, as indicators of soil water availability, that represent the degree of ease of absorbing soil water for crops (de Lima et al., 2020; Silva et al., 2019; Sun et al., 2018). We found that both Sw and WRI had a significant influence on SWS (Figure 4-6) because increasing the degree of SWR could cause the preferential flow to reduce soil water content in the soil surface layer and decrease soil evaporation (Rye and Smettem, 2017). In addition, SWR can reduce the capacity to transport soil water to upper layers by capillary rise and then increase SWS (Bachmann et al., 2001). Notably, the effect of SWR on soil water content became more obvious with the decrease in soil moisture following rainfall. The SWS was higher for the NT than CT treatment and there was a positive correlation between WRI and SWS (Figure 4-2). Our results also suggested that Sw and WRI were capable of impacting LLWR and PAW (Figure 4-6). The reason why WRI had a significant influence on PAW and no effect on LLWR in 5-10 cm and 10-20 cm layers is that LLWR can be affected by not only soil matric potential but also penetration resistance (Asgarzadeh et al., 2010; Silva et al., 2019). Previous studies have shown that the degree of SWR can strongly influence soil water retention curve that describes the relation between soil matric potential and soil moisture (Hassan et al., 2014; Liu et al., 2012; Naasz et al., 2008). In addition, our previous studies have shown that soil water availability strongly influences on grain yield under conservation agriculture (Li et al., 2020). Hence, we believed that SWR could have the potential to influence on grain yield by changing soil water availability (SWS, LLWR, and PAW).

We also used RDA to further reveal how SWR affect corn yield through a comparative analysis with PR, TP, MWD, and SOC (Figure 4-7). Like MWD, WRI was favorable for soil water storage compared with PR, SOC, TP, and Sw (Figure 7) because WRI could reduce evaporation loss (Rye and Smettem, 2017). Although WRI is advantageous to SWS, it could restrict plant growth because it also reduces the soil water availability and increases the difficulty of absorbing soil water by crops (Li et al., 2019; Madsen et al., 2012; Mcmillan et al., 2010). Moreover, Sw was the most effective variable for increasing grain yield compared with other soil properties in the present study (Figures 6 and 7). The relationship between Sw and WRI is inverse and increasing Sw can reduce WRI (Behrends et al., 2019; Vogelmann et al., 2017). These results indicate that crop yield could be improved by reducing the degree of SWR and increasing the ability of soil water absorption (Sw) under conservation tillage practices. The conclusion that increasing the degree of SWR has the potential to reduce crop yield was further confirmed. Besides the potential effect of SWR on grain yield under conservation tillage practices, previous studies have shown that SWR can influence other soil behavior and environments, such as improving soil aggregate stability and carbon sequestration (Blanco-Canqui, 2011; Lamparter et al., 2009; Sepehrnia et al., 2017). Hence, a focused effort to study the effect of SWR on plant growth and soil behavior will improve our understanding of the role of conservation tillage practices in the sustainable development of agriculture. The Sw was a more important factor for increasing grain yield than MWD, PR, SOC, TP, and RI. This further confirmed that grain yield could be improved by increasing Sw under tillage management. The grain yield under RT treatment was highest by increasing Sw, LLWR, and WUE. From this, we concluded that RT was the most effective tillage practice compared to CT and NT from the perspective of grain yield.

2. General conclusions and perspectives

Our study shows that soil physical properties (e.g. bulk density, penetration resistance, pore size distribution, mean weight diameter, LLWR, PAW, and soil water repellency) were significantly affected by tillage management. Furthermore, we used X-ray computed tomography to study the effect of soil pore structure and hydrophobic substances on soil water repellency (SWR) at the same time. To fill the knowledge gap that there is a lack of research on the impact of SWR on grain yield under conservation tillage practices, we used the sorptivity method to measure SWR and then assessed the mechanism of the effect of SWR on grain yield from soil water availability perspective.

