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Comparison of three tillage systems in the wheat-maize system on carbon sequestration in the North China Plain

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ABSTRACT

Whether farmland serves as a carbon (C) source or sink depends on the balance of soil organic carbon (SOC) sequestration and greenhouse gas (GHG) emissions. Tillage practices critically affect the SOC concentration, SOC sequestration rate and soil carbon storage (SCS). The objective of this paper is to assess the tillage effects on SOC sequestration, SCS and C footprint. Tillage experiments were established on a double cropping system of winter wheat (*Triticum aestivum* L.) and summer corn (*Zea mays* L.) in the North China Plain since 2001 with three treatments: no tillage (NT), rotary tillage (RT) and conventional tillage (CT). In order to assess SOC sequestration efficiency under different tillage systems, SCS, SOC sequestration rate, hidden carbon cost (HCC), indexes of sustainability (I_s) and C productivity (CP) were computed in this study. Results showed that the SCS increased with years of residue retention. The SCS attained the highest degree in 2007, which was about 25%–30% higher than that in 2004. The net SOC sequestration rate was the highest in NT and lowest in CT, while HCC was lowest under NT and highest under CT. The value of I_s for CT, RT and NT treatments was 1.46, 1.79 and 1.88, respectively, and that of CP was 11.02, 12.79 and 10.57, respectively. Therefore, it can be concluded that NT provides a good option for increasing SOC sequestration for agriculture in the North China Plain.

1. Introduction

Global warming has become a concerning issue due to the potential impacts on resources, agriculture, energy use, weather patterns and environment etc. Massive greenhouse gas (GHG) emissions have been released from rapidly developing industry and agriculture (IPCC, 2007). Agriculture is the largest terrestrial biome, occupying as much as 35% of the earth's land area (Asner et al., 2004). Agricultural cleaner production and farm product consumption in relation to environmental impacts have become the focus of attention of scientists and policy makers (Lal, 2003).

The processes of crop production influence GHG emissions and soil organic carbon (SOC) sequestration. Cleaner production management in agro-ecosystems can play a major role in reducing the rate of enrichment of atmospheric GHG because of the huge potential of soil carbon storage (SCS) in soils (Lal, 2003, 2007). The soil carbon (C) pool can be a source or sink for an atmospheric C pool, depending on land use and management (Schimel et al., 2001). Hence, proper management practices are encouraged to sequestrate atmospheric C into the soil (Lal, 2004a).

Numerous cleaner production technologies (e.g., conservation tillage, reasonable fertilization and crop rotation) can reduce GHG emissions, increase SOC sequestration, enhance SCS and improve crop yield (Schlesinger, 1999). Conservation tillage, one of recommended management practices (RMPs), has become a major technology for sustainable agriculture because of its numerous benefits (e.g., reducing soil erosion, saving water/labor/time/fuel and improving soil quality) (Fowler and Rockstrom, 2001; Hargrove, 1990; Lal et al., 1990). Tillage can strongly alter soil properties and SOC distribution along with attendant changes in characteristics of GHG emissions and SCS (Ussiri and Lal, 2009). Most previous studies have shown that no tillage (NT) and minimum tillage can increase SOC because of minimal soil disturbance and residue retention (Duiker and Lal, 1999; Lal and Kimble, 1997; Puget and Lal, 2005).

The concept of C footprint has been used in many studies related to climate change. Carbon footprint is the total set of GHG

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emissions caused by a product (Pathak et al., 2010), which is often expressed in terms of the CO_2 equivalent of all GHG emitted. Carbon footprint on a small scale remains well-studied, especially on agricultural food products and household C footprints (Biswas et al., 2010; Weber and Matthews, 2008). The method of C footprint can also be used to fully describe the C used during the crop production process. The total field C footprint of one kind of crop production, or the C footprint of land use change, is widely studied in agriculture (Ponsioen and Blonk, 2012). Yet, studies on C footprint of the whole agro-ecosystem with specific farm operations are not common. Tillage is among the most important primary source of CO_2 emission (Lal, 2004c). The inputs components of C footprint in different tillage systems differ from each other because of different doses of chemicals, human labor and fuel use (Larsen and Hertwich, 2011; Lal, 2004b). Thus, tillage plays an important role in cleaner production for agriculture in the context of climate change. However, most previous studies on SOC sequestration in different tillage systems focused on SOC changes from a micro-scale rather than a meso- or macro-scale. Therefore, there is a strong need to assess the SOC sequestration and C use for the specific farm operations from a meso- or macro-scale, which is critical for screening appropriate agricultural technology, especially for agricultural cleaner production. The objective of this paper is to assess the differences of SOC sequestration rate, C footprints and C sequestration benefits under different tillage treatments, and to identify optimal C-friendly tillage systems for the North China Plain.

