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Effects of tillage practices on water consumption characteristics and grain yield of winter wheat under different soil moisture conditions

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ABSTRACT

A serious water shortage is threatening agricultural sustainability in the Huang-Huai-Hai Plain of China. Long-term reduced tillage (shallow rotary tillage) has led to thickening of the plough pan, which prevents the infiltration of precipitation and inhibits the root growth of wheat. Moreover, the topsoil was usually too loose to retain soil moisture. These conditions were not conducive to the highly efficient use of limited water for wheat production. The experiment was conducted from 2011 to 2013 using a split plot design. The main plots contained five different tillage treatments, and the subplots consisted of the two following different irrigation treatments: rain fed and supplemental irrigation (SI). Subsoiling promoted soil water consumption and crop evapotranspiration as well as significantly increased the water potential (ψ_L), transpiration rate (T_r) and net photosynthesis rate (P_n) of the flag leaves. Furthermore, subsoiling increased the 1000-grain weight and grain yield of winter wheat under both the rain fed and SI conditions compared with long-term rotary tillage. Subsoiling could even increase spike number under SI conditions, but could not increase the agronomic water use efficiency (AWUE). Harrowing or moderate topsoil packing before seeding increased the water content of the topsoil, the water consumption from the deep soil layers, the P_n of the flag leaves, and the 1000-grain weight, grain yield and AWUE in plots that were subsoiled. However, excessive topsoil packing significantly decreased the ψ_L, T_r, P_n and water use efficiency (WUE_{leaf}) of flag leaves as well as the 1000-grain weight, grain yield and AWUE under both the rain fed and SI conditions.

1. Introduction

Winter wheat (*Triticum aestivum* L.) production in the Huang-Huai-Hai Plain (Shi et al., 2013) accounts for approximately 60% of all wheat production in China (National Bureau of Statistics of China, 2013). In recent years, the benefit of planting winter wheat in this area is low. In order to reduce cost, ploughs were gradually replaced by rotary tillage. However, the depth of the cultivated layer changed from 25 cm to 10–15 cm (Kong et al., 2013; Lei et al., 2011). The compactness of soil under the cultivated layer caused by traffic increased year after year, with the constant improvement of wheat production mechanization (Zhang, 2013; Jung et al., 2010). The plough pan rising and thickening gradually prevented the precipitation from penetrating into deep soil and also decreased the proliferation of wheat roots (Whitmore et al., 2011), and wheat yield (Mao, 2009). In addition, topsoil broken by rotary tillage was so loose that the soil lost water quickly through evaporation. The germination rate decreased, and the roots could not contact the soil tightly, and low temperatures and drought stress in winter killed some young winter wheat plants (Guo et al., 2009).

Drought is influenced by both the ability of the soil to capture water (infiltration rate) and to store water in its pores. Infiltration was increased by 84–400% in the absence of wheel compaction, and an increased ability to store water has also been found (Chamen et al., 2015). Taylor et al. (1966) measured the number of cotton plant taproots that penetrated compacted layers of different soils (soil types: Quinlan, Columbia, Naron and Miles) and characterized the state of soil compaction using a cone penetrometer. They found that the number of roots penetrating the soil was reduced drastically as the penetration resistance approached 2 MPa. Mechanical subsoil loosening (subsoiling) can be used to reduce soil strength beneath the plough layer, and has been shown by several investigations to increase root penetration (Marks and Soane, 1987; Hipps and Hodgson, 1988; Olesen and Munkholm, 2007). However, the physical effects of subsoiling often do not last more than 1–2 years, after which the plough pan must be

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reestablished (Hipps and Hodgson, 1988; Tessier et al., 1997). Our previous research has also shown that the 1-year subsoiling plus 2-years of strip rotary tillage helped to increase wheat yield and water use efficiency (Chu et al., 2010). Another study reported that four years of no-till operations followed by 1 year of subsoiling provided some relief from accumulated soil compaction (He et al., 2007). Other studies reported that compaction can also have positive effects on some crops, and an optimum state of compactness for plant growth may exist (Gemtos et al., 2000; Arvidsson et al., 2012). So far, few studies have focused on the effects of topsoil packing before seeding (in order to avoid soil that is too loose) on the water consumption and grain yield of winter wheat by comparing subsoiling and rotary tillage.

