Nitrogen storage in density and size fractions varied with tillage practices and cropping systems under residue return

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Abstract

Residue return can prevent or restore the degradation of cropland, meanwhile, additional N input from residue return inevitably result in the changes of soil nitrogen (N) pools. Our objectives were to evaluate these changes in a 16-year field experiment. The residue return experiment consisted of no-tillage (NT) and mouldboard plough (MP), combined with continuous maize (*Zea mays* L.) (MM) and maize-soybean (*Glycine max* Merr.) rotation (MS) cropping systems, that is, NTMM, NTMS, MPMM, MPMS; conventional tillage (removal of crop residue and deep plough) with continuous maize (CTMM) was included as a control. The soil was separated into density (LF, light fraction) and particle size (sand, silt and clay) fraction. In 0-5 cm and 5-10 cm layers, soil TN content in NT was higher than MP, whereas the opposite trend was observed in 10-20 cm. Thus, the stratification ratio of soil TN was greater under NT. Cropping system affected soil TN as MM > MS. Residue return increased soil N storage by 6.44%-24.85% in the plough layer. Taking CTMM as the baseline, NTMM and MPMM increased the N storage in all physical fractions, while the decrease of silt-N storage was observed in NTMS and MPMS. Under residue return, the distribution of N storage changes in LF and sand fraction was affected by tillage practice, and that in silt and clay fraction was affected by cropping system. In summary, NTMM is effective for soil N accumulation due to its highest N storage and all physical fractions of N storage was enhanced.

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Keywords: residue return; nitrogen storage; physical fractions

1. Introduction

Crop residue return can prevent or restore the degradation of cropland (Zhang et al., 2019), it has been recommended as an eco-friendly practice for increasing soil fertility, enhancing crop production and saving labor (Bailey and Lazarovits, 2003; Wang et al., 2015; Zhang et al., 2018). What's more, returning crop residue could promote soil N pool by 10.7% (Wang et al., 2018). It is well documented that crop residue return, especially combined with no-tillage (NT) increases the soil N storage significantly (Chen et al., 2009; Ramnarine et al., 2015; Varvel and Wilhelm, 2011). In additional, soil N storage was also varied with the types of returned crop residue due to its difference in quantity and quality (Jagadamma et al., 2007; Congreves et al., 2016).

Nitrogen (N) plays an important role in determining plant growth and often a limited nutrient in terrestrial ecosystems (Fowler et al., 2013). Excessive N input from fertilizer has been applied to improve crop yields owing to the demand by the growing global human population (Galloway, 2003; Vitousek et al., 2009). Meanwhile, N losses from agriculture is a major threat to the ecological environment, human health and economic development (Bowles et al., 2018). Soil total nitrogen (TN) content is a valuable indicator for soil fertility and its storage can reflect the net balance between N inputs and outputs (Cassman et al., 2002). Combining the physical density and size fractionation method helps to understand the component and characteristic the soil N pools (Diochon et al., 2016), which has been widely applied in studies of soil organic carbon (SOC) (Cyle et al., 2016). The different properties of N physical fractions are important for soil fertility, crop growth and N loss. Numerous researchers have already studied how residue return affect soil N storage, whereas studies on N storage changes in physical fractions are rare.

In this study, soil physical fractionation method was used to determine N concentrations in bulk soil (TN), LF (LF-N), sand (sand-N), silt (silt-N) and clay (clay-N) fractions under contrasting tillage practices with two different cropping systems in a long-term residue return field experiment in black soil. Our objectives were: 1) to quantification the soil N storage in the plough layer under residue return; 2) to evaluate the changes of N storage in physical fractions under different tillage practices and cropping systems with residue return.

