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Crop yield and soil carbon responses to tillage method changes in North China

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ABSTRACT

Subsoil compaction at 15–30 cm depths due to the increase of bulk density or decrease in porosity after long-term no tillage or reduced tillage (e.g. rotary tillage or harrow tillage) is of growing concern. Deep tillage is generally regarded as an important method to reduce subsoil compaction due to long-term conservation tillage and thereby improve crop production and soil conditions. We compared the responses of crop yield and soil carbon (C) among 10-year no tillage (NT), rotary tillage (RT), and harrow tillage (HT) treatments, and their conversions to deep tillage (DT) for 4 years involving NT-DT, RT-DT and HT-DT treatments. The soil organic carbon (SOC) pool under the NT treatment was 29 and 91% higher than the SOC pools of the HT and RT treatments, respectively, whereas the NT annual yield decreased by 0.6 $\text{Mg ha}^{-1}\,\text{yr}^{-1}$ over 10 years. The NT-DT, RT-DT and HT-DT treatments increased crop yield by 35, 24 and 24% and altered the SOC pool by −1.5, 15.6 and 13.2 Mg ha^{-1} over the 4 years of deep tillage compared with the corresponding values for NT, RT, and HT, respectively. Therefore, conversion to DT after long-term NT, RT, and HT use can benefit crop yield and play an important role in improving soil carbon sequestration following the long-term adoption of RT and HT systems in North China.

1. Introduction

Achieving food security is an urgent, high-priority issue in China (Chen et al., 2011a). As a result, the continuous improvement of crop yield is a prominent goal in agricultural research. Mitigating and preventing further soil degradation due to erosion and soil organic carbon (SOC) loss are crucial for accomplishing this goal. Conservation tillage, which is generally defined as minimal soil disturbance resulting in a residue retention of at least 30% (Zhang et al., 2005), is becoming an economical and ecologically viable option for conserving energy and providing favorable soil conditions for sustainable crop production, soil carbon (C) sequestration, and efficient nitrogen fertilizer use (Mazzoncini et al., 2011; Chen et al., 2011b; Pramod et al., 2012). Currently, conservation tillage is used on 11% of the total global agricultural cropland (FAO, 2010). In China, the area under conservation tillage increased to 8.5 Mha in 2011, equivalent to 4.7% of the total agricultural cropland (Geng, 2012), and most of them use wheat-maize double cropping system in silt loam soils under temperate monsoon climates in the North China (Zhang et al., 2014).

Harrow tillage (HT), rotary tillage (RT) and no-tillage (NT) are frequently used to mitigate soil erosion and loss of SOC in North China (Zhang et al., 2005). However, after several successive years of these reduced tillage (i.e., only tilling to a depth less than 20 cm) or no-tillage systems, subsoil compaction at 15–30 cm depths appears to be increasing due to the increase of bulk density resulted by water infiltration and sowing and harvesting machineries (Kong et al., 2010; Wang et al., 2014). Furthermore, although adopting some form of conservation tillage is generally beneficial for increasing SOC levels and sequestering C in the topsoil (Ussiri and Lal, 2009; Martinez et al., 2013), the reduced incorporation of

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Abbreviations: NT, no tillage; RT, rotary tillage; HT, harrow tillage; DT, deep tillage; NT-DT, no tillage converted to deep tillage; RT-DT, rotary tillage converted to deep tillage; HT-DT, harrow tillage converted to deep tillage; SOC, soil organic carbon.

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crop residues has been reported to increase subsoil bulk density and reduce crop root proliferation (Figuerola et al., 2012), thereby limiting water and nutrient availability (He et al., 2009) and resulting in reduced crop yields (Bhatia et al., 2010; Arvidsson et al., 2014). For example, many studies have demonstrated that decreases in crop yield in response to long-term NT adoption may be caused by reduced seed germination and emergence, lower early season soil temperatures, below-optimal plant populations, poorer weed control, delayed plant development and maturity, increased grain moisture content, and lower grain yield potential following adoption of NT (Toliver et al., 2012; Kovar et al., 1992; Fortin, 1993; Swan et al., 1994). Therefore, understanding the responses of SOC and crop yield to long-term conservation tillage is very important in China because achieving sustainable high yields and soil quality is a fundamental precondition for adopting conservation tillage.

Deep tillage (DT) to a depth more than 30 cm is an effective method to break up compacted subsoil layers and decrease soil bulk density (He et al., 2007; Hou et al., 2012). It has positive effects on soil structure, soil C sequestration, and crop yield in North China (Huang et al., 2006; Wang and Li, 2014; Xu et al., 2015). A previous study has demonstrated the bulk density was decreased by 8.7–11.8% and significant increased soil total porosity of the 10–40 cm layers after the long-term conservation tillage conversion to DT (Nie et al., 2015), which played an important role for the disruption of the compacted zone. However, the effects of tillage conversion on crop productivity and the SOC pool were unknown. Therefore, our objectives were to (1) quantify crop yield and SOC responses to 10-year HT, RT, and NT treatments and (2) determine how the conversion of these three conservation tillage methods to DT affected yield and SOC following the first 4 years after conversion to deep tillage.

