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Winter wheat grain yield, water use, biomass accumulation and remobilisation under tillage in the North China Plain

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ABSTRACT

We conducted a two-year experiment (2007–2009) in the North China Plain with supplemental irrigation to investigate the effects of tillage practices on the water use, biomass accumulation and remobilisation of winter wheat. Five tillage treatments were tested: strip rotary tillage (SR), rotary tillage (R), mouldboard ploughing (P), strip rotary tillage after subsoiling (SRS) and rotary tillage after subsoiling (RS). SRS significantly promoted the changes in soil water storage (ΔS) at soil depths of 60 cm to 160 cm, and the lowest ΔS level was observed in the SR treatment. The 60 cm to 140 cm soil moisture content in the SRS treatment was higher by 10.84% than that of the SR treatment before sowing in 2008–2009 and lower by 14.85% at maturity. The lowest dry matter remobilisation during grain filling (*DMR*) was detected in the SRS treatment. This value was 22.22% and 30.27% lower than those of the SR treatment in 2007–2008 and 2008–2009, respectively. However, the SRS treatment exhibited the highest contribution of dry matter accumulation during grain filling (*CDMRG*), in which high flag leaf photosynthetic rate (P_n) was observed from anthesis to maturity. The SRS and RS treatments exhibited the highest grain yields (9237.20 and 9261.31 kg ha^{-1} for two-year average) with no significant difference between the two treatments. The highest grain yields for the two treatments were 10.76% and 11.05% higher than those of the P treatment, correspondingly. The average water-use efficiency (WUE) for the two growing seasons was 20.49 kg ha^{-1} mm^{-1} in the SRS treatment, which was higher than those in the SR, R, P and RS treatments by 17.02%, 13.42%, 8.73% and 3.83%, respectively. Hence, SRS would be a preferable tillage system for planting wheat in this region.

1. Introduction

The North China Plain (NCP) accounts for approximately 50% of the wheat production in China, but this area suffers from severe water shortage (Fang et al., 2010a). A highly intensive winter wheat and summer maize double-cropping system is the dominant cropping system in the region, and this system consumes 800 mm–850 mm of water annually (Yang et al., 2015). Moreover, 70% of water resources are used to produce winter wheat (Li et al., 2005). Rainfall in the NCP presents high seasonal variability, with almost 80% rainfall during the monsoon period from June to September (Piao et al., 2010). Precipitation during the growing season of winter wheat (from October to June) ranges from 90 mm to 300 mm, which is significantly less than the estimated water requirement of this crop (Wu et al., 2006). Consequently, additional irrigation is essential to maintain high crop yield in the NCP, particularly to produce winter wheat (Fang et al., 2010a; Liu et al., 2016). Thus, proper cultivation management to improve water-use efficiency (WUE) is critical for sustainable crop production in this area (Lu et al., 2016).

Studies have suggested that conservation tillage technologies, such as no-tillage, reduced tillage and surface covering of organisms, can promote WUE by maintaining or increasing the grain yield and simultaneously reducing the seasonal evapotranspiration (SET) (Sainju et al., 2011; Verhulst et al., 2011b; Jemai et al., 2013). Conservation tillage can improve the soil structure and increase the available water in the soil profile, whilst reducing soil water evaporation, compared with conventional tillage (mouldboard plowing)

Abbreviations: DAA, day after anthesis; WUE, water-use efficiency; SET, seasonal evapotranspiration; ΔS, apparent change of soil water storage; P_n, photosynthetic rate; NCP, North China Plain.

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(Li et al., 2007; Aziz et al., 2013). However, roots tend to concentrate in the shallow soil layers, where water easily evaporates in the conservation tillage system (Martínez et al., 2008; Munoz-Romero et al., 2010). Consequently, soil compaction resulting from no-tillage has become an extensive problem (Taboada et al., 1998). This process restricts root exploration and reduces soil water storage in the soil profile (Motavalli et al., 2003). The mean weight and diameter of the soil aggregates, as well as the penetration resistance are higher without tillage (Medeiros et al., 2011; Verhulst et al., 2011a). Thus, the suitability of conservation tillage practices should be locally assessed first before their extensive application in any particular region (Su et al., 2007).

A proper tillage system should increase the amount of water available to the crop by facilitating root growth (Lampurlanés et al., 2001). Subsoiling can enhance the root growth and improve soil water infiltration (Wang et al., 2014), whilst increasing the amount of water available to the crop (Mohanty et al., 2007), by breaking up dense soil without turning over the subsoil at the top (Ma et al., 2015). Annual subsoiling was not found to remarkably enhance the soil water contents, crop yields and WUE (Zhang et al., 2009). However, long-term studies have suggested that conservation tillage coupled with subsoiling can significantly improve the grain yield and WUE of winter wheat in northern China (He et al., 2007). Ma et al. (2015) showed that subsoiling with an interval of 3 years significantly improved the soil moisture content in the 100 cm to 160 cm soil layer before sowing, compared with plowing for 6 years. Moreover, subsoiling with no-tillage after 2 years can increase the soil water storage and improve the WUE and crop yields (Qin et al., 2008). In addition, He et al. (2007) observed that subsoiling after 4 years of no-tillage can reduce the inhibitory effect of soil compaction on root growth and improve the economic benefit of winter wheat by 20.9%, compared with traditional tillage.

