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Unexpected stimulation of CH_4 emissions under continuous no-tillage system in mono-rice paddy soils during cultivation

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ABSTRACT

No-tillage (NT) is known as an effective method of soil management that has the potential to increase soil organic carbon (SOC) accumulation in arable lands. Unlike upland soils, the increase of SOC accumulation in paddy soils under continuous NT is likely to increase methane (CH_4) emissions during rice cultivation. However, the interaction between the SOC accumulation and CH_4 emission characteristics associated with continuous NT in rice paddies has not been well elucidated. To investigate the effects of continuous NT on SOC accumulation and CH_4 emissions, conventional tillage (CT) and NT plots were installed in a typical mono-rice paddy soil classified as a fine-silty, mixed, nonacid mesic Typic endoaquept in the southern part of the Korean peninsula in 2007. In the 1st, 2nd and 5th years after installation, the CH_4 emission patterns were characterised during rice cultivation and rice grain yield and soil properties were investigated at the harvesting stage. Compared with CT (381 – 363 kg CH_4 ha^{-1}), NT effectively decreased total CH_4 fluxes by approx. 20-27% in the 1st and 2nd years (279 – 291 kg CH_4 ha^{-1}) after installation. However, a much higher CH_4 flux (approx. 36%) was observed in the NT (385 kg CH_4 ha^{-1}) than the CT (287 kg CH_4 ha^{-1}) plots in the 5th year. The SOC content in the NT plots clearly increased over the study years (14.5 – 15.6 g kg^{-1}) compared with that under CT (14.4 - 14.3 g kg^{-1}) which did not change significantly during the study period. Similar to the increase of the SOC content observed under NT, the concentrations of labile C forms such as water-extractable C (WEC) and hot water-extractable C (HWEC) and labile C availability in the surface soil dramatically increased over the study years, which may have increased *mcr*A gene copies as a methanogen population abundance (5.7×10^6 *mcr*A gene copy number g^{-1} soil) and CH_4 production potentials in the 5th year compared with CT (4.2×10^6 *mcr*A gene copy number g^{-1} soil). Rice productivity was slightly lower in the NT than the CT treatment, though this difference was not statistically significant across the study years. These findings led to the conclusion that because continuous NT can increase CH_4 emissions during rice cultivation under flooded paddy soil conditions due to the increased availability of labile forms of SOC, therefore, other soil management regimes that can decrease CH_4 emissions, such an intermittent drainage, should be introduced along with continuous no-tillage.

1. Introduction

Rice (*Oryza sativa* L.) is the most important food for more than 50% of the world's population. Currently, 79 million ha (approx. 75%) of the world's rice area are under irrigation (Qin et al., 2006). However, irrigated rice fields are regarded as one of the major anthropogenic sources of CH_4 (IPCC, 2007) and are estimated of CH_4 emissions from rice fields range between 39 and 112 Tg CH_4 per year (Denman et al., 2007). With the rapid population growth and scarcity of arable land, agricultural field has been intensified to meet the food demand. With an increasing demand for rice, annual worldwide rice production may increase up to 700 million tonnes by the year 2025 (Bhardwaj et al., 2014), which may approximately require an additional 15-20 million ha to be cultivated (IRRI, 2011) to potentially increase CH_4 emissions from the rice paddies in the future.

The CH_4 dynamics from flooded rice paddies are influenced by agricultural practices such as tillage, fertilization, rice cultivar and water management (Gutierrez et al., 2013). In particular, tillage can affect physical, chemical and biological properties in rice fields, thereby influencing the CH_4 emission process. Recently, there have been several reports indicating that no-tillage (NT) can suppress CH_4 emissions from rice paddy soils (Hanaki et al., 2002; Ahmad et al., 2009; Ali et al., 2009). A reduction of the total CH_4 flux of greater than 50% was observed in NT rice fields in Japan compared with tilled fields (Hanaki et al., 2002). Ahmad et al. (2009) also found that NT could significantly reduce CH_4

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emissions from rice paddies compared with conventional tillage (CT). These authors suggested that NT increased soil bulk density subsequently reducing CH_4 emissions. Soil compaction due to NT might reduce the volumetric fraction of large pores and inhibit the decomposition of organic matter. We obtained similar results in South Korean paddy field (Ali et al., 2009). However, these studies were carried out only over one rice growing season, or not on a long-term basis.

