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Alleviating global warming potential by soil carbon sequestration: A multi-level straw incorporation experiment from a maize cropping system in Northeast China

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ABSTRACT

Straw incorporation exerts important roles on greenhouse gas emissions and soil carbon (C) sequestration. However, few studies have comprehensively assessed the effects of straw incorporation on net global warming potential (NGWP) considering both emissions of greenhouse gas (GHG) and accumulation of SOC in Northeast China, the most important agricultural regions across the nation. An ongoing straw incorporation experiment was initiated in a maize cropping system of Northeast China from 2010, including three treatments: no straw incorporation (CK), incorporation of maize straw at a low level of 4000 kg ha^{-1} (S_4), and at a high level of 8000 kg ha^{-1} (S_8). At 2015, the crop yield was significantly elevated (11% and 21% for S_4 and S_8, respectively) by the straw additions resulting from improved soil fertility. During the growing season of 2015, we found that the straw additions did not affect seasonal patterns of the N_2O and CH_4, but changed their seasonal magnitudes. Averaged over this period, CH_4 flux was very low based on its GWP, and straw incorporation tended to reduce the CH_4 emissions (6.6, 3.6 and 4.3 kg CO_2 eq ha^{-1} for CK, S_4 and S_8, respectively); while straw incorporation significantly enhanced N_2O emissions with the value of 429, 590 and 746 kg CO_2 eq ha^{-1} for CK, S_4 and S_8, respectively. On the other hand, a significantly linear relationship (SOC sequestration rate = 0.29 × annual C input–0.57, R^2 = 0.99, $P < 0.05$) was detected between annual straw C input and SOC sequestration rate over the 5-year cycles, indicating the soil we studied was still not C-saturated at least during the experimental interval. More notably, the C conversion rate (29%, the slope of the equation) was generally larger than the values reported in other region of China. These results implied and confirmed that the soil of Northeast China possessed greater potentials to sequestrate external C. Taken together, the SOC accumulation accounted for major portion of the NGWP and counteracted the extra emissions of GHGs (492, −1183 and −3040 kg CO_2 eq ha^{-1} for NGWP of CK, S_4 and S_8, respectively). Therefore, the agricultural practise of straw incoporation was strongly recommended to be adopted in Northeat China to improve the soil productivity and simultaneously mitigate the negative influence of GHG emissions.

1. Introduction

Global warming is undoubtedly ascribed to human-induced greenhouse gas (GHG) emissions, among which nitrous oxide (N_2O) and methane (CH_4) are the two important GHGs because of their positive increases for radiative forcing and the longevity in the atmosphere (Montzka et al., 2011). Agricultural soils are significant sources of GHGs, accounting for more than 50% of the global anthropogenic emissions of N_2O and CH_4 (Zhao et al., 2016). In addition to edaphic condition and meteorological factor, agricultural managements such as tillage, fertilization, irrigation and organic amendment application could markedly influence N_2O and CH_4 flux (Smith et al., 2008; Snyder et al., 2009; Huang et al., 2013; Thangarajan et al., 2013). The agricultural fields all over China produced up to 620 Tg crop straw every year, and it still presented an increasing trend (for annual rate of 1.4%) (Zeng et al., 2007). In order to save time and labor, the farmers were used to directly burning straw in fields, causing serious atmosphere

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pollution. Therefore, the government had forced farmers to return the straw to fields, and this technique became widespread across the nation (Lu et al., 2009). The mechanisms by which the straw incorporation on N_2O and CH_4 flux are complex, both positive and negative effects have been reported (Abalos et al., 2013; Zhang et al., 2015). It is normally believed that returned straw offers additional source of readily available C and N for the relevant soil microbes, subsequently stimulating the emission of N_2O and CH_4 (Thangarajan et al., 2013). Meanwhile, straw incorporation could also influence the GHGs through altered soil physical properties (such as aerobic conditions, temperature and moisture) (Yao et al., 2009; Liu et al., 2011; Chen et al., 2013; Xiong et al., 2015). Recently, a meta-analysis summarized that the impacts of crop residue on N_2O emissions was rather variable and no statistically significant effect was identified, resulting from land use types (upland or paddy) (Shan and Yan, 2013). Another synthesis pointed out that added straw stimulated CH_4 emissions by up to 110% in paddy soil (Liu et al., 2014). However, the author could not draw general conclusion about the response of CH_4 flux to straw incorporation from upland cropping systems duo to lack of enough data sources. Thus, more field studies, especially in upland fields, are required to reduce uncertainty and explore the underlying mechanisms.

