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Nitrogen management to reduce yield-scaled global warming potential in rice

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ABSTRACT

Fertilizer N is usually required to achieve optimal yields but when applied in excess there is increased risk of pollution, including higher greenhouse gas (GHG) emissions. Thus, optimal N management must consider both yields and environmental effects. Yield-scaled GWP (Global Warming Potential), which is the GWP (in CO_2 equivalents) per Mg of grain yield, is a useful metric for evaluating management options where the goal is to achieve both high yields with minimal environmental burden. A 6-year field study was conducted to test the hypothesis that the lowest yield-scaled GHG emissions for rice occur when N is applied at optimal N rates for maximum yields, independent of the source of N applied. We tested this hypothesis for organic (manure) and inorganic (urea) N sources. The N rates and sources in each growing season were: 0, 90, 180 and 270 kg N ha^{-1} applied as either urea alone or pig manure combined with urea (where N was added as manure and supplied 60% of the total N rate). The N rates to achieve maximum yields (90 to 180 kg N ha^{-1} depending on year) were similar for both N sources. Seasonal CH_4 and N_2O emissions varied significantly between years but the magnitude of emissions was determined largely by N source. Across N rates, application of manure increased GWP by almost 60% relative to the urea treatments due to higher CH_4 and N_2O emissions. When urea was used as the sole N source, yield-scaled GWP (87 kg $CO_{2\ eq.}$ Mg^{-1} grain) was lowest at optimal N rates for maximum yields. In contrast, when manure was used, yield-scaled GWP was higher than for urea and increased with increasing manure-N rates (from 104 to 171 kg $CO_{2\ eq.}$ Mg^{-1} grain). The lowest yield-scaled GWP for manure was when no manure was applied – despite the low yields. Thus, when manure is used as an N source in flooded rice systems, over application should be avoided.

1. Introduction

Flooded rice (*Oryza sativa* L.) systems emit both CH_4 and N_2O, however they are the largest agricultural source of CH_4 emissions and account for 5–19% of the annual global CH_4 emissions (IPCC, 2007). Despite N_2O being a greenhouse gas (GHG) that is 12 times more potent than CH_4 (IPCC, 2001), results from a recent meta-analysis (Linquist et al., 2012b) reported that CH_4 emissions accounted for almost 90% of total global warming potential (GWP) from rice systems and concluded that efforts to reduce GWP of rice systems should focus on CH_4.

China grows rice on approximately 30 million ha per year and is the world's leading producer (FAO, 2012). It is estimated that 7.7–8.0 Tg CH_4 and 138–154 Gg N_2O are emitted from Chinese rice fields (Yan et al., 2003; Zheng et al., 2004), with a GWP between 219 and 229 Tg $CO_{2\ eq}$. In recent years rapid urbanization in China has increased pressure to intensify agricultural production in places such as the Taihu Lake region; and as a result, rice growers are applying more N (Ju et al., 2009). As the recovery of applied fertilizer N is usually less than 20% (Wang et al., 2003) it can contribute to the high GWP from the rice systems (Huang and Tang, 2010), along with other environmental and economic concerns. Therefore, it is necessary to establish management practices that optimize N use to achieve high yields with minimal environmental cost – the basis of sustainable intensification (Godfray et al., 2011).

Whether in this region or globally, rice production must increase to meet food demand. Mueller et al. (2012) reported that closing the rice grain yield gap to 100% of attainable yields would require a 47% increase in global rice production. Increasing rice production will inevitably increase CH_4 and N_2O along with its associated GWP, however attempts must be made to increase production with the lowest GWP. Linking grain yield with GWP provides a metric to

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quantify economic viability (yields) with environmental concerns. This metric has been termed GHG intensity (Mosier et al., 2006) or yield-scaled GHG emissions (van Groenigen et al., 2010) and is reflected in the GWP in CO_2 equivalents per unit of grain yield. Although soil CO_2 fluxes also represent a source of GHG emissions, on a global scale they are largely offset by high rates of net primary productivity and atmospheric CO_2 fixation by crop plants, and are estimated to contribute less than 1% to the GWP of agriculture (Smith et al., 2007). Therefore, CO_2 as a contributor to GWP was not included in our analysis. van Groenigen et al. (2010) reported that yield-scaled GHG emissions were lowest where N was applied at optimal rates and excessive N rates led to high yield-scaled emissions.

Yield-scaled emissions are affected by both N input and source (Shang et al., 2011). In many regions of the world farmers have a choice between organic and inorganic sources of N. Urea and pig manure are the two main N sources applied to rice systems in this region of China. The effect of N source on rice productivity is conflicting with some claiming manure to be more effective than urea at improving yields and N use efficiency (Pan et al., 2009; Bi et al., 2009; Duan et al., 2011) while others urea (de Ponti et al., 2012).