2. Materials and methods

2.1 Experimental site

The long-term field experiment was initiated in fall 2001, and was located at the Experimental Station (44°12'N, 125deg33'E) of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, in Dehui County, Jilin Province, China. This site is in the North Temperate Zone and belongs to a

continental monsoon climate with 4.4 mean annual temperature and 520 mm mean annual precipitation. More than 70% of the annual precipitation occurs during the plant growing season from June to August. Soil is classified as Typic Hapludoll (USDA Soil Taxonomy) with a clay loam texture (36% clay, 24.5% silt and 39.5% sand). Continuous maize and intensive deep tillage were the prevalent agriculture management in this region and had been applied for more than 15 years continuously prior to initiation of the field experiment. Soil properties were given by Liang et al., (2007).

2.2 Field experimental design

The long-term experiment was a split-plot randomized block design with four replications. Tillage including no-tillage (NT) and mouldboard plough (MP) was applied at the whole plot level (10.5 m x 20 m). Cropping system was set as the sub-plot (5.2 m x 20 m) treatment and included continuous maize (MM) and 2-year maize soybean rotation (MS). Therefore, this study involves four residue return treatments: no-tillage with maize-soybean (NTMS) or continuous maize (NTMM); mouldboard plough with maize-soybean (MPMS) or continuous maize (MPMM); and the control: conventional tillage with continuous maize without residue return (CTMM), this is the traditional management system in the region. The average annual amount of residues returned to the field was 2.6 Mg ha⁻¹ for soybean and 11 Mg ha⁻¹ for maize. In the NTMS and NTMM plots, the only soil disturbance was by a no-tillage planter (KINZE-3000, Williamsburg, IA, USA). The other three treatments (MPMS, MPMM and CTMM) had ridge building in June and mouldboard plough ([?] 20 cm) after harvest. The only difference between CTMM and MPMM is whether or not residues were returned.

The amount of fertilizer applied was different for maize and soybean. For maize, N, P₂O₅ and K₂O fertilizers were applied at 100, 45.5 and 78 kg ha⁻¹, respectively, as starter fertilizers. At the maize V6 growth stage (six maize leaves with collars), an additional 50 kg N ha⁻¹ was applied as top dressing. For the soybean, only starter fertilizer was applied, N, P₂O₅ and K₂O fertilizers were 40, 60 and 80 kg ha⁻¹, respectively. Starter fertilizers were applied with the side-banding attachment on the no-tillage planter.

2.3 Soil sampling and measurements

Seven soil core samples were collected from each plot in MM and the maize phase of the MS rotation using a 2.64 cm diameter hand auger before seeding in 2017. Soil cores were separated into three segments, 0-5 cm, 5-10 cm and 10-20 cm, and all cores for each depth segment of the same plot were thoroughly mixed to form a composite sample for the respective depth. Stubble and stones were removed, and air-dried soil was sieved to pass a 2 mm sieve and stored in glass bottles for future analysis. The soil bulk density (BD) was measured using the cutting ring method, the soil samples were oven-dried at 105 degC to a constant weight to calculate water content and subsequently calculate soil BD.

The soil physical fractionation followed a protocol described by Diochon et al., (2016). First, NaI solution (1.7 g cm⁻³) was used to separate two density fractions: < 1.7 g cm⁻³ (light fraction, LF) and > 1.7 g cm⁻³ (heavy fraction, HF). Then HF samples were separated into three size fractions: > 53 µm (sand), 5-53 µm (silt) and < 5 µm (clay), by wet sieving method (Magid and Kjærgaard, 2001) and Stokes's law (Kroetsch and Wang, 2006). After separation, all the physical fractions were dried at 60 in an oven to a constant weight. The concentration of N in bulk soil (TN) and four physical fractions (LF-N, sand-N, silt-N, clay-N) was measured with an Elementar Vario EL Cube (Elementar Analysis system GmbH, Hanau, Germany).

2.4 Data analysis

Soil N storage (Mg N ha⁻¹) was calculated on the basis of equivalent soil mass according to the procedure of Ellert and Bettany (1995).

The stratification ratio (SR) of soil TN was calculated by:

$$SR = TN_{0-5} / TN_{10-20} \quad (1)$$

where TN₀₋₅ and TN₁₀₋₂₀ are the soil TN contents (g N kg⁻¹ soil) in the 0-5 cm layer and 10-20 cm layer, respectively.

