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Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input

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ABSTRACT

Fertilizer nitrogen (N) has been shown to impact both N_2O and CH_4 emissions from flooded rice systems, yet there is limited research on the effects of N rate when assessing global warming potential ($GWP = N_2O + CH_4$) per unit area and per unit grain yield (yield-scaled) on a seasonal and annual basis. A two-year on-farm experiment was conducted from 2010–2012 to test the hypothesis that optimal N rates result in maximum agronomic productivity and minimal yield-scaled GWP in water-seeded rice systems experiencing continuously flooded conditions during the growing season and fallow period. Five fertilizer N rates (0, 80, 140, 200 and 260 kg N ha^{-1} yr^{-1}) were applied as aqua ammonia and annual N_2O and CH_4 emissions were quantified using the vented, closed chamber method. Results indicate that low N_2O emissions occurred regardless of N rate when a permanent flood was maintained, but that large N_2O fluxes occurred during discrete field drainage periods prior to harvest, particularly at high N rates. Hence, cumulative N_2O emissions increased with N rate in a nonlinear manner during the growing season. Over the entire cropping cycle, the highest CH_4 fluxes occurred during the middle of the growing season and following field drainage periods prior to harvest and at the conclusion of the fallow period. Mean seasonal and annual CH_4 emissions tended to increase with N addition compared to the control, but significant differences were not observed between N rates. While CH_4 and N_2O emissions were generally not affected by N rate during the fallow period, the fallow period contributed significantly to annual emissions (e.g. 56% of annual N_2O emissions across N rates). Across years, CH_4 represented 94% of total GWP and as a result, mean annual GWP increased with N rate up to 140 kg N ha^{-1}. Maximum yields occurred between 140 and 200 kg N ha^{-1}, thus by employing the yield-scaled metric to begin to integrate climate change and global food demand concerns, mean annual yield-scaled GWP significantly decreased by 49% at these N rates. These findings suggest that optimal yields can be achieved with simultaneous reductions in yield-scaled GWP through efficient fertilizer N management in water-seeded rice systems experiencing continuously flooded conditions during the growing season and fallow period.

1. Introduction

Amid global efforts to increase food production to meet growing demand, it is clear that new strategies are needed to achieve dual goals of ensuring food security while protecting natural resources and the environment through reduced greenhouse gas (GHG) emissions (Burney et al., 2010; Tilman et al., 2011). Agricultural nitrous oxide (N_2O) and methane (CH_4) emissions have gained considerable attention recently as they are estimated to have 298 and 25 times the radiative forcing potential of CO_2, respectively, over a hundred year time horizon (Houghton et al., 2001). It is projected that N_2O and CH_4 emissions may increase by as much as 35–60% and 60%, respectively, by 2030 (Smith et al., 2007). Flooded rice soils represent an important source of global CH_4 emissions (Le Mer and Roger, 2001; Yan et al., 2009). Moreover, it is increasingly recognized that rice-based cropping systems can emit substantial amounts of N_2O (Zou et al., 2009), with fluxes occurring during transition periods between crops (Zhao et al., 2011), the rice season itself (Wang et al., 2011), or under crop rotations such as wheat (Liu et al., 2010). Accordingly, an improved understanding of CH_4 and N_2O emissions from rice systems is required to identify mitigation opportunities and develop appropriate climate change strategies for the future.

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Fertilizer N management is a critical component for reducing environmental impacts associated with GHG emissions in rice systems (Linquist et al., 2012b; Shang et al., 2011). Ammonium based fertilizer N addition can influence CH_4 emissions (Cai et al., 2007), with recent field studies suggesting that high N rates can decrease net CH_4 emissions from rice systems by roughly 30–50% (Xie et al., 2010; Yao et al., 2012). It has been proposed that high soil NH_4-N concentrations may stimulate methanotrophic activity and CH_4 oxidation in rice soils, thereby reducing overall CH_4 emissions (Banger et al., 2012; Bodelier and Laanbroek, 2004). However, experimental results are inconsistent, with others reporting that fertilizer N addition may increase CH_4 emissions due to increased rice biomass which can facilitate gas transport through rice plants (Singh et al., 1999), as well as enhance carbon substrate availability for methanogens (Lu et al., 2000; Schimel, 2000). In direct-seeded rice systems, Lindau et al. (1991) found that urea N addition increased CH_4 emissions approximately 40–75% compared to control plots. Recent meta-analyses on this topic indicate that the response of CH_4 emissions may be N rate dependent, where N addition tends to stimulate CH_4 emissions at low N rates but can potentially mitigate emissions at high N rates (Banger et al., 2012; Linquist et al., 2012b). Overall, the effects of fertilizer N rate on CH_4 emissions from water-seeded rice remain unclear.

Fertilizer N also strongly impacts N_2O emissions in rice systems (Cai et al., 1997; Kreye et al., 2007). While there is large body of work on factors regulating CH_4 emissions (Conrad, 2002; Wassmann and Aulakh, 2000; Yan et al., 2005), there is relatively limited information on management practices and soil variables controlling N_2O emissions from rice (Akiyama et al., 2005; Zou et al., 2007). High N rates generally lead to greater cumulative N_2O emissions, yet results vary by location with fluxes being highly variable and peak emissions often being driven by management events including fertilizer N application, soil submergence, and field drainage cycles (Becker et al., 2007; Kreye et al., 2007; Zhao et al., 2011). Moreover, field measurements are typically confined to the rice growing season, yet up to half of annual GHG emissions can occur during fallow periods (Fitzgerald et al., 2000; Liang et al., 2007). Hence, approaches to quantify annual rather than seasonal emissions are needed. Furthermore, although it is known that mitigation efforts aimed at CH_4 emissions tend to increase N_2O emissions and vice versa (Cai et al., 1997; Ma et al., 2007; Zou et al., 2005), many studies have failed to account for the combined effects of management practices on both gases (Linquist et al., 2012a). Given that the radiative forcing potential of N_2O is approximately 12 times greater than CH_4, strategies to simultaneously reduce both gases should be considered (Johnson-Beebout et al., 2009).

