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Effects of steel slag application on greenhouse gas emissions and crop yield over multiple growing seasons in a subtropical paddy field in China

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ABSTRACT

Asia is responsible for over 90% of the world's rice production and hence plays a key role in safeguarding food security. With China being one of the major global producers and consumers of rice, achieving a sustainable balance in maximizing crop productivity and minimizing greenhouse gas emissions from paddy fields in this country becomes increasingly important. This study examined the effects of applying steel slag, a residual product derived from the steel industry, on crop yield and CH_4 and N_2O emissions over multiple growing seasons in a Chinese subtropical paddy field. Average CH_4 emission was considerably higher during the periods of rice crop growth compared to that during the periods of fallowing and vegetable crop growth, regardless of the amount of steel slag applied. When compared to the controls, significantly lower mean emissions of CH_4 (1.03 vs. 2.34 mg m^{-2} h^{-1}) and N_2O (0.41 vs. 32.43 μg m^{-2} h^{-1}) were obtained in plots with slag addition at a rate of 8 Mg ha^{-1} over the study period. The application of slag at 8 Mg ha^{-1} increased crop yields by 4.2 and 9.1% for early and late rice crops, respectively, probably due to the higher availability of inorganic nutrients such as silicates and calcium from the slag. Slag addition had no significant effect on the concentrations of heavy metals in either the soil or the rice grains, although a slight increase in the levels of manganese and cobalt in the soil and a decrease in the levels of manganese and zinc in the rice grains were observed. Our results demonstrate the potential of steel slag as a soil amendment in enhancing crop yield and reducing greenhouse gas emissions in subtropical paddy fields in China, while posing no adverse short-term impacts on the concentrations of heavy metals in the soil or the rice grains. However, long-term implications of this management practice and the cost/benefit remain unknown, so further studies to assess the suitability at large scale are warranted.

1. Introduction

Methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases that together account for about 20% of the global greenhouse effect (Smith et al., 2007). From 1990 to 2005, agricultural CH_4 and N_2O emissions have increased by about 17% (IPCC, 2007). Rice production in particular can lead to substantial emissions of both CH_4 and N_2O into the atmosphere, owing to the dominance of a flooded environment, and the large inputs of nitrogen from chemical fertilizers and manure, respectively (FAO, 2003), which together exacerbate the problem of global climate change (van Groenigen et al., 2013). Global rice production is projected to increase from 473 million tonnes in 1990 to at least 781 million tonnes by 2020 (IRRI, 1989). Given that the paddy fields in China account for 23% of all cultivated lands in the country, and nearly 20% of the world's total rice production area (Frolking et al., 2002), it is of national and global significance to examine the dynamics of greenhouse gas emissions from the Chinese paddy fields for their implications to both atmospheric chemistry and climate change (Hou et al., 2012).

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Recently, a number of agricultural management strategies have been proposed, including the development of new rice varieties (Ma et al., 2012), as well as the selection of appropriate water management approaches (Ma et al., 2013), cultivation methods (Liu et al., 2013), and fertilisation schemes (Linquist et al., 2012; Liang et al., 2013), in an attempt to boost up rice yield and mitigate greenhouse gas emissions. Meanwhile, the application of exotic materials, for example, biochar (Zhang et al., 2010), steel slag (Wang et al., 2012), and straw rice (Müller-Stöver et al., 2012), is also a typical method of improving the soil quality and productivity of paddy fields. Steel slag, a residual product of the steel industry, contains high concentrations of electron acceptors such as active and free oxide forms of iron. While slag application has been proven to be effective in reducing CH_4 emissions from the temperate paddy fields (Furukawa and Inubushi, 2002; Ali et al., 2008), its effectiveness in mitigating N_2O emissions is not clear. Moreover, steel slag is thus far less commonly applied in the subtropical region compared to the temperate counterpart. With 90% of the paddy fields in China being located in the subtropics, such as in Fujian, Jiangxi, and Hunan provinces, there is a need to develop a better understanding of the effects of steel slag additions on the yield and greenhouse gas emissions from the subtropical Chinese paddy fields. Furthermore, it is important to assess the impacts of steel slag applications on the heavy metal contents in the rice grains and paddy soils, which are largely unknown at the moment but can have considerable health implications.

In a previous study, we found that steel slag was an effective amendment in reducing CH_4 flux and increasing rice yields of a subtropical paddy field in Fujian Province of China over a short growing season (Wang et al., 2014), However, it is not known whether slag application would affect N_2O emissions and whether the beneficial effects arising from such addition would persist for more than one growing season and would not negative short-term impacts on the concentrations of heavy metals in the soil or the rice grains. This study aims to fill this knowledge gap by: (1) determining the response of CH_4 and N_2O emissions to steel slag application over multiple growing seasons; (2) assessing the impacts of slag addition on crop productivity; and (3) determining the heavy metal concentrations in paddy soils and rice grains following slag application. The steel slag used in this study is derived from the steel industry, and contains high levels of iron that can serve as an alternative electron acceptor and potentially reduce CH_4 and N_2O production (Huang et al., 2009). It is also rich in silicon, calcium, and potassium, which are essential nutrients for rice growth (Luo et al., 2002).

