Agriculture, Ecosystems and Environment 177 (2013) 10–20

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

Cameron M. Pittelkow*, Maria A. Adviento-Borbe, James E. Hill, Johan Six, Chris van Kessel, Bruce A. Linquist

Department of Plant Sciences, University of California, Davis One Shields Avenue, Davis, CA 95616, USA

ARTICLE INFO

Article history:
Received 10 October 2012
Received in revised form 1 May 2013
Accepted 11 May 2013
Available online 28 June 2013

Keywords:
Annual GHG emissions
Rice
CH_4
N_2O
Fertilizer nitrogen
Yield-scaled global warming potential
Greenhouse gas intensity

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.

* Corresponding author. Tel.: +1 530 752 3457; fax: +1 530 752 4361.
E-mail address: cpittelkow@ucdavis.edu (C.M. Pittelkow).

0167-8809/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agee.2013.05.011

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.

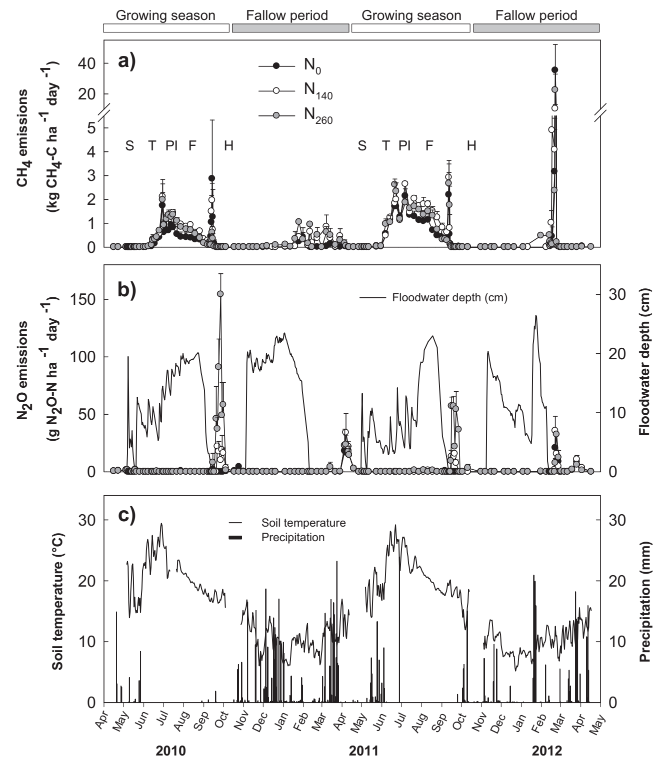

Fig. 1. (a) CH_4 and (b) N_2O emissions with corresponding floodwater depth, and (c) soil temperature (5 cm depth) and precipitation over two annual rice cropping cycles. Note the break in the *y*-axis of panel (a). Dates of rice seeding, tillering, panicle initiation, flowering, and harvest for each 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

Table 1
The annual sequence of crop management events for the water-seeded rice field observed in this study. A continuous flood was maintained during the growing season, straw was incorporated following harvest, and the field was flooded during the fallow period. CH_4 and N_2O measurements covered two complete annual (growing season plus fallow period) rice production cycles.

Management practice	2010–2011	2011–2012
Spring tillage initiated	April 27, 2010	April 14, 2011
N fertilizer application	May 6, 2010	April 29, 2011
Field flooded for planting	May 7, 2010	May 1, 2011
Seeding	May 9, 2010	May 2, 2011
Field drained prior to harvest	September 12, 2010	September 12, 2011
Harvest	October 4, 2010	October 12, 2011
Straw incorporation	October 14, 2010	October 25, 2011
Field flooded for fallow period	November 5, 2010	November 9, 2011
Field drained in spring	February 9, 2011	February 12, 2012

