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# Contrasting effects of straw and straw-derived biochar amendments on greenhouse gas emissions within double rice cropping systems

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ABSTRACT

The amendment of biochar derived from crop residues to soil has been proposed as a potential mitigation strategy for tackling greenhouse gas (GHG) emissions in cropping systems. A field experiment was carried out to investigate GHG emissions from rice paddy fields treated with straw incorporation and straw-derived biochar amendment at various rates during two consecutive rice growing seasons in double rice cropping systems. The treatments included the following: control (no straw incorporation and no biochar amendment), low straw (rice straw incorporated at 3 t $ha^{-1}$), high straw (rice straw incorporated at 6 t $ha^{-1}$), low biochar (straw-derived biochar amended at 7.5 t $ha^{-1}$ in 2011 and adjusted to 24 t $ha^{-1}$ in 2012) and high biochar (straw-derived biochar amended at 22.5 t $ha^{-1}$ in 2011 and adjusted to 48 t $ha^{-1}$ in 2012). The results showed that straw incorporation significantly increased $CH_4$ emissions relative to the control treatment, whereas biochar amendment significantly reduced $CH_4$ emissions at the highest application rates (48 t $ha^{-1}$), possibly due to a biochar-induced increase in soil pH. The seasonal cumulative $CH_4$ emissions from the low and high straw treatments were 3.0–4.1 and 6.4–8.6 times greater, respectively, in the 2011 late rice season and 7–13 and 13–23 times greater, respectively, in the 2012 early rice season than those from both biochar treatments. In contrast, $N_2O$ emissions decreased by 26–68% in comparison with the control when straw was applied to the soil, but increased by 0.13–0.80 times in the presence of biochar, possibly due to the increased availability of $NH_4^+$ or $NO_3^-$ originating from the added biochar. The seasonal cumulative $N_2O$ emissions were relatively low (15–200 g N $ha^{-1}$) across all the treatments. The estimated seasonal gross global warming potentials (GWP) of $CH_4$ plus $N_2O$ among the treatments showed a similar pattern to the seasonal cumulative $CH_4$ emissions due to the dominance of $CH_4$ to gross GWP (83–99% of the total). As rice straw incorporation also reduced rice grain yield, especially during the early rice season, the yield-scaled GWPs were even higher in the straw amendment treatments compared with the biochar treatments (3.2–4.0 and 7.1–8.8 times in 2011 and 9.4–13 and 18–25 times in 2012 for the low and high straw treatments, respectively). The lower gross and yield-scaled GWPs in paddy fields amended with biochar indicated that transforming straw to biochar and subsequent addition to paddy fields has potential to mitigate GHG emissions in double rice cropping systems.



## 1. Introduction

In rice production systems, incorporating straw from the previous cropping cycle is a common practice for maintaining soil quality and aiding replenishment and recycling of mineral nutrients. When straw incorporation into paddy fields is practiced in many countries worldwide, it has frequently drawn criticism due to its potential to increase greenhouse gas (GHG) emissions from soils (Sass et al., 1991; Yan et al., 2009). Such an exacerbation in GHG is largely attributed to the increase in methane ($CH_4$) emissions as methanogens degrade the carbon (C)-rich straw (Conrad, 2002; Kimura et al., 2004). In contrast, few studies have examined the impact of straw incorporation on nitrous oxide ($N_2O$)

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emissions from paddy fields. Recent studies have shown that straw incorporation into paddy soils can reduce seasonal $N_2O$ fluxes (Zou et al., 2005; Wang et al., 2011). However, due to the much greater increase in $CH_4$ emissions relative to the reduction in $N_2O$ emissions, current studies suggest that straw incorporation into paddy soils may result in a net increase in global warming potential (GWP). In addition to being incorporated into soil, rice straw is also frequently burnt in the fields, resulting in serious smog pollution (Bossio et al., 1999). Therefore, alternative, less environmentally damaging uses of rice straw need to be developed within agronomic systems.

Recently, the addition of biochar (derived from the pyrolysis of crop residues) to soil has been advocated as a potential way of simultaneously improving crop yields, reducing or offsetting GHG emissions and enhancing soil C sequestration (Lehmann and Joseph, 2009). In upland soils, field experiments have shown that biochar amendment decreases $N_2O$ emissions (Aguilar-Chávez et al., 2012; Case et al., 2012; Spokas et al., 2009). This might be attributed to (i) improved aeration that leads to lower denitrification rates, (ii) increased adsorption of ammonium ($NH_4^+$), (iii) microbial or physical immobilization of nitrate ($NO_3^-$) in soils, (iv) increased capacity of biochar to catalytically reduce $N_2O$ to dinitrogen ($N_2$), or (v) even adsorption of organic compounds that are toxic to the microbial community (Castaldi et al., 2011). Biochar amendment has shown no consistent effects on soil $CH_4$ emissions. For example, Karhu et al. (2011) found that biochar amendment increased soil $CH_4$ consumption, and ascribed this to the improved soil aeration, whilst Spokas et al. (2009) found that biochar amendment decreased $CH_4$ oxidation most likely due to suppressed microbial activity. Other researchers have found that biochar amendment has no net effect on $CH_4$ emissions. The reasons for these variable responses remain unclear, largely due to the lack of mechanistic studies. Biochar application may also enhance crop yields (Major et al., 2010; Jones et al., 2012), but the co-benefit of reducing GHG emissions may not occur synchronously.