We found that these soil physical properties changed with the growth period. Considering seasonal variations in soil physical properties under conservation tillage practices is helpful to better understand how soil physical properties affect plant growth. Bulk density, porosity, S index, and mean weight diameter showed an irregular and different relationship with grain yield during the growth period. This result suggests that these soil physical properties were not effective indicators to explain the changes in grain yield under the three tillage managements. The range of LLWR was narrower than PAW during the growth period and more sensitive to assess soil water availability under CT, RT, and NT treatments. LLWR was a more efficient indicator to influence grain yield than PAW. LLWR was an aggregative indicator including not only soil penetration resistance but also air porosity and soil water potential, which can better explain the change of grain yield under the long-term tillage management in the semi-arid region. Redundancy analysis further indicated that maize yield was mainly driven by a lower limit of LLWR and penetration resistance in our rather dry context. NT treatment showed higher lower limit of LLWR than RT treatment, which increased soil water availability. Therefore, RT treatment had higher grain yield compared with NT treatment, even if the water content remained lower under RT treatment. It is necessary to determine both LLWR and soil water content for a better understanding of soil-crop relationship from the view of soil water availability.

Soil water repellency (SWR) is an intrinsic physicochemical property and could influence soil water status. Hence, it is essential to study the effect of tillage management on SWR. In our study, X-ray computed tomography made it possible to study the impact of pore structure and hydrophobic substances on SWR at the same time. The porosity of >165 μm in diameter had no significant link with SWR properties that were measured by an unsaturated flow method. RT and NT treatments could improve porosity and connectivity to enhance sorptivity, while NT could increase surface area (S_{area}) to decrease water sorptivity due to hydrophobic substances. Soil organic carbon and microbial biomass carbon, both of them as hydrophobic substances, were higher under RT and NT treatment than CT. Microbial biomass carbon was more positively correlated to SWR than soil organic carbon and the result further indicated that microbial biomass carbon was a better indicator explaining tillage effects on SWR. RT and NT treatments could enhance ethanol sorptivity by increasing pore connectivity. However, pore connectivity had no effect on water sorptivity because the increment of hydrophobic substances under RT and NT could decrease it. NT treatment also reduced water sorptivity by increasing pore surface area and hydrophobic substances. Although the porosity and connectivity could improve sorptivity, WRI of the two conservation tillage managements (RT and NT) still decreased under the control of MBC, SOC, and S_{area}. The change of pore structure after the addition of maize residue not only increased sorptivity by improving porosity and connectivity but also decreased sorptivity by increasing S_{area} due to the hydrophobicity. Hence, RT and NT treatments could increase the water repellency index, which was a result of the interactions between pore structure and hydrophobic substances. In order to unravel the mechanisms underlying conservation tillage impacts on SWR more accurately, it is essential to determine both pore structure and hydrophobic substances at the same time.

NT treatment increased the degree of SWR compared to CT treatment. Furthermore, compared to NT treatment, RT treatment increased Sw that shows the ability of soil water absorption, which indicates that increasing soil disturbance by reduced tillage could increase Sw and decrease the degree of SWR. Sw and WRI had influences on soil water availability (soil water storage, LLWR, and PAW). However, although both WRI and Sw can reflect the nature of SWR, Sw had a significant influence on grain yield and WRI had no direct effect on grain yield. This suggested that Sw has a closer relationship with grain yield than WRI and more fully explained the effect of SWR on grain yield under conservation tillage practices. WRI had no significant relationship with grain yield, but it could have an indirect effect on grain yield by changing soil water availability. In addition, Sw was the most favorable for increasing grain yield compared with soil organic carbon, mean weight diameter, penetration resistance, and total porosity. This further confirms that grain yield could be improved by increasing Sw and reducing the degree of SWR under conservation tillage practices. Despite no direct relationship existed between WRI and grain yield, SWR had the potential influence on grain yield by changing soil water availability and the effect of SWR on crop yield was worthy of further study under conservation tillage practices. The grain yield under RT treatment was highest by increasing Sw, LLWR, and WUE. From this, we conclude that RT is the most effective tillage practice compared to CT and NT from the perspective of grain yield.

