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Integrated rice-duck farming mitigates the global warming potential in rice season

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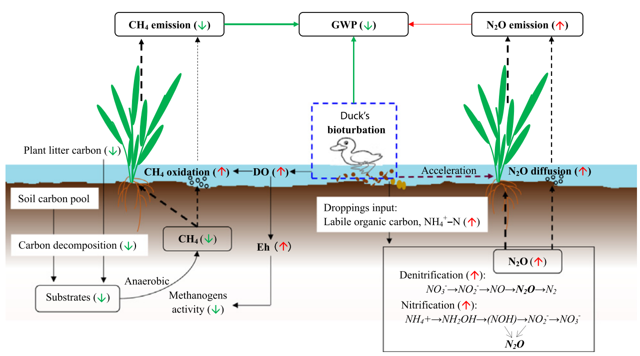
HIGHLIGHTS

- Integrated rice-duck farming (IRDF) mitigates the GWP without rice yield losses.
- Fermenting straw aerobically before its incorporation is good for relieving GWP.
- IRDF reduced CH_4 emission by increasing soil Eh and DO content in water layer.
- IRDF results in maximum effect on CH_4 and N_2O emissions under RWS system.

GRAPHICAL ABSTRACT



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ABSTRACT

Integrated rice-duck farming (IRDF), as a mode of ecological agriculture, is an important way to realize sustainable development of agriculture. A 2-year split-plot field experiment was performed to evaluate the effects of IRDF on methane (CH_4) and nitrous oxide (N_2O) emissions and its ecological mechanism in rice season. This experiment was conducted with two rice farming systems (FS) of IRDF and conventional farming (CF) under four paddy-upland rotation systems (PUR): rice-fallow (RF), annual straw incorporating in rice–wheat rotation system (RWS), annual straw-based biogas residues incorporating in rice–wheat rotation system (RWB), and rice-green manure (RGM). During the rice growing seasons, IRDF decreased the CH_4 emission by 8.80–16.68%, while increased the N_2O emission by 4.23–15.20%, when compared to CF. Given that CH_4 emission contributed to 85.83–96.22% of global warming potential (GWP), the strong reduction in CH_4 emission led to a significantly lower GWP of IRDF as compared to CF. The reason for this trend was because IRDF has significant effect on dissolved oxygen (DO) and soil redox potential (Eh), which were two pivotal factors for CH_4 and N_2O emissions in this study. The IRDF not only mitigates the GWP, but also increases the rice yield by 0.76–2.43% compared to CF. Moreover, compared to RWS system, RF, RWB and RGM systems significantly reduced CH_4 emission by 50.17%, 44.89% and 39.51%, respectively, while increased N_2O emission by 10.58%, 14.60% and 23.90%, respectively. And RWS system had the highest GWP. These findings suggest that mitigating GWP and improving rice yield could be simultaneously achieved by the IRDF, and employing suitable PUR would benefit for relieving greenhouse effect.

Abbreviations: FS, rice farming system; PUR, paddy-upland rotation system; IRDF, integrated rice-duck farming; CF, conventional farming; RF, rice-fallow; RWS, annual straw returning in rice–wheat rotation system; RWB, annual straw-based biogas residues returning in rice–wheat rotation system; RGM, rice-green manure; DAT, days after transplanting; SMPP, soil methane production potential; DO, dissolved oxygen content.

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1. Introduction

Rice (*Oryza sativa* L.) is one of the most important food crop in the world, and it is cultivated in large arable land in Asia (Sui et al., 2016). However, rice field is an important source of methane (CH_4) and nitrous oxide (N_2O) emissions (Zhang et al., 2014; Sun et al., 2016). CH_4 and N_2O emissions from rice fields have been estimated to account for about 30% and 11% of global agricultural CH_4 and N_2O emissions, respectively (Liu et al., 2015b). CH_4 and N_2O are two major potent greenhouse gases (GHG), 28 and 265 times higher in global warming potential (GWP) than carbon dioxide (CO_2) on a 100-year time horizon, respectively (IPCC, 2013). The increase concentrations of atmospheric CH_4 and N_2O have negative effects on biogeochemical cycles. For example, CH_4 react with free radicals at the troposphere, thus weaken its digestion of chlorofluorocarbons leading to the other GHG emission (Le Mer and Roger, 2001). N_2O reduces atmosphere transparency by absorbing infrared light in order to reduce earth surface radiation. Moreover, the increase of N_2O in atmosphere could aggravate the destruction of the ozone layer (Zhang et al., 2016).

