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# Changes in soil carbon and nitrogen pools in a Mollisol after long-term fallow or application of chemical fertilizers, straw or manures

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ABSTRACT

Appropriate fertilizer management can effectively restrain decreases in soil carbon (C) and nitrogen (N) in agricultural Mollisols in northeast China. A 22-yr-old field experiment was employed to explore the effects of fallow, chemical fertilizer N, phosphorus (P), potassium (K), or straw or manure combined with NPK (SNPK, MNPK), and 1.5 times the N rate of MNPK (1.5MNPK) application on soil C and N pools. Soil organic C (SOC), total N (TN), inorganic C (IC), and mineral N ($NO_3$-N, $NH_4$-N) to 100 cm soil depth and C and N in particulate organic matter (POC, PON), soil microbial biomass (MBC, MBN), and dissolved organic matter (DOC, DON) to 40 cm soil depth were determined. In all treatments, the 1.5MNPK treatment had the significantly highest ($P < 0.05$) SOC and TN concentrations above 40 cm soil depth and the SNPK treatment had the significantly highest ($P < 0.05$) IC concentration at 40–60 and 60–80 cm soil depths. Comparing the other treatments to 40 cm soil depth, in most cases 1.5MNPK and MNPK treatments at each depth had significantly higher ($P < 0.05$) POC, PON concentration, POC/SOC and PON/TN. SNPK treatment had significantly higher ($P < 0.05$) MBN and MBN/TN at 10–20 and 20–40 cm soil depths and the fallow treatment had significantly higher ($P < 0.05$) MBC and DOC concentrations and higher DOC/SOC ratio at each soil depth. The optimum combination of manure, straw and NPK therefore favored C and N storage in this agricultural Mollisol.



## 1. Introduction

Soil carbon (C) and nitrogen (N) stocks have become a subject of unprecedented concern in the desire to mitigate increasing global atmospheric greenhouse gas emissions (Sainju et al., 2008; Gattinger et al., 2012; MacBean and Peylin, 2014; Shcherbak et al., 2014) because soil C storage benefits C trading and decreases $CO_2$ emissions and also improves soil quality. Increasing soil N immobilization can also reduce the application rate and cost of fertilizer N and protect the environment from the negative effects of reactive N species. Soil C and N are more vulnerable and complex in agricultural systems than in natural ecosystems due to disturbance resulting from management practices such as fertilizer applications and tillage practices. The accumulation and dynamics of soil C and N are long-term processes and their study requires long-term fertilization experiments (Qiu et al., 2010; Mazzoncini et al., 2011; Meng et al., 2014; Tripathi et al., 2014).

Fertilization practices used in agricultural systems include the application of chemical N, phosphorus (P), and potassium (K) fertilizers, organic fertilizers and animal manures or straw, or combinations of chemical fertilizers and organic sources of nutrients. Nitrogen, P, and K are macronutrients necessary for crop growth and the application of the chemical fertilizers can affect soil C and N accumulation through increasing biomass production (Tang et al., 2008; Lu et al., 2009; Mazzoncini et al., 2011; Qiu et al., 2014; Zhao et al., 2014). Application of organic

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fertilizers or combinations of chemical and organic fertilizers can further increase soil organic C (SOC) and total N (TN) concentrations because of enrichment with C sources and additional macronutrients and micronutrients present in organic fertilizers and especially in manures (Watts et al., 2010; Zhao et al., 2014). Overall, the storage of SOC or TN depends on the input and output balance of C or N when other nutrients are present at concentrations that do not limit crop growth. Some studies have reported that unbalanced nutrients (van Groenigen et al., 2006) or excessive nutrient application (Qiu et al., 2010) may constrain soil C and N storage, for example soil acidification due to excessive N application (Guo et al., 2010) can result in the loss of soil carbonates and further decrease soil total C storage (Qiu et al., 2010). Moreover, excessive N application will increase the risk of N loss under the limitation of available C sources (Qiu et al., 2013, 2015b). Regardless of the contribution of crop yield for food demand, the conversion of agricultural soil to fallow may increase SOC and TN storage in the surface soil due to vegetation recovery and annual plant residue return to the surface soil (Zhou et al., 2013). However, croplands in developing countries are required to be used for intensive food production to meet the needs of an increasing population and it is difficult to include fallow land in the intensively managed arable systems used. The selection of rational fertilization practices in arable areas therefore plays a vital role in controlling soil C and N storage but little information of soil C and N storage (including carbonates) is available and long-term field experiments are required to explore the relationships between fertilization practices and soil organic matter dynamics.

