Soil & Tillage Research 146 (2015) 286–295

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Tillage practices effect on root distribution and water use efficiency of winter wheat under rain-fed condition in the North China Plain

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ARTICLE INFO

Article history:
Received 2 April 2014
Received in revised form 3 September 2014
Accepted 18 September 2014

Keywords:
Tillage practices
Root growth
Soil water content
Water use efficiency
Grain yield
Winter wheat

ABSTRACT

Water shortage has limited the agricultural sustainable development of North China Plain (NCP), where winter wheat (*Triticum aestivum* L.) is the major irrigated crop that consumes 60–80% of available deep groundwater for agriculture production, leading to the significant decline in groundwater resource. The protection of water resources is important for the sustainable development of agriculture in NCP. The objective of this study was to evaluate the effect of plow-tillage (PT), rotary-tillage (RT) and no-tillage (NT) on root growth, water consumption characteristics, grain yield, water use and water use efficiency (WUE) under rain-fed condition conducted in a field with 20-year of rotary tillage history. Findings of this research show that plow-tillage (PT) and rotary-tillage (RT) decreased the soil bulk density in the 0–20 cm soil depth and the penetration resistance in the 0–30 cm soil depth. During two growth seasons, PT had greater root weight density (RWD), root length density (RLD) and root surface density (RSD) than those under NT across the 0–110 cm soil profile at the tillering stage and in the 0–40 cm soil profile at the flowering stage, respectively. However, RWD, RLD and RSD of PT were lower than NT at 0–10 cm soil depth and greater at 10–20 cm soil depth at the ripening stage. Similar trends were observed under RT compared with NT. Soil water content (SWC) under PT and RT were lower compared with NT from tillering to flowering stage across 0–110 cm, but higher than under NT in 0–20 cm soil profile at ripening stage. Evapotranspiration (ET) values under PT were higher than under NT from sowing to flowering stages, but significantly lower at the ripening stage. Moreover, tillage practices had no notable influences on pre-planting soil water storage and total ET under rain-fed condition during two growing season, but PT significantly enhanced grain yield through higher spike number and grain weight compared with NT, which led to higher WUE under PT. The findings of this study show that PT practice can reduce soil bulk density and penetration resistance at the tillage zone, which can lead to greater RWD, RLD and RSD and greater ET from tillering to flowering stage. This can increase plant population and cause greater WUE and grain yield under rain-fed condition.

1. Introduction

The shortage of water resources worldwide becomes a limiting factor for agricultural development, which can lead to severe threat to the global food security. The North China Plain (NCP), covering approximately 18.3% of the national total farm lands and producing approximately 25% of the total grain yield in the country, is the largest region of agricultural production in China (Zhao et al., 2013). However, the decrease in available water results in a great crisis in the sustainability of NCP agriculture production and contribution to China's food supply. Currently, rivers in this region have been depleted of water and about 70% of the water need for agricultural production depends on groundwater (Brown and Halweil, 1998). As a result, there is persistent decline of water table that has been caused by excessive exploitation of groundwater resources from shallow and deep aquifers for irrigation. Even in the significant zones of groundwater depression, such as

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http://dx.doi.org/10.1016/j.still.2014.09.016
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Shijiazhuang, Cangzhou and Tianjin, etc., the groundwater table depth is declining by one m/year in the northern part of the NCP during the last 20 years (Jia and Liu, 2002).

The annual double-cropping system of winter wheat-summer maize is the dominant cropping system in NCP, and the average annual water consumption is about 450 mm for wheat and 360 mm for maize (Liu et al., 2001). Due to a summer monsoon climate, the rainfall in the NCP exhibits variable spatial and temporal distributions. Approximately, 70–80% of the mean annual rainfall (550 mm) occurs in the summer (July to September), and the rainfall (early-October to mid-June) can only meet 25–40% of the wheat water requirement during the growing season (Liu et al., 2001; Zhang et al., 2006). In normal rainfall (550 mm) years, irrigation of the summer maize is not required and soil water reserves are abundant after summer maize season. However, to maintain high winter wheat yield, especially in the northern part of the NCP, where 75% of the agricultural land is irrigated, where 70–80% of the total water resource was consumed (Lin et al., 2000). Therefore, it is critically important to reduce irrigation events to save groundwater in the NCP during winter wheat growing season. To explore the water use efficiency (WUE) of winter wheat under rain-fed condition, it is very essential to establish the feasible irrigation strategy in the NCP, but little has focused on how to increase its WUE under rain-fed condition in this region.

Due to high evapotranspiration (ET) that exceeds precipitation amount in the growing season, winter wheat under rain-fed condition mainly relies on soil water storage. Soil management practices can influence conservation and use efficiency of stored water (Sarkar and Singh, 2007). According to Wang et al. (2002), deep tillage can store about 90% rainfall in the summer. In addition, deep tillage (25–30 cm) coupled with crop residue mulching can reduce surface runoff by 50% and soil erosion by 90% compared with plow-tillage (15–20 cm) without mulching, which is commonly practiced by farmers in the NCP (Jin et al., 2006). These suggest that tillage practices can affect the soil water storage in the rainy season, but few studies reports that tillage practices can modulate the use efficiency of stored water for winter wheat in the dry season.

Soil evaporation is an important component of ET and can be regulated by soil surface management, such as tillage, crop residue cover, and mulching, thus alter the WUE (Shangguan et al., 2001; Li et al., 2007a; Wang et al., 2007). Although there is a great variability in WUE as reported by several studies across different soil and climate conditions (Hatfield et al., 2001; Strudley et al., 2008), plow tillage exhibits 29% higher WUE than zero tillage for wheat in the NCP (Li et al., 2007b). Proper selection of tillage can increase water availability for crops by increasing soil water storage capacity, reducing soil evaporation and allowing a better development of root systems (Lampurlanés et al., 2001).

Root systems serves as a bridge between the impacts of agricultural practices on soil and changes in shoot function and harvested yield (Klepper, 1990). Some of the practices such is tillage affects root development and function, which by far the most important component in crop growth (Godwin, 1990). As with impact of tillage on root distribution, no-tillage causes greater and deeper water accumulation in the soil profile and greater root growth (Lampurlanés et al., 2001). Merrill et al. (1996) observes that spring wheat roots penetrate to greater soil depths under no tillage than under spring disking, with larger root length density due to the cooler soil and superior soil water conservation in the near-surface zone. However, no-tillage practice can gradually increase mechanical impediment of the surface soil, limiting the distribution of roots in the upper soil profile and root downward progression (Mosaddeghi et al., 2009). The roots are also thicker with less absorbing surface area in rotary-tilled soil than plow-tilled soil. Roots are also finer and longer roots under tilled soil compared with no-tilled soil, and are generally more abundant under plow tillage than no tillage at all depths (Karunatilake et al., 2000).

