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Tillage practices affect dry matter accumulation and grain yield in winter wheat in the North China Plain

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ABSTRACT

Tillage is an important management tool for tackling and promoting water conservation and improving crop yield in northern China, where winter wheat production is frequently threatened by drought. Although plowing (P) and rotary tillage (R) practices are widespread in the region, only few studies have focused on subsoiling. Three practices, namely P, R, and RS (rotary tillage every year and subsoiling interval of 2 years), were evaluated under field conditions over a period of 7 years. The average soil water consumption from RS increased by 24.6% and 69.0% compared to that from P and R, respectively, from sowing to jointing in the 40–100 cm soil layer, and increased by 54.2% and 81.6% compared to that from P and R, respectively, from jointing to maturity in the 80–180 cm soil layer. The net photosynthesis rate and stomatal conductance of flag leaf from RS treatment from 20 days after anthesis (DAA) to 30 DAA were significantly higher than those from P and R, which is likely the reason for the higher dry matter accumulation at maturity in RS than that in P and R. The 4-year average of grain yield and water use efficiency from RS increased by 22.7% and 37.0%, respectively, compared to that from P and by 7.7% and 11.9%, respectively, compared to that from R. Thus, RS is the best method for increasing grain yield and water use efficiency of winter wheat in northern China.

1. Introduction

Wheat (*Triticum aestivum* L.) is the third most commonly grown crop in the world and is grown on over 200 million ha annually (Rajaram and Braun, 2008). With an area of 320,000 ha and a population of over 200 million, the North China Plain (NCP) produces 50% of China's wheat (Zhang et al., 2005). Over the past 33 years, the grain yield of winter wheat at a specific site in the NCP has improved by more than 45% (Zhang et al., 2013). However, changes in climate, water resources and soil fertility threaten winter wheat production (Zhang et al., 2013; Garg and Dadhich, 2014; Hartmann et al., 2014). Agricultural scientists have identified tillage in the field as one of the most important agricultural management practices for improving winter wheat production (Brenna et al., 2014).

Conservation agriculture, which consists of reduced tillage and no-till practice, are important strategies for combating soil degradation through erosion and compaction in crop fields (FAO, 2008; Van den Putte et al., 2010). Compared to conventional tillage practices, such strategies are useful for protecting the soil and preventing water loss, improving crop productivity and soil fertility, as well as reducing the costs of field preparation, fuel, equipment, and labor (Wang et al., 2006). However, reduced tillage often increases soil bulk density in the top 10–20 cm soil layer in the absence of plowing; this leads to reduction in air-filled pore space (Václav et al., 2013), which is not beneficial for growing winter wheat. Moreover, although reduced tillage has no effect on grain yield in the first 3 years, grain yield decreases by as much as 31.83% in subsequent years (Jia et al., 2004). Thus, optimizing tillage practice is essential for winter wheat production.

Arvidsson et al. (2014) found that the mean relative yield of winter wheat for no-till farming was 9.8% lower than that for moldboard plowing. Brenna et al. (2014) reported that the yield did not differ between conventional tillage and reduced tillage in the first winter wheat growing season (2009), but conventional tillage produced significantly higher grain yield than reduced tillage in the subsequent season (2010). Reduced tillage produced the highest yields in 2011. The reasons for these differences are unknown and need to be investigated.

Abbreviations: P, plowing; R, rotary tillage; R, Srotary tillage after subsoiling; DAA, days after anthesis; NCP, North China Plain; WUE, water use efficiency; P_n, net photosynthesis rate; DMA, dry matter accumulation; SI, supplemental irrigation; SI_a, the amount of supplemental irrigation; SWC, soil water content; DMT, Dry matter translocation; ET, evapotranspiration.

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Table 1
Operation procedures and the equipment used of different tillage practices.

Tillage	Operation procedure
Plowing tillage (P)	Returning maize straw (about 10,000 kg ha^{-1}) to the field → Base fertiliser spreading → Mouldboard plowing once with ILFQ330 turnover plough [a] (working depth was about 25 cm) → Rotary cultivating two times with IGQN-200K-QY rotary cultivator [b] (working depth was about 15 cm) → Harrowing two times → Forming the border-check → Seeding with common seeder
Rotary tillage (R)	Returning maize straw (about 10,000 kg ha^{-1}) to the field → Base fertiliser spreading → Rotary cultivating two times with IGQN-200K-QY rotary cultivator [b] (working depth was about 15 cm) → Harrowing two times → Forming the border-check → Seeding with common seeder
Rotary tillage after subsoiling (RS)	Returning maize straw (about 10,000 kg ha^{-1}) to the field → Base fertiliser spreading → Subsoiling once with the ZS−180 vibration subsoiler [c] (working depth was about 38 cm) → Rotary cultivating two times with IGQN-200K-QY rotary cultivator [b] (working depth was about 15 cm) → Harrowing two times → Forming the border-check → Seeding with common seeder

[a] The manufacturers of ILFQ330 turnover plough is Runlian scientific and technological development Co., Ltd.
[b] The manufacturers of IGQN-200K-QY rotary cultivator is YTO Group Corporation.
[c] The manufacturers of ZS-180 vibration subsoiler is Yuncheng Gongli Co., Ltd.

