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Responses of soil properties, root growth and crop yield to tillage and crop residue management in a wheat–maize cropping system on the North China Plain

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ABSTRACT

Crop residue removal and subsoil compaction are limiting to yield improvement in the North China Plain (NCP). We conducted a field study composed of six consecutive crop growing seasons from 2010 to 2013 in Henan province, China, to determine responses of soil properties, crop root distribution and crop yield to tillage and residue management in a wheat–maize cropping system under irrigated conditions. Tillage practices comprised mouldboard ploughing (MP) to a depth of 15-cm, deep mouldboard ploughing (DMP) to a depth of 30-cm, and chisel ploughing (CP) to a depth of 30-cm. Crop residue management included crop residue retained (CRRet) and crop residue removed (CRRem). The results indicated that yields in DMP and CP increased by 6.0% and 7.3% for wheat and by 8.7% and 9.0% for maize, respectively, relative to MP. The CRRet treatment also increased wheat yield by 6.7% and maize yield by 5.0%. The yield increases under DMP and CP were related to reduced bulk density and soil penetration resistance, increased soil water content, improved total N distribution and improved root density (0–60-cm). Compared with MP, the root mass density under DMP and CP were increased by 43.4% and 42.0% for wheat and by 40.6% and 39.4% for maize, respectively. The yield increases under CRRet were also related to increased soil water content, reduced penetration resistance and increased N status (0–40-cm). Overall, for DMP + CRRet and CP + CRRet, a more favorable soil environment alongside greater root mass density and suitable spatial distribution resulted in higher grain yields of wheat and maize. Thus, compared with conventional shallow tillage practice, DMP or CP with residue application could improve soil quality and agricultural productivity under irrigated areas with loam soil in the NCP.

1. Introduction

Winter wheat–summer maize rotation is the main two-crop-per-year cropping system in the North China Plain (NCP). Under the traditional cropping system, crop residue was traditionally removed from the field during crop harvest to be used as biofuel or forage. However, it is now a universal phenomenon that straw is burned in fields after harvesting, which has become a significant seasonal source of air pollution (Qu et al., 2012). In today's farming system, winter wheat is planted following ploughing to a depth of 15-cm after the fall maize harvest, and no ploughing is implemented after the wheat harvest in summer because summer maize is seeded using a no-till planter along with fertilizer application. These crop residue management and tillage practices not only resulted in decrease of soil organic carbon content due to residue removal (Du et al., 2010), but subsoil compaction caused by the ploughing tillage practice and tractor wheel traffic in the plough furrow during the primary, 15-cm-deep mouldboard ploughing operation, and subsequent traffic by seeding, harvesting and spreading of chemicals or fertilizers operations (Hamza and Anderson, 2005). According to our survey on the four main soil types (sandy loam, loam, clay loam and clay) in the whole NCP in 2008, soil bulk density within the hardpan about at 17–27-cm soil depth are 1.50–1.54 Mg m^{-3}, which is much higher than the optimum soil bulk density of 1.0–1.3 Mg m^{-3} for maize in a

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Eutric Cambisol sandy loam (Li et al., 2002). Soil compaction in subsoil layers restricts root penetration and plant access to water and nutrients in the subsoil, limiting plant growth and yield potential (Bengough et al., 2011; Clark et al., 2003).

Deep tillage (e.g. subsoiling, deep ploughing, or ripping, to a depth >20-cm) has been shown to improve the structure and health of compacted soils (Hall et al., 2010; Hamza and Anderson, 2005). Tillage affected various soil physical, biological and chemical properties and thus also influenced crop yield. Previous studies have shown that deep tillage improved the soil properties in the tilled layer by reducing soil bulk density and penetration resistance (Varsa et al., 1997), increasing soil porosity, hydraulic conductivity and infiltration rate (Laddha and Totawat, 1997), and created a more favorable soil environment for root growth and crop production than shallow tillage. Nitant and Singh (1995) showed that subsoiling tillage increased the biomass of root distributed in a deeper soil profile by 127% for redgram (*Cajanus Cajan* L.) compared with shallow tillage on a sandy loam soil. Similarly, Varsa et al. (1997) concluded that deep tillage (subsoiling to 40, 60 and 90-cm depth) increased the proportion of maize root distributed below the 20-cm depth compared with no-till on Stoy silt loam soil. Another study found that mouldboard ploughing to a depth of 30-cm led to higher values of root length density in maize with lower values of both penetration resistance and soil bulk density, while the no-till resulted in lower root length density and higher penetration resistance and soil bulk density values (Mosaddeghi et al., 2009). In a wheat and soybean double-cropped system on a Goldsboro loamy sand soil (Busscher et al., 2000), deep tillage decreased mean profile penetration resistance compared with surface tillage; for every megapascal decrease in mean profile penetration resistance, wheat yields increased 1.5–1.7 Mg ha^{-1} and soybean yields increased 1.1–1.8 Mg ha^{-1}. By contrast, Lampurlanés et al. (2001) concluded that no tillage favored water accumulation in the soil profile and improved root growth above that under other tillage practices (minimum tillage, subsoiler tillage) on a loamy soil. However, negative effects of deep tillage have also been reported in previous literature. Deep tillage has been shown to require higher fuel consumption and energy input, and has lower energy use efficiency and higher CO_2 emissions than reduced or no tillage practices (Šarauskis et al., 2014). Increasing tillage intensity may also lead to a reduction in soil macro-aggregates, cause a substantial decrease of soil organic matter content, and an increase of nitrogen and carbon mineralization rate, and result in higher emissions of CO_2 and N_2O gases (Andruschkewitsch et al., 2014; Chatskikh and Olesen, 2007; Kristensen et al., 2003).