It is of great significance to understand the soil water storage contribution during the winter wheat growing season in the NCP to determine the effect of saving irrigation on groundwater decline (Liu et al., 2001; Zhang et al., 2010). Little research has focused on the influence of tillage practices on yield, WUE and root growth and spatial distribution in winter wheat under rain-fed NCP conditions. This study aimed to determine the response of winter wheat yield and root growth (root length density, root surface density and biomass) to tillage practices, evaluate tillage practices effect on soil water content and ET during the growing season, and explore the relationship between winter wheat root system and water consumption and yield under rain-fed condition.

2. Materials and method

2.1. Site description

Field experiments were conducted at Wuqiao Experiment station (37°41′N, 116°37′E) of China Agricultural University at Cangzhou, Hebei province, China, in the 2011–2012 and 2012–2013 winter wheat growing seasons. The study site is located in a warm temperate zone with semi-arid continental monsoon climate (Zhang et al., 2004; Zhao et al., 2013). The mean annual rainfall is 500–600 mm, and more than 75% of the rainfall occurs during the rainy season from June to September. Because of the decrease in rainfall and the interception of water by upstream dams, most rivers water flow has decreased significantly since 1980s. Only a few rivers can flow for a short time in the rainy season. These changes in surface water availability caused significant increase in consumption use of groundwater. Since the 1970s, groundwater has been used as a major water supply for agricultural demands. Winter wheat and summer maize is the local main cropping system, and growing season of winter wheat is from early-October to mid-June, and for maize from mid-June to early October. Prior to initiation of the experiment, the tillage systems were rotary-tillage (RT) for winter wheat and no-tillage (NT) for summer maize in the double cropping system for 20 years. Plow tillage (PT), RT and NT were conducted in 2010 before winter wheat planting. For summer maize the same tillage practices were used as with winter wheat in this experiment. The average annual temperature is 12.9 °C with 201 frost-free days. The soil texture is light loam and soil properties were measured at the beginning of the field experiments, and the soil contained 17.4 g kg^{-1} organic matter, 1.12 g kg^{-1} total N, 41.2 mg kg^{-1} available P, and 127.0 mg kg^{-1} available K at the 0–20 cm tillage layer.

2.2. Site Management and experimental design

Winter wheat (Jimai 22), a local elite winter wheat cultivar from the Hebei Province, was sown manually in 15 cm wide rows at a seeding rate of 300 kg ha^{-1} on October 8, 2011 and October 10, 2012. No irrigation was applied before sowing for both years. A completely randomized block design with four replications was used in the experiment. The plot size was 80 m^2 (8 m wide by 10 m long). In both years, all experiments received 185 kg ha^{-1} N, 207 kg ha^{-1} P_2O_5 and 75 kg ha^{-1} K_2O before sowing. Under no-till system (NT), fertilizers were placed in a narrow band using a hand hoe. The placement band was approximately 7.5 cm to the side and 5 cm below the seed-row zone. A hand-hoe was also used in planting wheat by creating 4 cm deep trench where seeds were drilled and covered with soil. Under the PT and RT systems, the fertilizer was broadcast by hand and incorporated into the soil to depth of 10 cm with secondary tillage using rotary blade. No supplemental fertilizer was applied during the winter wheat growing season.

In the no-till system (NT), crop residues after maize harvest were chopped, and approximately 0.3 t ha^{-1} maize residues (dry shoot matter) was flattened and kept on the soil surface, and only disturbance to the soil was during planting and fertilization application. The RT was done to 10 cm depth after summer maize harvest with a 1GKN-250 model rotary tiller (Yun gang xuan geng ji xie Co., Ltd., Lianyungang, Jiangsu Province, China), and 3 t ha^{-1} maize residues (dry shoot matter) were incorporated into the soil. The rotary tool bar was equipped with rotary blade spaced 75 cm apart and set of finishing disks behind the blade for breaking large soil clods. The PT involved complete soil inversion and burial of 3 t ha^{-1} maize residues (dry shoot matter) to a depth of 25 cm, by using 1L-220 model machine (Yili machine Co., Ltd., Yu Cheng, Shandong Province, China). Moreover, the 3-YHV306 V model roller (Xingtai first tractor manufacturing Co., Ltd., Xingtai, Hebei Province, China) was used to firm the soil after PT and RT to reduce water loss. In all tillage practices, within the growing season, weeds were controlled using 10% fenoxaprop-P-ethyl at the rate of 500 ml ha^{-1}.

Wheat was harvested on June 10, 2012 and June 14, 2013. All plants from two 1 m^2 plots (avoiding border rows) were harvested at ripening for the determination of grain yield in each plot. From this sample, spikes per m^2, grain number per spike and 1000 grains weight were determined, and grain yield per m^2 was oven dried at 80 °C to determine yield at 14% moisture content. Also, uniform spikes within the same flowering time were tagged. Ten spikes from each treatment were sampled every 5 day interval from flowering to maturity. Grains were threshed and grain numbers were recorded. The grains were dried at 80 °C to constant weight and single grain weight was calculated.

2.3. Root sampling

Roots were sampled at tillering stage (157 days after sowing (DAS) in 2011–2012 and 144 DAS in 2012–2013), flowering stage (212 DAS and 213 DAS) and ripening stage (249 DAS and 245 DAS) in 2012 and 2013, respectively by taking soil cores according to Li et al. (2010). Each treatment was sampled by collecting soil cores with a hand-held auger at three separate locations in planting rows. The diameter of the corer was 8 cm and cores were obtained at 10 cm increments down to 110 cm. The soil cores were soaked in plastic containers and poured into a sieve (0.25 mm^2 mesh size). The sieve was suspended in a large water bath and shaken continuously until the roots were washed free of soil. Soil materials remaining on the sieve were removed manually. The live roots (white or pale brown) on the sieve were separated from the organic debris and dead roots (dark color) afterwards according to Gregory (1994). Root image from each core was obtained using a scanner (Epson V700, Indonesia). The images were analyzed using the software WinRHIZO version 5.0 (Regent Instruments Inc., Quebec City, Canada). The root length density (RLD, cm root cm^{-3} soil), root surface area density (RSD, cm^2 root cm^{-3} soil) and root weight density (RWD, mg root cm^{-3} soil) were calculated (Mosaddeghi et al., 2009; Li et al., 2010; Qin et al., 2006). Root dry weight was determined after drying in an oven at 65 °C for 48 h.

