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Combined application of biochar and slow-release fertilizer reduces methane emission but enhances rice yield by different mechanisms

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ABSTRACT

There has been an increased interest in and wide application of biochar and slow-release fertilizer (SRF) to agricultural soils in recent years because they can reduce greenhouse gas emissions, but increase rice productivity. However, the studies considering combined effects of biochar and SRF are rare. This study examined the combined effects of biochar and SRF on the biogeochemistry, rice productivity, methane emission, and microbial abundances in rice paddy. The study sites included six different treatment combinations: urea (NU), SRF (NS), straw + urea (SU), straw + SRF (SS), biochar + urea (BU), and biochar + SRF (BS). Both the biochar and SRF reduced the methane emission, and the BS paddy soil had the lowest methane emission, while it had the highest rice yield. The biochar inhibited methanogenesis by increasing the soil aeration and oxygen availability. The SRF decreased the plant biomass, thus they may decrease plant-mediated methane transport and carbon substrate from plant debris and root exudates. Increasing in the abundance of methane-oxidizing bacteria was assumed to have critical impact on the reduction in methane emission by biochar. In conclusion, combined application of biochar and SRF highly recommended in rice cultivation, because they can minimize the methane emission but maximize rice yield.

1. Introduction

Biochar has been applied in a variety of terrestrial ecosystems in order to sequester biomass carbon into the ecosystems. In addition, many studies have sought ways to reduce methane emissions from rice paddies by applying biochar, because rice cultivation is a major source of methane. The global emission of methane from the rice paddy soil represents 30 to 40 Tg CH_4 a year, which accounts for almost 10% of the total anthropogenic methane emissions (Kirschke et al., 2013), and it's still increasing due to rising demand for rice (Nguyen and Ferrero, 2006). Previous studies have reported that rice paddy with biochar had 8.8 to 28.0% higher rice yield than rice paddy without biochar (Zhang et al., 2010, 2012; Wang et al., 2012), while biochar application reduced methane emission (Rondon et al., 2005; Karhu et al., 2011; Feng et al., 2012; Wang et al., 2012; Ly et al., 2015). Feng et al. (2012) suggested that increasing in methanotrophic proteobacterial abundances was responsible for decreasing in methane emission in biochar amended paddy soil. Zhang et al. (2010) showed that application of urea can increase rice productivity in rice paddy with biochar, but other types of N fertilizer are not considered in that study.

At the same time, slow-release fertilizer (SRF) has been applied to increase N use efficiency (NUE) and reduce emission of GHGs, without compromise in crop productivity (Abao et al., 2000; Li et al., 2006; Miao et al., 2015; Zhang et al., 2016). Zhang et al. (2016) reported that SRF-treated paddy soil had the lowest methane emission but the highest rice yield when compared with other types of nitrogen fertilizers. Miao et al. (2015) found that SRF significantly improved NUE, so rice yield was also improved. Although agricultural usage and academic interest of SRF have rapidly increased, but the effects of SRF on GHGs emission and other biogeochemical characteristics have not been fully understood in rice paddy ecosystem (Zhang et al., 2016). In addition, the effects of biochar and SRF on GHGs emission and soil biogeochemistry have been elucidated separately, but combined effects of biochar and SRF on rice paddy ecosystem still remain unclear.

Berger et al. (2013) suggested that methane emission from rice paddies is strongly affected by the microbial community of paddy soils, and Conrad (2002) suggested that integrated investigations on methanogens, methanotrophs and environmental factors are required to understand methane dynamics in rice paddy. Rice paddy is waterlogged soil ecosystem, so this ecosystem is basically anaerobic. How-

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ever, atmospheric oxygen could be supplied by diffusion and gas transport through aerenchyma, so aerobic methane oxidation could occur. Even though there are many studies having investigated methanogen and methanotroph in conventional rice paddy (Conrad 2002; Shrestha et al., 2010; Ma et al., 2012; Lee et al., 2014), the study considering methanogen and methanotroph in rice paddy with biochar and SRF is rare. In this study, therefore, we investigated the aspect of microbiology in addition to biogeochemistry.

Overall, the study aimed to determine the combined effects of biochar and SRF on the biogeochemistry, productivity, methane emission, and microbial abundances from rice paddies over a cultivation period. Two types of C treatments (straw and biochar) and N fertilizers (urea and SRF) were used in this experiment. We designated an experimental rice paddy and cultivated rice using six different fertilization practices. We identified the mechanisms involved in the reduction of methane emissions from biochar and SRF, and conducted a microbial analysis to determine the effects of biochar and SRF on the abundances of related microbes.

