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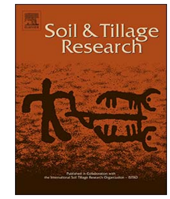

Ridge tillage is likely better than no tillage for 14-year field experiment in black soils: Insights from a ^{15}N-tracing study

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ABSTRACT

Conservation tillage practices, such as no tillage (NT) and ridge tillage (RT), have been widely proposed for use in many countries to increase carbon sequestration. However, understanding of how conservation tillage affects soil gross N transformation is still very limited. In this study, a ^{15}N-tracing experiment was carried out to investigate the effects of 14 years of RT and NT practices on the gross N transformation rates in black soils of northeast China. Based on the results for soil N transformations, soil organic carbon (SOC) sequestration, and crop yields, we propose suitable conservation tillage practices. The results showed that the NH_4^+ immobilization rates were significantly higher under RT than NT. The heterotrophic nitrification rate in RT was significantly higher than in either conventional tillage (CT) or NT, contributing more than 89% of the total nitrate production in RT. NO_3^- immobilization was negligible under NT and CT, but this process was significantly stimulated by RT. Consequently, relative to NT and CT, a long-term RT treatment can stimulate inorganic N retention capacity and thus provides greater capacity to supply available N for uptake by crop plants. In addition, the average concentrations of SOC and total nitrogen (TN) in the 0–15 cm soil layer under RT were significantly higher than those under NT and CT. The average maize yields (2011–2015) under RT were similar to NT, both of which were significantly higher than under CT. Therefore, RT is arguably a more suitable tillage practice than NT and CT for enhancing the N retention, maize yield, and C sequestration for the studied black soils.

1. Introduction

Conservation tillage practices, such as no tillage (NT) and ridge tillage (RT), have been widely proposed for use in many countries to slow down or offset their carbon emissions while enhancing soil fertility by improving the content of soil organic carbon (SOC) (Blanco-Canqui and Lal, 2008). It is generally accepted that conservation tillage can increase SOC and total nitrogen (TN) contents in the upper soil layers (Franzluebbers et al., 1994; McCarty et al., 1995). However, systems are not often adopted, probably because they can temporarily reduce the available N supply to plants and crop production (Annunziata et al., 2013; De Vita et al., 2007; Martínez-Mena et al., 2013). Since the effects of different tillage practices on SOC and TN contents can depend on the type of soil (Yang et al., 2008; Yoo et al., 2006), they will also support specific nitrogen (N) transformations (Booth et al., 2005). Soil N transformations govern soil N availability and inorganic N retention ability, and are thus related to crop yield and N loss potential (Wang et al., 2015; Zhang et al., 2016). Nitrogen is a critical element for crop production, yet excessive fertilizer N inputs are of environmental concern as they can cause surface and ground water pollution and the emission of the potent greenhouse gas, nitrous oxide (N_2O) (Zhu and Chen, 2002; Chen et al., 2014). Therefore, it is crucial to obtain a better understanding of soil N transformations under different conservation tillage practices to optimize N fertilizer management, to increase crop production, and to use N efficiently. To date, however, our understanding of how conservation tillage affects soil gross N transformation is still very limited.

Effects of conservation tillage on soil N transformations have been mainly studied via net mineralization and nitrification rates (Franzluebbers et al., 1994; Hart et al., 1994; McCarty et al., 1995).

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These net rates are useful methods that can provide insight into plant available N and the risks of N leaching, but they do not provide details of the individual N transformation processes (Hart et al., 1994). Gross N transformation rates, as determined by ^{15}N-tracing techniques, are now widely used to quantify individual N turnover rates; hence, this method can provide a process-based understanding of soil N cycling processes (Wessel and Tietema, 1992; Lang et al., 2016). To our best knowledge, to date only a few studies have investigated the long-term effects of conservation tillage on soil gross N transformation rates (Gómez-Rey et al., 2012; Dong et al. 2012). In particular, how certain individual N transformation processes—such as dissimilatory NO_3^- reduction to NH_4^+, oxidation of recalcitrant soil organic N to NO_3^-, and mineralization of labile soil organic N to NH_4^+—differ among conservation tillage systems has not been studied thus far.

Black soil is a major soil resource in the Northeast Plains of China. Because of its high organic matter and soil fertility, this soil type is heavily used for crop growth and is especially important for sustaining grain production (especially of maize) in China (Liu et al., 2006; Wang et al., 2011). However, the recent decades of intensive cultivation have reduced soil organic C and degraded soil quality, a situation which now threatens food production in China (Xu et al., 2010). To mitigate this risk, conservation tillage practices, including those of NT and RT, have been proposed as a viable alternative to conventional tillage (CT). The effects of conservation tillage on the SOC and TN content, the soil microbial community, and soil aggregation have been reported on already, with RT being apparently more beneficial for C sequestration than is NT (Liang et al., 2014; Zhang et al., 2013; Jia et al., 2016; Sun et al., 2016). A recent study found that, compared with CT, the long-term practice of NT could increase gross N mineralization and autotrophic nitrification rates in the topsoil layer, with a significant reduction of the N immobilization rate, thus resulting in the buildup of an NO_3^- pool (Liu et al., 2017). Soil N transformations are regulated by both the SOC and TN contents, which includes any non-decomposed residues (Recous et al., 1998). However, the SOC and TN concentrations respond under RT relative to NT are likely different because the former practice incorporates such residues (Jia et al., 2016).

