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Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam

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ABSTRACT

The reduction of CH_4 and N_2O emissions from rice paddies is of utmost importance in minimizing the impact of rice production on global warming. A field experiment was therefore conducted in farmers' field in Hanoi, Vietnam to examine whether the use of straw compost or straw biochar, in combination with the safe alternate wetting and drying (AWD) has the potential to suppress both CH_4 and N_2O emissions from rice paddies while maintaining the rice yield. The study compared the proposed strategies with local farmers' practice of permanent flooding (PF) and farmyard manure (FYM) incorporation, respectively. A control treatment without organic matter incorporation in both AWD and PF water regimes was also included in the study; all treatments received equal amounts of mineral fertilizer. Gas emissions were monitored using the closed chamber method at seven-day intervals during the first 50 days and at 15-day intervals thereafter. Addition of FYM, straw compost and biochar increased CH_4 emissions by 230%, 150% and 38%, respectively, when compared with the control treatments in both the AWD and PF water regimes. Within AWD, FYM increased N_2O emissions by 30%, straw compost and biochar displayed similar amount of N_2O emissions as the control treatment. Within PF, N_2O emissions under FYM and straw compost were 40% and 35% higher than the control treatment, respectively, and biochar once again displayed similar amount of N_2O emissions as the control treatment. Yield difference was not significant ($p > 0.05$) between any of the treatments. These results indicated that the straw compost incorporation might not reduce the global warming potential (GWP) and yield-scaled GWP of rice production, whereas biochar in combination with AWD has the potential to maintain the GWP and yield-scaled GWP of rice production at lower level than the farmers' practice.

1. Introduction

Methane (CH_4) and nitrous oxide (N_2O) are the most important long-lived greenhouse gases (GHGs). Agriculture accounts for approximately 50% and 60% of global anthropogenic emissions of CH_4 and N_2O, respectively (Smith et al., 2007). Rice paddies have received increasing global concerns for their contribution of approximately 4.4–19.2% of total global anthropogenic CH_4 emissions (Denman et al., 2007). Due to permanently flooded condition in rice paddies, they were previously considered to be a less important source of N_2O emissions; however, more recent studies have suggested that the increasing use of mineral nitrogen (N) in rice paddies can contribute to significant N_2O emissions (Cai et al., 1997; Zou et al., 2005). When there are readily decomposable organic matters, such as animal manure and crop residue, into the permanently flooded soils, methanogens, i.e. a group of anaerobic archae in soil, produce CH_4 during the final stage of the decomposition of organic carbon (C) (Le Mer and Roger, 2001). Draining rice paddies prevents the development of strongly anaerobic environments in the soil and can considerably reduce CH_4 emissions (Cai et al., 1997; Zou et al., 2005). However, a partially anaerobic condition is created in the soil during drainage where nitrification and subsequent denitrification of the available N source can take place simultaneously, and can significantly enhance N_2O production (Webster and Hopkins, 1996). Rice plants themselves also play an important role in the emissions of both of these GHGs by supplying organic C through root exudates as well as transporting 80–90% of the GHGs from the soil to the atmosphere through aerenchymatous tissues (Yu et al., 1997).

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Vietnam is one of the world's top two rice-producing and exporting countries, with more than seven million hectares (ha) of land under paddy rice (FAO, 2013). Application of farmyard manure (FYM) together with N fertilizer in rice fields is a common farmers' practice in the Red River Delta in Vietnam (Dung et al., 1999). FYM supplies readily available C and N to the soil and N fertilizer supplies readily available N precursor for nitrification and subsequent denitrification resulting in a high amount of CH_4 (Debnath et al., 1996) and N_2O emissions (Pathak et al., 2002). Therefore, the existing farmers' practice of rice cultivation might have high global warming impact. In addition, more than 80% of the straw produced in Vietnam is burnt in the field (Truc et al., 2012). As a consequence, organic C content in the straw is lost and a considerable amount of CO_2 and CH_4 is emitted into the atmosphere (Miura and Kanno, 1997). Therefore, there is an urgent need to reduce CH_4 and N_2O emissions from the rice production system in Vietnam if the country's goal of reducing GHG emissions from agriculture and rural development sectors by 20% till 2020 is to be met (UN-Viet Nam, 2013).

As water and nutrient management are the most important factors determining CH_4 and N_2O emissions from rice paddies (Cai et al., 1997; Zou et al., 2005), mitigation strategies for the impact of rice production on global warming should focus on combining strategies for water and fertilizer management that minimize both CH_4 and N_2O emissions. The International Rice Research Institute (IRRI) has proposed a 'safe alternate wetting and drying (AWD)' technique to reduce the high irrigation water requirement for paddy rice, which is also expected to reduce CH_4 emissions by 70% (IRRI, 2013). As AWD involves frequent wetting and drying of soil without allowing the water level to fall below a soil depth of 15 cm, it prevents occurrence of very low redox potential in soil and can suppress CH_4 emissions. On the other hand, this kind of drainage practice can contribute greatly to triggering N_2O emissions and might outweigh the benefit of reduced CH_4 emissions. A pot experiment without rice plants conducted by Johnson-Beebout et al. (2009) indicated that the enhanced N_2O emissions could outweigh the benefit of reduced CH_4 emissions under the AWD strategy. The study of Zou et al. (2005) in particular suggested that when intermittent irrigation is combined with organic amendment, the overall GWP of the strategy is higher than the continuously flooded strategy with no organic matter amendment. However, there is still a shortage of studies investigating both CH_4 and N_2O emissions and overall GWP from rice paddies under the AWD water regime recommended by IRRI, specifically when in combination with various complex organic substrates as manures, composts etc.