Paddy soils have very different chemical, physical and biological properties than upland soils due to long-term waterlogging during the rice growing season. However, the effects of biochar amendment on GHG emissions from paddy soils are not well established. Some recent studies have shown that biochar application in paddy fields increases $CH_4$ emissions (Knoblauch et al., 2011; Zhang et al., 2010a, 2012), possibly due to the inhibitory effects of chemicals present in the biochar on the activity of methanotrophs, but decreases $N_2O$ emissions (Zhang et al., 2010a, 2012) possibly due to improved aeration, which decreases the activity of denitrifiers. Other researchers have reported that biochar reduces $CH_4$ emissions (Feng et al., 2011) due to an increased abundance of methanotrophic proteobacteria and decreased ratios of methanogen to methanotroph. These diverse responses of GHG emissions to biochar amendment in upland and lowland paddy soils indicate that the impact of biochar amendment on soil GHG emissions is complex, with differences probably related to differences in soil properties (e.g., soil texture, soil water content and pH; Yanai et al., 2007; Spokas and Reicosky, 2009), or biochar properties (e.g., total C content, C/N ratio, pH or specific surface area; Spokas and Reicosky, 2009; Feng et al., 2011). Therefore, quantifying changes in soil properties in response to biochar addition may help to explain why differences in GHG emissions occur.

The double rice cropping system (two rice seasons per year) is an important cropping system in southern China, is distributed mainly in provinces of Hunan, Jiangxi, Hubei, Zhejiang, Guangxi, Anhui, Guangdong, Hainan, Yunnan and Fujian, and accounts for an area of approximately six million hectares (Xin and Li, 2009). Accompanying rice grain production, large quantities of rice straw are also produced. Currently, there are few industrial outlets for this waste straw, resulting in large quantities (~60%) of straw being left in fields after harvest for late incorporation into soils by plowing or for on-site burning (Gao et al., 2002). Straw-derived biochar exhibited positive effects on reducing GHG emissions based on some reported field experiments. Therefore, transforming rice straw to biochar shows promise as a potential strategy to mitigate GHG emissions and reduce airborne smog pollution. However, little is known about the differences in GHG emissions under straw incorporation and straw-derived biochar amendment in paddy fields in a double rice cropping system. In addition, field studies on the relationships of soil properties and GHG emissions as impacted by biochar in double rice cropping systems are limited. In this study, we present our field measurements of $CH_4$ and $N_2O$ emissions and related soil properties in paddy fields, under straw incorporation and straw-derived biochar amendment at various rates during two consecutive rice growing seasons in a double rice cropping system region in southern China. The objectives of this study were: (i) to quantify the $CH_4$ and $N_2O$ emissions and the gross and yield-scaled GWP as affected by straw and biochar amendments, and (ii) to identify the key soil parameters that influence $CH_4$ and $N_2O$ emissions from paddy soils with straw and biochar amendments.

## 2. Materials and methods

### 2.1. Experimental site

The experimental site (113°19′52″E, 28°33′04″N, 80 m a.s.l.) is located in Jinjing town, Changsha County, Hunan province, China. Two typical paddy fields, which have a tillage history of more than 1000 years for rice production (double rice rotation per year, with early rice grown in late April to mid-July and late rice grown in mid-July to late October), were chosen as the experimental fields (one for the late rice season experiment and the other for the early rice season experiment). The soils of the experimental fields are classified as Stagnic Anthrosols (Gong et al., 2007), which are derived from granite red soil. The basic properties of the soils present in the two experimental fields are shown in Table 1. Soil organic C and total soil N were determined using an automated C/N analyzer (vario MAX, Elementar Analysensysteme GmbH, Germany), soil bulk density using the cylinder ring (volume 100 $cm^3$, inner diameter 5 cm) sampling method, soil pH using a pH meter (Delta 320, Mettler-Toledo Instruments Co., Ltd., China) with a soil/water ratio of 1:2.5, and soil particle composition using a laser particle size analyzer (Mastersizer 2000, Malvern Instruments Ltd., UK). The study region is characterized by a subtropical humid monsoon climate with the following annual means: precipitation, 1330 mm; air temperature, 17.5 °C; sunshine, 1663 h and frost-free period, 274 days.

### 2.2. Field experiments

Field experiments were conducted during the late rice season in 2011 and during the early rice season in 2012. Five treatments were adopted in this experiment: NPK (the control treatment, use of chemical N, P, K fertilizer only, with no straw incorporation and no biochar amendment), NPK + LS (rice straw incorporation at a rate of 3 t dry matter $ha^{-1}$), NPK + HS (rice straw incorporation at a rate of 6 t dry matter $ha^{-1}$), NPK + LB (straw-derived biochar incorporation at a rate of 7.5 t dry matter $ha^{-1}$ during the 2011 late rice season and at a rate of 24 t dry matter $ha^{-1}$ during the 2012 early rice season), and NPK + HB (straw-derived biochar incorporation at a rate of 22.5 t dry matter $ha^{-1}$ during the 2011 late rice season and at a rate of 48 t dry matter $ha^{-1}$ during the 2012 early rice season). The low and high straw application rates used in the study were equivalent to 50% and 100% of the rice straw produced during a single growing season, respectively. Because biochar is usually used for soil quality improvement, the biochar application rates