Decreasing tillage intensity has been adopted as options for increasing the SOC (Johnson, 1995; Cheng-Fang et al., 2012). Cheng-Fang et al. (2012) reported that NT significantly increased soil organic carbon (SOC) by 7-48% in the surface layer in rice paddy soils compared with CT. Modulating agricultural field management practice such as CT and NT farming is one of the important parameters influencing the rate of SOC losses through CO_2 and CH_4, which can significantly affect SOC accumulation in arable lands including rice paddy soils. Moreover, the increase of SOC content in NT may stimulate microbial activities related to carbon (C) cycling such as fermenters and methanogens, which can adversely accelerate the decomposition process of SOC in long- term rice paddy soils, in particular CH_4 emissions. The increase of SOC contents with no-tillage can increase CH_4 production potential in a long term rice paddy soils, but there are no available reports regarding the interaction between the increased SOC accumulation due to continuous NT and CH_4 emissions including dynamics of methanogenic population in paddy fields during rice cultivation.

We hypothesized that continuous NT is expected to increase SOC contents with lapse of years, which can stimulate CH_4 emissions in flooded paddy soils. In order to investigate the effects of continuous NT on SOC contents and CH_4 emission characteristics as well as rice productivity during rice cultivation, NT and CT plots were installed in a typical mono-rice paddy soil in 2007, and CH_4 emissions and soil and rice yield properties were then investigated in the 1st, 2nd (short-term) and 5th years (long-term) after installation.

2. Materials and methods

2.1. Experimental field preparation and rice cultivation

A typical mono-rice paddy field was selected for evaluating mainly the long-term effect of NT on CH_4 emissions and soil properties at the Agronomy Field of Gyeongsang National University, Jinju City, South Korea (GPS coordinates: 35° 06' 32.50" N, 128° 07' 05.96" E). The study region displays a typical monsoonal climate within a temperate zone and the annual mean temperature and total precipitation were reported to be 13.1 °C and 1513 mm per year, respectively, over a 30 year period (1980-2010) (Fig. 1) (KMA, 2012). This field has been managed under general farming practices for rice cropping over the past several decades. The soil belongs to the *Pyeongtaeg* series (fine-silty, mixed, nonacid, mesic Typic Endoaquept) (USDA, 2010). Prior to the experiment, the soil displayed the following properties: a neutral pH 6.2 ± 0.2 (1:5 with H_2O), an SOC content of 14.4 ± 2.8 g kg^{-1}, available P_2O_5 of 68.9 ± 2.9 mg kg^{-1}, exchangeable Ca^{2+}, Mg^{2+} and K^+ contents of 6.3 ± 0.2, 1.0 ± 0.2 and 0.3 ± 0.1 cmol$^+$ kg^{-1}, respectively.

The NT and CT treatments were installed in 2007 and maintained thereafter under the same conditions. Two treatments were randomly arranged with three replicates each, and each plot had a size of 10 m × 10 m. A concrete barrier was laid down between each treatment to form buffer zones (0.6 m) to avoid mixing effects (Fig. S1).