Incorporating fresh straw into the flooded soil supplies readily available organic substrates and accelerates the reduction process in the soil, and in addition it also supplies C substrates to methanogens (Zou et al., 2005). As a consequence, CH_4 production is enhanced. On the other hand, the readily available C in fresh straw enhances complete denitrification, resulting in a lower N_2O:N_2 emissions ratio (Swerts et al., 1996). Furthermore, addition of labile C may reduce nitrate levels in soil via N immobilization, and hence lowers the potential for denitrification. However, the benefit of reduced N_2O emissions from straw may well be outweighed by the enhanced CH_4 emissions (Zou et al., 2005). In contrast to fresh straw, aerobically composted straw has been suggested as potential organic matter for mitigating CH_4 emissions from rice paddies since it contains more stabilized form of C (Corton et al., 2000; Khosa et al., 2010). In addition, straw compost has also shown potential for maintaining N_2O emissions at a low level (Yao et al., 2010). As another alternative to fresh straw, straw biochar (a product after the pyrolysis of straw) has also been suggested as a potential soil amendment to reduce CH_4 emissions from rice paddies due to its recalcitrant C component (Liu et al., 2011; Feng et al., 2012). In addition, straw biochar can also suppress N_2O emissions by enhancing complete denitrification of NO_3^-–N_2 due to its alkaline properties (Yanai et al., 2007). However, there is still a shortage of studies comparing both CH_4 and N_2O emissions from rice paddies incorporated with these two soil amendments and, in particular, no study has investigated both CH_4 and N_2O emissions from this stabilized form of straw in combination with the AWD strategy.

Therefore, in the current study we hypothesized that the use of straw compost or straw biochar in combination with the AWD strategy has the potential to suppress CH_4 emissions without triggering N_2O emissions. The obvious benefit of implementing the AWD strategy is the reduction in water use, and the benefit of utilizing straw is the reduction in the practice of burning straw in countries such as Vietnam. Most importantly, it has also been shown that straw compost has a beneficial effect on rice yield (Corton et al., 2000; Khosa et al., 2010), but the effect of biochar on rice yield is still inconclusive (Haefele et al., 2011; Zhang et al., 2012). Therefore, we conducted a field experiment in Hanoi, Vietnam with the objectives of (1) testing the potential of AWD to reduce CH_4 emissions from rice paddies as compared to the normal practice of permanent flooding, (2) exploring whether the benefit of reducing CH_4 emissions by implementing AWD is outweighed by the increase in N_2O emissions, (3) evaluating the potential of straw compost and straw biochar amendments for reducing CH_4 and N_2O emissions from rice fields as compared to the existing FYM incorporation practice, and (4) evaluating the combined impact of water and organic matter management strategies on the global warming potential of rice fields and on rice yield.

2. Materials and methods

2.1. Experiment site

A field experiment was conducted in a paddy rice field during spring season from February 2013 to June 2013 in the Thanh Tri district of Hanoi (20°55′60″N and 105°50′54″E), Vietnam (Fig. 1). The climate in the area is humid tropical, the mean annual temperature is 24 °C and mean annual precipitation is 1689 mm, with maximum rainfall occurring between May and September (year range and source: 1970–2000, Lang Station, Hanoi). Rainfall and the temperature across the rice growing period studied are presented in Fig. 2. The average elevation of the experiment site is 3–4 m above mean sea level. The soil in the region is derived from lacustrine and shallow-sea sediment. The sediment formations in Hanoi are predominantly soft soils with the domination of illite and subsequently by kaolinite and chlorite clay minerals (Kirov and Truc, 2012). The soil was slightly acidic (pH = 5.7), containing 12.55 g kg^{-1} total organic C and 1.63 g kg^{-1} N in the topsoil (0–15 cm), C/N of 7.7. The bulk density of the topsoil was 1.37 g cm^{-3} with 26.8% clay, 22% sand and 52.2% silt.

2.2. Field experiment

For the spring rice crop in this experiment, fifteen-day-old rice (*Oryza sativa* L. indica, cv. Khang Dan) seedlings from a nursery bed were transplanted to the experimental plots on 23 February. Transplanting was performed with 2–3 seedlings per hill and with 20 cm × 20 cm spacing between hills. The experiment was designed using a 2 × 4 factorial randomized complete block design with triplicates on a plot size 4 m × 5 m each. The first factor was water management and the second factor was organic matter management. Permanent flooding (PF) was the first level within water management in which the water level was maintained at 3–7 cm above the soil surface, starting from one week before transplanting until 15 days before harvest. The second level was a