2.4. Soil bulk density and penetration resistance

The soil bulk density was measured at jointing stage using metal rings (inner diameter 8 cm, length 5 cm) method was used to measure soil bulk density (Doran and Jones, 1996). The cores were taken at depths of 0–10, 10–20, 20–30, and 30–40 cm at two sites per plot. The penetration resistance was measured with hand-held TJSD-750 model electronic cone penetrometer (Zhejiang TOP Instrument Co., Ltd., Hangzhou, Zhejiang Province, China). The penetration resistance was measured at 10–40 cm soil depths.

2.5. Soil water content and evapotranspiration

Soil water content (g g^{-1}) was determined gravimetrically at sowing, tillering, jointing (189 DAS and 177 DAS in 2011–2012 and 2012–2013, respectively), flowering and ripening stages. Soil samples were taken from 0 to 200 cm soil depth at increments of 20 cm by using a 5 cm diameter soil auger, and dried at 105 °C to constant weight. The total water consumption (ET) during the whole season was calculated according to water balance equation

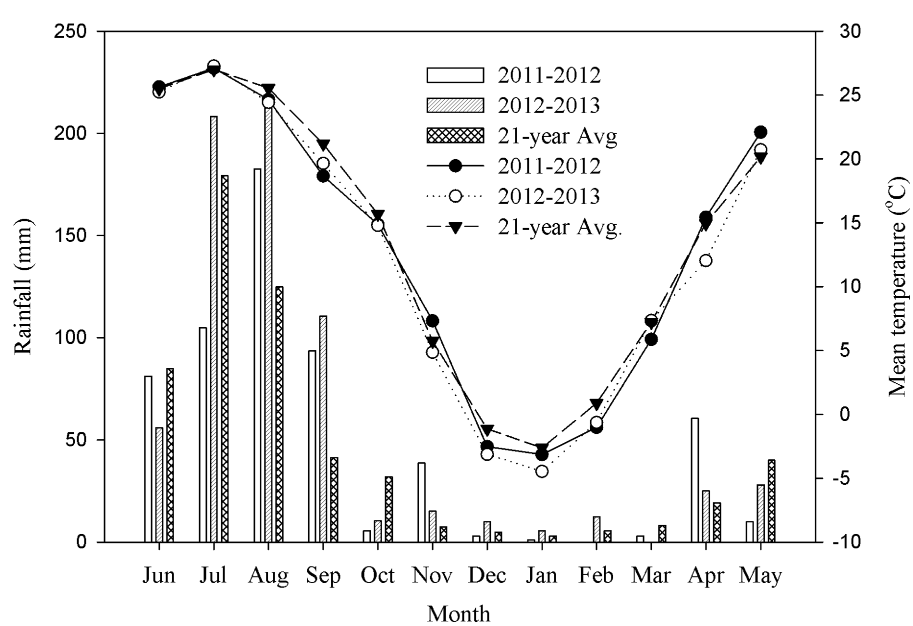

Fig. 1. Monthly rainfall distribution (Bar) and mean temperature (Line) all over the year in 2011–2012 and 2012–2013 and the 21-year average.

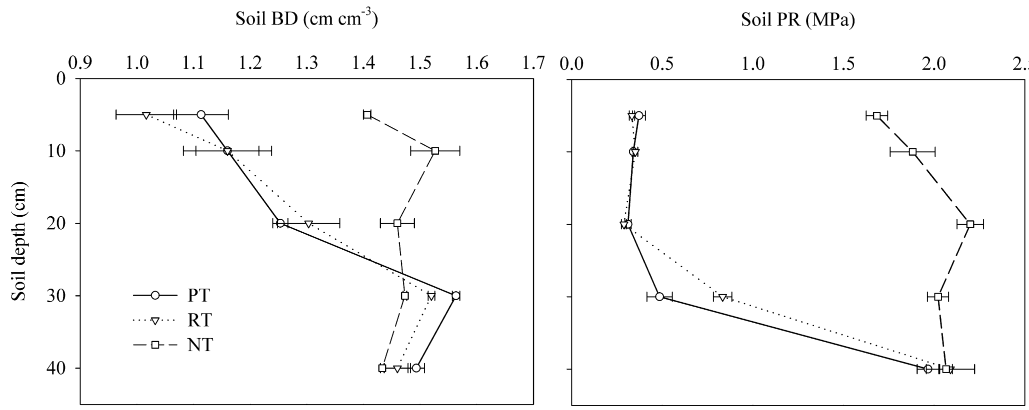

Fig. 2. Effect of different tillage practices on soil bulk density (BD) and penetration resistance (PR) in the 0–40 soil depth at jointing growth stage in 2012–2013 winter wheat growing season. Horizontal bars are standard errors.

described below (Bandyopadhyay et al., 2005; Saleh et al., 2008):

$$ET = P + I + SW - R - D$$

where ET is the total soil water consumption (include soil evaporation and plant transpiration); P (mm) is the rainfall and I (mm) is irrigation amount (here $I = 0$), respectively; R (mm) is the surface runoff, which was assumed as not significant; D (mm) is the water drainage below the crop root zone, which was negligible since soil moisture measurements indicated that drainage at the site was insignificant; SW (mm) is the soil water change from sowing to maturity.

That is crop consumptive use of water in soil moisture from 0 to 200 cm soil depth, including soil water evaporation and crop transpiration, is equal to ET. The water consumption at different growth stages was also examined according to equation $ET = P + SW$, in which ET is water consumption at different growth stage; P is rainfall; and SW is the soil water change between different growth stages.

Water use efficiency (WUE, kg ha^{-1} mm^{-1}) was calculated by the equation: WUE = grain yield/ET according to Wang et al. (2011).

2.6. Data analysis

The experiments were carried out under randomized complete block design with four replications. All the data were subjected to analysis of variance using the general linear model procedures of SAS statistical software (V8, SAS Institute Inc., Cary, NC, USA). Treatment means separation were based on Fisher's-protected least significant difference (LSD) at the 0.05 level of probability.

