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Effects of tillage alteration on soil water content, maize crop water potential and grain yield under subtropical humid climate conditions**

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A b s t r a c t. Seasonal drought stress is common in farmland even under humid climate conditions. Low soil water content and high penetration resistance in clayey soil are both factors that limit crop growth, which is significantly affected by tillage. In a two-year (2014-2015) field experiment conducted in Hubei, China, the effects of conventional tillage, along with occasional deep tillage and no-till, on the soil water content and penetration resistance values of red soil and on the crop water potentials of the maize crop (*Zea mays* L.) were tested. Compared to conventional tillage, deep tillage reduced the difference in the soil water characteristic curve between 0-40 cm soil layers, resulting in a more loose and homogeneous topsoil. The deep tillage significantly ($p<0.05$) decreased soil penetration resistance, increased soil-available water content and soil water content during the dry period, promoted an increase in maize root density by 11.4~31.6%, and increased the water potential of the maize root and leaf during most growth stages. In contrast, the effect of no-till was opposite to that of deep tillage, reducing maize grain yield by 25.3~26.3%. The results confirmed that no-till is not appropriate for the clayey red soil but rather that tillage is needed. This suggests that occasional deep tillage is helpful in mitigating seasonal crop drought stress under the conditions of a humid climate.

K e y w o r d s: soil penetration resistance, occasional deep tillage, no-till, seasonal drought

INTRODUCTION

There are many factors that limit crop growth in soils. Drought stress is a predominant cause of low yields worldwide (Bodner *et al.*, 2015). Even in humid regions, short-term drought may also result in crop loss (Bodner *et al.*, 2015; O'Connell *et al.*, 2018). In the farm system, it has been reported that drought stress may be ameliorated by tillage practices. Conservation tillage which includes a variety of reduced and no-till (NT) techniques has increasingly been adopted as the agricultural best management practice to relieve crop water stress and increase yield. For example, the practice of no-till agriculture, which is usually associated with soil cover, can improve soil hydraulic conductivity (Wu *et al.*, 1992; Benjamin, 1993; Feiziene *et al.*, 2018), increase soil water content (θ), crop water potential, and yield (Al-Darby *et al.*, 1987; Wang *et al.*, 2014; Kühling *et al.*, 2017). Under no-till cultivation with straw mulching, the daily average value of the leaf-water potential (ψl) of spring wheat was higher than those under other tillage treatments (Li *et al.*, 2012), indicating that the no-till policy improved the crop water status.

However, a no-till policy may not be an agronomic and environmental panacea in all situations. Many studies have reported the negative effects of a continuous no-till policy on soil and on crops. For example, a no-till policy appears to have a limited positive effect on soil hydraulic properties (Blanco-Canqui *et al.*, 2017), but it may cause the stratification of soil organic C and lack the effective control of herbicide application (Schlegel *et al.*, 2020), poor soil physical condition for crop growth due to macroporosity reduction (Tormena *et al.*, 2017) and lower crop yield (Romaneckas *et al.*, 2020). In some regions, conservation

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tillage practices did not increase or decrease crop yield but deep tillage (DT) was beneficial (Liu and Wiatrak, 2012; Salem *et al.*, 2015; TerAvest *et al.*, 2015). In their review, Schneider *et al.* (2017) summarized that deep tillage slightly increased yield, but individual deep tillage effects were highly site-specific, including an approximately 40% yield depression observed after deep tillage. Studies have shown positive, negative or an absence of net effects of tillage on soil and crop yield. The different results of tillage practices under a range of conditions imply various interactions among the different soil types, climate factors, and management practices (Strudley *et al.*, 2008).

Apart from the drought stress effects on crops in farmland, high soil mechanical resistance or penetration resistance (PR) is another crop yield-limiting factor. Soil PR stress is not an uncommon abiotic stress in many clayey and compact soils (Whalley *et al.*, 2008; Tracy *et al.*, 2011; Gao *et al.*, 2012; Arvidsson and Håkansson, 2014). In farmland, the PR increases dramatically with soil drying and becomes a significant stress on crop growth along with drought stress (Whitmore and Whalley, 2009), resulting in a combined abiotic stress. In some drying soils, the effect of PR on crop growth is greater than the direct effect of water stress (White and Kirkegaard, 2010). Conservation tillage practices with no-till can strengthen the soil compaction condition rapidly and consequently increase PR. Tillage practices have a significant impact on both soil θ and soil PR. The total effects of tillage alteration on the soil are not immediately apparent during the short transition period, but soil θ and PR can be changed rapidly, thus, the immediate effects on crop growth cannot be ignored.