The overall environmental risk of N_2O and CH_4 is usually expressed as global warming potential (GWP) (in terms of CO_2 equivalents, CO_2 eq). It has been estimated that the GWP of the two GHGs originating for global agricultural fields is about 5.1–6.1 Pg CO_2 eq yr^{-1} (1 Pg = 10^{15} g) (Smith et al., 2008). On the other hand, if we take reasonable measures, the mitigating potential is also dramatically impressive (up to 5.5–6.0 Pg CO_2 eq yr^{-1}) (Smith et al., 2008). This is because we could accelerate accumulation of soil organic carbon (SOC) to offset the negative impact of increased emissions of GHGs (Jarecki and Lal, 2003; Snyder et al., 2009). Chinese cropland has relatively lower SOC density compared to the average value around world (Qin et al., 2013). Consequently, great opportunity for C sequestration exists if adopting improved agricultural techniques, among which straw return is regarded as the most promising one (Lu et al., 2009). However, the Lu et al. (2009) still admitted that due to limited field experimental sites and data (particularly relatively long-term data set), their estimations needed to be treated with caution. In order to comprehensively evaluate an agricultural techniques, the concept of net global warming potential (NGWP) was employed in the field research, which considering the net impacts of GHG emissions and the SOC changes (Shang et al., 2011; Bayer et al., 2016).

Northeast China, the most important base of crop production across the nation, accounts for about 35% of total maize production and 31% of national maize growing area, and it is also the main maize commodity grain base, contributing above 80% commodity rate (National Bureau of Statistics of China (NBSC), 2014). Due to long-term intensive agricultural production, Northeast China has been suffering from considerable soil C losses, while it is also characterized by a large surplus of crop straw. Thus, it has been suggested that agro-ecosystems in Northeast China have greater opportunities for soil C sequestration by straw incorporation (particularly for upland systems) than other region of China by combining remote sensing and model simulation (Qin et al., 2013; Yan et al., 2007). However, related empirical research was very rare, and *in situ* field experiments were urgently needed to corroborate this opinion. Simultaneously determining the changes of grain yield, soil properties and GHG flux in response to straw incorporations in Northeast China could not only help to replenish the soil fertility and guarantee the nation's grain security, but also contribute to reducing the uncertainty when estimating the NGWP of cropland in China.

Based on a multi-level straw incorporation experiment in a maize field from Northeast China, one growing season measurements of CH_4 and N_2O flux and 5-year monitoring of soil and crop properties were conducted. The specific object of this study was to: (1) characterize the dynamics of CH_4 and N_2O flux and explore the potential mechanisms about the effect of straw input; (2) identify the traits of the soil C sequestration and compare to others across the nation. Overall, we hypothesize that straw incorporation would greatly promote SOC sequestrations in Northeast China, and subsequently alleviate the negative effects of extra emissions of CH_4 or N_2O.

2. Materials and methods

2.1. Straw return experiment

Field experiment was conducted at Shenyang Experimental Station (41°32′ N latitude, 123°23′ E longitude and at an altitude of 31 m above sea level), Chinese Academy of Sciences, Liaoning Province. The station is located at south of Northeast China, which is characterized by warm-temperate continental monsoon climate. The mean annual temperature is 7.5 °C (maximum, 39.3 °C; minimum, −33.1 °C), and the frost-free period is 147–164 days. More than 80% of annual precipitation (mean annual precipitation: 520 mm) is concentrated from May to September. The soil contains 24.1% caly and is classified as Alfisol.

The straw return experiment was established in 2010, including three levels of straw input: no straw incorporation (CK), incorporation of maize straw at a low rate of 4000 kg ha^{-1} (S_4) and incorporation of maize straw at a high rate of 8000 kg ha^{-1} (S_8). The treatments distributed in a randomized complete block design with three replicates. All experimental plots were 1.8 × 4 m. In every October after harvest of all aboveground biomass, chopped straw of the previous crop was manually incorporated into the top 20 cm of soil. Maize was planted in every May, using a spacing of 60 cm between rows and the maize was seeded at 25 cm intervals following regional recommendations. The variety we used was Dongdan 72. Fertilizer was applied at a rate of 150 kg ha^{-1} $year^{-1}$ of N and 90 kg ha^{-1} $year^{-1}$ (P_2O_5) of P for each treatment. P was mixed into the top 20 cm of soil by plowing before sowing of maize, and N was applied three time during the growing season: at seeding stage, jointing stage and booting stage, respectively (with a ratio of 3:4:3). The N fertilizer was evenly used with the method of banding application on either side of the crop stem (within about 5 cm), and was then plowed into about 10 cm soil layer by spade. There was no artificial irrigation during the experiment period, and manual weeding was performed throughout the experiment.

2.2. Soil sampling and analyses

Soil samples from the 0–20 cm layer were collected in October of 2010 and 2015, respectively, before straw return. One composite soil sample consisted of five soils from different sites was randomly collected from each plot. After removing visible roots and organic debris, the fresh samples were passed through 2-mm sieve and were used for measuring available N (Alkali hydrolysable N). A sub-sample of fresh soil was dried in open air and then was ground to pass through a 0.15 mm sieve to determine total N and SOC concentration using an elemental analyzer (VariEL III, Elementar, Germany).

2.3. Air sampling and analyses

Static closed chamber was used to collect air sample as described by Jiang et al. (2010) in detail. Briefly, the chamber base, made of stainless steel (60 cm × 25 cm), was inserted to a depth of