3. Results

3.1. Weather conditions

Total rainfall during October–June winter wheat growing season was 144.4 mm in 2011–2012 and 134 mm in 2012–2013, which was 8.7% and 0.9% greater than that of 21-year average

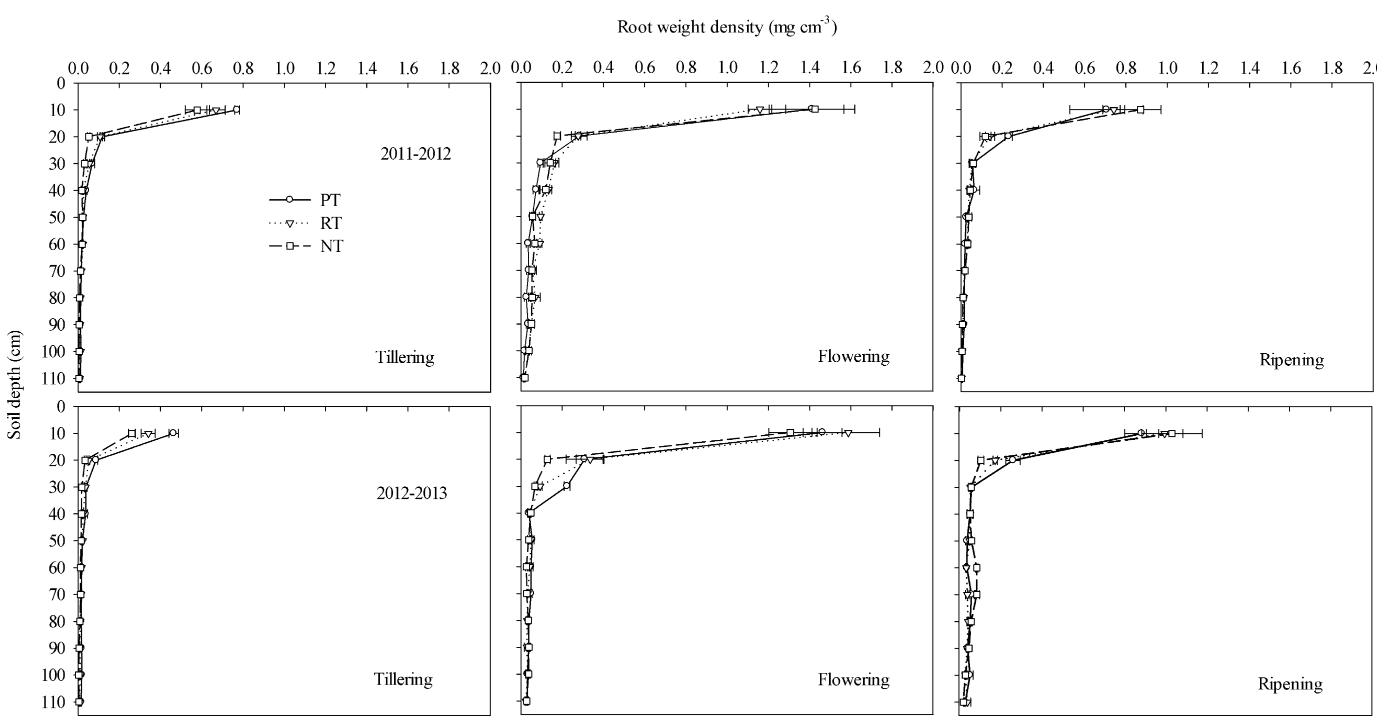

Fig. 3. Effect of different tillage practices on root weight density at tillering stage (157 DAS in 2011–2012 and 144 DAS in 2012–2013), flowering stage (212 DAS and 213 DAS) and ripening stage (249 DAS and 245 DAS) in two winter wheat growing seasons. Horizontal bars are standard errors.

rainfall (Fig. 1), respectively. Rainfall distribution within the growing seasons was highly variable and the coefficients of variation (CV) for rainfall distribution were 130.7% in 2011–2012 and 66.6% in 2012–2013. There was no difference in rainfall between sowing and tillering (October–March) during the two winter wheat growth seasons and the 21-year average. From the booting stage until ripening (May–June), the rainfall was 45.3% in 2011–2012 and 8.1% in 2012–2013, lower than the 21-year average rainfall, respectively. This distribution pattern during winter wheat growing season had affected the water requirements needs for winter wheat. Total rainfall during the June–October maize growing season was 439.6 mm in 2011 and 564.5 mm in 2012, which accounted for 76.8 and 81.3% of the annual rainfall, respectively. The average annual rainfall in the area over 21 years was 478.3 mm during June–October, and was 8.8% higher than that in 2011 and 65.2% lower than that in 2012 during the summer corn growing season. Rainfall in July and August represented 65.4 and 75.3%, respectively, of the total rainfall in 2011 and 2012, which met the maximum water need for corn growth season period.

Mean temperatures during winter wheat growing reason ranged between 8.2 °C and 9.2 °C across the two years. Minimum winter temperature ranged between −3.1 °C and −1.0 °C in 2011–2012 and between −4.5 °C and −0.6 °C in 2012–2013. During the grain filling period (May–June) the mean temperature was 23.5 °C in 2012 and 22.2 °C in 2013 (Fig. 1). The mean temperature in April 2013 was below the long-term average (21-year). The mean of maximum temperature was in July in these two years, but the mean of temperature during maize grain filling and maturity period (August–October) was lower in 2011 and 2012 than that of 21 years average.

3.2. Soil surface properties and root biomass

Changes in soil physical properties induced by tillage practices, such as soil bulk density and penetration resistance were observed. The tillage practices significantly influenced the bulk density and penetration resistance in the 0–40 cm soil depth (Fig. 2). The soil bulk density under NT in the 0–20 cm soil depth was higher than that of PT and RT, but it reversed in the 20–40 cm soil depth. The penetration resistance under NT was higher than that under PT and RT in the 0–30 cm soil depth, but no difference in penetration resistance between the tillage practices at the 40 cm soil depth.

The tillage practices significantly affected root biomass across 0–110 cm soil profile for all growth stages and years (Fig. 3). Root weight density (RWD) under PT and RT was higher than that under NT over the whole soil profile at the tillering stage during the two growing seasons. At the flowering stage, RWD under PT had greater values than that with NT at 10–110 cm soil profile in 2011–2012 and at 0–80 cm (except for 30–40 cm) soil depth in 2012–2013. At the ripening stage, RWD under NT was higher than that under PT and RT at the top 10 cm soil depth, but lower compared to that under PT and RT at the 10–20 cm soil depth. Otherwise, there was no significant difference between tillage practices in the 30–110 cm soil profile (except for 50–80 cm soil depth in 2012–2013) at the ripening stage.