In the subtropical humid areas of southern China, there is limited documentation available concerning the effects of tillage practices on soil conditions. In this area, the soil is characterized by distinct wet and dry conditions due to the subtropical monsoon climate with abundant annual precipitation. The clayey soil has poor physical and chemical properties, such as low pH, low fertility, low available water content, low hydraulic conductivity and low air permeability, which limit crop performance. Because of the poor physical properties of the soil, even intermittent drought may cause severe harm to crops. In order to optimize the complex interactions between these various conditions, soil properties such as texture, mechanical resistance and water holding capacity must be considered when adopting a tillage method in a farm system with due attention to their site-specific interactions.

Therefore, it is necessary to reveal the immediate effects of tillage changes on soil properties and crop performance, particularly tillage effects on soil water content during the dry season. The hypothesis of the research assumed that occasional deep tillage which was used as an alternative to conventional tillage (CT) can mitigate the effects of short-term drought stress on crops in clayey red soil in a humid climate. The aims of this study were to (1) investigate the immediate effects of occasional deep tillage and no-till on the soil water retention curve, θ and PR in the field, and (2) investigate the effects of occasional tillage alteration on maize crop root distribution in the soil, water potential of maize root and leaf, and grain yield. Thus, this study attempted to evaluate the appropriate tillage practices in clayey soil to alleviate seasonal drought under the conditions of a humid climate.

MATERIALS AND METHODS

The experiment was carried out at the Red Soil Experimental Station, Huazhong Agricultural University. The station (30.01678 N, 114.36638 E) is located at Xianning, Hubei province, China, it is characterized by a subtropical humid monsoonal climate with distinct wet and dry seasons. In the last 30 years, the annual average air temperature is 16.6°C, with the lowest value of 4°C in January and the highest value of 28.7°C in July. The average potential evaporation is 1497 mm and precipitation is 1 474 mm, of which 46.1% or 680 mm occurs in the wet season from April to June. But only 21% or 318 mm falls in the dry season from July to September, when the potential evaporation is as high as 619 mm (annual 41.4%). Hence, seasonal or intermittent drought occurs frequently in the summer and autumn (especially during August and September), causing adverse effects to local crops including soybean, peanut, and maize. The surrounding terrain is gentle hills with an average elevation of 44.3 m above sea level, but the farmland is flatter.

The soil is derived from Quaternary red clay and classified as red soil in China (equivalent to Ultisol in the Soil Taxonomy System of the USA or Haplic Alisol in the World Reference Base for Soil Resources), it is characterized by a high clay content, deep profile, and a high degree of compaction. The clayey soil has poor physical and chemical properties, with a high bulk density (1.43 g cm^{-3}), low organic matter content (2.38 g kg^{-1}) and low available N (22.98 mg kg^{-1}) and P (5.89 mg kg^{-1}) nutrient contents on average at depths of 0-40 cm (Table 1). In particular, this soil has a high <0.002 mm clay content (>54%) and low available water content (~0.10 g g^{-1}) with an average wilting point of 0.216 g g^{-1} at a depth of 0-40 cm. These characteristics indicate that the clayey red soil is highly sensitive to drought.

The experimental field has been planted with a maize crop with winter fallow annually since 1998. The maize crop was sown in June and harvested in October; a conventional tillage of the soil was performed to a depth of 0.18 m with a wide blade plough driven by local farm cattle and fertilization was implemented before sowing. The tillage depth of 0.18 m is the same as that of conventional tillage performed by farm machinery or by farm cattle in the local cropland. The rectangular field was divided into plots that had dimensions of 2.7 × 12 m as determined by a cement ridge; all of the plots were subject to the same field management techniques.

Table 1. Selected properties of the clayey red soil before the experiment

Soil depth (cm)	Particle size distribution (%) 2-0.05	0.05-0.002	<0.002	Bulk density	Organic matter	Alkeline N	Oslen P	Available K	pH
	(mm)			($g\ cm^{-3}$)	($g\ kg^{-1}$)	($mg\ kg^{-1}$)			
0-10	7.77	37.42	54.81	1.37	3.11	22.51	2.94	143.77	6.52
10-20	7.91	36.28	55.81	1.45	2.31	21.59	8.99	134.33	6.72
20-30	8.88	28.51	62.61	1.41	1.96	23.57	6.04	64.00	6.36
30-40	8.78	29.28	61.94	1.48	2.14	24.23	5.57	47.87	5.27
Mean				1.43	2.38	22.98	5.89	97.49	

