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Research article

Early thawing after snow removal and no straw mulching accelerates organic carbon cycling in a paddy soil in Northeast China

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ABSTRACT

Variations in soil organic carbon (SOC) have implications for atmospheric CO_2 concentrations and the greenhouse effect. However, the effects of snow cover and straw mulching on the variations in SOC fractions across winter remain largely unknown. In this study, soil samples were collected during different stages of winter from an *in situ* experiment comprising three treatments: 1) snow removal with no straw mulching (Sn-SM-); 2) snow cover with no straw mulching (SC), and; 3) snow cover with straw mulching (SC + SM+). Results showed that labile organic carbon, semi-labile organic carbon, recalcitrant organic carbon (ROC), the light fraction of organic carbon (LFOC), and easily oxidized organic carbon (EOC) contents did not vary significantly ($P > .05$) during the unfrozen to hard frost stages. Compared to the unfrozen stage, microbial biomass carbon (MBC) contents decreased by 519.03 mg kg^{-1}, 325.21 mg kg^{-1}, and 244.09 mg kg^{-1} and dissolved organic carbon (DOC) contents increased by 473.36 mg kg^{-1}, 348.10 mg kg^{-1}, and 258.89 mg kg^{-1} at the hard frost stage in Sn-SM-, SC, and SC + SM + treatments, respectively. Throughout all thawing stages, > 61% and 59% of SOC and ROC accumulation, respectively in the three treatments were observed in thawing stage II, indicating that higher temperatures and microbial activities in thawing stage II accelerated the inputs of SOC and ROC. ROC accumulation accounted for >65% of the SOC accumulation and the proportions of ROC in SOC increased in the three treatments during the thawing stages. SC + SM + treatment maintained lower EOC contents during thawing stages than other treatments. The observation of lowest SOC and LFOC accumulation and contents in the SC + SM + treatment during thawing stages showed that SC + SM + experienced the least inputs of SOC in the soil.

1. Introduction

Soil contains the largest organic carbon (C) pool, thereby providing energy and substrates for microbial metabolism (Li et al., 2016) in the global terrestrial ecosystems (Lal, 2008; Wang et al., 2012). The soil organic C (SOC) pool exceeds the sizes of the atmospheric C pool and biomass C pool by factors of 2.2 and 2.8, respectively (Lal, 2004; Schimel, 1995). Minor variations in the SOC pool could lead to significant impacts on the atmospheric CO_2 concentration (Yang et al., 2017). Therefore, the SOC pool is regarded as an important potential carbon sink to mitigate the greenhouse effect (Bolin and Sukumar, 2000; Belay-Tedla et al., 2009). Increasing C sequestration or storage and minimizing greenhouse gas emissions to alleviate global warming has received worldwide attention. The SOC pool consists of three major pools, frequently separated using the acid hydrolysis method (Rovira and Vallejo, 2002): 1) a labile organic C (LOC) pool; 2) a semi-labile organic C (SLOC) pool, and; 3) a recalcitrant organic C (ROC) pool. In general, soil LOC and SLOC pools have faster decomposition and turnover rates (Zou et al., 2005) and are more sensitive to environmental impacts (Zhang et al., 2006) than the ROC pool, whereas the ROC pool has the highest proportions (49.4%–66.3%) (Liu et al., 2017) of SOC and dominates long-term C storage (Belay-Tedla et al., 2009; Ding et al., 2012). Therefore, the LOC and SLOC, including

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microbial biomass C (MBC), dissolved organic C (DOC), light fraction of organic C (LFOC), and easily oxidized organic C (EOC), etc. have been regarded as early indicators for carbon stock changes and soil quality (Li et al., 2016; Zhang et al., 2006), and are very important factors determining the future soil C balance (Dutta et al., 2006; Neff and Hooper, 2002). Environmental changes may disrupt the previous balance between C inputs and outputs (Wang et al., 2012) by accelerating the decomposition of LOC and SLOC. However, a growing body of evidence has shown that the decomposition of ROC can be stimulated by environmental changes (Fontaine et al., 2007; Xu et al., 2010; Liu et al., 2017). Therefore, ample description of the dynamics of LOC, SLOC, and ROC is essential to the understanding of the C transformation and assessment of C storage.

Winter in middle-high latitudes is characterized by drastic temperature fluctuations which lead to the freeze-thaw cycles (FTCs) and freezing of soil. Some previous studies have suggested that the FTCs may increase SOC (Makarov et al., 2015); however, other studies have shown that repeated FTCs (Feng et al., 2007; Kim et al., 2017; Schmitt et al., 2008) or frost (Schmitt and Glaser, 2011) had no significant influence on SOC contents. Most studies of the effects of freeze-thaw and frost have focused on LOC fractions, such as DOC and MBC in incubation experiments, and few studies have considered total LOC, SLOC, ROC, LFOC, and EOC. Several studies have shown that FTCs (Kim et al., 2017; Shang et al., 2016; Wang et al., 2014b) or soil frost (Haei et al., 2012) significantly increased the DOC concentrations, whereas other studies have found that freeze or thaw (Treat et al., 2016) or thaw after mild freeze treatments (Gao et al., 2015) resulted in no significant change in DOC. Some results showed that the MBC first decreased and then increased as the number of FTCs increased (Wang et al., 2014a, 2014b) whereas some other studies showed that freeze-thaw processes may merely decrease (Fan et al., 2012; Makarov et al., 2015) or increase MBC (Fan et al., 2012). Hence, a scientific consensus on the effects of freeze-thaw processes and frost on SOC, DOC, and MBC has not yet emerged. Furthermore, most of these studies were conducted in laboratory experiments operating under conditions different from natural conditions. Consequently, ample knowledge of the responses of SOC and its fractions, particularly SLOC, ROC, LFOC, and EOC to freeze-thaw and frost *in situ* is necessary to facilitate the preservation of C.