The changes of N storage ([?]N storage, kg N ha⁻¹yr⁻¹) in residue return treatments was calculated as:

$$[?]N \text{ storage} = (N_r \text{ storage} - N_{CTMM} \text{ storage}) \times 1000 \quad (2)$$

where N_r storage represents the N storage (Mg N ha⁻¹) in treatments with residue return (NTMS, NTMM, MPMS and MPMM), N_{CTMM} storage represents the N storage (Mg N ha⁻¹) in CTMM, 1000 is the conversion from Mg to kg.

The storage of N in physical fractions (F-N storage, kg N ha⁻¹) was calculated by:

$$F-N \text{ storage} = (F-N_{percentage} / 100) \times \text{soil N storage} \times 1000 \quad (3)$$

where $F-N_{percentage}$ is the percentage of N in each fraction (%), 1000 is the conversion from Mg to kg.

Two-way ANOVA analysis was used to examine the effects of tillage practice and cropping system on soil TN content and the SR of TN. We conducted variance partitioning analysis to assess the relative contribution of tillage practice and cropping system to the change of N storage in physical fractions (F-[?]N storage) and its relatively distribution (%). All the statistical analyses were carried out with SPSS 16.0 (SPSS Inc., Chicago, Illinois, USA) and the R software (version 3.6.2).

3. Results

3.1 Soil TN content and its stratification ratio, and N content in physical fractions

Soil TN was significantly ($P < 0.01$) affected by tillage practice (T) and cropping systems (CS) in three layers. In the surface 0-5 cm (Figure 1, a) and 5-10 cm layers (Figure 1, b), the content of soil TN under NT treatments was higher than MP treatments and CTMM under the same cropping system; in 10-20 cm layer (Figure 1, c), the content of soil TN under MP was higher ($P < 0.01$). The effect of cropping system on soil TN was consistent in three soil layers (Figure 1, a-c) with MM > MS ($P < 0.01$). Additionally, the content of TN at 5-10 cm soil layer (Figure 1, b) was also ($P < 0.01$) affected by the interaction of tillage practice and cropping system (TxCS). The stratification ratio (SR) of soil TN was significantly ($P < 0.001$) affected by tillage practice (T) (Figure 2), and it was much higher in NT treatments (1.70 on average) than in MP treatments (1.13 on average) and CTMM (1.14).

The effects of tillage practice (T), cropping system (CS) and their interaction (TxCS) on the N contents in physical fractions (F-N content) and the percentage of N in each fraction ($F-N_{percentage}$) are shown in Table 1. In the 0-5 cm layer, tillage significantly ($P < 0.001$) affected the F-N contents and the $F-N_{percentage}$ except silt- $N_{percentage}$ (Table 1). Under the same cropping system, the F-N contents in treatments with NT were significantly ($P < 0.001$) higher than with MP. The LF-N content of NT treatments was 5.2 times (MS) and 3.8 times (MM) higher than MP treatments. The LF- $N_{percentage}$ and sand- $N_{percentage}$ in NT treatments were also higher. In addition, the silt-N content and silt- $N_{percentage}$ were affected by cropping system ($P < 0.001$) and TxCS interaction ($P < 0.001$), the silt-N content was greater in treatments with MM than with MS, and was the highest in NTMM. However, the clay- $N_{percentage}$ in NT treatments was lower than MP treatments even though clay-N content in NT treatments was higher. In the 5-10 cm layer, the F-N contents in all fractions except clay were significantly ($P < 0.05$) affected by cropping system with MM > MS (Table 1). Compared with MS, the LF-N content and silt-N content in treatments with MM were 76.9% and 83.3% higher in NT, 15.4% and 26.3% higher in MP, respectively. The LF-N content and sand-N content were also significantly affected by tillage practice ($P < 0.05$) and TxCS interaction ($P < 0.05$). Except for the clay- $N_{percentage}$, the F-N content and $F-N_{percentage}$ of all fractions in NTMM treatment was the highest among all treatments. In the 10-20 cm layer, the F-N content in all fractions except sand-N were significantly ($P < 0.001$) influenced by tillage practice, cropping system and TxCS interaction (Table 1). The LF-N content, sand-N content, LF- $N_{percentage}$, and sand- $N_{percentage}$ were higher in MPMM than in the other treatments. The clay-N content in four residue return treatments was higher than CTMM.