3.3. Root length density and root surface area density

The root length density (RLD) under PT was much higher than that under NT across the 0–110 cm soil profile at the tillering stage during the two growing seasons (Fig. 4). At the flowering stage, RLD under PT was higher at the 0–110 cm (except for 20–50 cm) soil depth in 2011–2012 and at the 0–40 cm soil depth in 2012–2013 than that under NT. At ripening stage, RLD under NT was higher than that under PT at the 0–10 cm soil depth in both growing reasons, but less than that under PT at the 10–20 cm soil depth. Moreover, RLD values showed no significant difference between PT and NT at 30–110 cm soil depth (except for NT at the

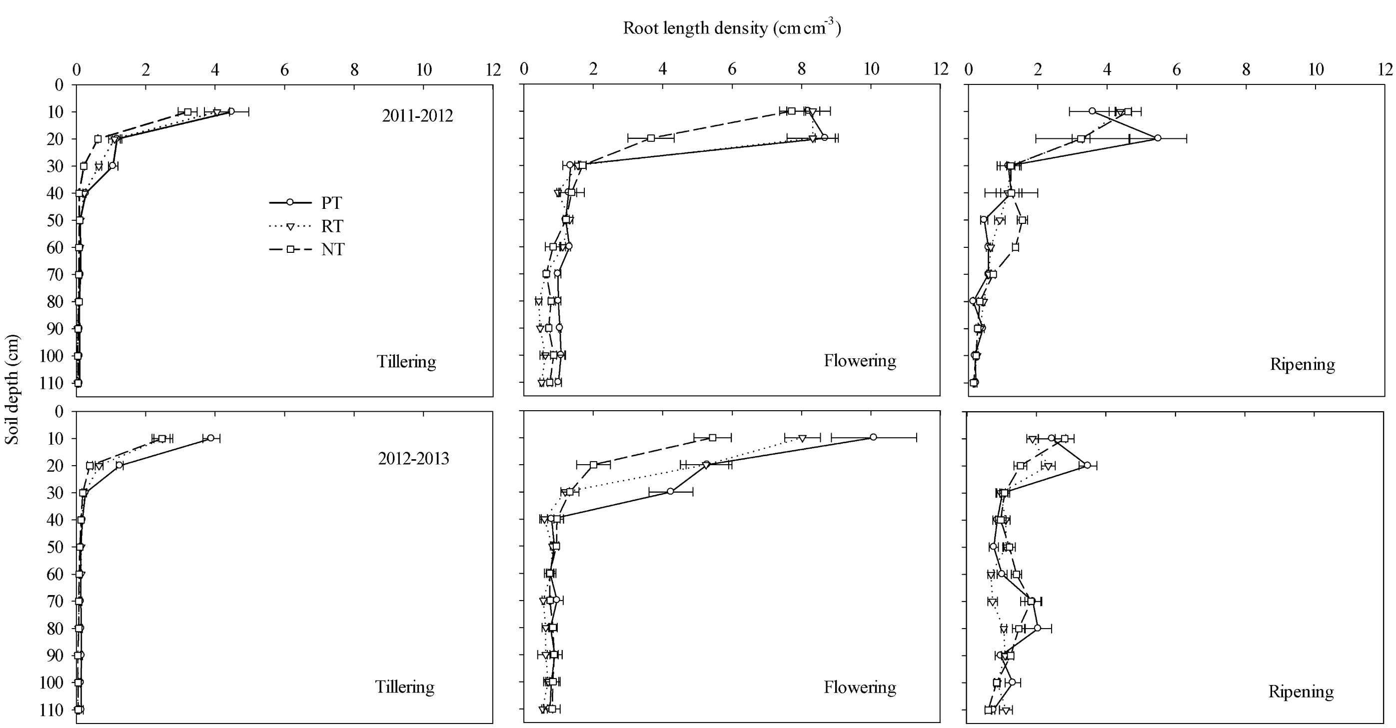

Fig. 4. Effect of different tillage practices on root length density at tillering stage (157 DAS in 2011–2012 and 144 DAS in 2012–2013), flowering stage (212 DAS and 213 DAS) and ripening stage (249 DAS and 245 DAS) in two winter wheat growing seasons. Horizontal bars are standard errors.

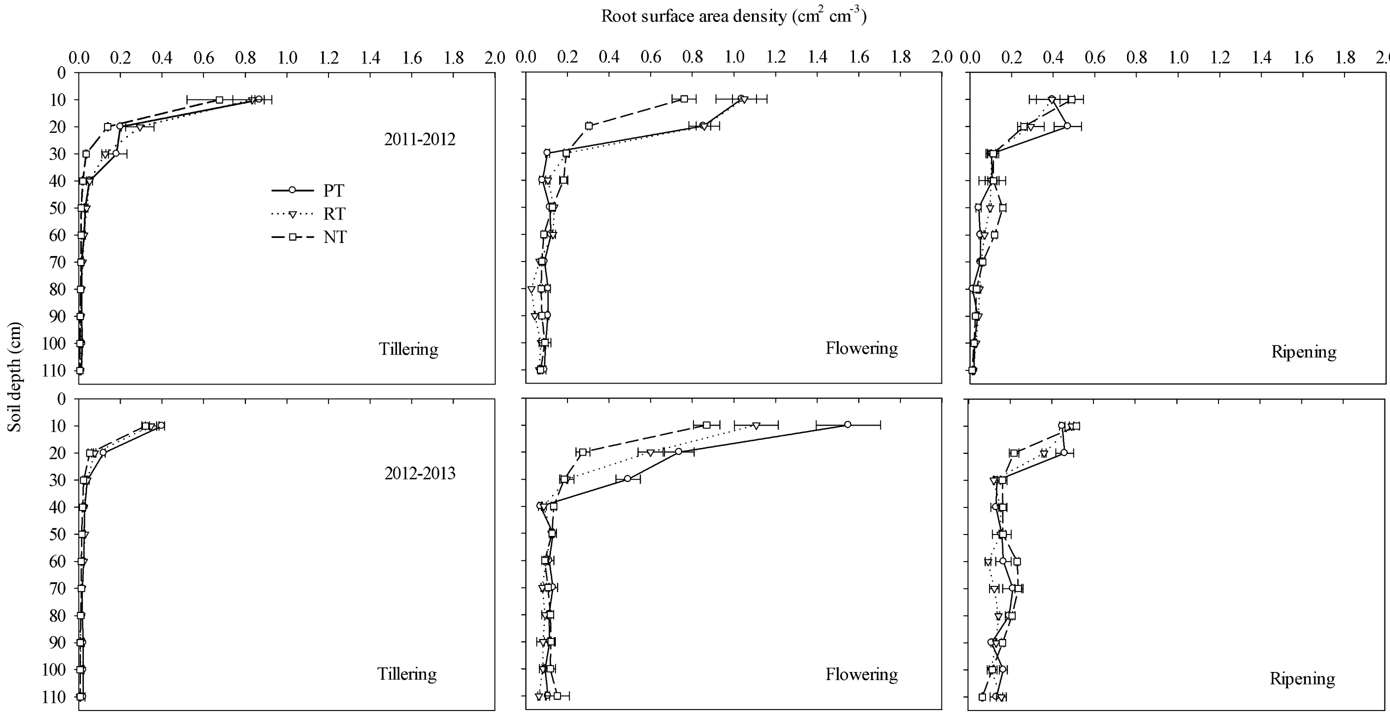

Fig. 5. Effect of different tillage practices on root surface area density at tillering stage (157 DAS in 2011–2012 and 144 DAS in 2012–2013), flowering stage (212 DAS and 213 DAS) and ripening stage (249 DAS and 245 DAS) in two winter wheat growing seasons. Horizontal bars are standard errors.