2. Materials and methods

Field experiment and simulation modeling were performed in this study. Soil basic parameters were obtained from the experiment. Field experiment was initiated in 2001 and the data of SOC used in this manuscript were collected from 2004 to 2011. The data of soil bulk density (ρ_b) and crop yield were based on 2008–2010. The C footprints of farm productions were analyzed and verified by denitrification-decomposition (DNDC) model based on field experimental data. Some necessary parameters were provided by the DNDC model.

2.1. Experimental site description

The experiment was conducted at the Luancheng Agro-Ecosystem Experimental Station (37°50′N, 114°40′E, elevation of this site is 50.1 m) of the Chinese Academy of Sciences. The station is located in the piedmont of the Taihang Mountains in the North Chain Plain, in Hebei Province, China. The annual average precipitation in this area is about 480.7 mm, in which 70% occurs in summer and the mean annual air temperature is 12.2 °C. The soil type is a silt loam with 15.01% clay, 1.39 g cm^{-3} ρ_b of the plow layer and 9.11 g kg^{-1} SOC of the top soil (0–10 cm). The double cropping system of winter wheat (*Triticum aestivum* L.) and summer corn (*Zea mays* L.) is the dominant pattern in this region. Crops are generally flood-irrigated with pumped groundwater. The principal soil properties (0–20 cm depth) are listed in Table 1.

Table 1
Principle soil properties of test soil.

Soil depth/cm	N/(g kg^{-1})	AN/(mg kg^{-1})	K/(mg kg^{-1})	P/(mg kg^{-1})	SOC/(g kg^{-1})
0–10	0.74	37.95	115.02	62.90	9.11
10–20	0.64	30.58	90.11	39.62	8.22

N, total nitrogen; AN, alkali-hydrolyzable nitrogen; K, available potassium; P, phosphorus.

2.2. Experimental design

The field experiment was laid out as a randomized complete block design with three replications and the area of each plot was 0.33 ha. Three tillage treatments were conducted in this experiment: CT, rotary tillage (RT) and NT. Residue of wheat and corn were retained in the field for all treatments. Different tillage practices were only conducted in the winter wheat season, while direct seeding without any tillage was conducted in the summer corn season for all the treatments.

Corn residue was chopped twice with a residue pulverizer in all treatments. Wheat was harvested by a combine harvester, and about 30 cm of wheat residue was left in the field in all treatments. The CT treatment was plowed once to a depth of 20 cm with a moldboard plow and then rotavated twice to a depth of 8–10 cm before seeding. The RT treatment was rotavated four times to a depth of 8–10 cm. The NT treatment was conducted with a NT planter which performed the residue cutting, seeding, fertilizer application and seedbed packing simultaneously. The seeding rate for wheat was 150 kg ha^{-1} and that for corn was 50 kg ha^{-1}. The quantities of wheat residue retained to the soil under CT, RT and NT were 9182.86, 8646.80 and 8955.54 kg ha^{-1}, respectively, and that of corn were 6636.51, 6539.56 and 5965.85 kg ha^{-1}, respectively.

Fertilizers for winter wheat were applied at the rate of 70 kg ha^{-1} N and 80 kg ha^{-1} P_2O_5 during sowing and another 70 kg ha^{-1} N at the regrowth stage. Shortly after jointing, summer corn was top-dressed at the rate of 210 kg ha^{-1} N. Winter wheat was irrigated three times (sowing, regrowth stage and jointing stage), at about 75 mm per application. During summer corn season, the field was irrigated only when it was necessary, with the same irrigation rate as that for winter wheat. Herbicides and insecticides were applied for both winter wheat and summer corn under different treatments. In order to effectively control weeds and insects, herbicides and insecticides were applied under NT one more time than that applied under CT and RT during the winter wheat season.

2.3. Soil sampling and analysis

Soil samples for SOC and ρ_b were both collected in triplicates during wheat and corn harvest times every year from 2004.

2.3.1. Soil organic carbon (SOC, g kg^{-1})

Soil samples were collected in different tillage treatments from the center of each plot, using a soil auger to a depth of 30 cm. The sampling depth intervals were 0–5, 5–10, 10–20 and 20–30 cm. Soil samples were air-dried in the laboratory and SOC was determined following a potassium dichromate oxidation titration method (Lal, 2003).

2.3.2. Soil bulk density (ρ_b, g cm^{-3})

Soil ρ_b was determined by use of the cutting ring core method at the depth of 0–5, 5–10, 10–20 and 20–30 cm. Soil samples in the rings were dried in the laboratory at 105 °C for 24 h for calculating soil ρ_b.

2.3.3. Soil carbon storage (SCS, kg ha^{-1})

SOC was obtained directly from the above chemical analysis. SCS in genetic horizons was calculated from the thicknesses (0–30 cm) of the horizons (Ellert and Bettany, 1995):

$$SCS = \rho_b \times T \times SOC \times 10000 \quad (1)$$

where, ρ_b is the mean ρ_b of 0–30 cm, T is the thickness of soil layer (m), 10000 is the conversion coefficient, and the unit of SCS is kg ha^{-1}.