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Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis

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ABSTRACT

Recently increasing studies suggest that a comprehensive assessment of cropping practices impacts on greenhouse gas (GHG) emissions at yield-scale will benefit cropping technique innovation and policy selection for higher-yield with less-emissions. In this paper, we conducted a meta-analysis to quantify the impacts of rice cropping practices on the global warming potential (GWP) of GHG emissions at yield-scale rather than area-scale in China. The results showed that the yield-scaled GWP of Chinese major rice cropping systems during rice growing season was in the order: double rice cropping system (1188.9 kg CO_2 equiv. Mg^{-1}) > rice-upland crop rotation system (777.0 kg CO_2 equiv. Mg^{-1}) > single rice cropping system (346.7 kg CO_2 equiv. Mg^{-1}). Nitrogen fertilization (50–300 kg N ha^{-1}) significantly increased rice yield with slight increments in the GWP of CH_4 and N_2O emissions, resulting in significant reductions in the yield-scaled GWP. The greatest reduction occurred at the application rate of 150–200 kg N ha^{-1} by 37% as compared to the non-fertilization control. For organic amendments, biogas residue application had no significant effect on the yield-scaled GWP, while manure application and straw recycling significantly increased the yield-scaled GWP by 54% and 154%, respectively. Intermittent irrigation significantly reduced yield-scaled GWP by 59% largely because of a significant reduction in CH_4 emission and a significant increment in rice yield. No-tillage showed lower CH_4 emission with similar rice yield in comparison with the conventional tillage, resulting in a reduction in yield-scaled GWP by 20%. These results indicate that there is a great potential to meet the new objective of higher-yield with less-GHG emissions through innovating rice cropping technique. More efforts should be paid on the field observations of GHG emissions during non-rice growing season, so as to perform a life-cycling assessment of GHG emissions from rice fields at yield scale under different cropping systems.

1. Introduction

More than half of the world's population take rice as their staple food, and rice sown area is about 153 million ha worldwide, approximately 11% of global arable land (FAOSTAT, 2011). In the next twenty years, the world demand for rice will increase by about 24% (Van Nguyen and Ferrero, 2006). Meanwhile, about 30% and 11% of global agricultural CH_4 and N_2O emissions were from rice fields, respectively (US-EPA, 2006; IPCC, 2007). The increasing demand for rice in future has induced tremendous concerns on the stimulation of GHG emissions (van Beek et al., 2010; Zhang et al., 2011). A trade-off between rice yield increase and GHG emissions reduction is urgent to be made for rice cropping technique innovation and policy selection. Recently increasing studies suggested that a comprehensive assessment of cropping practices impacts on GHG emissions per unit yield (yield-scale) rather than land area (area-scale) will benefit the trade-off decision making (Van Groenigen et al., 2010; Linquist et al., 2011).

Many studies have been conducted to assess the impacts of rice cropping practices; however, most of those studies were focused on the impacts on one side of rice yield or GHG emissions at area-scale (Yan et al., 2003b; Akiyama et al., 2005; Peng et al., 2010). The integrated effects of cropping practices on rice yield and GHG emissions are still unclear. For example, according to existing observations, intermittent irrigation was widely recommended as an effective measure to mitigate CH_4 emission from rice fields (Wassmann et al., 2000; Yan et al., 2003b). However, the impacts of intermittent irrigation on rice yield can be significantly negative (Towprayoon

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et al., 2005), or significantly positive (Qin et al., 2010), or not obvious (Wassmann et al., 2000) as compared to the continuous flooding. The integrated effects of intermittent irrigation on rice yield and GHG emissions are not well documented. Nitrogen (N) fertilizer was a major practice to enhance rice production, but field measurements showed contradictory results about CH_4 emissions caused by N fertilization. Some studies reported that N fertilization could significantly stimulate CH_4 emission (Lindau et al., 1991; Singh et al., 1996), other studies showed a significant reduction in CH_4 emission caused by N fertilization (Zou et al., 2005; Xie et al., 2010). Based on existing understandings, it is difficult to determine an optimal rate of N fertilization for higher rice yield with lower GHG emissions. Organic matter amendments can significantly enhance soil quality of rice field (Pan et al., 2009), but they simultaneously stimulate GHG emissions significantly (Lu et al., 2000b; Wang et al., 2000). Obviously, it is well known that one cropping practice, which is optimal for rice yield enhancement, may not benefit GHG emission mitigation, and vice visa. Thus, only to learn the impacts of cropping practices on rice yield or GHG emission at area-scale is not enough to provide good references to cropping technique innovation and policy selection for higher-yield with less-emissions.