Other studies have reported that manure N sources increase GWP particularly because of higher CH_4 emissions in flooded rice systems (Yang et al., 2010; Shang et al., 2011); and based on a meta-analysis, Linquist et al. (2012a) reported that manure applied at similar N rates as urea resulted in 26% higher CH_4 emissions but no significant difference in N_2O emissions. In addition, some studies have also evaluated the effect of varying rates of mineral fertilizer N on CH_4, N_2O and GWP (i.e. Yao et al., 2012). However, no study has determined how N source (mineral vs. organic) affects yield-scaled GWP. Such studies require an evaluation across a range of N rates and sources to adequately identify optimal N rates for each source and determining GHG emissions from these N treatments. Therefore, we initiated a 6-year field study to test the hypothesis that the lowest yield-scaled GWP for rice is when N is applied at optimal N rates for maximum yields, independent of the source of N applied. Our objective was to determine yield-scaled GWP when different rates of inorganic (urea) or organic (pig manure) N are applied. It is anticipated that the outcome of this research will provide a basis to develop efficient management strategies that address the need for high yields while also addressing environmental concerns.

2. Materials and methods

2.1. Site description

The field experimental site was located in the Taihu Lake region, Jiaxing City, Zhejiang Province, China (120°40′E, 30°50′N). The climate is a subtropical monsoon climate with mean annual temperature and precipitation of 15.7 °C and 1200 mm, respectively. Prior to the experiment the field had been continuously cropped with rice for more than 700 years (Cao, 2008). The soil was classified as a gleyed paddy soil (clay loam, mixed, mesic Mollic Endoaquepts) derived from the riverine-lucustrine sediments. The initial soil properties of the plow layer (0–15 cm) were: pH, 6.9; organic C, 18.2 g kg^{-1}; total N, 2.65 g kg^{-1}; total P, 1.51 g kg^{-1}; CEC, 8.12 cmol kg^{-1}; sand content,12.1%; clay content, 51.7%; and bulk density, 1.33 g cm^{-3}.

2.2. Fertilization treatments and management

The experiment was established in 2005 with treatments arranged in a randomized complete block design with three replications. The cropping system was a rice-rape (*Brassica napus*) system with rice being grown in the wet season and rape in the dry season. Only results related to rice are reported here. Each plot was 4 m × 5 m. Throughout the six-year experiment, the N treatments remained the same for each plot. To reduce edge effects, non-experimental guard plots planted with rice were established around the entire experiment. In each rice season the following were identical: the variety (cv. JIA 9321), transplanting 25 day old seedlings on July 1, drainage (October 3), and harvest (October 30).

There were seven N treatments: a control (no N) and three rates of N (90, 180, and 270 kg N ha^{-1}) applied either as urea (90U, 180U and 270U) or a combination of manure and urea (90 M, 180 M and 270 M). For urea treatments the N was applied in three doses (basal fertilizer/1st topdressing/2nd topdressing) at a ratio of 3:1:1. For manure treatments, pig manure (C: 8.5%; N: 0.56%; P: 0.43%; K: 0.40%) was applied as the basal N fertilizer and the remaining 40% of the N rate was applied as urea in two equal topdressing doses-similar to the urea treatments. Thus, manure provided 60% of 90, 180 and 270 kg N ha^{-1}, or 54, 108, and 162 kg N ha^{-1}, respectively. To ensure that P and K were not limiting, the control and all urea treatments received 40 kg P_2O_5 ha^{-1} (superphosphate) and 150 kg K_2O ha^{-1} (KCl) and the 90 M treatment received 73 kg K_2O ha^{-1}. These fertilizers were broadcast onto soil surface by hand and incorporated with the 0–5 cm soil layer by puddling at the same time as the basal N fertilizer was applied. The urea topdress application was broadcast onto the flooded field 2 and 4 weeks after transplanting (WAT) each year to all treatments except the control. The irrigation water level was maintained at 5–8 cm from transplanting until the drainage which occurred between 13 and 14 WAT. Other field practices, such as field preparation, tillage, puddling, and weed control, were carried out manually according to the local farming practices.

2.3. Sampling and analysis

Flux measurements of N_2O and CH_4 were performed simultaneously using static Plexiglas chambers and gas chromatography (GC) techniques. The Plexiglas chamber, covered on the outside with bubble foil insulation, was modified from Ni and Zhu (2004) with dimensions of 0.6 m × 0.6 m and a height of 0.6 or 1.2 m depending on plant height. A small fan was fixed to the interior top surface to mix the chamber air before sampling. During each rice growing season, gas samples were taken from 08:00 to 10:00 h weekly. For each sampling event gas samples were taken at 0, 15, 30, 45 min from the middle space of each chamber and transferred into 15 mL vacuum vials and analyzed for CH_4 and N_2O using a GC (Shimadzu, GC-14B series). In addition the temperature inside the chamber was measured for the flux calculation. The gas flux rates were determined from the linear increase in gas concentrations within the chamber over time. The GWP of N_2O and CH_4 emissions was calculated in units of CO_2 equivalents ($CO_{2\ eq.}$) over a 100-yr time horizon. A radiative forcing potential relative to CO_2 of 298 was used for N_2O and 25 for CH_4 (IPCC, 2001).

At harvest, the aboveground biomass and grain yields were determined from a 1 m^2 area within each plot. After oven drying to a constant weight at 60 °C the biomass was weighed to determine yields. The biomass was then ground and analyzed for N content using an Elemental Analyzer (Vario Max, Germany). N recovery efficiency (NRE) was calculated as:

$$\text{NRE} = [\text{N uptake(N treatment)} - \text{N uptake (control)}]/\text{N applied.}$$

2.4. Data analysis

The seasonal CH_4 and N_2O emission totals from all the treatments and rice growing seasons were computed directly from the