A two-year (2014-2015) experiment was conducted to test the immediate effects of tillage alteration on the soil and maize crop. The conventional tillage practice was temporarily shifted to three distinct tillage treatments for this study. (1) Conventional tillage (CT), the soil was consistently subjected to an annual till to an 0.18 m depth as before. (2) Deep tillage (DT), the soil was occasionally subjected to an annual till by a wide blade plough but with a 0.30 m depth. (3) No-till (NT), the maize was planted directly into the soil without plough out. The no-till practice is suggested in order to reduce soil erosion in cropland in this region. Each tillage treatment was repeated three times in a total of nine plots.

Each plot received the same amount of chemical fertilizer which was applied in a small shallow hole near the plant at the time of sowing, based on the conventional rate in this area. The nitrogenous fertilizer was urea which was applied at a rate of 140 kg ha^{-1} (N), the phosphorous fertilizer was ordinary superphosphate and was applied at a rate of 120 kg ha^{-1} (P_2O_5), and the potassium fertilizer was potassium sulphate applied at a rate of 140 kg ha^{-1} (K_2O). Maize (*Zea mays L.*, Zhengdan 958) crops were planted on 3 July and 29 June, and harvested on 8 October and 2 October, in 2014 and 2015, respectively. The crop was grown at a rate of 55 000 plants ha^{-1} after thinning, with a total of 180 plants in each plot. Weed control was primarily implemented by using bentazone herbicides (CAS No. 25057-89-0).

A weather station was installed beside the experiment field; the rainfall and air temperature were recorded automatically. The monthly precipitation and temperature values are shown in Fig. 1, indicating the obvious dry and wet periods occurring over the two-year experiment. Less rain fell in 2015 (1 254 mm) than in 2 014 (1 353 mm), with distinct wet and dry seasons in both years. The precipitation during the dry season from July to October was 454.2 mm in 2014 and 241.3 mm in 2015. Thus, a more obvious seasonal drought period was observed in the drier year of 2015. Hence, in the dry seasons of the two years, the maize crop suffered from soil water shortages to a varying degree.

At the beginning of the experiment, soil samples were collected before tillage and the physical and chemical properties were measured using conventional methods.

Field measurements were conducted at different growth stages of the maize crop. In order to test the immediate effects of tillage changes on the physical properties of soil, undisturbed soil cores were sampled in each plot using cutting rings at depths of 0.1, 0.2, 0.3 and 0.4 m at the seedling stage of the maize crop in 2015. The soil cores were used to measure the soil water characteristic curve (SWCC) using a high speed centrifuge (CR21G, Hitachi, Japan) with a special rotor for soil cores (Bassouny and Chen, 2016). The soil penetration resistance (PR) was also measured at the seedling stage by a soil penetrometer (SC-900, Spectrum Technologies, US) in each plot when the soil water content was at the field capacity. After a period of rainfall when the soil moisture was at a high level, additional water was irrigated to a small square (30 × 30 cm) in each plot, thereby

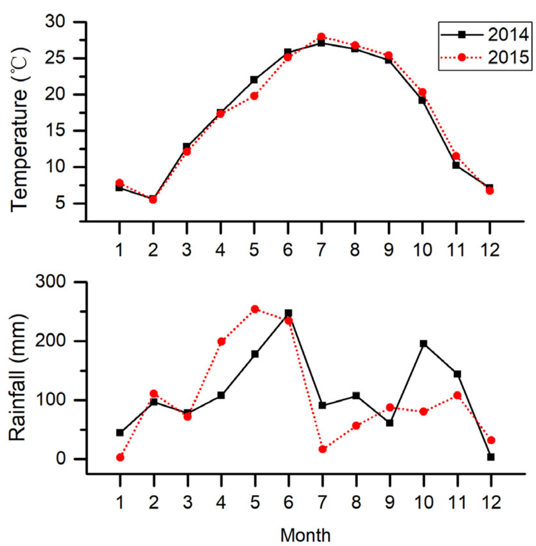

Fig. 1. Monthly air temperature and rainfall in 2014 and 2015.

ensuring that the soil water content reached the field capacity. Then, the penetrometer was inserted into the soil slowly at a constant speed until it reached a depth of 45 cm; the values of soil PR were recorded at 5 cm intervals.