3.2 Soil N storage in bulk soil and correlation parameters

After 16-year agriculture management, soil N storage of residue return treatments was significantly ($P <$

0.05) increased compared with CTMM in 0-20 cm depth (Table 2), and the descending sequence of soil N storage was NTMM (4.46 Mg N ha⁻¹) > MPMM (4.10 Mg N ha⁻¹) > NTMS (3.92 Mg N ha⁻¹) [?] MPMS (3.80 Mg N ha⁻¹) > CTMM (3.57 Mg N ha⁻¹). The increment of [?]N storage in NTMM was the highest with 887.03 kg N ha⁻¹. The annual N input of residue ($N_{a-residue}$) in MM treatments (83.6 kg N ha⁻¹ yr⁻¹ on average) was higher than MS (62.6 kg N ha⁻¹ yr⁻¹ on average including both maize and soybean phases), whereas CTMM was the lowest (27.4 kg N ha⁻¹ yr⁻¹). Soil N storage was positively related to the annual N input of residue (Figure 3). The maize yield in MS treatments (10.64 Mg ha⁻¹ on average) was higher than MM (9.31 Mg ha⁻¹ on average), and they were both significantly higher than CTMM with 8.94 Mg ha⁻¹. There was no difference in soybean yield between NTMS and MPMS.

3.3 N storage change in physical fractions of residue return treatments

Taking CTMM as the baseline, the change of the N storage in physical fractions (F-[?]N storage) varied among residue return treatments (Figure 4, a). Considering the variable of soil N storage changes in residue return treatments (Table 2), the distribution of F-[?]N storage (%) was calculated for each treatment (Figure 4, b). Treatments with MM enhanced the F-[?]N storage in all fractions, while the decline of silt-[?]N storage under treatments with MS was observed. The LF- and sand-[?]N storage were both the highest in NTMM than other treatments, while the distribution of LF-[?]N storage in NTMS was the highest. The reduction of silt-[?]N storage in NTMS (-206.2 kg N ha⁻¹) was greater than MPMS (-59.9 kg N ha⁻¹), and the increase of silt-[?]N storage in NTMM (204.2 kg N ha⁻¹) was greater than MPMM (67.9 kg N ha⁻¹). The distribution of silt-[?]N storage (%) in treatments showed the same trend with silt-[?]N storage. The accumulation of clay-[?]N storage was the highest among all physical fractions, and ranged from 318.4 kg N ha⁻¹ to 448.5 kg N ha⁻¹. The clay-[?]N storage was significantly ($P < 0.05$) higher in NT treatments than MP treatments, whereas the distribution of clay-[?]N storage varied with cropping systems (MS > MM).

The variation partitioning demonstrated that tillage practice (T) and cropping system (CS) accounted for 74.8%-99.2% of the variation in N storage change in physical fractions (F-[?]N storage) (Figure 5, a-d). The LF-, sand- and clay-[?]N storage were mainly determined by tillage practice, which explained respectively 77.8%, 57.8% and 90.8% of the variation; the silt-[?]N storage was mainly determined by cropping system (81.8%). However, the distributions of LF- and sand-[?]N storage were influenced by tillage practice (Figure 5, e-f), 65.1% (LF) and 95.0% (sand) of the variation was explained, whereas the distributions of silt- and clay-[?]N storage were influenced by cropping system, 90.4% (silt) and 99.3% (clay) of the variation was explained (Figure 5, g-h).

