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Effects of different irrigation regimes on soil compaction in a winter wheat–summer maize cropping system in the North China Plain

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ABSTRACT

An adjusted irrigation regime may help to minimize the risk of soil compaction, which is a major yield constraining factor in global crop production, constituting a serious issue in the winter wheat–summer maize double cropping system of the North China Plain. Thus this study aimed to evaluate the natural changes of soil penetration resistance (PR) and soil bulk density (BD) caused by freezing/thawing (FT) and wetting/drying (WD) cycles. This was tested under full irrigation (FI) and deficit irrigation (DI) over three double cropping seasons from 2011 to 2014, following a conventional tillage sequence of shallow, deep and shallow tillage before the first, second and third season, respectively. The results showed that in the deeper soil layer FT during winter reduced the PR by 22.9%, 34.7% and −18.7% under FI for the three seasons, respectively. The values under DI were 4.5%, 8.0% and −33.8% for the three seasons, respectively. However the compaction alleviating effects due to FT were only of temporary nature. Furthermore FI caused a stronger recompaction after deep tillage compared to DI, mainly attributed to increased slumping of soil. On the contrary DI reduced the BD by 8.4% in the deep soil layer by fostering intensive cycles of WD over the three double cropping seasons. Results also showed that DI resulted in a higher physical quality of subsoil, expressed by the value of S, compared to FI. It was concluded that irrigation intensity should be reduced after deep tillage to minimize and slow down subsequent recompaction.

1. Introduction

Soil compaction due to intensive farming conducted with heavy loading machinery has become a major limiting factor for crop production in many parts of the world (Hamza and Anderson, 2005; Tracy et al., 2011). As soil compaction reduces soil porosity and increases soil bulk density (BD) (Becerra et al., 2010), water movement in the compacted soil is restricted and potential root growth is hindered (Bengough et al., 2006; Lipiec and Hatano, 2003). Furthermore, nutrient uptake by the root system is reduced in compacted soil layers (Ahmad et al., 2009). Therefore, soil compaction hinders the growth of the root system, which results in reduced above-ground biomass and consecutive yield losses (Tubeileh et al., 2003; Ma et al., 2013).

Generally the BD larger than 1.55 g/cm^3 in a silt loam soil is considered to impede crop growth (Kaufmann et al., 2010). However, the effects depend on the specific soil type and crop management. Subsoil compaction can be reduced by natural physical processes such as freezing and thawing (FT) and wetting and drying (WD) cycles, as well as by biological activity (Håkansson et al., 1987). Among all soil faunas, earthworms are considered the most important factors for improving soil structure (Whalley et al., 1995). However, all major agronomic management factors driving earthworm abundance, i.e. fertilization and residue handling (Zhiping et al., 2006), were kept constant over all experiment treatments in the current study. Thus the focus of the current study was on investigating the physical processes related to soil compaction and alleviation of compaction, while potential impacts of biological activity were not investigated.

The NCP is one of the most important regions for crop production in China, though suffering from severe water shortage (Fang et al., 2010). The highly intensive winter wheat and summer maize (WW–SM) double cropping system is the dominant cropping system of the region. Due to insufficient and seasonally unbalanced precipitation, additional irrigation is essential to ensure crop growth and yield formation in this double cropping system, especially during winter wheat production season (Liu et al., 2013). Generally, additional irrigation should lead to reduced soil compaction (Vaz et al., 2001, 2013). However, opposing results are reported by previous studies. Porter et al. (1999) observed no effect of supplemental irrigation on soil compaction, while Bhattacharyya et al. (2008) observed an effect of irrigation timing on soil compaction in rice fields. Zhang et al. (2013) even observed an increased BD after alternating flooding and drying cycles. The contradicting results are most likely related to the concrete irrigation regimes and soil characteristics of the specific studies. Irrigation affects soils'

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pore structure and related water infiltration capacity through altering hydraulic stresses (Peng et al., 2007). Soil porosity is reported to increase (Bodner et al., 2013) or decrease (Sarmah et al., 1996) depending on the specific characteristics of WD cycles and soil type. The effectiveness of FT cycles is considered higher under lower soil temperature, higher soil moisture and larger amplitude of FT (Oztas and Fayetorbay, 2003). This shows that different irrigation regimes exert different effects on soil compaction. It is of crucial importance to specify the effects of alternative irrigation regimes on soil compaction to guide local agricultural management. Yet, there are very few relevant studies and insufficient knowledge on this issue in the NCP.