At the growth stage of V12 (the 12th leaf, about 28 days after emergence), V16 (the 16th leaf), and VT (tasselling, about 60 days after emergence), the soil samples at a depth of 0.1, 0.2, 0.3 and 0.4 m were collected by an auger in each plot. The soil water content (θ) was measured using the drying and weighing method. At the same time as θ was measured, the crop leaf water potential (ψl) was also measured using a plant pressure chamber (1505D, ICT International, US) at the V12, V16 and VT stage, respectively. The measurement was performed at the fourth leaf (not too wide) from the top on three plants in each plot. All of the ψl measurements were conducted in the morning before 7:00 AM.

At harvest time in September or October, all maize grains were collected, air-dried in the laboratory for two weeks, dried in an oven at 40°C for 8 h, and then weighed to obtain the yield. After the maize crop harvest, the root distribution in the soil profile was measured. In order to collect the maize crop root sample from each plot, a soil column with a diameter of 15 cm that surrounded a plant was dug up manually with a shovel at depths of 0-10, 10-20, 20-30, and 30-40 cm. Within the removed soil column, the second-order lateral roots of the plant were collected and the fresh tips were selected for root water potential (ψr) measurement using a plant pressure chamber. The removed soil column at each soil depth, plus the roots that have been measured for ψr, were immersed in a basin of water for half an hour and then washed repeatedly in a 1 mm sieve. The water-washed root was dried at 60°C in the laboratory, accordingly, the root mass density was calculated based on dry weight.

A statistical analysis was performed using IBM SPSS 19.0 Windows (SPSS Inc., Chicago, USA). The significance of the differences between the treatments was calculated with a one-sample test. All tests were conducted at the 5% significance level.

RESULTS

There were differences in the soil water characteristic curves (SWCC) between the depths, with the highest water holding capacity at the 30-40 cm depth and the lowest at 20-30 cm (Fig. 2). After the alteration of tillage from CT, the difference in SWCC immediately reduced in DT by homogenizing the soil. Compared to CT, DT also slightly increased the soil water field capacity (θ at a matric potential of -30 kPa) and available water content (AWC, the difference between the matric potential of -30 kPa and -1 500 kPa) at a depth of 0-40 cm. In contrast, NT amplified the difference in SWCC between the soil layers of 0-40 cm, and decreased the AWC to 0.097 g g^{-1} on average compared with a value of 0.107 g g^{-1} under CT.

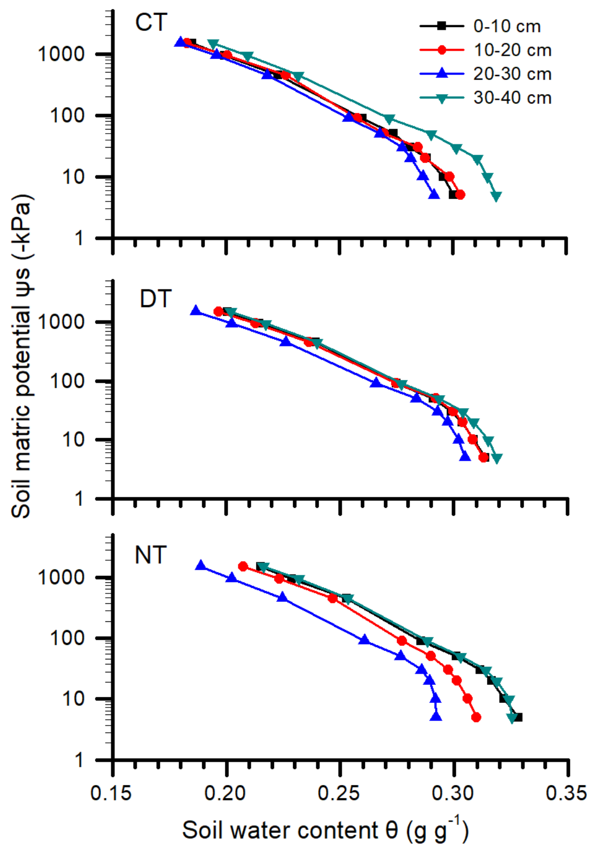

Fig. 2. Soil water characteristic curves (SWCC) under the three tillage treatments CT – conventional tillage, DT – deep tillage, NT – no till.