4. Discussion

4.1 Effects of tillage practice and cropping system on soil TN content and its storage under residue return

Our research showed that tillage practice had significant impact on soil TN in the plough layer (0-20 cm), and the impact varied with soil layers (Figure 1). In the 0-5 cm and 5-10 cm layer, soil TN content was higher in NT than MP, whereas the reverse trend was observed in 10-20 cm layer. The results were consistent with researches in other regions (Angers et al., 1997; Spargo et al., 2008). Franzluebbers (2002) introduced the concept of soil stratification ratio (SR) of SOM pools as an indicator to evaluate soil quality, and emphasized that high SR was good. Similar to SOM, the SR of soil TN under MP (1.1-1.8) was generally lower than NT (1.6-3.2) (Franzluebbers, 2002; Sa and Lal, 2009). In this study, the SR of soil TN in MP and NT treatments was 1.13 and 1.70 on average, respectively (Figure 2), which represented that soil quality in NT was better. Although crop residue was returned to the soil in NT and MP, tillage in MP makes residue evenly distributed in the plough layer and accelerates the mineralization of N (Allmaras et al., 2004; Abreu et al., 2011; Zuber et al., 2015). Rossella et al. (2007) indicated that the effect of tillage practice on soil TN was mainly related to soil texture, climate and cropping system.

Cropping systems with different crop species could change soil microbial dynamics and nutrient supply therefore altering N cycles (McDaniel et al., 2014; Tian et al., 2015). In our research, cropping system had significant effect on soil TN in all three layers, and the soil TN content in MM was higher than MS under the same tillage practice, NT or MP (Figure 1). The residue quantity (above- and below-ground) of maize is

about two-fold greater than soybean as annual crops (Prince et al., 2001), thus about 18.6-31.9 kg ha⁻¹yr⁻¹ extra N was returned in MM cropping system (average of maize and soybean phases) (Table 2). In addition to the quantity of crop residue, the different chemical composition of maize and soybean residue resulted in a different turnover rate of crop residue which was also a major factor affecting soil TN. Blanco-Canqui and Lal (2004) found soybean residue decomposed faster for its lower C:N ratio, and maize residue usually decomposed over a longer period (Abail and Whalen, 2018; Dou et al., 2018). Recently, Zheng et al., (2021) demonstrated that slowly decomposing residues favor soil N store in relative to more rapidly decomposing residues. These results are consistent with the results of this study.

The N storage in croplands is strongly influenced by agricultural management such as tillage practice, cropping systems and residue management. The soil N storage in residue return treatments was 6.44%-24.85% higher compared with CTMM in plough layer (0-20 cm) (Table 2), which highlighted the importance of crop residue retention to soil N storage. Some studies also indicated that the positive effects of residue return on soil N storage mainly occurred in 0-20 cm layer, but a generally equal or substantial reduction in deeper layer under NT (Dolan et al., 2006; Gal et al., 2007). In our study, the stratification of soil TN was observed under NT in plough layer, but the N storage indeed increased which was related to the annual N input of residue (Figure 3). In comparison with CTMM, the [?] N storage of NTMM was the highest for 887.03 kg N ha⁻¹ (Table 2), equivalent to increase soil N storage by 59 kg N ha⁻¹ yr⁻¹ on average. This was higher than the average increment of N storage with 28 kg N ha⁻¹ yr⁻¹ under NT reported by Franzluebbers (2004), but less than the accumulation rates of N storage with 100 kg N ha⁻¹ yr⁻¹ under NT in subtropical region in 0-30 cm (Bayer et al., 2000). The ability of N fixation under residue return was differ in diverse regions, soil depth and cultivation years. Overall, the positive impact of NTMM on soil N storage can be explained from two main aspects, first is the increase of N derive from crop residue (Mazzoncini et al., 2011; Dolan et al., 2006), and second is the decrease of N loss due to less soil disturbance (Sainju et al., 2009).