With the exception of the tillage practices, the two treatments were controlled under the same conditions. The CT plots were mechanically tilled at 0-15 cm depth one week before rice transplantation after the irrigation. Irrigation water was maintained at 5-7 cm depth during the whole cropping season. Mineral fertilisers were applied to all plots at rates of 110 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1}, and 58 kg K_2O ha^{-1}, which are the recommended fertilisation levels for rice cultivation in Korea (RDA, 1999). Basal mineral fertilisers were applied with the rates of 55 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1}, and 40.6 kg K_2O ha^{-1} in the form of urea, super phosphate and potassium chloride one day before transplantation. The fertilisers were mechanically mixed with the surface soil in the CT plots, but were only broadcast on the surface in the NT treatment. Thirty-day-old rice seedlings (3 plants per hill, *Dongjinbyeo*, Japonica) were transplanted by hand with a spacing of 30 cm x 15 cm in mid-June (June 10-15) in every study year. In the NT plots, rice seedlings were gently put into the surface soil after digging a hole (1-2cm) manually on the field.

First topdressing (22 kg N ha^{-1}) at tillering stage was broadcast 2 weeks after rice transplantation and second topdressing (33 kg N ha^{-1}, 17.4 kg K_2O ha^{-1}) at panicle initiation stage 7 weeks after transplantation. In both treatments, weeds are manually removed monthly during the rice growing period.

Irrigation water was drained 3 weeks before rice harvesting. Rice plants (72 hills under 3.3m^2) were harvested to determine grain yield in every year in mid-October (October 10-20). After removing the above ground biomass (rice straw) harvested, the field was maintained under upland conditions without irrigation and vegetation such as cover crops in the following season.

2.2. Gas sampling and analysis

Rice was cultivated for 5 years, from 2007 to 2011, under the same agricultural management regimes. However, the characteristics of CH_4 emissions and rice yields were investigated only for 3 years, in the 1st, 2nd and 5th years after the installation due to confirming the no-tillage effects on both short- (1st and 2nd years) and long-term periods (5th year) in rice paddy soils. CH_4 emission rates were estimated using the closed chamber method (Rolston, 1986) for the entire cropping period as described in our previous studies (Kim et al., 2012, 2013a,b; Gutierrez et al., 2013). Transparent acryl chambers (62 cm length × 62 cm width × 112 cm height) were permanently installed on the flooded soil with three replicates in each plot. Eight rice plants were covered by each chamber. There were 4 holes in the bottom of each chamber, through

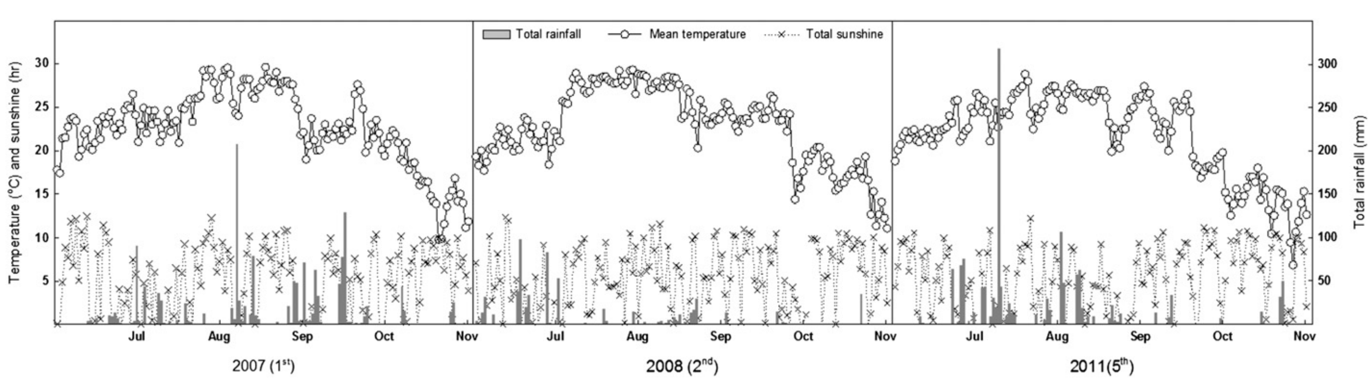

Fig. 1. Meteorological conditions over whole experimental periods during rice cultivation.