Soil active C and N pools respond sensitively to fertilization practices and affect nutrient supply or storage (Wander, 2004; Andruschkewitsch et al., 2013). These active pools can be denoted by C and N in particulate organic matter (POC, PON), microbial biomass (MBC, MBN), and dissolved organic matter (DOC, DON). Particulate organic matter (POM) is a nucleus for aggregates (Marriott and Wander, 2006a,b), represents a substantial fraction of the fresh plant residues, and is readily accessible for microbial decomposition (Yang et al., 2012). Soil microorganisms turn over the soil organic matter (SOM), and the soil microbial biomass (SMB) represents a nutrient reservoir that contributes to maintaining the sustainability of cropland. Dissolved organic matter (DOM) can be derived from decomposed SOM, the intermediate compounds of microbial metabolism or the death of microorganisms, plant debris, and root excretion (Kalbitz et al., 2000). POM also provides C or N substrates for microorganisms (Wander, 2004; Marriott and Wander, 2006a,b) and may be bound by polysaccharides and hyphae from SMB or DOM (Mendham et al., 2004; Wander, 2004; Qiu et al., 2010). Thus, the differences in the quantity and quality of these active pools after different long-term fertilization practices or fallow can effectively indicate the mechanisms of C and N storage in soils.

The C/N ratio is a key parameter in the evaluation of the quality of soil organic matter or different soil active pools and further reflects soil C and N cycling or status in different soil pools. Application of different chemical or organic fertilizers can affect the soil C/N. A low C/N ratio (<20:1) of exogenous substrates will promote net N mineralization (Stevenson and Cole, 1999) and a higher C/N ratio (>30:1) will lead to transient competition for N between soil microorganisms and crops and increase soil N immobilization. Soil C/N ratio is also under the influence of climatic conditions (temperature, precipitation) and crop rotations from year to year and long-term field experiments are necessary for the study of soil C/N ratio responses to different fertilization practices. Long-term experiments can be used to identify which factors are associated with changes in C/N ratio and which fertilization practices contribute to C and N storage in different soil pools.

The spring maize region in Jilin province in northeast China is predominantly under rain-fed agriculture with highly fertile Mollisol soils and produces 12.6% of the total Chinese maize yield (Qiu et al., 2014; 2015a). However, the soil organic carbon content in this region has decreased markedly since the 1980s (Huang and Sun, 2006) and this situation has further affected soil N storage and buffering capacity. Numerous studies have reported soil C and N pools in surface soils after long-term fertilization practices in China (Cong et al., 2012; Meng et al., 2014) but there is little information regarding the response of C and N pools deeper in the soil profile to different fertilization practices. The upper 100 cm of the soil profile can reflect soil C and N storage because 70% of SOC is located in this zone (Eswarran et al., 1993) and it is also regarded as the available soil depth for optimum N rate recommendations in the $NO_3$-N test method (Chen et al., 2011). Furthermore, DOM and $NO_3$-N can easily leach to the deeper soil but the upper 40 cm of the soil profile can indicate changes in C and N in different active soil pools due to the presence in this zone of >80% of crop roots and the effects of agricultural management practices on the growing roots (Peng et al., 2010; Qiu et al., 2010).

The objectives of the present study were therefore to compare soil total C and N storage in the upper 100 cm of the soil profile under different fertilization practices and fallow in northeast China and to explore the changes in C and N in different soil active pools in the upper 40 cm of the soil after different long-term fertilization practices and fallow in this region.

## 2. Materials and methods

### *2.1. Site*

The field experiment was established in 1990 at Jilin Academy of Agricultural Science's Gongzhuling experiment station (43°30′N, 124°48′E, 200 m above sea level), Gongzhuling county, Jilin province, northeast China. This region has a typical continental monsoon climate, is predominantly under rain-fed agriculture and is a major maize producing region. The annual mean temperature is 4–5 °C and the annual cumulative mean temperature for days with mean temperatures above 10 °C is 2000–3600 °C. The annual frost-free period is 125–150 d. The annual precipitation in the maize production area is 500–900 mm with 60% of rainfall occurring during the summer (July–September). The soil is classified as a Haplic Phaeozem by the FAO-UNESCO classification system and as a Mollisol in the USDA classification (Boerma et al., 1995). The top 20 cm of the soil profile was sampled at the start of the field experiment and after the maize harvest in October 1989 and the basic soil properties are shown in Table 1.

### *2.2. Experimental design*

The field experiment was composed of seven treatments with three replicates in a completely randomized block design. The treatments were (1) fallow, no nutrient application or tillage; (2) control (CK), no nutrient application; (3) application of fertilizer nitrogen only (N); (4) combined application of fertilizer N, phosphorus (P) and potassium (K) (NPK); (5) combined application of fertilizer NPK plus straw return (SNPK), with a ratio of chemical fertilizer N to straw N of 7:3; (6) combined application of fertilizer NPK plus horse manure application (MNPK), with a ratio of chemical fertilizer N to manure N of 3:7; (7) MNPK treatment at 1.5 times each fertilizer rate (1.5MNPK). The equivalent fertilizer rate in treatments (2)–(6) was 165 kg N $ha^{-1}$ as urea, 36 kg P $ha^{-1}$ as triple superphosphate, and 68 kg K $ha^{-1}$ as potassium chloride. The area of each plot was 220 $m^2$. All the treatments except for the fallow treatment were planted with maize. Treatments (2)–(4) were chemical fertilizer applications and the control treatment