Conservation tillage has been proven to improve soil physical properties and increase the grain yield and WUE of winter wheat. However, limited information is available on the dry matter remobilisation under conservation tillage coupled with subsoiling. Dynamic changes in the soil moisture content in the different soil layers during the whole growing season are seldom reported for irrigated conditions. In the present study, the effects of tillage practices on soil water use, dry matter remobilisation, grain yield and WUE of winter wheat under high-yield conditions were examined by implementing strip rotary tillage, rotary tillage, mouldboard ploughing, strip rotary tillage after subsoiling and rotary tillage after subsoiling. This study aimed to elucidate the effects of tillage practices on the water consumption of winter wheat. Moreover, the response of flag leaves to photosynthesis and dry matter accumulation to tillage practices is investigated. Finally, whether the optimised tillage treatments can increase the grain yield and WUE of winter wheat was evaluated.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted during two growing seasons from 2007 to 2009 in Yanzhou (35.41°N, 116.41°E), Shandong province in the NCP. The NCP is a semi-humid region with a continental climate. The mean annual temperature is 14.1 °C. The average annual rainfall is 660.1 mm, and 70% of which occurs between July and September. Rainfall data during the 2007–2009 growing seasons are presented in Fig. 1. The soil was light loam composed of 29.6% clay, 37.3% silt and 33.1% sand, with a pH of 7.6. The chemical properties of the soil on the top 20 cm layer are listed in Table 1.

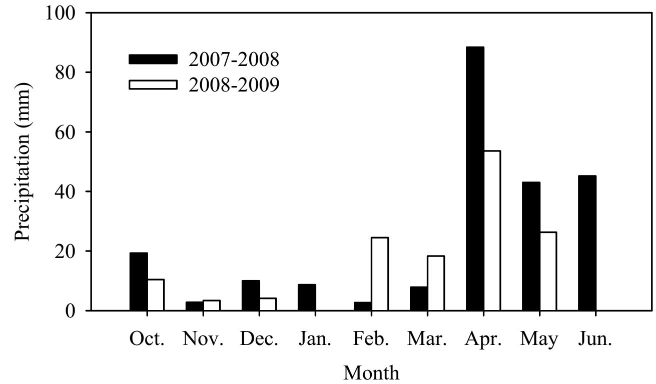

Fig. 1. Precipitation in the growing seasons of winter wheat in 2007–2008 and 2008–2009.

2.2. Experimental design

Triticum aestivum L. cv. 'Jimai 22,' which is the most widely planted commercial cultivar in the NCP, was used for the two wheat-growing seasons. The tillage treatments designed from 2007 to 2008, as presented in Table 2, were as follows: strip rotary tillage for two years (SR); rotary tillage for two years (R); mouldboard ploughing for two years (P); strip rotary tillage after subsoiling for the first year (2007–2008) and strip rotary tillage without subsoiling for the following year (2008–2009) (SRS); and rotary tillage after subsoiling for the first (2007–2008) year and rotary without subsoiling for the second (2008–2009) year (RS). The total maize straw (approximately 10000 kg ha^{-1}) was chopped in all the treatments conducted from 2007 to 2009 and left as mulch before winter wheat sowing. Each treatment was replicated thrice in a randomised complete block design. Each plot was 8 m wide and 30 m long.

2.3. Crop management

Wheat was sown on 8 October 2007 and 10 October 2008 and then harvested on 6 June 2008 and 8 June 2009, respectively. The seeds were sown at 4 cm depth with a seedling density of 180 plants m^{-2}. Urea (N content: 46.4%), diammonium phosphate (P_2O_5 and N contents: 46% and 18%) and potassium sulphate (K_2O content: 52%) fertilisers were applied as basal fertilisers during the planting stage to provide 105 kg N ha^{-1}, 112.5 kg P_2O_5 ha^{-1} and 112.5 kg K_2O ha^{-1}, respectively. Moreover, urea fertilizer with 135 kg N ha^{-1} was added during the jointing stage.

The average relative soil moisture content in the upper 140 cm soil layer increased to 70% at jointing and 75% at anthesis of the field water capacity by supplemental irrigation (SI). Soil moisture content prior to SI was measured to calculate the amount of irrigation water by using the following equation:

$$\text{Amount of irrigation water (mm)} = 10\gamma H \times (\beta_i - \beta_j) \quad (1)$$

where H is the depth of the soil layer that would be irrigated (cm), γ is the bulk density of the planned wet soil layers (140 cm) (g cm^{-3}), β_i is the target soil moisture content (%) with 70% at jointing and 75% at anthesis after supplemental irrigation and β_j is the content measured in the field by weight (%) before irrigation. Irrigation water was sprayed on the experimental plots under pressure. A flow meter was used to measure the amount of water applied.

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