Paddy-upland rotation system (PUR) is the most important cropping system in China (Zheng et al., 2016). Previous studies indicated that the PUR can improve soil redox potential and eliminate toxic substances (Motschenbacher et al., 2011). Moreover, it promotes the mineralization of soil organic matter and increased availability of nutrients in the soil (Zheng et al., 2016). However, the direct incorporation of upland crop straw into paddy soil supplies abundant labile organic carbon for methanogens, leading to stimulates CH_4 emissions from rice fields (Zou et al., 2005; Sang et al., 2012; Linquist et al., 2012). For example, rice–wheat rotation systems is the dominant cropping system in the middle and lower reaches of Yangtze River (Yao et al., 2013). Nowadays, crop straw directly incorporated into the soil has been widely recommended in this region, due to a high degree of mechanization (Xiong et al., 2015) and as a measure to promoting closure of the global energy and nutrient cycles (Yao et al., 2013). But this measure undoubtedly induces greater CH_4 emission from rice fields (Zou et al., 2005; Ma et al., 2009). What's more, many efforts to reduce the high CH_4 emission from rice–wheat rotation system have been done, including fermented straw aerobically in biogas digesters before its incorporation (Xia et al., 2016). The application of biogas residue into soil could decrease CH_4 emissions compared to fresh straw (Linquist et al., 2012; Xia et al., 2016), however, this soil amendment may also contribute to the GHG emissions when compared to no organic matters treatments (Odlare et al., 2012). In addition, with the problem of soil degradation becoming more and more severe, green manure planting in upland cultivation had received widespread attention (Yang et al., 2014). Application of green manure is an important soil management practice (Elfstrand et al., 2007), while green manure incorporation attributed to the more labile organic matter, and then stimulated the GHG emissions (Sang et al., 2012). All in all, incorporating these organic matters (i.e., wheat straw, biogas residue, and green manure) supplies activate carbon to the paddy soil, which further enhanced GHG emissions from rice fields. Considering the adverse effect of increasing GHG emission, it is important to find a proper way to reduce GHG emissions from rice fields under paddy-upland rotation systems.

Integrated rice-duck farming (IRDF), in which ducks feed on insects and weeds in paddies and fertilize rice plants, has positive effects on rice production and rice ecosystem. With paddling, trampling and foraging, the presence of ducks in rice fields can not only effectively control weeds, pests and plant diseases, improve soil properties and soil aeration (Pernollet et al., 2015; Zhen et al., 2007), but also reduce N runoff and leakage loss in rice fields (Yu et al., 2009). In addition, IRDF has increased rice population dry matter accumulation, root activity and stem strength (Liu et al., 2015c; Wang et al., 2008). Furthermore, the bioturbation of ducks may also change the environmental factors of rice fields, and lead to affect the GHG production and emission in the paddy soil. However, there is limited knowledge regarding the effects of IRDF on GHG emissions and the relationship between GHG emissions and environmental factors in rice fields, especially in different paddy-upland rotation systems.

In light of the above, this study measured the effects of IRDF on CH_4 and N_2O emissions in rice season under different PUR. Overall, this study aims to gain an insight into the effects of IRDF and PUR on CH_4 and N_2O emissions, then evaluate the rice yield and GWP in rice season, and finally investigate the relationship between GHG emissions and soil/water factors in rice fields.

2. Materials and methods

2.1. Experimental site

The field experiment was carried out in a typical rice–wheat rotation system at the Baiwei Farm of Nanjing Agricultural University (32°35′N, 120°24′E). The experimental region is characterized by a subtropical monsoon climate, with an annual average air temperature of 14.5 °C and precipitation of 1025 mm. In 2014 and 2015, during the experimental period, the daily mean temperatures were 23.41 °C and 24.41 °C, respectively, and the precipitation were 691.4 mm and 927.5 mm, respectively (Fig. 1). The soil texture was clay, with soil properties as follows: pH 6.53, organic matter 25.3 g/kg, total N 1.39 g/kg, available N 97.7 mg/kg, available P 23.7 mg/kg, and available K 95.4 mg/kg.

2.2. Experimental design

The field experiment was carried out in 2014 and 2015 from May to October, and the rice variety was Nanjing 9108. Seeds were sown on May 23rd, transplanted on June 14th with average spacing of 13.3 cm × 30 cm and four seedlings per hole, and harvested on October 21st. The experiment employed a double-factor split-plot design with three replicates. The area of each plot was 150 m^2 (10 m × 15 m), separated by film-wrapped ridges, and irrigated separately. The main plots included four paddy-upland rotation systems (PUR), namely, rice-fallow rotation system (RF), annual straw incorporating in rice–wheat rotation system (RWS), annual straw-based biogas residues incorporating in rice–wheat rotation system (RWB), and rice-green manure rotation system (RGM). Alfalfa (*Medicago sativa* L.) was used as Green manure. In RWB system, the crop straw was fermented aerobically in biogas digesters before its incorporation, and the amount of the N in the incorporated biogas residue was equal to the amount of N in incorporated fresh straw. The crop straw and alfalfa were chopped in situ and plowed into the soils. Organic matter was used as basal fertilizer. All treatments received the same amount of nutrient in rice season, including 270 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, 120 kg K_2O ha^{-1}. N was used as base fertilizer, tiller fertilizer and panicle fertilizer at the rate of 20%, 40% and 40%, respectively. Tiller fertilizer was applied with equal amounts on the 7th and 14th days after transplanting (DAT), phosphorous was used entirely as basal fertilizer, and potassium was used as basal fertilizer and panicle fertilizer at equal amounts. Due to the difference of properties and incorporating amount of organic matter existing in different treatments, chemical fertilizer used in different systems were shown in Table 1 according to the principle of equal nutrient.

The experiment applied rice farming systems (FS) as sub-plots, included the conventional rice farming (CF) and integrated rice-duck farming (IRDF). Ducklings were introduced into the IRDF area with a density of 225 ducks ha^{-1} at the 17th DAT. These IRDF fields were surrounded by nylon nets (0.8 m in height) to prevent the ducks from escaping, and a shed for the ducks was also built in the corner of each IRDF plot. During the first 3 weeks, fed ducks regularly every day, then reduced forage gradually to promote ducks to feed themselves in the field. The ducks were retrieved at heading stage. During rice growth, water management were as follows: floodwater layer of 5–8 cm in depth at the early stage (1–41st DAT), mid-season drainage (42–50th DAT), alternate wetting and drying (51–123rd DAT), and field drainage