The clayey red soil had a high PR value which is unfavourable to crop growth. The soil PR (at field capacity) significantly increased after the shift of CT to NT, while it did not change significantly after the CT shift to DT (Fig. 3a). During the growth of the maize crop in 2014 and 2015 (Fig. 3bc), soil PR increased notably due to the soil θ decrease (lower than the field capacity), especially at the soil depth of 0-20 cm. In the drier year of 2015, the soil PR at a depth of 15-20 cm exceeded the value of 2.0 MPa, which is the critical value that would considerably impede the elongation of the crop root in soil. In addition, the peak value of PR appeared at a depth of around 0.15 m in 2014 but shifted down to a 0.20 m depth in the drier year of 2015, showing that the high PR zone became thicker due to soil drying.

The drier weather in 2015 resulted in lower soil moisture for the three tillage treatments, but the soil water shortage during the dry season was mainly observed in the topsoil. As shown in Fig. 4, soil θ clearly increased with depth. With the growth of the maize crop and the continuation of the drought period, the soil θ gradually decreased. At the growth stage of V16 and VT, the soil θ (0.149 g g^{-1}) was less than the wilting point (0.191 g g^{-1}) at the topsoil of 10 cm. At the most vigorous growth stage and maximum

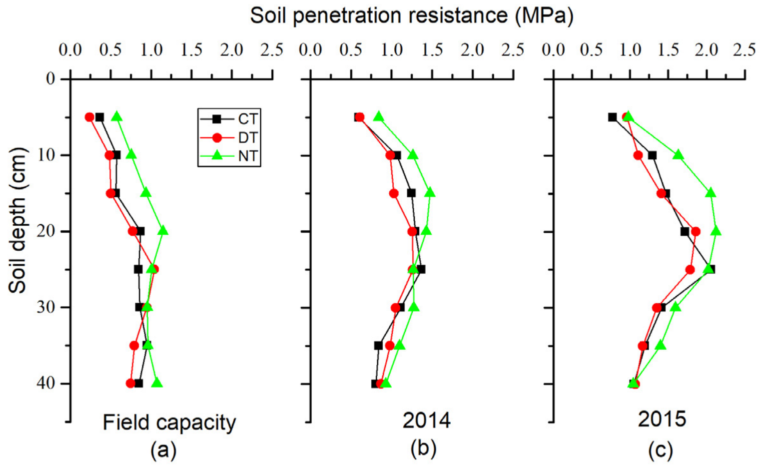

Fig. 3. Soil penetration resistance under different soil water content: a) on field capacity, b) at 12th leaf stage in 2014 and c) in 2015. Other explanation as in Fig. 2.

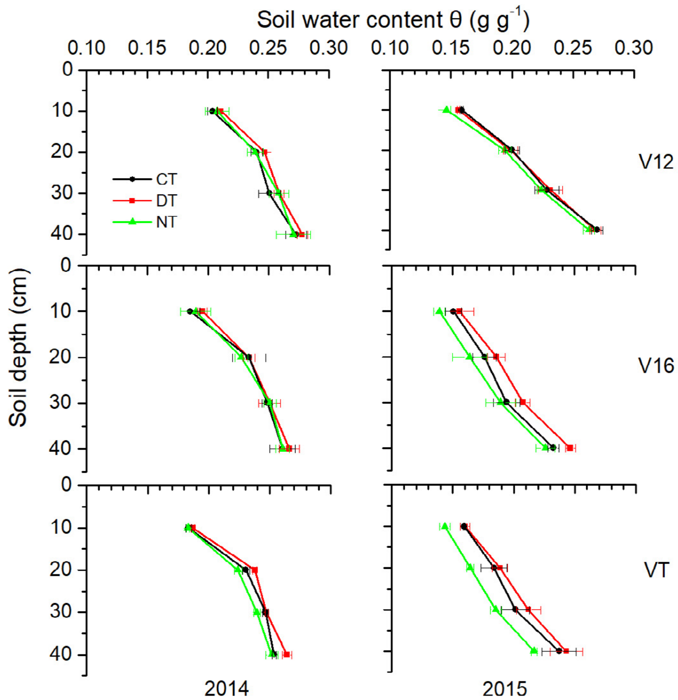

Fig. 4. Soil water content at the growth stage of V12 (12th leaf), V16 (16th leaf) and VT (tasselling) of the maize crop in 2014 and 2015. Other explanation as in Fig. 2.

soil depth, soil θ in the root zone was significantly different between the tillage treatments ($p<0.05$). A higher θ was observed in DT (0.224 g g^{-1}) than in CT (0.219 g g^{-1}) and NT (0.211g g^{-1}). The differences in soil θ between the tillage treatments were magnified in the drier year of 2015 and at the drier period of the VT stage, showing that tillage had more significant effects on soil θ in a drier soil condition.