Recognizing the importance of fertilizer N in sustaining crop yields, new metrics have been proposed to begin to integrate environmental concerns with increasing global food demand when evaluating GHG emissions from agriculture. For instance, in addition to the standard practice of reporting GHG emissions per unit area or per unit N applied (e.g. fertilizer-induced N_2O emissions), one option is to assess GHG emissions per unit yield, either termed 'yield-scaled emissions' (Van Groenigen et al., 2010) or 'greenhouse gas intensity' (Mosier et al., 2006). These metrics are related to the concept of agricultural intensification, where efforts are focused on increasing productivity per unit area instead of expanding agriculture to new farmland. Despite the potential for increased emissions at the individual farm scale, agricultural intensification efforts to date have reduced global GHG emissions from agriculture (Burney et al., 2010). Moreover, in a recent meta-analysis on GHG emissions from the world's major cereal crops, Linquist et al. (2012a) determined that the lowest yield-scaled emissions from rice were very close to maximum yield.

There is limited data linking seasonal and annual GHG emissions with yield for water-seeded rice systems in California, particularly for N_2O emissions for which no published estimates are available. In the present study, we assessed the relationship between CH_4, N_2O, and rice yield in response to incremental increases in N rate to test the hypothesis that yield-scaled GWP will be minimized at N rates that produce optimal yields. In a two-year on-farm experiment, the specific objectives were to (i) quantify seasonal and annual CH_4 and N_2O emissions, (ii) determine optimal yields in response to N rate, and (iii) evaluate total GWP on an area and yield-scaled basis.

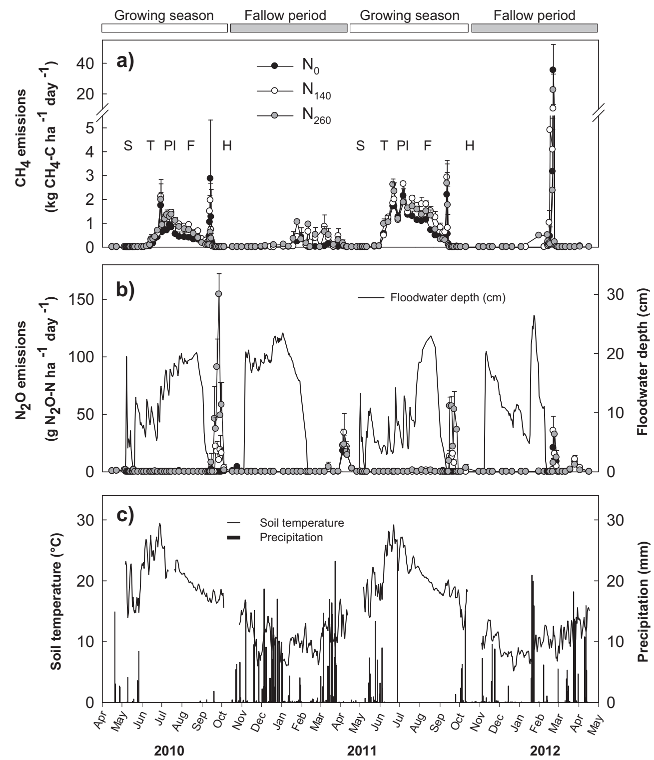

Fig. 1. (a) CH_4 and (b) N_2O emissions with corresponding floodwater depth, and (c) soil temperature (5 cm depth) and precipitation over two annual rice cropping cycles. Note the break in the *y*-axis of panel (a). Dates of rice seeding, tillering, panicle initiation, flowering, and harvest for each growing season are indicated by S, T, PI, F, and H, respectively. Error bars represent the standard error of three replicates. For clarity only the low (N_0), middle (N_{140}), and high (N_{260}) N rates are displayed.

2. Materials and methods

2.1. Site description and experimental design

A two-year experiment was conducted from 2010 to 2012 in a commercial water-seeded rice field approximately 50 ha in size near Arbuckle, CA (39°0′48″ N, 121°55′43″ W). Soils at this site are classified as the Clear Lake Clay series (Fine, smectitic, thermic Xeric Endoaquerts). Selected soil characteristics for the 0–15 cm depth include: 6.2 pH, 50.4 $cmol_c$ kg^{-1} CEC, 1.75% organic C, 0.14% total N, 0.45 dS m^{-1} EC, 7.1 mg kg^{-1} Olson P, 217 mg kg^{-1} extractable K, 9% sand, 35% silt, and 57% clay. Annual precipitation during the experiment followed typical patterns for a Mediterranean climate with an average of 368 mm of rainfall occurring primarily outside the growing season (Fig. 1c) and average air temperatures of 20.6 and 10.0 °C during the growing season and fallow periods, respectively.

The field trial was arranged as a randomized complete block design with three replications. Crop management events are listed in Table 1. Spring tillage consisted of several passes with a chisel-plow and disk, followed by final seedbed preparation with a triplane and roller. Five fertilizer N treatments (0, 80, 140, 200, and 260 kg N ha^{-1}) were applied to plots of 6 by 9.14 m in size the