40–60 cm soil depths in 2012–2013). The RLD under RT was greater than that under NT across 0–40 cm soil depth at the tillering stage during two growing seasons (except for 0–10 com depth in 2012–2013). At the flowering stage, the RLD under RT was higher than that under NT at the 0–20 cm soil depth in both growing reasons. RLD under RT was higher than that under NT at the 10–20 cm soil depth in both growing reasons, but it was less than that under NT at the top 0–10 cm depths at the ripening stage.

Root surface area density (RSD) showed similar trend with RLD in both growing seasons (Fig. 5). The RSD under PT and RT was greater than that under NT across 0–110 cm soil profile at the tillering stage during the two growing seasons. At the flowering stage, RSD under PT was higher than that under NT at the 0–110 cm soil depth (except for 30–50 cm soil depth) in 2011–2012 and at the 0–70 cm soil depth (except for 30–40 cm soil depth) in 2012–2013, respectively. The RSD under RT was higher than that under NT at the 0–30 cm soil depth in both growing reasons, but less than that under NT at the 30–110 cm soil depth. At the ripening stage, RSD under PT and RT was less than that under NT at the 0–110 cm soil depth (except for 10–20 cm soil depth) in both growing reasons.

3.4. Water consumption characteristics and water use efficiency

Soil water contents (SWC) in the 0–200 cm soil profile were affected by tillage practices at the different growth stages during both growing seasons (Fig. 6). The SWC showed no significant difference among tillage practices at tillering stage during both growing season. The difference of SWC was observed at the jointing stage in the 0–80 cm soil depth, when NT had the largest SWC compared to PT and RT in 2011–2012, where the largest value of SWC was measured under NT compared to under PT and RT at the top 0–20 cm soil depth in 2012–2013. At the flowering stage, the SWC values under NT were significantly higher than those under PT at the 0–160 cm soil depth, except for 20–40 cm soil depth in 2011–2012 and at the 60–160 cm soil depth in 2012–2013. There was no difference in SWC through the entire soil profile, except for 0–20 and 40–60 cm soil depths between NT and RT in both growing seasons. However, the SWC value under NT was significantly lower at ripening stage in the 0–20 cm soil depth than that under PT in both growing seasons and under RT in 2011–2012 only.

Variation in SWC can affect the evapotranspiration (ET) of winter wheat in both growing seasons (Table 1). ET value under PT was significantly higher than that under NT from sowing to tillering period in both growing seasons, and it was significantly higher compared to that under RT in 2011–2012. There was no difference in ET between PT and RT practices in 2012–2013, but ET value under RT was significantly greater than that under NT. During the tillering to jointing period, ET value under PT was significantly higher than that under NT in both growing seasons, and it was greater compared to that under RT in 2012–2013. The ET value under RT was significantly greater than that under NT in 2011–2012. There was no significant difference in the ET values with all the tillage practices in 2011–2012. Also, no difference in ET value between PT and NT practices in 2012–2013 during the jointing to flowering period, while ET values under PT and NT were greater compared to that under RT in 2012–2013. However, ET value under PT was significantly lower than that under NT during the flowering to ripening period in both growing seasons. The ET value under RT was lower compared to that under NT in 2011–2012, but no difference in ET was observed between RT and NT practices in 2012–2013. In spite of the large variation in ET values across tillage practices at the different growth stages, the total ET values did not show significant difference between tillage practices in the growing season.

Tillage practices were applied on previous crop, summer maize, under rain-fed condition, which could not significantly affect pre-planting soil water storage for winter wheat in two years. The total soil water depletion in the growing season had not been significantly affected by the tillage practices in both growing seasons. The high variability in rainfall in both growing seasons affected the water use efficiency (WUE) within different tillage practices. The WUE under PT was significantly greater than that