The root system of the maize crop mainly developed in the shallow layer of the clayey red soil. On average, 55, 70 and 95% of the root weight were distributed at a depth of 0-10, 0-20 and 0-40 cm, respectively (Fig. 5). In the topsoil of 0-10 cm, the average root weight density was 2.42 mg cm^{-3} in the drier year of 2015 which was lower than that of 3.16 mg cm^{-3} in the normal year of 2014 ($p<0.05$). Even though these values were the highest ones measured as compared with the deep soil, the root density was actually very low. At a depth of 0-40 cm over the two years, the root weight density was lower with a mean of 1.21 mg cm^{-3}. At a depth below 40 cm, no obvious root was found, and the root weight density was negligible.

The alteration of tillage significantly changed the root weight density in the soil at a depth of 0-40 cm. The NT treatment decreased the root weight density by 23.3 and 18.7%, while DT increased by 11.4 and 31.6%, in 2014 and

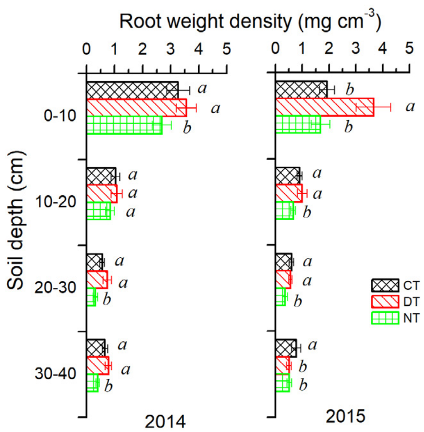

Fig. 5. Maize root weight density in the soil profile in 2014 and 2015. The different lower case letters indicate that there were significant differences between the tillage treatments at the same soil layer. Other explanation as in Fig. 2.

2015, respectively ($p<0.05$). The changes in root weight density were mainly observed in the topsoil of 0-10 cm, in which DT promoted but NT restrained maize root growth. At a depth of 20-30 and 30-40 cm, the effects of tillage on root weight density were reduced. The results showed that there was a negative correlation between root weight density and soil PR (Figs 3 and 5).

Maize crop water potentials (root water potential, ψr, and leaf water potential, ψl) changed with the growth stage, tillage, and year (Fig. 6). In the drier year of 2015, ψl was significantly lower (with a larger negative value) than that of 2014. Despite the different weather conditions in the two years, tillage treatments had a significant influence over ψr and ψl alike in both years. Generally, for a total of 12 cases (ψr and ψl at 3 growth stages in 2 years), DT increased while NT decreased maize crop water potentials, this change was significant ($p<0.05$) in 9 cases and insignificant in only 3 cases. For example, DT resulted in the highest ψr and ψl (smaller negative value) at the growth stage of V12, V16 and VT in both years. On the contrary, the NT treatment resulted in the lowest ψr and ψl in both years. The results showed that the alteration of tillage had immediate effects on the crop water potential, in particular, the shift to NT worsened the soil crop water relationship in the dry period.

There was a significant difference between the maize grain yields in the two years, with lower yields in the drier year of 2015, as shown in Fig. 7. In the same year, tillage treatments influenced the grain yield significantly. Compared with the CT treatment, NT significantly ($p<0.05$) decreased grain yield by 26.3 and 25.3% in 2014 and 2015, respectively. On the contrary, DT increased the grain yield, but the difference was not statistically significant ($p>0.05$).

DISCUSSION

The two-year field experiment showed that there were distinct wet and dry seasons in the red soil region of the humid monsoon climate. In the dry season of summer to autumn, soil water content (θ) in the root zone was low but the deep soil θ was still high. Unfortunately, the water in the deep soil layers cannot be absorbed directly by the maize crop due to its shallow root system. Therefore, the crops were vulnerable to seasonal drought, which was