Here, we hypothesized that gross N transformation rates under RT would differ significantly from those under an NT treatment. The objectives of this study were to: (i) investigate the long-term effects of conservation tillage, particularly of RT, on the soil gross N transformation rates, (ii) evaluate the effects of conservation tillage on both soil N availability and inorganic N retention ability, and (iii) propose suitable conservation tillage practices for the vital black soils of northeast China.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at the Experimental Station (44°12′N, 125°33′E) of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, located in an area of flat ground in the county of Dehui in Jilin Province, China. The region is characterized by a typical temperate continental monsoon climate. The mean annual temperature is 4.4 °C; the lowest mean monthly temperature occurs in January (−21 °C) and the highest in July (23 °C). The mean annual precipitation is 520 mm, most if which comes between May and September. The soil is derived from loamy loess, and it is classified as a Black soil in Chinese soil classification system—-equivalent to a Hapudoll in the USDA soil taxonomy system—with a clay loam texture consisting of 36.0% clay (< 2 μm), 24.5% silt (2–20 μm), and 39.5% sand (20–200 μm). Before starting the tillage trials, the field had been continuously cropped with maize (*Zea mays* L.) under conventional tillage for > 20 years (Liang et al., 2007).

2.2. Experimental design and management practices

A long-term tillage experiment was established in a split-plot design with four replicates in autumn 2001. Each main plot (10.4 m × 20 m) was split into two 5.2-m × 20-m sub-plots. The NT, CT, and RT tillage systems were applied randomly at the main plot level to 12 plots in total; a maize-soybean (*Glycine max* Merr.) rotation was applied at the sub-plot level, with both crops planted in each whole plot every year. That is, in one sub-plot, maize was planted in odd-numbered years and soybean in even-numbered years, while this planting pattern was reversed in another sub-plot in the same main plot. All the main plots were on flat ground (slope of < 1°) and they had similar SOC and TN concentrations before the three tillage treatments were applied (Table S1).

The NT treatment was left undisturbed, except during the planting of crops with a no-till planter. Soil management in the CT treatment included mouldboard plowing (20 cm deep) after the maize harvest in autumn, followed by disking (7.5–10 cm deep) and harrowing to prepare the secondary seedbed in the spring. In the RT treatment, the ridges were maintained yearly with a cultivator in June, and a modified lister and scrubber were used to form and press the ridge (each 16 cm in height and 75 cm in width). The crops were planted in May and harvested in September. Once harvested by hand, the maize stalks in the NT and RT plots were manually cut into 30-cm-long pieces, leaving 30–35 cm of stubble on the soil surface; any soybean residues were directly left on the soil surface. In the RT plots, the crop residues were incorporated into the soil by the ridging operation done yearly in June. In the CT plots, all of the maize residues aboveground were removed before the plowing in the fall, while the soybean residues were left on the soil surface.

The application rates of N, P, and K were kept the same in all three tillage treatments. For soybean, 40 kg N ha^{-1}, 49 kg P_2O_5 ha^{-1}, and 53 kg K_2O ha^{-1} were applied as the base fertilizer. Likewise, for maize, 100 kg N ha^{-1}, 51 kg P_2O_5 ha^{-1} and 51 kg K_2O ha^{-1} were applied yearly, with an additional 50 kg N ha^{-1} applied as top a dressing at the V-6 growth stage (i.e., six leaves with collars). Base fertilizers for all the plots were applied as a sideband when planting by using the banding attachment on the no-till planter. Weeds in NT and RT plots were controlled by using broad-spectrum herbicides before and after sowing (Table S2); weeds in the CT plots were removed with a manual brush hoe when necessary during the growing season. Because the herbicide dosage used was very small in NT and RT, its effects on soil N transformation could be neglected along with those of manual weeding (Bai et al., 2014).

2.3. Soil properties and crop yield measurements

Soil samples were collected from three of the four field replicates in October 2015—i.e., during year 14 of the experiment—from the maize-planted sub-plot of each tillage system after the harvest. Seven core samples were taken at random from each maize-planted sub-plot. Each core sample was first separated into two segments of 0–5 and 5–15 cm, then these seven segments per depth layer were combined into a single composite sample for each plot. Because it was in the dry season, the soil water content was low (14%–20% mass water content). So, once collected, all the soils were immediately passed through a 2-mm sieve, and stored at 4 °C for 1 week until the incubation experiment and physicochemical analyses.

Soil bulk density (BD) of 0–5 cm, 5–10 cm and 10–15 cm was measured using a soil-cutting ring (5-cm height × 5-cm diameter) with seven replicates. Soil pH was determined in a 1:5 soil/water mixture by a DMP-2 mV/pH detector (Quark Ltd, Nanjing, China). Soil water-holding capacity (WHC) was measured by soaking sieved soil samples (20 g) in water for 2 h, then draining them for 6 h (Niemi et al., 2008). After removal of all crop residues (including undecomposed and semi-decomposed crop residues) from the samples, their total carbon and