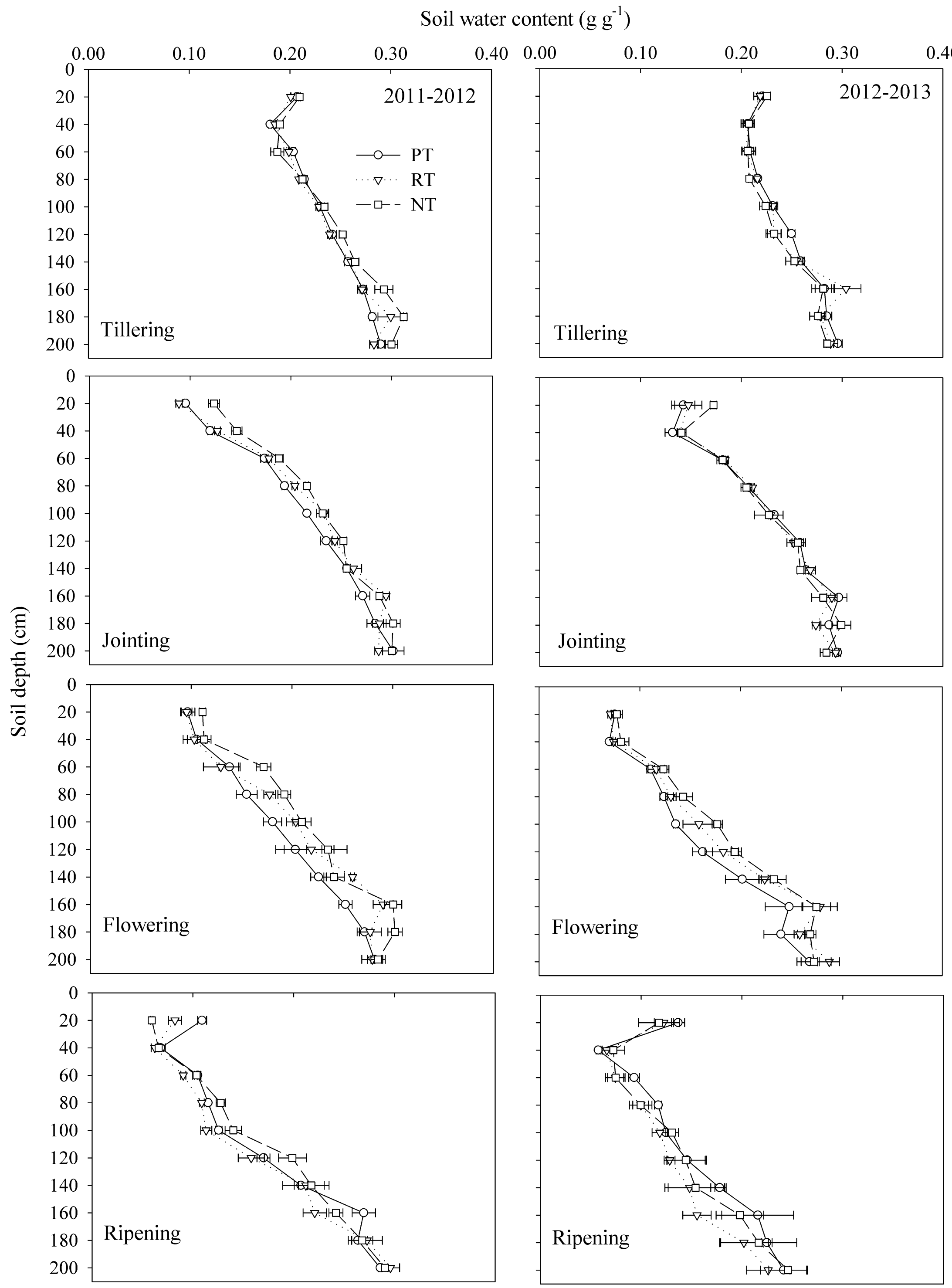

Fig. 6. Effect of different tillage practices on soil water content at tillering stage (157 DAS in 2011–2012 and 144 DAS in 2012–2013), flowering stage (212 DAS and 213 DAS) and ripening stage (249 DAS and 245 DAS) in two winter wheat growing seasons. Horizontal bars are standard errors.

under NT in both growing seasons and under RT in 2011–2012. Otherwise, the WUE under RT was 5.1 and 4.5% higher than that under NT in 2011–2012 and 2012–2013, respectively.

3.5. Shoot biomass, grain yield and other yield components

The shoot biomass, grain yield and other yield components were significantly affected by the different tillage practices under rain-fed condition. The shoot biomass under NT was greater by 3.7 and 15.9% in 2011–2012 and by 7.6 and 10.0% in 2012–2013 than that under PT and RT (Table 2), respectively. However, the grain yield of PT and RT was higher by 10.6 and 6.9% in 2011–2012 and by 5.2 and 2.7% in 2012–2013 than that of NT, respectively. The spike numbers under PT were higher by 16.9% in 2011–2012 and by 14.0% in 2012–2013 than that under NT, but there was no significant difference in spike numbers between RT and NT. Moreover, the 1000-grain weight under PT was higher than that under NT over two years, and there was no significant difference in 1000-grain

Table 1
Evapotranspiration (ET) and water consumption components at the different growth stages of winter wheat with different tillage practices.

Year	Tillage	Pre-planting soil water storage* (mm)	Soil water storage depletion (mm)	Rainfall (mm)	ET (mm)				
					Sowing-tillering	Tillering-jointing	Jointing-flowering	Flowering-ripening	Total
2011–2012	PT	649.3a	209.3a	144.4	65.2a	77.1a	100.8a	110.6c	353.7a
	RT	673.8a	229.4a	144.4	44.5b	80.6a	101.9a	146.8b	373.8a
	NT	660.9a	221.7a	144.4	44.8b	56.7b	91.6a	173.0a	366.1a
2012–2013	PT	716.8a	293.4a	134.0	97.3a	51.9a	180.4a	97.8b	427.4a
	RT	733.3a	295.2a	134.0	88.6a	36.9b	150.7b	153.0a	429.2a
	NT	741.9a	301.2a	134.0	62.7b	34.7b	174.5a	163.3a	435.2a

Means of different parameters within each column for each year with the same letters are not significantly different at $P < 0.05$.
*The depth of soil profile for water storage was same as the depth of soil for water content measurement (0–200 cm).

Table 2
Comparison of wheat yield, yield components, shoot biomass, and grain water use efficiency (WUE) under different tillage treatments in two growing seasons.

Year	Tillage	Spike number (spike m^{-2})	Grain numbers per spike (Grain $spike^{-1}$)	1000-grain weight (g)	Grain yield (kg ha^{-1})	Shoot dry biomass* (kg ha^{-1})	WUE (kg ha^{-1} mm^{-1})**
2011–2012	PT	706.3a	27.0b	41.78a	7177a	1255.7a	20.3a
	RT	615.3b	29.3ab	40.77ab	6938ab	1124.4b	18.6b
	NT	604.0b	31.8a	39.83b	6489b	1303.3a	17.7b
2012–2013	PT	741.0a	31.7b	36.46b	8208a	1311.9ab	19.2a
	RT	631.0b	33.6ab	37.95a	8017ab	1283.8b	18.7ab
	NT	650.0b	35.0a	35.21c	7804b	1411.9a	17.9b

Means of different parameters within each column for each year with the same letters are not significantly different at $P < 0.05$.
* Exclude grain dry weight.
** WUE is calculated as a ratio of grain yield/total consumptive use of water.

weight between RT and NT in 2011–2012. However, under RT 1000-grain weight was significantly greater than that under NT in 2012–2013. The grain numbers per spike under PT was lower than that under NT in two years, and there was no significant difference in grain numbers per spike between RT and NT in both growing seasons.

4. Discussion

4.1. Tillage practices effects on root distribution under rain-fed condition

The rainfall can only meet 25–40% of the winter-wheat water requirements in the NCP, which leads to the 200–300 mm water deficit during the growing season under rainfed condition (Liu et al., 2001; Zhang et al., 2006). Root growth is critical for crops consumptive use of water and subsequent yield under water-limited conditions (Robertson et al., 1993). Tillage practices are important soil management practices that impact root growth (Mosaddeghi et al., 2009). Many previous studies indicated that tillage practices influence temporal and spatial changes in soil structure, which can affect wheat root attributes under various irrigation, soil and climatic conditions in different countries (Martínez et al., 2008; Muñoz-Romero et al., 2010; Huang et al., 2012). The findings of this study showed that NT significantly increased the soil bulk density and penetration resistance compared to PT and RT at the top soil depth, significantly affected the spatial and temporal pattern of root weight density through the 0–110 cm soil profile. The PT and RT significantly improved the root weight density compared to NT in the early growth stages (before grain filling stage), but NT showed better root weight density in later growth stage. These results were consistent with Pearson et al. (1991) and Munkholm et al. (2008) under normal water supply condition.

