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

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