China ranks the first in annual rice production in the world (FAOSTAT, 2011). In order to ensure the food security for the increasing population, Chinese rice production needs to be increased by 20% by 2030 (Peng et al., 2009). Meanwhile, the CH_4 emission from Chinese rice fields was estimated the highest in global rice cropping countries (Yan et al., 2009). It is very urgent and necessary to improve rice cropping technique for higher-yield with less-GHG emissions. During the past decades, many studies have been conducted on the effects of cropping practices on rice yield (Peng et al., 2006; Xu et al., 2010b) or GHG emissions (Cai et al., 1997; Yan et al., 2003a; Zou et al., 2005; Shang et al., 2010) at area-scale in China. Those studies provide a good chance to quantify the impacts of cropping practices on GHG emissions at yield-scale using meta-analysis. Therefore, we conducted a meta-analysis to quantitatively assess the impacts of Chinese major cropping practices, including cropping systems and soil fertility management practices, on yield-scaled GHG emissions. Our objectives are to provide references to rice cropping technique innovation and rice production policy selection for higher-yield with less-GHG emissions.

2. Materials and methods

2.1. Data selection

In this meta-analysis, we conducted a literature survey of peer-reviewed papers related to rice yield and CH_4 and N_2O emissions from Chinese rice field published before December 2011. To include as many studies as possible, the papers published both in English and in Chinese were collected from two databases of the Web of Science and the China National Knowledge Infrastructure (CNKI), the largest Chinese Academic Journals database. Twenty-four papers including 150 measurements were collected according to the following criteria: (1) the measurements must be conducted under field conditions; (2) CH_4 and N_2O fluxes must have been measured for an entire growth period of rice using static chamber method; (3) both rice yield and GHG emissions have been determined simultaneously. Since some authors published their results about rice yield and GHG emissions separately in different papers, some rice yield data were obtained from other publications. Based on a survey of existing rice cropping techniques in China, two kinds of major copping practices, rice cropping systems and soil fertility management practices, were assessed in this analysis. The detailed database is listed in Appendix S1.

2.2. Data analysis

2.2.1. Calculation of global warming potential

Two global warming potential (GWP) indexes (area-scaled and yield-scaled GWP) were calculated for each observation to evaluate the integrated impacts of cropping practices on GHG emissions and rice yields. Area-scaled GWP represented the overall GWP of CH_4 and N_2O emissions per unit rice field (ha), which was used to evaluate the impacts of cropping practices on CH_4 and N_2O emissions; yield-scaled GWP represented the overall GWP per unit rice yield (Mg), which was used to evaluate the comprehensive impacts of cropping practices on GHG emissions and rice yields. The 100-year radiative forcing potential coefficients relative to CO_2 were 25 and 298 used for CH_4 and N_2O, respectively (IPCC, 2007). In some studies, the same treatment was measured more than one year, thus the mean value of the results measured in different years was calculated as one single observation.

2.2.2. Impacts assessment of rice cropping systems

Major Chinese rice cropping systems were divided into three groups. Group I is the annual single rice cropping system mainly located in North China, and it accounts for 17.0% of the total rice production in China (National Bureau of Statistics of China, 2011). Group II is the annual rice-upland crop rotation system (rice–wheat or rice–rape seed rotation) mainly located in Central China, and it accounts for 49.0% of Chinese total rice production (National Bureau of Statistics of China, 2011). And Group III is the annual double rice cropping system mainly located in South China, and it accounts for 34.0% of the total rice production in China (National Bureau of Statistics of China, 2011). We followed the method used by Linquist et al. (2011) to evaluate the mean GHG emissions, area-scaled GWP, rice yields, and yield-scaled GWP for the three cropping systems. Formulas were as follow:

$$M = \frac{\sum (Y_i \times W_i)}{\sum W_i} \tag{1}$$

$$W_i = n \times \frac{f}{o} \tag{2}$$

Formula (1) was used to calculate the weighted mean values for three cropping systems. In formula (1), M is the mean value of CH_4, N_2O, area-scaled GWP, rice yield and yield-scaled GWP for the three cropping systems, respectively. Y_i is the observation of CH_4, N_2O, area-scaled GWP, rice yield and yield-scaled GWP at the ith site, respectively. W_i is the weight for the observations from the ith site and was calculated by formula (2). In which, n is the number of replicate in the field experiment. f is the number of GHG measurement per month for the weight of GHG emissions and GWP indexes. In order to prevent studies with high sampling frequency from being assigned extreme weight, it was assigned the maximum value of $f = 5$ when GHG fluxes were measured more than once a week. As for rice yield, set $f = 1$, since it was measured once per growing season. o is the total number of observations from the ith site. This weighting approach assigned more weight to the field measurements that were well replicated and more precise fluxes estimated, and adjusted the weights by the total number of observations from one site to avoid studies with many observations in one site dominating the data set (Linquist et al., 2011).

In this assessment of cropping systems, we only selected the experiments with widespread cropping practices which had been widely used by local farmers. The experiments with rare cropping practices which were only used by researchers, such as plastic mulches (Kreye et al., 2007) and slow-releasing urea (Yue et al., 2005), were excluded in this analysis.