day prior to the permanent flood. Per conventional practice, N was applied as aqua ammonia injected 7–10 cm below the soil surface. The full N rate was applied as a single dose following recommended practices for this region (Linquist et al., 2009). Due to reduced soil conditions following flooding, aqua ammonia applied at the start of the growing season is protected from losses which results in higher yields and greater N recovery than when a portion of N is applied to the soil surface (Linquist et al., 2009). As typical fertilizer N rates are close to 168 kg N ha^{-1} in California rice systems (Williams, 2010), N treatments were selected to include deficit and surplus N rates. Although 260 kg N ha^{-1} is well above common N rates for this region, this treatment was included to examine the response of N_2O emissions to N rates beyond that required to achieve maximum yield. To ensure that other nutrients were not limiting, 46 kg K and 24 kg P ha^{-1} were applied to the soil surface as potassium sulfate and triple super phosphate, respectively, on the same day as fertilizer N application. To avoid the residual effects of fertilizer N over time (Reddy and Patrick, 1978), the experiment was moved to a new location within the same field in the second cropping cycle.

After fertilization and flooding, pre-germinated rice seeds (variety M-206) were aerially sown at a rate of 224 kg ha^{-1}. Fertilizer N application dates were May 6, 2010 and April 29, 2011 and planting dates were May 9, 2010 and May 2, 2011. Plots were briefly drained for several days during the seedling stage to promote root development (Fig. 1b). Water management during the growing season followed typical water-seeded irrigation practices for the region, where a permanent flood of 5–20 cm was maintained until the field was drained approximately one month prior to harvest. Weeds and pests were controlled as needed following recommended practices for the region (Fischer and Hill, 2004). After harvest, straw residue was chopped into 10–15 cm lengths and incorporated into the top 15 cm to simulate tillage. The field was then flooded from approximately early November to the middle of February each fallow period (Table 1). Flooding during the fallow season is a common practice in the region, primarily due to legislation limiting rice straw burning (Fitzgerald et al., 2000; Linquist et al., 2006). Rice fields are often flooded following straw incorporation to aid straw decomposition, as well as provide waterfowl habitat for migratory bird populations during the fallow period (Hill et al., 2006; Linquist et al., 2006).

2.2. CH_4 and N_2O measurements

Gas sampling was conducted using the vented, closed chamber method with precautions taken at each stage of the chamber design/deployment, gas sampling, and gas analysis process to improve the reliability and accuracy of data (Parkin and Venterea, 2010; Rochette and Eriksen-Hamel, 2008). Chambers consisted of a base inserted into the soil, a chamber extension to accommodate rice plants, and an air-tight chamber lid. Chambers were 30 cm in diameter and constructed from opaque PVC. Each spring, prior to planting and N application, gas fluxes between tillage events were measured using one chamber per block inserted to a depth of 7.5 cm. Bases were inserted immediately after tillage and allowed to equilibrate for a minimum of 24 h before sampling. During each growing season and fallow period, chamber bases were inserted to a depth of 15 cm immediately following N application and straw incorporation, respectively, and remained in place throughout the full measurement period. One base per plot was used in 2010–2011 and two bases per plot in 2011–2012 (sampling alternated between bases in the second year). Wooden boardwalks were installed in the rice field prior to all flooded periods to prevent soil disturbance while sampling. During each gas sampling event, chambers were closed for 60 min with three (0, 30, 60 min) or four gas samples (0, 21, 42, and 63) being obtained at regular intervals during the first and second annual cropping cycle, respectively. Chamber lids were covered with a reflective insulation and equipped with (i) vent tubes that varied in size according to Hutchinson and Mosier (1981), (ii) battery operated fans to ensure sufficient mixing of headspace air, (iii) thermocouple wires to measure air temperatures, and (iv) gas sampling ports. Headspace gas samples were obtained with air-tight 30 mL propylene syringes and were immediately pressurized into pre-evacuated 12 mL glass Exetainer® vials (Labco Ltd., Buckinghamshire, UK). A layer of silicone was applied to septa during vial preparation to create a double barrier and prevent contamination with ambient air.