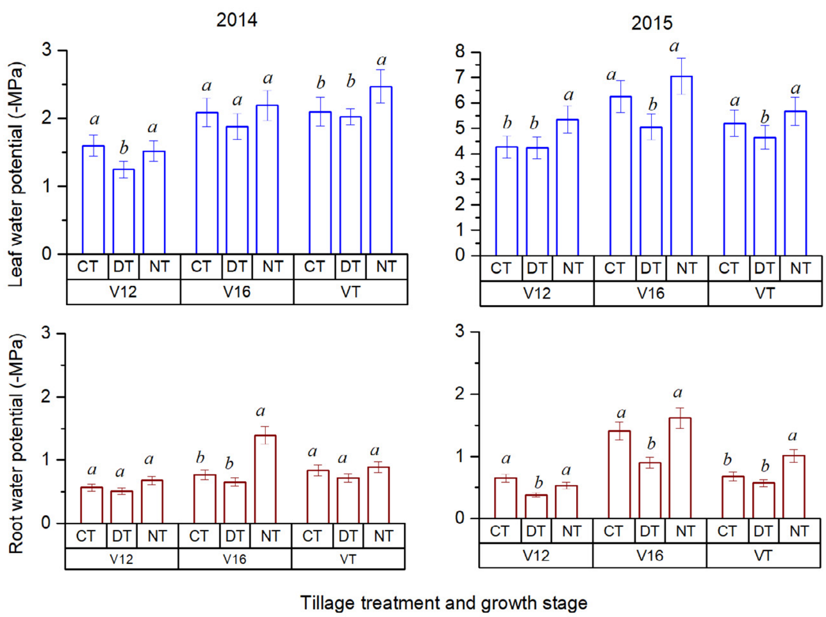

Fig. 6. Root water potential (below) and leaf water potential (upper) at V12 (12th leaf), V16 (16th leaf) and VT (tasselling) growth stages under different tillage treatments in 2014 and 2015. The different lower case letters indicate that there were significant differences between the tillage treatments at the same growth stage. Other explanation as in Fig. 2.

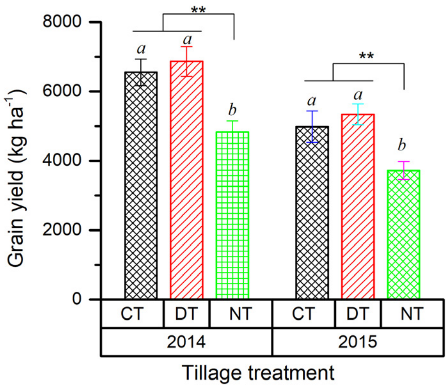

Fig. 7. Maize grain yields of tillage treatments in 2014 and 2015. The different lower case letters indicate that there were significant differences between the tillage treatments ($p<0.01$) in the same year. Other explanation as in Fig. 2.

characterized by a water shortage that only occurred in the topsoil. The present study shows that the alteration between conventional tillage (CT) and no-till (NT) or to deep tillage (DT) significantly influenced the topsoil water content, maize crop root growth, crop water potential, and grain yield. These influences should be taken into account in efforts to mitigate seasonal drought using tillage practices.

As an important crop management practice, tillage has manifold influences on both the soil and crops, which are subjected to the local climate, soil type, soil water status, and tillage time (Sağlam *et al.*, 2014). In order to balance the effect of different tillage practices, occasional tillage, also termed as "one-time tillage", has been evaluated as a potential tillage practice (Nunes *et al.*, 2015; Blanco-Canqui and Wortmann, 2020). Some researchers (Çelik *et al.*, 2019; Schlegel *et al.*, 2020) showed that occasional tillage increased the macro and total porosity compared to no till. Similar results were obtained in this study. Occasional deep tillage (DT) increased the soil available water and homogenized the soil at the 0-40 cm depth, thereby increasing soil θ. On the contrary, no-till (NT) significantly decreased θ. However, this result is inconsistent with some reports in arid and semi-arid regions (Kahlon *et al.*, 2012; Aziz *et al.*, 2013; TerAvest *et al.*, 2015). Salem *et al*. (2015) reported that the highest soil θ was recorded under no-till in central Spain. In Athens, the no-till system was associated with significantly higher soil θ throughout the observation period, this was caused by the vetch mulch (Karamanos *et al.*, 2004). It should be noted that these no-till practices are usually associated with mulch (*e.g.*, crop residues), which is the main reason for the increase in θ (TerAvest *et al.*, 2015). Strudley *et al.* (2008) it was also reported that the associated management of the mulch played a key role in the θ value. No mulch was involved in this study; the reasons that DT increased soil water levels included the local humid climate and relatively high soil θ in the deep soil layer.

