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Subsoil compaction and irrigation regimes affect the root–shoot relation and grain yield of winter wheat

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ABSTRACT

The combined effects of soil moisture and physical parameters are important concerns in crop production. A three-season field experiment and a two-season tube experiment were performed to examine the effects of subsoil bulk density (BD) on the performance of winter wheat associated with irrigation regimes. Tubes (19.2 cm in inner diameter and 1 m in depth) were compacted with soil to create different BD ranging from 1.4 to 1.8 g/cm^3 at a subsoil layer (20–40 cm). The field study was conducted under deep tillage (DT) and rotary tillage (RT) that created two different BD at the subsoil layer (1.57 and 1.67 g/cm^3, respectively). Two irrigation regimes (deficit and adequate) were applied to both the field and the tube experiments. Results from the tube tests showed that total root weight (TRW) was reduced with the increase in the BD, especially the root weight under the subsoil pan. TRW was positively related to the total shoot weight; whereas the final grain yield was not linearly related to the shoot weight, due to the different effects of BD and irrigation on harvest index. Moderate subsoil BD (1.5–1.6 g/cm^3) produced the highest harvest index and grain yield. Results from the field experiment showed that the lower subsoil BD under DT improved the root growth in the deep soil layer, resulting in more soil water utilization under deficit irrigation, as compared with the higher subsoil BD under RT. Thus the yield under DT was improved under deficit irrigation. No significant difference in yield under adequate irrigation was found between the two tillage methods. The results testified that the effects of subsoil compaction on crop performance were associated with soil water conditions. Under relative dry condition, higher than optimum subsoil BD would negatively affect crop performance more significantly than that under sufficient water supply. The subsoil BD should be maintained below 1.6 g/cm^3 under the growing conditions of this study. The long-term RT had increased the subsoil BD over this limit. Optimizing the subsoil BD by tillage management would benefit crop production.

1. Introduction

Soil compaction is one of the major concerns for many farmers as well as for scientists, as it has led to the yield reduction of most crops throughout the world due to intensive farming and heavy loading machinery (Hamza and Anderson, 2005; Tracy et al., 2011; Nawaz et al., 2012). Soil compaction can be defined as “the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density” (SSSA, 1996). Therefore, soil compaction represents physical degradation and includes increased soil strength, decreased soil porosity and reduced hydraulic conductivity (Tracy et al., 2011). Soil bulk density (BD) is an important factor influencing soil properties of macrospores (Carter, 1990). The changing in BD is often used to quantify the effects of soil compaction (Tracy et al., 2012; Paz-Ferreiro et al., 2013). Many studies have combined BD with soil penetration resistance to illustrate the degree of soil compaction (e.g., Motavalli et al., 2003; Beutler et al., 2005; Reintam et al., 2009). These characters indicate that soil compaction caused by mechanized tillage would result in a plough pan below the tilled layer. The modified physical properties in the pan layer could be a potential limiting factor for crop growth.

The effects of soil compaction on crop growth depend on the load of farm machinery, the soil type and the crop systems (Lipiec and Hatano, 2003; Chan et al., 2006; Adapa et al., 2009; Alvaro-Fuentes et al., 2009; Toliver et al., 2011; Soane et al., 2012). Its effects on root and crop growth have been extensively reported (e.g., Baumhardt et al., 2010; Bengough et al., 2011; Hou et al., 2012). Because of the

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limited water and nutrient availability for crop roots in the compacted soil (Sadras et al., 2005; Ahmad et al., 2009), the elongation ability of roots is restricted and even would cease at 2 MPa of soil strength (Bengough et al., 2006). The soil strength–root relation has been widely reviewed in the literature (e.g., Kirby and Bengough, 2002; Bengough et al., 2011). The restricted root growth, in turn, might affect crop seeding (Jordan et al., 2003), leaf expansion and stomatal conductance (Lipiec and Hatano, 2003), shoot biomass, canopy size (Ekwue and Stone, 1995), yield product and quality (Hassan et al., 2007; Chen and Weil, 2010). However, soil compaction also has some positive effects on crop growth. Moderate soil compaction could increase the root–soil contact, allowing the crop root to extract adequate resources (Atkinson et al., 2009). In some soil types, including coarse-textured soils, soil compaction could reduce percolation losses, increase soil water storage and enhance crop yield (Stone and Schlegel, 2009; Morell et al., 2011). These advantageous effects suggest that there is an optimum degree of compaction for crop growth in different environments (Arvidsson and Håkansson, 2014). But the optimum level of soil compaction depends on soil water content (Håkansson and Lipiec, 2000) and there are few systematic studies on the response of crops to soil compaction under different water regimes.

