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Influence of nitrogen fertilization on the net ecosystem carbon budget in a temperate mono-rice paddy

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ABSTRACT

In temperate rice paddy fields, mono-rice is cultivated under flooding for < 120 days during summer, and thereafter, soil is maintained under the dried upland condition during the cold fallow season. In this region, rice is generally only cultivated by chemical fertilization without organic amendment. Furthermore, almost all rice straw is removed as a livestock feeding material, and then, soil organic carbon (SOC) stock is rapidly depleted with cropping practices. However, the seasonal and annual variations of the soil C balance have not been evaluated in this paddy field. To investigate the nitrogen (N) fertilization effect on SOC stock changes in mono-rice paddy fields, urea was applied at different levels (0–180 kg N ha^{-1}) as a N fertilizer and the annual C balances were determined by analyzing the net ecosystem C budget (NECB) for 2 years. The annual NECB was a negative value (minus 1192 to minus1434 kg C ha^{-1} $year^{-1}$), irrespective of the N fertilization rates. This means that these levels of SOC stock could be depleted with cropping practices. The negative NECB was mainly influenced by the highly mineralized C loss during the fallow season and harvest removal during the rice cultivation season. More specifically, the seasonal NECB was largely negative (minus 1679 to minus 1969 kg C ha^{-1}) during the dried fallow season, but slightly positive (375–661 kg C ha^{-1}) during flooded rice cultivation. However, the annual and seasonal NECBs were changed by N fertilization according to a quadratic response model. The annual and seasonal NECBs increased with the increasing N fertilization level, maximized at 113–127 kg N ha^{-1}, and thereafter, decreased. This indicates that the optimum level, not the excess level, of N fertilization is favorable to increase the soil C stock in a temperate mono-rice paddy soil.

1. Introduction

Soil is an important terrestrial carbon (C) reservoir which plays an important role in the global C cycle. In recent years, much attention has been focused on soil organic C (SOC) sequestration because of its possible impact on global climate change (Lal, 2004a; Li and Zhang, 2007; Pan et al., 2009; Bhattacharyya et al., 2010; Li et al., 2010). However, depending on soil use and management, soil may function as either a C sink or an emission source. In addition to increasing SOC stock, and thus improving soil quality and productivity, SOC accumulation could be a strategy for mitigating the potential greenhouse gas (GHG) effect (Lal, 2004b). Several techniques, such as no-till or minimum tillage, perennial or extended cropping systems and adequate fertility management, can be implemented to improve SOC stock in agricultural fields.

Among agricultural practices, fertilization with nitrogen (N) is regarded as a key factor that controls biomass productivity and, thus, may influence SOC storage changes. However, the effect of N fertilization has been debated to have both positive (Buyanovsky and Wagner, 1998) and negative (Khan et al., 2007) effects on SOC stock. In many field studies (Majumder et al., 2007; Reid, 2008; Tong et al., 2009; Batlle-Bayer et al., 2010), N fertilization was effective in increasing SOC stock, since inorganic N fertilizers can improve crop residue returns. In other studies (Manna et al., 2006; Khan et al., 2007; Li and Zhang, 2007), N fertilization significantly decreased SOC stock since N fertilization promoted the decomposition of organic residues and SOC, a process which may offset the possible increase in SOC stock from crop residues (Nayak et al., 2009). Considering the widespread use and the uncertain effects on SOC, N fertilization is perhaps the greatest factor affecting SOC dynamics in arable lands. The uncertainty of N fertilization effects on SOC arises from the unknown balance between crop residue production and SOC mineralization loss.

Paddy soil is well known to have a high C sequestration potential (Pan et al., 2004; Zheng et al., 2008; Lu et al., 2009; Shang et al., 2010).

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In temperate countries, such as Korea, where the climatic condition during winter is characterized by dry and cold weather, mono-rice is cultivated under flooding for < 120 days during the summer season, but the soil is maintained under the dried upland condition for over 200 days during the cold fallow season. Therefore, SOC dynamics might be very different with continuously flooded or dried soils. In particular, the ever-increasing demand for rice straw as a feedstuff in cattle industries has limited its application in rice fields in most Asian countries, and thus the effect of N fertilization on SOC stock changes might be very different compared with upland soils of Western countries.

It is not easy to adequately detect a small change in SOC stocks over short periods (Ellert et al., 2001; Post et al., 2001) due to a number of factors, including the difficulty in observing a small change against a large background in SOC and great spatial variability in SOC stocks at multiple scales. Theoretically, the changes in soil C storage depend on the balance between C input and output. The net ecosystem C budget (NECB) analysis was developed as a precise tool to estimate soil C balance between C sequestration and mineralization loss (Chapin et al., 2006; Smith et al., 2010). Basically, the net C balance of an ecosystem is the difference between C gains and losses, which can show whether an ecosystem is a C sink or source (Heimann and Reichstein, 2008).

In this study, to determine the effect of N fertilization on the SOC stock changes in a mono-rice paddy, urea was applied as a fertilizer at different levels for rice cultivation, and soil C balances were evaluated by analyzing the annual NECB for two years.