Gas fluxes were measured during all phases of the annual cropping cycle which included preseason tillage and land preparation, crop establishment through harvest, and the winter fallow period until tillage the following spring. During event-related transition periods (i.e. following N application and the permanent flood as well as the drain prior to harvest and the spring drain following the flooded fallow period), intensive measurements were conducted every 1–3 days to capture the temporal variability of N_2O and CH_4 fluxes. During flooded periods characterized by more stable soil conditions, the frequency of flux measurements was generally every 7 days which has been determined to be an accurate approach for estimating seasonal CH_4 emissions from rice systems (Minamikawa et al., 2012). This corresponded to a total of 79 and 66 sampling events for the first and second annual cropping cycles, respectively. Gas sampling occurred midday (11:00–15:00 h) when soil temperatures were expected to represent average daily values (Bossio et al., 1999).

Concentrations of CH_4 and N_2O were analyzed using a GC-2014 gas chromatograph (Shimadzu Scientific, Inst, Columbia, MD) with a ^{63}Ni electron capture detector (ECD) for N_2O and flame ionization detector (FID) for CH_4. The GC detection limits were 0.3 pg s^{-1} for N_2O and 2.2 pg s^{-1} for CH_4. Gas samples were analyzed within two weeks of collection. Chamber gas concentrations were converted to mass per volume units (g N_2O or CH_4 L^{-1}) using the Ideal Gas Law and measured chamber air temperatures and volumes. Fluxes of N_2O and CH_4 were calculated using linear regression of gas concentration versus chamber closure time and the enclosed soil surface area (6.8×10^{-6} ha). Fluxes were set to zero if the change in gas concentration during chamber enclosure fell below the minimum flux detection limit determined for the GC, and flux values were rejected (i.e. treated as missing data) if they passed the flux detection test but had a $r^2 < 0.90$. In a few circumstances during the spring drain of 2012, where large CH_4 fluxes occurred within relatively small chamber volumes and the possibility of headspace saturation was observed, regression was performed on the linear portion only using the first three data points.

2.3. Soil and plant measurements

Field floodwater levels were monitored hourly during the experiment with two water depth sensors (Global Water Instrumentation, Inc., Riverside, CA) positioned between blocks which were averaged and reported as daily averages. Soil temperature was measured hourly using two Hobo temperature probes and data loggers (Onset Applications, Bourne, MA) installed at 5 cm and reported as daily averages. Precipitation data was averaged from California Irrigation Management Information System weather stations in Colusa and Nicolaus located 26 and 36 km, respectively, from the study site (California Department of Water Resources, Sacramento, CA).

To determine soil inorganic N contents and dissolved organic C (DOC) concentrations during the growing season, soil samples were obtained from plots without fertilizer N addition (N_0) and plots receiving 140 kg N ha^{-1} (N_{140}). Due to limited resources, only these treatments were evaluated (with N_0 representing indigenous soil N dynamics and N_{140} representing a typical aqua ammonia rate for this region), thereby providing insights into the effects of N addition under recommended N management practices for this region on soil processes contributing to N_2O and CH_4 emissions. It is acknowledged that the data are incomplete due to limited resources and therefore a complete analysis of these soil variables across N rates is not possible. Nonetheless, as there is relatively little information in the literature quantifying soil N and DOC transformations with respect to N_2O and CH_4 emissions from rice, presentation of these results likely holds value and may potentially inform future research activities. At 1–2 week intervals, four soil cores 3.5 cm in diameter and 15 cm in depth were composited for each plot. Immediately after sampling, soils were extracted in duplicate with 0.5 M K_2SO_4 (soil:solution ratio of 1:10) and analyzed for NO_3-N (Doane and Horwath, 2003) and NH_4-N (Verdouw et al., 1978; Forster, 1995). Soil bulk density measurements (0–15 cm depth) were made prior to the growing season and during flooded periods. Soil DOC concentrations of K_2SO_4 extracts were determined on a Shimadzu TOC-V_{CSH} analyzer (Shimadzu Corp., Kyoto, Japan) (first cropping cycle), or a UV persulfate TOC analyzer (Phoenix 8000, Tekmar Dohrmann, Cincinnati, Ohio) (second cropping cycle).