Moreover, all mechanized crop management measures (e.g. sowing, harvest) are conducted twice as often in the double cropping system compared to alternative single cropping systems (e.g. cotton or spring maize), which exert a strongly increased risk of soil compaction in this system. Furthermore, a tremendous increase in agricultural mechanization occurred in the NCP over the last decades leading to a strongly increasing risk of machine induced soil compaction (Feike et al., 2012). Consistently shallow tillage using heavy machinery (local farmers' tradition) tends to increase BD in the below tillage soil layer in the NCP (Zhang et al., 2004, 2012). Deep plowing is an effective way to break the plow pan and is thus recommended every 3–5 years to reduce the soil compaction (He et al., 2007). However it is expensive and energy intensive, and its benefits may be short-lived due to potential recompaction in deeper soil layers (Botta et al., 2006). Abundant precipitation may increase this risk of recompaction after deep tillage (Busscher et al., 2002; Hao et al., 2011), resulting in potential yield reductions (Arvidsson et al., 2013). Thus it is important to synchronize irrigation and tillage within the WW–SM system under the soil and climatic conditions of the NCP to successfully manage soil compaction and realize more sustainable agricultural production.

Therefore, the specific aims of the current study are to (1) assess the developments of soil compaction, and (2) analyze the effectiveness of the natural alleviation processes of WD and FT under two irrigation treatments over three double cropping seasons following a conventional farmers' tillage sequence (shallow–deep–shallow).

2. Materials and methods

2.1. Study site

The study was conducted from October 2011 to October 2014 at Luancheng Agro-Eco-Experimental station (37°53'N and 114°41'E; elevation 50 m) of the Chinese Academy of Sciences, which is located in the northern part of the NCP. The annual average temperature is 12.4 °C with a monthly average maximum of 26.3 °C in July, and a minimum of − 3.9 °C in January. The average annual rainfall is 482 mm with 352 mm falling in the growing season of maize between June and September. Daily rainfall and average air temperature during the entire growing season of winter wheat and summer maize in 2011–2014 seasons are displayed in Fig. 1. The soil at the experiment is light loam, and the detailed soil characteristics can be found in Zhang et al. (2012).

2.2. Irrigation treatments

The study and the respective field irrigation treatments were conducted as part of a long-term irrigation experiment run since 1997, which involves six irrigation treatments for winter wheat and summer maize. Within the long-term experiment shallow tillage was consistently applied since 1997. The crop residues of winter wheat and summer maize were continuously returned to the field. Winter wheat was sown in early October and harvested around June 10 in the following year. Subsequently summer maize was manually planted immediately after the harvest of winter wheat. Two irrigation treatments were chosen for investigation in the present study: full irrigation (FI) and deficit irrigation (DI). The FI plots were irrigated five times (before winter, recovery, jointing, heading, flowering or grain-filling) for winter wheat and one to three times of irrigation for summer maize based on

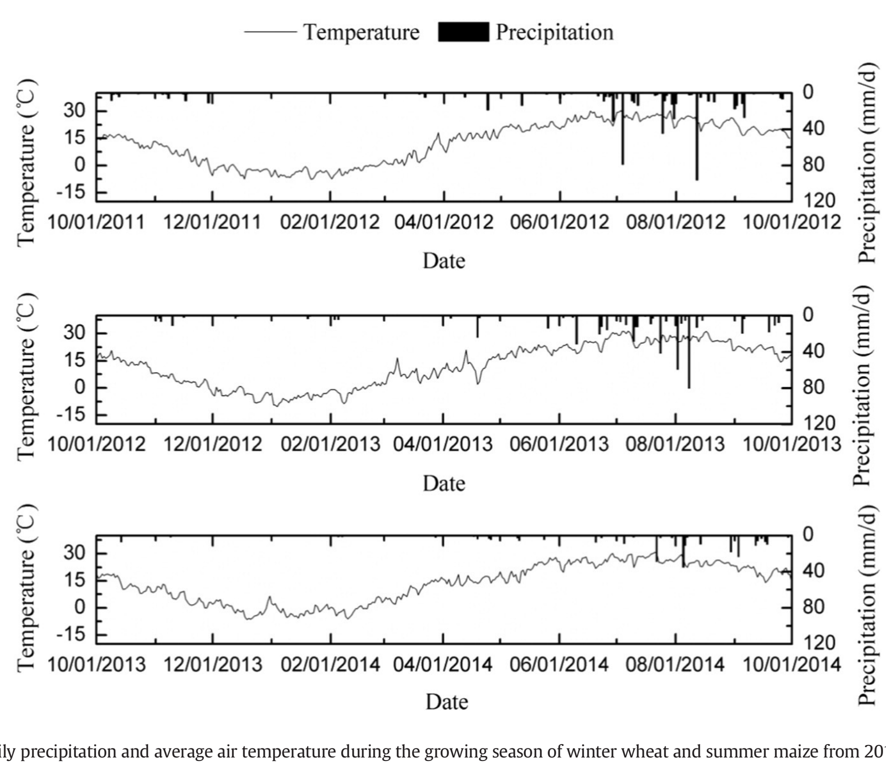

Fig. 1. Daily precipitation and average air temperature during the growing season of winter wheat and summer maize from 2011 to 2014.