Based on these results in our study, the following points are recommended to better understand the potential benefits of conservation tillage practices:

(1) Assess the temporal or seasonal changes of soil physical properties under conservation tillage practices, especially for the soil pore structure measured by some non-destructure techniques (e.g. X-ray computed tomography);

(2) Consider the effect of soil pore structure on soil water repellency. The phenomenon of SWR is described by the behavior of soil water on the soil surface under the condition of unsaturated flow most of the time, which has a strong influence on soil water movement that is affected by pore structure. Hence, only considering hydrophobic substances is unreasonable when studying the effect of SWR on soil processes (e.g. carbon sequestration, aggregate stability, and soil erosion) and it is essential to determine both pore structure and hydrophobic substances at the same time. Notably, the relative weight of soil pore structure and hydrophobic substances regarding the effect on SWR should be further studied;

(3) Reveal the mechanism of how soil water repellency influences soil hydraulic properties (e.g. infiltration) and grain yield at different degrees of precipitation under conservation tillage practices;

(4) Study the mechanism of how soil pore structure affects C storage. Some organisms (e.g. bacteria, fungi, protists, nematodes, and microarthropods) are unable to directly create pores and they depend on access via soil pore

structure. Previous studies have shown that 15-50% of soil pore spaces are inaccessible to bacteria because of critical pore diameter smaller than 0.2 μm, which prevents bacteria to access carbon sources. Similar results can be also found for other soil organisms. In addition, the solid phase comprises 90-99% mineral elements and a combination of organic compounds to mineral phases can further restrict the accessibility of C sources to microbes. All these could be influenced by soil pore structure (pore size, critical pore diameter, connectivity, and surface area);

(5) Establish the relationship between soil pore structure and soil biodiversity. Soil aeration, water content, and food accessibility constrained to soil structure are three major drivers of microbial diversity and community composition. Soil pore structure could affect the three factors to select for certain microbial species and communities and then promote microbial diversity. Besides, soil pore structure could limit the mobility of mesofauna species resulting in their co-existence and the survival of weak competitors, which also increase soil biodiversity;

(6) Reveal how SWR affects crop yield combined with some soil properties (e.g. soil water availability, soil pore structure, aggregate stability, and soil organic carbon). Some previous studies had found that drought could increase SWR and the degree of SWR increase with a decrease in soil water content. Hence, it is essential to increase the focus on studies of the impact of tillage management on SWR under rainfed agriculture because climate extremes and drought severity increase as global warming intensifies;

(7) Study the effect of climate and soil texture and type on crop yield and further propose the adaptional conditions of specific tillage management. Agricultural climate resources (e.g. rainfall, radiation, and heat) have a direct influence on the agricultural production process, particularly the distribution of these climate resources play a critical role during the crop growth period. Soil texture and type is also another important factor for the adaption of tillage practices. Therefore, understand the effect of climate and soil texture and type can improve agricultural production and avoid some disadvantages produced by tillage management.

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Appendix-Publications

Scientific publications

(1) First author:

Li, S., Wu, X., Liang, G., Gao, L., Wang, B., Lu, J., Abdelrhman, A. A., Song, X., Zhang, M., Zheng, F., Degré, A. (2020). Is least limiting water range a useful indicator of the impact of tillage management on maize yield?. *Soil & Tillage Research*, 199, 104602. https://doi.org/10.1016/j.still.2020.104602

Li, S., Lu, J., Liang, G., Wu, X., Zhang, M., Plougonven, E., Wang, Y., Gao, L., Abdelrhman, A. A., Song, X., Liu, X., Degré, A. (2020). Factors governing soil water repellency under tillage management: the role of pore structure and hydrophobic substances. *Land degradation & Development*, 1-14. https://doi.org/10.1002/ldr.3779

Li, S., Lu, J., Wu, X., Liang, G., Zhang, M., Plougonven, E., Gao, L., Wu, H.,Wang, Y., Xu, H., Han, Z., Degré, A. (2020). Effects of long-term tillage management on grain yield and some physical parameters: Insight to soil water repellency. *Geoderma.* (Major revision)

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