Traditional tillage practices in agriculture, including plowing tillage and rotary tillage, are common in China. Plowing tillage has higher costs than other practices due to the requirement of expensive farming machinery. In contrast, rotary tillage cannot break the 20–40 cm soil layer, which stops rain infiltration and water absorption by winter wheat (He et al., 2006; Mohanty et al., 2007). Subsoiling is a process by which the hardpan layer, the compacted layer of soil, is broken without turning over the infertile subsoil at the top (Singh et al., 2013) and can improve soil structure by eliminating soil compaction, thereby increasing both yield and water use efficiency (WUE; Pikul and Aase, 1999; Pikul and Kristian, 2003). No-till farming for 4 years followed by single subsoiling reduced mechanical input by 62%, whereas annual subsoiling decreased it by only 25% (He et al., 2007).

The studies mentioned above focused mainly on one soil tillage practice, i.e. reduced or no-till tillage, rotary tillage, plowing tillage, and subsoiling, on soil structure, grain yield or WUE; however, studies on the effect of soil tillage practices, especially mixed soil tillage practices, such as rotary tillage with subsoiling, on winter wheat soil water use, photosynthetic characteristics and grain yield are limited. Accordingly, we undertook this study with the objective of assessing tillage practices: plowing tillage, rotary tillage and rotary tillage after subsoiling (at 2 year intervals) in terms of their impact on (i) net photosynthesis rate (P_n) of flag leaves, (ii) dry matter accumulation (DMA) post-anthesis, and (iii) grain yield and WUE of winter wheat over 4 years.

2. Materials and methods

2.1. Site description

The experiment was conducted from 2007 to 2014 under standard field conditions in the village of Shijiawangzi (35°40′N, 116°41′E, 55 m above sea level), Yanzhou, Shandong Province, northern China. The cropping pattern of this area is largely a winter wheat–summer maize double-cropping system, with rotary tillage (R) for wheat and no-till farming for maize, which is typical for the NCP. The loam soil in this village has been intensively cultivated for many centuries; it has a pH of 7.6 and is composed of 29.6% clay, 37.3% silt, and 33.1% sand based on the measurement descripted by Forth (1975). The organic matter content is 14.1 g kg^{-1} as determined by the hydration heat heavy acid potassium oxide—colorimetric method described by Lu (2000).

2.2. Experimental design

The field was prepared using a randomized block design with three replicates. Three tillage treatments were applied for 7 years: P (plowing tillage), R (rotary tillage), and RS (rotary tillage after subsoiling practice, with subsoiling implemented only in the 2007–2008, 2010–2011 and 2013–2014 winter wheat growing seasons, and rotary tillage practice implemented every season). The operational procedures of tillage practices and equipment used in the NCP are listed in Table 1. The experimental plot was 40 m × 4 m, with a 2-m wide isolation area preventing water penetration between contiguous plots.

In this study, data collected from 2010 to 2014 were analyzed. The nutrient conditions of the 0–20 cm soil layer before sowing are shown in Table 2. Total precipitation of the four growing seasons was 147 mm, 183 mm, 238 mm and 170 mm, respectively; the monthly precipitation is shown in Fig. 1, these data were obtained from the local meteorological bureau of Yanzhou.

Winter wheat (*T. aestivum* L.) 'Jimai 22' was planted on October 7, 2010, October 8, 2011, October 8, 2012, and October 8, 2013 and harvested on June 13, 2011, June 13, 2012, June 13, 2013, and June 6, 2014, respectively. At the sowing stage, 105 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1}, and 150 kg K_2O ha^{-1} were applied to the soil as urea, diammonium phosphate, and potassium chloride, respectively. At the trefoil stage or Z13 (when the 3 leaves unfolded), 180 plants m^{-2} remained. At the jointing stage or Z31 (when the first node is detectable) (Zadoks et al., 1974), 135 kg N ha^{-1} was applied to the soil by ditching.

Supplemental irrigation (SI) was applied at the jointing or Z31 (first node detectable) and anthesis or Z61 (beginning of anthesis) (Zadoks et al., 1974) stages of winter wheat. The amounts of irrigation during the growing seasons are shown in Table 3. The soil water content (SWC) in the 0–140 cm soil layers was tested to calculate the required amount of SI. The SWC (gravimetric water content, %) was determined using the oven-drying method (Ma et al., 2015):

$$SWC = \frac{Soil\ fresh\ weight - Soil\ dry\ weight}{Soil\ dry\ weight} \times 100$$

Table 2
Nutrient condition of the top soil layer (0–20 cm) at the experimental site.

Soil nutrient	Growth seasons				
	2010–2011	2011–2012	2012–2013	2013–2014	Average of 2010–2014
Total nitrogen (g kg^{-1})	1.06	1.01	1.14	1.23	1.11
Hydrolysable nitrogen (mg kg^{-1})	98.48	109.99	105.84	123.16	109.37
Available phosphorus (mg kg^{-1})	31.58	31.58	39.11	46.70	37.24
Available potassium (mg kg^{-1})	86.93	95.39	101.54	91.93	93.95