The application of organic matter to soil is a practical method to stabilizes soil structure and makes it more resistant to degradation (Ekwue, 1990; Hamza and Anderson, 2005). Application of animal manure to soil has been shown to decrease soil bulk density, increase total water stable aggregates, improve soil aggregate stability, and help to maintain soil fertility for crop growth (Darwish et al., 1995; Mosaddeghi et al., 2009). Crop straw is an accessible and common organic material to help farmers improve soil fertilities and achieve higher yields. Crop residues, whether retained on the surface or incorporated by tillage, influence soil physical, biological and chemical properties. Retaining crop residue on the soil surface improves the agricultural ecological environment by moderating soil temperature, decreasing soil water evaporation and retaining more soil moisture (Li et al., 2013), and reducing runoff and soil erosion (Bhatt and Khera, 2006). Incorporation of crop residues increases soil organic matter (Choudhury et al., 2014), increases the stability and strength of aggregates, and hence decreases compactibility (Soane, 1990). Conversely, residue retention may suppress the germination and seedling growth by posing allelopathic and physical effects (Khaliq et al., 2011), and increase the occurrence of diseases, such as barley net-blotch disease (Mathre et al., 1997) and maize root-rot (Govaerts et al., 2007). Currently, in China, producers often burn straw in the field, despite the ban on this practice by government (Qu et al., 2012), to facilitate seeding and reduce crop disease and weed populations. Straw burning is known to damage farmland ecosystem, by reducing soil organic C and N, causing soil desiccation, which produces a hard and less friable soil (Malhi and Kutcher, 2007), and contaminating air by releasing $PM_{2.5}$, SO_2, NO_x and CO (Qu et al., 2012; Streets and Waldhoff, 2000). Therefore, the proper utilization of crop residues produced from the field is critically important to promote grain yields by reducing soil compaction and also to reduce air pollution.

Improved knowledge of the effects of tillage practices including crop residues on soil compaction and crop yields may assist in the development of agricultural management practices to mitigate the effects of compaction on agricultural production and environmental resources. To our knowledge, little research has focused on the influence of soil tillage, crop residue management and their interaction on soil characteristics, root growth and crop yield under wheat–maize cropping systems in the irrigated areas of the NCP. The objective of our study was to determine the level of soil compaction, and the responses of root distribution and crop yield to different tillage and residue management practices in a summer maize and winter wheat double–cropping system.

2. Materials and methods

2.1. Study site description

A 3-year field experiment including six crop growing seasons was conducted from October 2010 to September 2013 at the Wen County Experimental Station (34° 57′ N, 113° 09′ E) in Henan, China. The soil is classified as Eutric Cambisol loam using FAO classification (FAO, 1995) with 48% sand, 40% silt and 12% clay. Mean monthly temperature and precipitation during the experimental period were obtained from a local weather station and are summarized in Fig. 1. Selected soil physical and chemical properties for 0–40-cm soil depth were determined prior to tillage implementation and the results are given in Table 1.

2.2. Experimental design and crop management

The experiment was arranged in a split-plot design with three replications. Tillage practices and crop residue management were the two factors of interest. The tillage treatments were randomly assigned to main plots and crop residue treatments were randomly assigned to subplots. The subplot size was 100-m × 4.8-m, and buffer rows between treatments were 1.2-m wide.

There were three tillage practice treatments: mouldboard ploughing (MP) to a maximum depth of 15-cm, chisel ploughing (CP) to a maximum depth of 30-cm, and deep mouldboard ploughing (DMP) to a maximum depth of 30-cm. There were two crop residue management types: crop residue retained (CRRet) and crop residue removed (CRRem). The tillage treatments were arranged once before winter wheat sowing in mid-October, while crop residue management was performed twice (before tillage implementation in mid-October and at maize sowing in mid-June). Each study year, the mean quantities of maize residue under CRRet were 7.49, 7.51, 6.90 t ha^{-1} for DMP, CP and MP, and wheat residue were 9.92, 10.16, 8.59 t ha^{-1} for DMP, CP and MP, respectively. The maize residues were treated before tillage implementation. For the CRRet treatment, maize residues were chopped and flattened by a 4J-150(B) model straw chopper (Henan Hao Feng Machinery Manufacturing Co., LTD, Henan Province, China). For the CRRem treatment, all maize residues above the soil surface were reaped by hand using a sickle and removed from the field manually. The