Root morphology can greatly affect water extraction and nutrient uptake efficiencies by crops (Fageria, 2004), and ultimately yield under water deficit conditions (Robertson et al., 1993). Root length density (RLD) and root surface area density (RSD) are important parameters for characterizing root systems (Amato and Ritchie, 2002; Doussan et al., 2006). The results of this research showed that RLD and RSD under PT or RT were greater than under NT through the 0–110 cm soil profile at the tillering stage during two seasons, but RLD and RSD under PT were significantly higher compared with NT for the depth of 0–70 cm at the flowering stage. Similar results were found by Munkholm et al. (2008), where decreased in tillage intensity resulted in reduction of early shoot and root growth in winter wheat. According to Fageria (2004), the development of a vigorous root system in the earlier growth period is particularly important for crop to adapt to semiarid water deficit environments. However, RLD and RSD under PT or RT were lower than under NT for the entire 0–110 cm soil profile, except for 10–20 cm soil depth at the maturity stage during two seasons. The NT system enhanced sterile tillers (shown at high aboveground biomass) and delayed maturity in the field that could promote root growth at the grain filling stage, which led to higher LSD and RSD under NT compared to PT and RT.

4.2. Tillage practices influence on consumptive use of water under rain-fed condition

The patterns of soil water uptake and depletion are correlated with the root spatio-temporal distribution (Gardner, 1983; Clothier and Green, 1994). Tillage practices can affect water availability to crops mainly through changes of soil structure which affects root length density and spatial arrangement (Ojeniyi, 1986; Gajri et al., 1992; Tardieu et al., 1992). In this study, PT and RT significantly decreased the soil bulk density and penetration resistance compared to NT at the top soil depth, which promoted root growth in the early growth stages before grain filling stage. This led to increase in water uptake under PT and RT compared to that under NT, which resulted in lower SWC under PT and RT before the flowering stage. This is in agreement with other studies (Su et al., 2007; Alvarez and Steinbach, 2009; Cullum, 2012). The SWC under NT are higher than moldboard and rotary plowing, especially in the 0–30 com soil depth (Liu et al., 2013). However, SWC was lower under NT compared to PT and RT at ripening stage in the 0–20 cm soil depth, which could be due to greater growth at later stages and higher shoot biomass under NT. Similar results were found by Rieger et al. (2008) and Verhulst et al. (2011), where the initial crop growth is slower with NT than under minimum tillage systems, but NT has greater growth later in the growing season.

With the crop consumptive use of water requirements exceeding precipitation in the growing season, winter wheat depends largely on soil water storage, especially for rain-fed and partially irrigated winter wheat (Mugabe and Nyakatawa, 2000; Zhang et al., 2004). Even though the effect of tillage practices on soil water storage depletion showed no significant difference during the growing season, tillage practices effects on ET were observed at different growth stages. The ET values under PT were higher than under NT from sowing to flowering stage, but significantly lower later in the growing season. These might be due to extensive root system with PT at the early growth stages, but relatively less root growth at the later growth stages compared with NT. The distribution of root systems can affect the patterns of soil water uptake or depletion (Clothier and Green, 1994). Karunatilake et al. (2000) found that the higher water loss under PT is due to water uptake resulting from an extensive root system. In addition, the greater LAI under NT during grain-filling (data not shown) also may result in greater transpiration compared with RT and PT.

4.3. Tillage practices effects on yield and water use efficiency under rain-fed condition

The effect of tillage practices on winter wheat yield and WUE could be attributed to year-by-year variation in growing season precipitation and pre-planting soil water storage under rain-fed condition. Although the precipitation in 2012–2013 was less than in 2011–2012 during the growing season, the yield in 2012–2013 was significantly higher compared to that in 2011–2012. This may be due to higher pre-planting soil water storage and optimal rainfall distribution. Wang et al. (2011) found that the rainfall distribution during winter wheat growing season affects the water consumption and yield. Stored soil water accounted for 60–70% of the water consumption in the growing season. This suggested that soil water storage played an important role in winter wheat performance under rain-fed condition. This finding is in agreement with those described by Mugabe and Nyakatawa (2000) and Karunatilake et al. (2000).

Even though tillage practices had no influences on pre-planting soil water storage and ET during winter wheat growing season period, PT practice significantly increased grain yield and WUE compared to NT practice. The PT system improved the spatial and temporal pattern of root systems distribution before flowering and the RLD before flowering is positively correlated with grain yield (Lzumi et al., 2004; Chakraborty et al., 2008). Similar results also showed that sub-soiling reduced soil compaction and enhanced yield and water use efficiency (Pikul and Aase, 1999; Pikul and Kristian, 2003). Deep tillage might break sub-soil compacted layers and promote root growth and penetration, thus increasing crop production (Bennie and Botha, 1986). In addition, PT could keep winter wheat ripening properly, but NT delayed maturity which resulted in lower grain weight, and WUE, but NT had better root systems at maturity stage. However, several studies reported, no-till practice can delay plant development and maturity (Fortin, 1993).

5. Conclusion

Finding of this research indicate that tillage practices had no significant influences on pre-planting soil water storage and total ET under rain-fed condition in the NCP. However, certain tillage practices such as PT significantly enhanced grain yield through greater spike numbers and 1000-grain weight compared with NT, which led to greater WUE. The tillage practices also influenced bulk density and penetration resistance, especially in the top 40 cm of soil profile, where PT and RT decreased soil bulk density and the penetration resistance in the tilled zone (0–30 cm). Thus, greater RWD, RLD and RSD observed as compared to NT across the entire soil profile (0–110 cm) at the tillering stage and at flowering. The SWC under PT and RT were lower compared with NT from tillering to flowering stage, but higher than under NT in 0–20 cm soil depth at ripening stage. ET values under PT were higher than under NT from sowing to flowering stages, but significantly lower at the ripening stage. These findings show that PT practice can reduce soil bulk density and penetration resistance at the tillage zone, which can lead to greater RWD, RLD and RSD and higher ET from tillering to flowering stage. This can increase plant population and cause higher WUE and grain yield under rain-fed condition. The water shortage in the NCP can limit agricultural sustainability and future development in this region, particularly rain-fed or partially irrigated winter wheat production. These results indicate that plow tillage can be a feasible tillage practice for winter wheat production under the rain-fed condition to reduce further decline in groundwater recourse in the NCP.

Acknowledgements

This work was supported by the Fundamental Research Funds for the Central Universities, National Science and Technology Supporting Program (2011BAD16B15) and National Public Sector (Agriculture) Research (201203031). The authors thank Dr. Calvin G. Messersmith, Professor Emeritus, Department of Plant Sciences, North Dakota State University, Fargo, ND, USA, for technical improvement of the manuscript.

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