Numerous articles have reported that compaction mitigation or avoidance can decrease the risk of flooding in wet conditions, and could decrease the risk of drought in dry conditions (Chamen et al., 2015). The combined effects of soil moisture and physical parameters are also important concerns in crop production. Lower subsoil bulk density under deficit irrigation improved winter wheat root growth in the deep soil layer resulting in more soil water utilization (Liu et al., 2015). On the other hand, deficit irrigation reduced the soil bulk density in the deep soil layer by fostering intensive cycles of wetting/drying over the three double cropping seasons (Liu et al., 2016). We have reported a method for determining the amount of supplemental irrigation (SI) required by winter wheat (Wang et al., 2013). The amount of SI was based on the soil water content before irrigation that reflected precipitation, the level of stored water in soil and water consumption by the crop. The objectives of this study were to investigate the effects of the following factors: (1) the topsoil packing before seeding on soil bulk density, and water consumption characteristics, photosynthesis, yield and agronomic water use efficiency of winter wheat, and (2) the differences in the regulation of winter wheat under different soil moisture conditions and soil physical parameters.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted from October 2011 to June 2013 in Shijiawangzi Village, Yanzhou, Shandong Province, China (116°41′E, 35°42′N). This village is located in the center of the Huang-Huai-Hai Plain, and its environment is representative of the Plain. The area has a warm, temperate, semi-humid continental monsoon climate, annual average temperature of 13.6 °C, annual accumulated sunshine hours of 2460.9 h, annual precipitation ranging from 480 to 850 mm, annual average precipitation of 621.2 mm, and a groundwater depth of 25 m. The soil is Haplic Luvisols (ISSS, ISRIC, FAO, 1998). The organic matter, total nitrogen, hydrolyzable nitrogen, available phosphorus and available potassium in the topsoil (0–20 cm) of the experimental plots were 18.0 g kg^{-1}, 1.0 g kg^{-1}, 109.9 mg kg^{-1}, 24.3 mg kg^{-1}, and 89.4 mg kg^{-1}, respectively. The amount of precipitation during the growing seasons in 2011/2012 and 2012/2013 is shown in Fig. 1.

2.2. Experimental design

Three experimental replicates were performed in a split plot design arranged in randomized blocks. The main plots contained five different tillage treatments: long-term rotary tillage (T1), subsoiling in the first year + rotary tillage every year (T2), subsoiling in the first year + rotary tillage + harrowing every year (T3), subsoiling in the first year + rotary tillage + one pass of soil packing every year (T4), and subsoiling in the first year + rotary tillage + two passes of soil packing every year (T5). Comminuted maize straw was returned to the field, which was followed by base fertilizer spreading before tillage in T1-T5. T1 treatment has been used as conventional tillage for over 10 years in this region. One pass of soil packing and two passes of soil packing represented moderate topsoil packing and excessive topsoil packing, respectively. The operating main points of rotary tillage, subsoiling, harrowing and soil packing is as described below:

Rotary tillage: with a horizontal rotary tiller to a depth of 150 mm.

Subsoiling: with a ZS-180 vibration subsoiler to a depth of 350 mm.

Harrowing: with a spike–tooth harrow to a depth of 100 mm.

Soil packing: with a 300 kg-weight 1500 mm-length 150 mm-diameter cylinder type packer. Ground contact pressure was 19.4 kPa. The soil water content at tillage in 2011/2012 and 2012/2013 was 26.1% and 16.5%, respectively. The soil water content at packing in 2011/2012 and 2012/2013 was 24.4% and 15.3%, respectively.

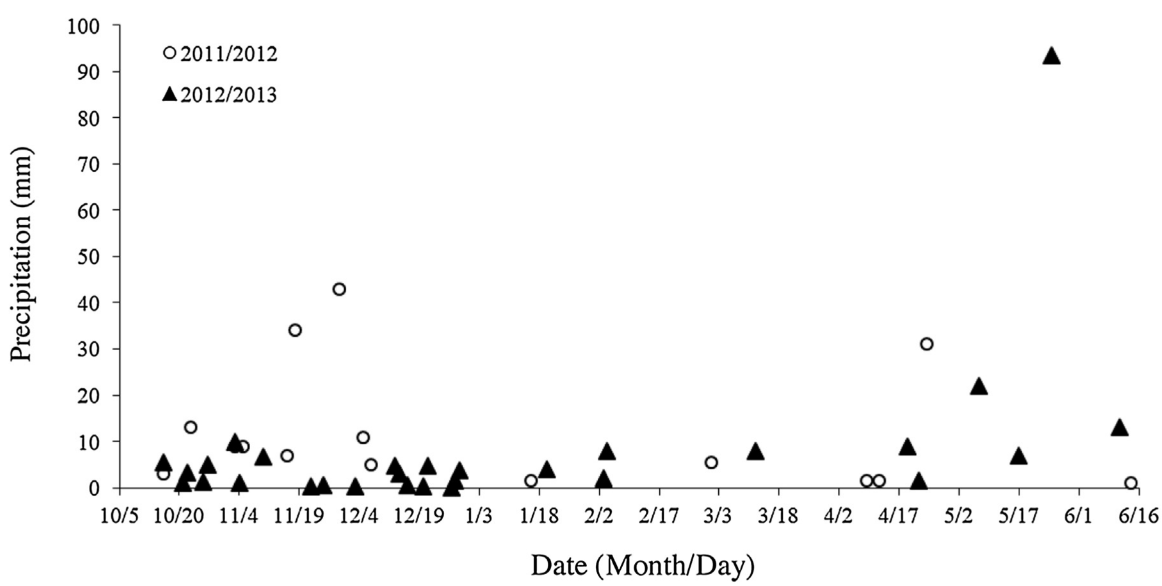

Fig. 1. Precipitation during the wheat growing season in 2011/2012 and 2012/2013.