Dissolved CH_4 in the soil solution was measured in N_0, N_{140}, and N_{260} plots using Rhizon soil samplers (Rhizosphere Research Products, The Netherlands) following Lu et al. (2000) and Alberto et al. (2000). Rhizon samplers (10-cm long porous microfiltration membranes 2.8 mm in diameter) were inserted diagonally into the soil between rice plants to a depth of 5–10 cm at the booting stage. During sampling, the dead volume was discarded and approximately 5 mL of soil solution was collected for analysis. Samples were shaken for 1 min and headspace gas was collected and analyzed on a GC as described in Section 2.2. Calculation of dissolved CH_4 concentrations followed equations provided by Alberto et al. (2000).

At physiological maturity, aboveground rice biomass was harvested (1 m^2), dried to a constant weight at 65 °C, and separated into grain and straw fractions to determine grain yields. Harvest occurred on October 4 and October 12 for the first and second cropping cycle, respectively. All grain yield results represent rough rice yields adjusted to 14% grain moisture content.

2.4. Data analysis

Analysis of variance was performed on cumulative CH_4, N_2O, GWP, grain yield, and yield-scaled GWP results using PROC MIXED in SAS® version 9.1 (SAS Institute Inc., 2004). For each model, N rate was designated as a fixed effect and block, year (where appropriate), and associated interactions were designated as random effects. Analysis of variance was performed across years unless significant year by treatment interactions were detected. If results violated ANOVA assumptions (homogeneity of variance and normality) they were transformed accordingly using $\log_{10}$ or power functions. Significant differences between N rates were determined using LS MEANS pairwise comparisons ($P < 0.05$). A repeated measures ANOVA was performed on soil DOC and dissolved CH_4 concentrations.

Estimates of cumulative CH_4 and N_2O emissions for each plot were based on linear interpolation, with the sum of cumulative growing season and fallow period emissions representing one annual cropping cycle. The growing season amounted to 174 and 183 days and the fallow season to 190 and 190 days in the first and second annual cropping cycles, respectively. The growing season covered the period from the start of spring tillage through harvest each year (i.e., spring tillage events, fertilizer N application, flooding, rice seeding, fall drainage prior to harvest, and harvest). The fallow period covered the period from harvest to the start of tillage the following spring (i.e. straw incorporation, winter flooding, spring drainage, and field dry down prior to tillage). Hereafter, 'seasonal' strictly refers to cumulative emissions for the growing season and 'annual' refers to cumulative emissions for the growing season plus the following fallow period. The term 'mean' is used to indicate the average of two annual cropping cycles within a single N rate (not the average value across N rates). Total GWP was calculated as CO_2 equivalents (CO_2 eq) over a 100-year time horizon using a radiative forcing potential of 298 for N_2O and 25 for CH_4 relative to CO_2 (Houghton et al., 2001).

3. Results

3.1. Seasonal and annual patterns of CH_4 and N_2O emissions

Each growing season (roughly May–October) was characterized by cool soil temperatures and several precipitation events during early crop establishment, but high solar radiation and limited precipitation thereafter until harvest (Fig. 1c). The majority of precipitation occurred during fallow periods (roughly November–April), when air and soil temperatures were much lower. In both years, CH_4 emissions began to occur within 3–4 weeks after seeding and increased rapidly through the tillering growth stage of rice (Fig. 1a). Emissions were highest from maximum tillering through panicle initiation, after which emissions declined until field drainage. A large peak in CH_4 emissions lasting 2–3 days was observed immediately after floodwater had drained in September 2010 and 2011. Although fields were flooded during the winter fallow period, CH_4 emissions remained relatively low during this time with the majority of fallow season emissions occurring after fields were drained in the spring, either through a period of moderate emissions (spring 2011) or a single peak (February 2012). On an annual basis and averaged across N rates, the growing season accounted for 78 and 76% of annual CH_4 emissions in the first and second cropping cycle, respectively (Table 2). Although the annual pattern of CH_4 emissions was relatively similar in both years, cumulative CH_4 emissions in the second cropping cycle were approximately twice those of the first cropping cycle.