2. Materials and methods

2.1. Experimental plot installation

A typical rice paddy field was selected for determining the effect of N fertilization on soil C stock changes at the Agronomy Experiment Field of Gyeongsang National University, Jinju, South Korea (35° 06′ 32.50″ N, 128° 07′ 05.96″ E). The selected region is located in a typical monsoonal and temperate climate zone, and the annual precipitation and mean temperature were approximately 1500 mm and 13 °C per year, respectively, over the last 40 years (KMA, 2012). The selected field has been controlled under general rice farming practices for over 50 years. The soil belongs to the Pyeongtaeg series (fine-silty, mixed, nonacid, and mesic Typic haplaquent). Before the experiment, the chemical properties of soil were: neutral pH (5.6 ± 0.2, 1:5 with H_2O), low SOC and total N contents (8.9 ± 0.6 and 0.65 ± 0.08 g kg^{-1}, respectively), and a low level of available P content (72.8 ± 2.5 mg P_2O_5 kg^{-1}).

In Korea, 90-45-57 kg ha^{-1} = N-P_2O_5-K_2O is recommended for rice cultivation (RDA, 1999). Four different levels of N fertilizer (0, 45, 90 and 180 kg N ha^{-1}) were used as treatments. According to the Korean standard for rice cultivation (RDA, 1999), 50% of N fertilizer was applied as basal fertilizer one day before rice transplanting, and 20 and 30% of N fertilizer were side-dressed on 14 and 42 days after transplanting, respectively. With the exception of the N managements, all treatments were controlled under the same conditions.

Four treatments were randomly arranged with three replicates, and each plot had a size of 100 m^2 (W. 10 m × L. 10 m). A concrete barrier was laid down between each treatment to make buffer zones (0.6 m) to minimize nutrient mixing effects. Twenty one day-old rice seedlings (4 plants per hill, *Sindongjinbyeo*, *Japonica*) were transplanted by hand with a spacing of 30 cm × 15 cm in late May in two study years. Irrigation water was maintained at 5–7 cm depth for 20 days before harvesting. Weeds were properly removed. Rice plants (18 hills under 1 m^2) were manually harvested to determine yield properties in mid-October. After rice grain and straw were harvested, the field was maintained under upland conditions without management during the fallow season.

2.2. Carbon mineralized losses

To evaluate the mineralized C loss from soil under different N fertilization levels, CO_2 and CH_4 emission rates were monitored using the closed chamber method (Rolston, 1986; Kim et al., 2016a, 2016b). Opaque acrylic column chambers (D. 24 cm × H. 25 cm) were permanently installed with three replicates in each plot. Rice was not cultivated in the inner chamber and weeds were properly removed. There were 2 holes in the bottom of each chamber, through which water movement was controlled during the flooded rice cultivation. The chambers were kept open in the field except during gas correcting. Each chamber was equipped with a thermometer and a circulating fan. Gas was corrected three times in on day (8.00–12.00–16.00) to obtain the mean daily CO_2 and CH_4 fluxes. Gas samples were collected once a week with 50 mL air-tight syringes equipped with a 3-way stop cock at 0, 15 and 30 min intervals after closing the top of the chamber. The collected gas samples were immediately transferred to 100 mL air-evacuated plastic bags for transporting to the laboratory for gas analysis.

The CO_2 and CH_4 concentrations in the collected air samples were measured via gas chromatography with a Porapak NQ column (Q 80–100 mesh) and a flame ionization detector (FID) with a methanizer. The temperatures of the injector, detector and column were controlled at 100, 110 and 80 °C, respectively. He and H_2 were used as the carrier and burning gases, respectively. The CO_2 and CH_4 emission rates were calculated from the slope between concentration and times of three samples, taken at 0, 15, and 30 min after chamber closed. If the correlation coefficient of regression did not show significance to the 95% confidence limit, the gas samples were discarded.

Carbon dioxide and CH_4 emission rates were calculated as the increase in CO_2 and CH_4 concentrations per unit surface area of the chamber for a specific time interval. A closed-chamber equation (Rolston, 1986; Lou et al., 2004) was used to calculate the seasonal fluxes from different N fertilization treatments:

$$F = \rho \times \left(\frac{V}{A} \times \frac{\Delta c}{\Delta t} \times \frac{273}{T}\right)$$

where, F is the CO_2 and CH_4 emission rates (mg m^{-2} h^{-1}); ρ is the gas density of CO_2 (1.965 mg cm^{-3}) and CH_4 (0.714 mg cm^{-3}) under a standardized state; V is the chamber volume (m^3); A is the chamber surface area (m^2); $\Delta c/\Delta t$ is the rate of increased CO_2 and CH_4 gas concentrations in the chamber (g m^{-3} d^{-1}); and T is 273 (absolute temperature) + average temperature (°C) in the chamber.

The seasonal CO_2 and CH_4 fluxes for the whole of each period were calculated by the following equation (Singh et al., 1999):

$$\text{Seasonal } CO_2 \text{ and } CH_4 \text{ flux} = \sum_{i}^{n} (R_i \times D_i)$$

where R_i is the CO_2 and CH_4 emission rates (g m^{-2} d^{-1}) in the ith interval of sampling; D_i is the number of days in the ith sampling interval; and n is the sampling number.

2.3. Net ecosystem carbon budget (NECB) calculation

Soil organic C stock changes were estimated using the NECB analysis (Ma et al., 2013; Haque et al., 2015a):

$$\text{NECB} = \Sigma\text{C input} - \Sigma\text{C Output} = (\text{NPP+Fertilizer}) - (R_h + \text{Harvest removal} + CH_4)$$

NPP is the net primary production during rice cultivation and fallow seasons; R_h is the CO_2 emission from the soil (heterotrophic respiration), which was measured by the closed chamber method; and Harvest is the rice grain and straw removal from each treatment at the harvesting state. Fertilizer C inputs were estimated using the C contents in urea (0.2) and its total urea application levels.

The NPP of rice and weeds were estimated using the following