2. Material and methods

2.1. Experimental design

Eighteen experimental plots were set up in a rice paddy in Hwaseong-si, Gyeonggi-do, South Korea (37°13'22"N, 127°02'32"E). The initial soil chemistry of the rice paddy soil is described in Table 1. The soil texture of the rice paddy was silt loam (Soil Survey Staff, 2014). The experiment had randomized 10 m × 5 m rectangular plots with three replications that had the following six different treatments; NU (No C treatment and Urea), NS (No C treatment and SRF), SU (Straw and Urea), SS (Straw and SRF), BU (Biochar and Urea), and BS (Biochar and SRF). The NU paddy soils were considered a control plot, as N fertilizers are necessarily used in all rice cultivation while C treatments are not. The amounts of the treatments applied to the rice paddies were 90 kg N ha^{-1}, 45 kg N ha^{-1}, 5000 kg ha^{-1}, and 2000 kg ha^{-1} for urea, SRF, straw, and biochar, respectively. Table 2 shows the details of the six treatments. All of the treatment application practices followed the Korean Agricultural Standards established by the Rural Development Administration of Korea. Urea, biochar, and straw were homogeneously applied on the surface of rice paddies before transplanting. SRF was applied at the root zone, 5 cm under the soil surface, for each rice plant before transplanting.

The urea and SRF treatments had included P_2O_5 and K_2O treatment. The N-P-K ratio of the urea and SRF treatments was 1:0.044:0.124 and 1:0.009:0.025, respectively. The biochar used in this study was commercial product which was produced by pyrolysis of rice (*Oryza sativa*) chaff at 600 °C for 20 min. The size of the chaff was around 5 mm. Detailed information about the biochar preparation can be found in a previous report (Yoo et al., 2014). Characteristics of the biochar and straw are presented in Table 3.

Rice (*Oryza sativa*) seeds were sown into the planting plate on April 25, 2014, and were transplanted to the rice paddy on May 25. The fully-grown rice was harvested on October 1. Water table was maintained at near 5 cm above the soil surface before Aug 25, and the rice paddy was drained. During the cultivation period, the mean daily temperature of the site ranged from 15.7 °C to 29.2 °C. Detail methods used for measuring basic soil chemistry (Table 1) and properties of C treatments (Table 3) are described in Yoo et al.'s (2014) study.

Table 1
Initial rice paddy soil chemistry.

pH	SOM (g kg^{-1})	Av. P_2O_5 (mg kg^{-1})	Ex. Cations (cmol kg^{-1})				Av. SiO_2 (mg kg^{-1})	Soil Texture
			K	Ca	Mg	Na		
5.4	22	44	0.23	6.7	1.5	0.33	68	Silt loam

Table 2
The amounts of urea, SRF, straw, and biochar used in each treatments. (NU = urea, NS = SRF, SU = straw + urea, SS = straw + SRF, BU = biochar + urea, BS = biochar + SRF).

Treatments	Urea (kg N ha^{-1})	Slow-release fertilizer (kg N ha^{-1})	Straw (kg ha^{-1})	Biochar (kg ha^{-1})
NU	90	–	–	–
NS	–	45	–	–
SU	90	–	5000	–
SS	–	45	5000	–
BU	90	–	–	2000
BS	–	45	–	2000

Table 3
Characteristics of C treatments used in this study.

C treatments	Carbon content (%)	Nitrogen content (%)	P (%)	K (%)
Straw	66.1	0.55	0.083	0.904
Biochar	45.4	0.57	0.079	1.245

2.2. Measurement of methane emission

We used a static chamber method to collect gas samples from June 2 to October 1. The number of gas-measuring days was 35, and the interval between the measurements was 1-4 days. We installed three acrylic chambers for replication in each plot. Gas samples of ten mL were collected from the chambers at 0, 5, 10, 15, and 20 min using 10 mL syringes. The concentrations of methane from the collected gas samples were measured through FID (flame ionization detector) gas chromatography (gas chromatograph: CP-3800 Varian, USA). The methane flux (in mg CH_4 m^{-2} h^{-1}) was calculated from the concentration differences over time:

$$CH_4flux = \frac{dCH_4}{dt} \times \frac{V}{A} \times \frac{P\times100\times MW}{R} \times \frac{273.15}{273.15+T} \quad (1)$$

where dCH_4/dt was the methane concentration gradient over time, V was the volume of the static chamber, A was the horizontal area of the static chamber, P was the atmospheric pressure, MW was the molecular weight of the methane (16 g mol^{-1}), R was the ideal gas constant (8.314 L mol^{-1} K^{-1}), and T was the temperature in Celsius degrees. The cumulative methane emission over the cultivation period (in mg CH_4 m^{-2} cultivation $period^{-1}$) was determined based on the average methane emission at a certain time interval:

$$CumulativeCH_4emission = \sum_{i=1}^{n-1}\left(\frac{(CH_4flux_i) + (CH_4flux)_{i+1}}{2} \times \Delta day_i\right) \quad (2)$$

where n was the number of gas-measuring days (35 days), and Δday_i was the interval between the i^{th} and $(i+1)^{th}$ measuring days.

2.3. Rice plant biomass and yield

To measure the plant biomass, we collected the above-ground biomass from a $1m^2$ quadrat in each plot on June 25, July 25, and October 1, and measured its weight after drying it at 60 °C for 24 h. The