Snow cover and its insulation effects (Campbell et al., 2005; Merbold et al., 2012) in a seasonally-frozen area collectively comprise a vital factor controlling ecosystem characteristics during winter, such as soil temperature and moisture (Liu et al., 2010), which may impact SOC fractions by influencing the freeze–thaw regime (duration, frequency, and degree) and microbial activity (Hu et al., 2014). However, limited studies of the effects of snow cover have focused on DOC and MBC. Studies has shown that snow duration had no significant effect on the MBC concentrations; however, the thickness of snow cover impacted MBC concentrations (Hu et al., 2014), and greater leaching of DOC was observed under thin snowpack (Fuss et al., 2016). However, other results have shown that DOC and MBC first increased significantly then declined in different snow depths (Liu et al., 2010). Therefore, more information regarding the effects of snow cover on MBC, DOC, and other fractions of SOC is needed. Straw mulching is a common agricultural management practice and plays a major role in the process of SOC sequestration. However, almost all past studies have focused on the positive contribution of the decomposition of straw on the SOC (Li et al., 2016; Wang et al., 2015; Zhao et al., 2016; Zhu et al., 2015) and its fractions (Li et al., 2016; Wang et al., 2015; Zhu et al., 2015), and few studies have investigated the effects of straw mulching on SOC fractions during winter.

China is the world's largest rice producer (Kögel-Knabner et al., 2010), with Northeast China being one of the important rice production areas. Compared to southern paddy fields, northeastern paddy fields experience a winter lasting approximately 5–6 months with drastic temperature fluctuations. Western Jilin Province located in Northeast China experiences extreme cold temperatures in winter with a large amount of snowfall, whereas rapidly rising temperatures and extreme dry conditions are experienced in spring. Soil experiences FTCs in early and late winter until the soil has frozen or thawed completely, respectively, between which the soil experiences hard frost in the study area. Every year, large amounts of straw are available after the harvest in October before the snow season. However, to date, little knowledge has been generated regarding the dynamics of SOC and its fractions, including LOC, SLOC, ROC, DOC, MBC, EOC, and LFOC under snow cover and straw mulching; therefore, the overall objectives of the present study were to: 1) characterize the dynamics of SOC and its fractions and; 2) access the effects of snow cover and straw mulch on SOC and its fractions during the entire winter period.

2. Materials and methods

2.1. Site and experimental design

Field experiments were conducted from October 2013 to April 2014 in a paddy field in Songyuan City (123°6′–126°11′ E, 43°59′–45°32′ N) in Western Jilin Province, China. The properties of the experimental soil in the 0–15 cm layer were showed in Table 1.

Given the large amount of snowfall during winter, the experiment consisted of three treatments: 1) snow removal with no straw mulching (Sn-SM-); 2) snow cover with no straw mulching (SC), and; 3) snow cover with straw mulching (SC + SM+), which were arranged in a randomized complete block design with three replicates. After the rice was harvested in October, 2013, dry rice straw was uniformly and completely spread on the soil surface to a thickness of approximately 5.0 cm for all straw treatment groups after the removal of the surface litter and aboveground vegetation. The underground litter comprising root and animal residue was kept intact. Each plot measured 4 m^2 (2 m × 2 m) and was insulated by three layers of heat-insulated plastic board (40 cm × 200 cm) buried to a depth of 40 cm below the soil surface to minimize the movement of DOC, MBC, etc., between plots via lateral water movement.

2.2. Soil sampling and analyses

Samples were collected on 28th October, 2013 (unfrozen stage), 5th December, 2013 (freezing stage: when the 0–15 cm soil layer of all groups was completely frozen), 10th February, 2014 (hard frost stage: when the soil in all groups had been frozen for an extended time and was under hard frost), 12th April, 2014 (the time point that the snow melted completely), 23rd April, 2014 (thawing stage I: when the 0–15 cm soil layer of all groups had completely thawed), and 6th May, 2014 (thawing stage II: when the 15–50 cm soil layer of all groups had completely thawed). Three parallel samples of 0–15 cm were randomly collected using soil drills in each treatment at every stage. Soil drills were cleaned with distilled water before any sampling to avoid contamination among samples. The measurements of temperature, frost thickness, and snow cover

Table 1
The physicochemical properties of the soil at a depth of 0–15 cm before freezing.

Type	pH	Moisture	Available N	Available P	Available K
Chernozem	7.8	34.6%	145 mg kg^{-1}	48 mg kg^{-1}	135 mg kg^{-1}