4.2 Effect of tillage practice and cropping system on the change of N storage in physical fractions under residue return

The traditional CTMM was practiced for more than 15 years on the field site prior to initiation of the long-term experiment, and consequently, the soil status was assumed to be the same for all treatments when the experiment was established in 2001. The gain/loss of soil N storage in residue return treatments were calculated based on CTMM, and are thus relative to any changes in CTMM.

After returning crop residues, the distribution of LF- and sand-[?]N storage were mainly influenced by tillage practice (Figure 5, e-f), the increase of LF- and sand-[?]N storage (0-20 cm) in NT treatments was significantly higher than MP treatments under the same cropping system (Figure 4a, 4b). This indicated that there was more undecomposed and semi-decomposed residue under NT, which was regarded as a potential active N pool (Coppens et al., 2010). Ramnarine et al., (2015) also found that LF-N storage (0-10 cm) was higher under NT in a silt loam in southern Ontario, Canada, the similar trend was observed in Ohio, USA by Tan et al., (2007). As newly incorporated and partially decomposed plant debris of soil, LF is the most sensitive fraction to agricultural management (Whalen et al., 2000; Ramnarine et al., 2015). LF together with sand-size fraction was often considered as particulate organic matter (POM) which was derived from plant residues (Jafarzadeh-Haghighi et al., 2016). Tillage practice under MP, like ploughing, can disrupt soil aggregate structure and release physically protected N (Fernandez-Ugalde et al., 2009), thereby accelerating the decomposition of relatively labile N pool. Thus, only 19.27% and 8.24% of the [?]N storage was accumulated in LF and sand size fractions under MPMM and MPMS, respectively. While LF- and sand-[?]N storage accounted for 31.29% (NTMM) and 39.12 % (NTMS) of the [?]N storage in this study (Figure 4b). Oorts et al. (2007) found that PON (particulate organic nitrogen, equivalent to the LF-N + sand-N) contributed about 50% to the variance of N storage after 32 years of NT. It can be inferred that the accumulation of these relatively labile N pools in response to residue return need time.

It was found that the distribution of silt- and clay-[?]N storage was mainly influenced by cropping system under residue return (Figure 5, g-h). The decomposability of crop residues was different owing to its substrate quality, and it was also determined by the activity of microbial (Cordova et al., 2018; Zuber et al., 2015).

More and more evidences indicate that SOM associated with silt- and clay-size fractions was primarily derived from microbial metabolism (Christensen, 2001; Cyle et al., 2016). Therefore, it has been generally considered that the silt-N and clay-N was relatively stable due to the physiochemical interactions (Six et al., 2002; Bol et al., 2009;), and the increase of N storage in silt size and clay size could enhance the stability of soil N pools. Of all physical fractions, the proportion of [?]N storage in clay size was the biggest under MS treatments (Figure 4b), however, the decrease of silt-[?]N storage was also observed (Figure 4a). This suggested that most of the N derived from crop residue under maize-soybean rotation was associated with clay size fraction, and this process was proved to be dominated by fungi activity (Helfrich et al., 2008; Soares and Rousk, 2019). Nevertheless, the maize-soybean rotation might stimulate the microbial to decompose the N associated with silt size in soil, increasing the risk of N loss.

5. Conclusion

Soil total nitrogen (TN) content showed significantly stratified in NT treatments than MP treatments. Cropping system affected the soil TN content with MM > MS. Relative to the CTMM, the highest and lowest [?]N storage was observed in NTMM and MPMS under residue return, respectively. Of all physical fractions, clay account for the most for the [?]N storage under residue return. Continuous maize (MM) enhanced N storage in all physical fractions, whereas the decline of silt-N storage was found under maize-soybean rotation (MS), this suggests that maize-soybean rotation affects the stability of N pools. The distribution of [?]N storage in LF and sand size fractions was influenced by tillage practice, whereas the distribution of [?]N storage in silt size and clay size fractions was influenced by cropping system. In summary, soil N storage in NTMM was the highest, and N storage in all physical fractions was enhanced. This indicates that NTMM is beneficial to plant growth, soil N storage accumulation and the stability of N pools from the perspective of physical N pools.

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