2. Materials and methods

2.1. Experimental site

All field experiments were carried out in the Wufeng Agronomy Field of the Fujian Academy of Agricultural Sciences (26.1°N, 119.3°E; Fig. 1) in the subtropical region of southeastern China. This field was managed following the common practice of growing one crop in each of the three growing seasons over a year, including two successive rice crops (early rice and late rice) followed by a vegetable (lettuce) crop, with intervening periods of drainage. The first early rice crop, the late rice crop, the vegetable crop, and the second early rice crop were grown during the period of 16 April-17 July 2011, 1 August-5 November, 2011, 17 December 2011-8 March 2012, and 11 April-13 July 2012, respectively. The whole study period lasted for 448 days. The site was flooded and drained during the growth of rice and vegetable, respectively.

The soil of the paddy field was moist, poorly drained, and had a ratio of sand: silt: clay content of 28:60:12 (Wang et al., 2013). The bulk density of the soil before the start of this study was 1.1 g cm^{-3}. Moreover, the soil had a pH value (1:5 with H_2O) of 6.5, and concentrations of organic carbon, total nitrogen, and total phosphorus of 18.1 g kg^{-1}, 1.2 g kg^{-1}, and 1.1 g kg^{-1}, respectively (Wang et al., 2012). The water level was maintained at 5–7 cm above the soil surface during the rice growth periods by means of an automatic water-level controller, and the paddy field was drained two weeks before harvesting.

2.2. Experimental design and treatment application

The experimental field had three independent replicate blocks, with each of them containing four treatment plots (50 m^2 each) being arranged in a randomised block design. We thus had three replicates for each treatment. The steel slag used in this study was granular, smaller than 2 mm in diameter, had a pH of 8.5, and was composed mainly of CaO (34.9%), SiO_2 (40.7%), and Fe_2O_3 (4.8%) (Wang et al., 2012), which was similar to those used in previous studies (Ali et al., 2008). The slag was applied to the paddy field at 0 (control), 2, 4, and 8 Mg ha^{-1}, which was equivalent to the addition of 0, 67.2, 134, and 269 kg Fe ha^{-1}, respectively, two days before rice transplantation for the first early rice crop. All control and treatment plots followed the same scheme of crop management, including conventional fertilisation. “For fertilization, the common practice among farmers in Fujian, China, was followed. Applied chemical fertilizers consisted of using a mix of complete fertilizer (N: P_2O_5: K_2O = 16%: 16%: 16%, Keda Fertilizer Co., Ltd., Shandong, China) and urea (46% N). Fertilizers were applied at a rate of 95, 70, and 70 kg ha^{-1} (N, P_2O_5, and K_2O, respectively) to the rice crops in each one of the three studied phases: before transplantation, at the tillering stage, and at the panicle-formation stage. In each phase the fertilizer was applied split in three times. Fertilizer was applied in 13 April, 2011, 27 April, 2011, 15 June, 2011 for the first early rice crop, in 29 July, 2011, 10 August, 2011, 9 October, 2011 for the late rice crop, and in 8 April, 2012, 20 April, 2012, 12 June, 2012 for the second early rice crop. Chemical fertiliser (N, P_2O_5, and K_2O at a rate of 200, 158, and 141 kg ha^{-1}, respectively) was applied once to the vegetable (lettuce) crop on 17 December, 2011. Fertilizer was applied on dry soil and incorporated and puddled, and the other two additional fertilizer broadcasts were applied on flooded water. For the vegetable the fertilizer was applied on dry soil and incorporated and puddled only one time. The field was ploughed to a depth of 15 cm with a mound board plough. The plough dates for the first early rice crop, the late rice crop, the vegetable crop, and the second early rice crop were 12 April, 2011, 28 July, 2011, 10 December 2011, 8 April, 2012, and the puddling dates for the first early rice crop, the late rice crop, and the second early rice crop were 14 April, 2011, 30 July, 2011, 9 April, 2012. The rice and lettuce varieties were Hesheng 10 and Kexing 5, respectively, and the spacing of the individual rice and lettuce plants was 14 × 28 cm and 40 × 60 cm, respectively. The yields of rice and lettuce were recorded after harvesting.

2.3. Measurements of CH_4 and N_2O emissions

Static closed chambers were used to measure the emissions of CH_4 and N_2O (Datta et al., 2013). The chambers were made of PVC and were constructed in two sections: a removable upper transparent compartment (100 cm in height, 30 cm in width, and 30 cm in length) placed on a permanently installed bottom collar. The bottom collars were 10 cm in height, 30 cm in width, and 30 cm in length, and inserted into the soil leaving a 2-cm collar protruding above the soil surface. Each chamber was equipped with a circulating fan for mixing gases, a thermometer to monitor temperature changes during the period of gas sampling, and a gas sampling port with a septum. Three chambers were deployed in each of the plots for all four crops, thus a total of twelve chambers were deployed