Under the conditions of a subtropical moist monsoon climate, DT in the clayey soil increased the shallow soil θ in the dry season for two reasons. Firstly, compared to no-till, DT (and CT) increased the number of macropores of the topsoil, which is equivalent to adding a loose surface with mulch. This loose surface is conducive to reducing the evaporation rate in the dry season. In contrast, NT can result in compact soil, reduced soil porosity and enhance the connectivity of the soil pore system under dry conditions, thus increasing the evaporation rate and decreasing θ. It should be noted that the effect of DT on increasing θ only operated well during a short dry period when the deep soil still had a high moisture level, which is usually the case in a humid climate. Secondly, compared to NT, DT (and CT) improved the hydraulic properties of the soil by homogenizing the soil profile (Fig. 1). Therefore, the homogenized soil can promote the movement of the deep water upward and retain more water in the root zone. Martínez *et al.* (2016) reported that the soil pore system showed a slightly higher specific diffusivity in the topsoil after mouldboard ploughing as opposed to no-till. Sağlam *et al.* (2014) also reported that for heavy clayey soils, tillage practices which included ploughing were thought to develop the physical soil qualities of root development and water movement.

The immediate effects of tillage alteration were not limited to soil θ; soil PR was also significantly influenced by tillage. In this study, a soil PR of 5 MPa was observed at 20 cm depth in the dry season. Under high soil PR conditions, the maize roots were limited to a shallow soil profile, with more than 70% of the total roots restricted to a depth of 0-20 cm, and almost no root was found below 40 cm. This root system architecture does not have any significantly harmful consequences for the crop during the wet season, however, it can easily induce crop drought stress during the dry season. This study shows that the maize crop root weight density was negatively correlated with soil PR among the various tillage treatments. The CT shift to DT reduced soil PR and increased the distribution of crop roots in the soil, thereby improving the crop-water relationship.

The maize crop water relationship, expressed in terms of ψr and ψl, were improved by DT in this study. In contrast, it has been reported that maize ψl was generally higher for no-till compared to conventional ploughing (Lal *et al.*, 1978). In the arid west of the Loess Plateau China, compared to conventional tillage, the five conservation agricultural patterns, including no-till, increased the ψl and leaf relative water content of the crops (Wang *et al.*, 2014). This study, however, shows that compared to CT, maize ψr and ψl increased with DT and decreased with NT. Such inconsistency is not surprising, considering that θ increased and PR decreased as a result of the two tilling treatments (CT and DT) used in this study. In fact, the different results produced by tillage under a range of conditions implies that there are various interactions between climate factors, soil types, and management practices (including mulch and tillage). It has been reported that soil compaction (with high PR) decreased the ψl of triticale and maize (Grzesiak, 2009), other researchers reported that soil PR has no effect on changes in crop ψl (Goodman and Ennos, 1999). But even so, it has been confirmed that root system architecture and morphology are largely influenced by soil PR (Bengough *et al.*, 2011; Tracy *et al.*, 2011; Valentine *et al.*, 2012; Andersen *et al.*, 2013). As a consequence, the change in root system architecture may affect the crop water relationship. This study implies that there is a strong possibility that increasing soil PR amplifies the effect of drought stress which is reflected by lower crop water potential. The present study confirmed that deep tillage can mitigate the effects of drought stress on the maize crop not only by increasing soil θ but also by decreasing PR in the root zone.

Colombi *et al.* (2018) reported the existence of a vicious circle between soil PR, root architecture, water uptake and crop growth, which suggests that the interaction between the factors have to be accounted for when developing strategies to alleviate water limitations in cropping systems. Maize, whose root growth was more heavily restricted by soil compaction compared to triticale showed a greater degree of damage to the physiological characteristics of its leaves (Grzesiak *et al.* 2013). In this sense, soil PR can change crop water potential via changes to the root system architecture. The DT which reduced soil PR before the dry season in a subtropical humid climate helps the plant to cope with seasonal drought and to increase the yield by deepening the root system, while NT acts in the opposite way. It has been reported that a significant decrease in maize yield occurs when NT is used in the short-term due to soil compaction and a higher maize yield was attained with conventional tillage (Liu and Wiatrak, 2012; Salem *et al.*, 2015). The present experiment clearly demonstrated that NT reduced the maize yield by decreasing θ and increasing PR in the clayey soil.

CONCLUSIONS

1. The two-year field experiment verified the hypothesis that seasonal drought stress on crops can be influenced by tillage management. Occasional deep tillage or conventional tillage improved maize crop root developing in clayey red soil, and is therefore helpful when developing strategies to alleviate the seasonal drought stress.

2. Occasional deep tillage or conventional tillage can increase soil water content in a dry period not only because it improves the soil hydraulic properties by homogenizing the root-zone soil profile but also because a high soil water content exists in the deep soil layer in the conditions of a subtropical humid climate.

Conflict of interest. The Authors do not declare any conflict of interest.

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