2. Materials and methods

2.1. Experimental site

The study site was located at Tai'an (North China, 36°09′N, 117°09′E), which typifies the soils and temperate continental monsoon climate of North China. The average annual precipitation and annual temperature were 710 mm and 13.8 °C, respectively, during the experiment. The soil is classified as Udolls according to the USDA Soil Taxonomy System (Soil Survey Staff, 1998). The soil texture is 40% sand, 44% silt and 16% clay. At the start of the experiment in 2002, the soil in the 0–30 cm layer had a pH of 6.8 (1:5 H_2O), an SOC of 6.73 $g\,kg^{-1}$, a soil total nitrogen content of 1.3 $g\,kg^{-1}$ and a total phosphorous content of 1.3 $g\,kg^{-1}$. The soil bulk density was 1.43 $g\,cm^{-3}$.

2.2. Experimental design

The study was based on a 10-year conservation tillage experiment that began in 2002. Conventional tillage, which were moldboard plowed to a depth of 20–25 cm, was used before 2002. The experiment was designed to evaluate three conservation tillage methods and involved no tillage (NT), hallow tillage (HT) and rotary tillage (RT) treatments with three replicates. Then, to evaluate the changes in crop yield and the SOC pool after the conversion from these three conservation tillage treatments to deep tillage, we established a deep tillage (DT) experiment that was based on the three conservation tillage treatments that began in 2008: each conservation tillage treatment (HT, RT and NT) was bisected, with one half maintained using the HT, RT and NT tillage methods and the other half converted to DT treatment, resulting in HT-DT, RT-DT and NT-DT treatments (2008–2012, Fig. 1). Each resulting plot was 35 m long and 4 m wide.

The experimental site was cropped with a rotation of winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). The wheat was sown in mid-October immediately after tilling the soil and was harvested at the beginning of June of the following year. The maize was sown directly after the wheat harvest and was harvested in early October. Wheat grains and maize cobs were harvested by a combine harvester-threshers, and all residues were returned in situ. The cutting and crushing of residues were simultaneously operated by the combine harvester-threshers, and mixed in the topsoil by a direct seeding machine with sowing. Seedbed was operated in about 5 cm soil depth during the direct seeding. The residue biomasses of wheat and maize were 11 and 10 $Mg\,ha^{-1}$ per year, respectively. All of the soil tillage practices were performed following the maize harvest. The operations of the HT, RT, NT treatments and their associated DT treatments were as follows:

HT: tilled to a depth of 10 cm using a disc harrow with a 89 kW tractor,

RT: tilled to a depth of 12 cm using a rotovator with a 89 kW tractor,

NT: no tillage, and

DT: tilled to a depth of 30 cm using a vibrating shank subsoiler with the shanks spaced 60 cm (from center to center) apart, powered by a 118 kW tractor.

Fertilizers were applied according to the recommended rates in this region. During the wheat growth period, fertilizer was used at a rate of 225 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1} and 105 kg K_2O ha^{-1}, and 100 kg N ha^{-1} was used as topdressing at the jointing stage with 160 mm of irrigation water. During the maize growth period, 120 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1} and 100 kg K_2O ha^{-1} were used collectively as a base fertilizer, and 120 kg ha^{-1} of N was used as topdressing at the jointing stage. The fertilizer types for N, P_2O_5 and K_2O were urea, triple superphosphate and potassium chloride, respectively.

2.3. Yield collection and analysis

Yield samples of both wheat and maize were collected in a 9-m^2 area in the central area of each plot to exclude edge effects at maturity. The samples were threshed, mechanically separated after air-drying and then oven-dried at 65 °C for 48 h, after which the dry weight was determined. Yield data for both wheat and maize in the three conservation tillage treatments (HT, RT and NT)

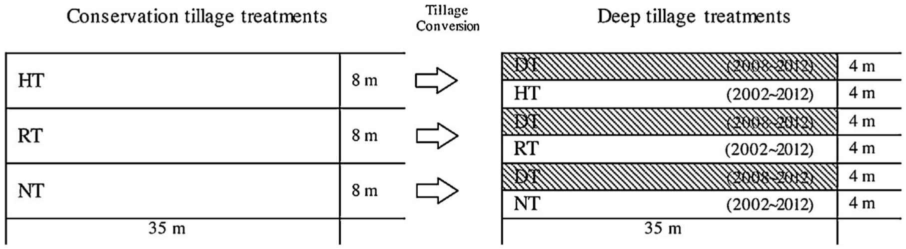

Fig. 1. Design of experimental treatments 2002–2012: splitting of long-term conservation plots conversion to deep tillage in 2008.