Winter wheat and summer maize are the dominant crops that together form an annual double-cropping system in the North China Plain (NCP). The annual cultivation practices, including incorporating the residue, ploughing, sowing and harvesting, require more frequency of farming operations using tractors than a one-crop-per-year system. Additionally, adequate soil moisture is needed to ensure good seed germination of winter wheat. Cultivation under wet soil conditions can lead to increasing soil compaction. Therefore, with the development of mechanized tillage, soil compaction is becoming a potential problem in the NCP (Liu et al., 2010). The results of Zhang et al. (2004, 2012) showed that the increased BD in the plough pan in this region has created unfavorable growing conditions for roots of winter wheat. Recent reports have mainly focused on the effects of different types of tillage, such as reduced tillage and deep ploughing, on soil properties and crop production in the NCP (Xu and Mermoud, 2001; Du et al., 2009, 2010; Dai et al., 2013). Few studies have focused on effects of the BD in the plough pan on crop performance. Especially in the NCP, soil water utilization played an important role in ensuring the high production of winter wheat (Zhang et al., 2008), due to the low rainfall amount during the growing season. The effects of subsoil compaction on root growth would be associated with irrigation regimes. Therefore, the purposes of this study are to examine: (1) the subsoil compaction on root and shoot growth and their relationship; (2) effects of subsoil compaction on soil water utilization; (3) subsoil compaction on crop production and water use efficiency (WUE). The results would provide references to make decisions regarding soil tillage and irrigation management to reduce the possible negative effects of subsoil compaction on crop performance.

2. Materials and methods

2.1. Experimental site

Both field study (from 2011 to 2014, three growing seasons of winter wheat) and tube study (from 2012 to 2014, two growing seasons of winter wheat) were conducted at the Luancheng Agro–Eco-Experimental Station (37°53′N and 114°41′E; elevation at 50 m) of the Chinese Academy of Sciences, which is located in the middle part of the NCP. The region is semi-arid with a monsoon climate. Winter wheat and summer maize are the two main crops in this area, forming the common double-rotation cropping system. Winter wheat is planted in early October and harvested the next June. June to September is the maize growing season. The average annual precipitation is approximately 484 mm, with 70% of the precipitation falling in the growing season of maize. During the growing season of winter wheat, average rainfall was around 120 mm, which was far less than the water requirement of this crop, which was around 450 mm (Liu et al., 2002). Irrigation is critical for the high yielding of this crop. The daily weather factors, including precipitation, air temperature, relative humidity, sunshine duration, radiation and wind speed, were monitored from a weather station nearby the experimental site.

2.2. Field experiment

2.2.1. Creating two subsoil BD

To create different BD for the plough pan, a uniform field was divided into two blocks, each with an area of $20 \times 50\,m^2$. Before beginning the field experiment, the two blocks were treated with different cultivation practices starting from 2005 onwards. One block was treated with deep tillage (DT) before sowing winter wheat; the depth of the chisel plow could reach 25–30 cm. The other block was treated with shallow or rotary tillage (RT) with working depth of 8–15 cm. Except for this cultivation practice, other practices such as sowing, harvesting, fertilizer, irrigation and straw management were the same for both blocks. At the start of the tillage practices in 2005 and the beginning of this study in 2011, BD was measured by taking four replicates down to 60 cm for each block. A metal ring of volume of $100\,cm^3$ was pressed into the soil to get an intact core, and then the core was oven-dried and the dry soil weight was recorded. BD was calculated as the dry weight divided by the volume of the metal ring. The soil texture and the average BD in 2005 and 2011 were presented in Table 1. The BD under RT was greater than that under the DT practice, especially for the subsoil layer of 20–40 cm (Table 1). Soil organic matter at the beginning of the study in 2011 was 18 g/kg, total N was 1.2 g/kg and available N, P and K were 80, 24 and 90 mg/kg, respectively, for the top tillage soil layer (0–20 cm).

2.2.2. Field management

Starting in October 2011 before sowing winter wheat, the DT and RT block was further divided into two sub-blocks. And the sub-blocks were further divided into small basins for irrigation management. The two irrigation treatments were one irrigation application (I1) and two irrigation applications (I2). I1 had one irrigation applied at jointing with irrigation amount at 80 mm as deficit irrigation treatment. I2 had one more irrigation applied at anthesis with another 80 mm as adequate irrigation treatment, based on the results from Zhang et al. (2008), which showed that for winter wheat in the NCP, two irrigations usually produced the highest yield of winter wheat. The seasonal rainfall was 96.4 mm in 2011–2012, 97.4 mm in 2012–2013 and 46.3 mm in 2013–2014.

Winter wheat was sown in October after maize was harvested, and the maize straw was chopped and incorporated into the top soil layer. The same winter wheat cultivar “Kenong199” was used for the three seasons. Row spacing was 15 cm, and seeding rate was 300 viable seeds/m^2. Before planting, diammonium phosphate (DAP) at 450 kg/ha, urea at 150 kg/ha and potassium chloride at 150 kg/ha were broadcast and incorporated into the soil. An additional 225 kg/ha of urea was top-dressed at jointing stage in early April with the irrigation at jointing. Winter wheat was harvested in the middle of June. Summer maize was planted manually without soil ploughing after winter wheat harvesting. The same field management (irrigation and fertilizing) was applied to summer maize for all the blocks.