The annual pattern of N_2O emissions was similar in both years, with low emissions (averaging 0.05 g N_2O-N ha^{-1} day^{-1} across all N rates) occurring when the field was flooded during the growing season and fallow period (Fig. 1b). However, distinct peaks in N_2O emissions were observed for 7–12 days following field drainage events, particularly in the fall as soil drying occurred prior to harvest. During the transition between the winter fallow period and planting each year, N_2O emissions were observed following the spring drain in 2012 but not in 2011. In contrast, as

Table 2
Cumulative CH_4 and N_2O emissions for each growing season, fallow period, and annual cropping cycle. Within each column and year, values followed by no letter or the same letter are not significantly different at $p<0.05$.

Year	N rate (kg ha^{-1})	Growing season		Fallow period		Annual	
		CH_4 (kg CH_4-C ha^{-1})	N_2O (g N_2O-N ha^{-1})	CH_4 (kg CH_4-C ha^{-1})	N_2O (g N_2O-N ha^{-1})	CH_4 (kg CH_4-C ha^{-1})	N_2O (g N_2O-N ha^{-1})
2010–2011	0	49	29 d	5 c	209	54 b	238 d
	80	88	65 c	10 bc	283	98 ab	349 cd
	140	80	223 b	34 a	300	113 a	523 bc
	200	82	374 b	26 ab	246	108 a	620 b
	260	69	1040 a	41 a	261	110 a	1301 a
2011–2012	0	113 b	77 d	63	201	176	277 b
	80	144 a	75 d	35	254	179	329 b
	140	156 a	173 c	44	233	200	407 b
	200	160 a	418 b	36	329	196	747 a
	260	139 ab	643 a	50	210	189	853 a
Mean	0	81 b	53 d	34 b	205	115 b	258 d
	80	116 a	70 d	22 ab	269	139 ab	339 d
	140	118 a	198 c	39 ab	267	156 a	465 cd
	200	121 a	396 b	31 ab	288	152 a	684 bc
	260	104 ab	842 a	46 a	235	150 ab	1077 a

the soil dried and soil temperatures increased leading up to tillage, elevated N_2O emissions occurred in 2011 but not 2012 (Fig. 1b).

3.2. N rate, CH_4 and N_2O emissions, and soil variables

The lowest cumulative CH_4 emissions occurred in N_0 during both growing seasons and the fallow period in the first cropping cycle (Table 2). Mean seasonal emissions for N_{80}, N_{140}, and N_{200} were on average 46% greater than N_0, while N_{260} was not significantly different from N_0. Average daily emissions for N_0, N_{140}, and N_{260} during the first and second growing seasons were 309, 414, and 333 g CH_4-C ha^{-1} d^{-1} and 618, 790, and 700 g CH_4-C ha^{-1} d^{-1}, respectively. During the fallow period, CH_4 increased with N rate during the first but not the second cropping cycle. Average daily emissions for N_0, N_{140}, and N_{260} during the first and second fallow periods were 29, 130, and 194 g CH_4-C ha^{-1} d^{-1} and 1617, 958, and 1274 g CH_4-C ha^{-1} d^{-1}, respectively. Mean annual CH_4 emissions were lowest at N_0 and highest at N_{140} and N_{200}.

There was a nonlinear response of cumulative N_2O emissions to N rate in both growing seasons, but N_2O emissions were similar across N rates during the fallow period (Table 2). Average daily emissions for N_0, N_{140}, and N_{260} during the first and second growing seasons were 0.15, 1.36, and 8.35 g N_2O-N ha^{-1} d^{-1} and 0.53, 1.37, and 6.47 g N_2O-N ha^{-1} d^{-1}, respectively. At low N rates (N_0, N_{80}), seasonal N_2O emissions accounted for an average of 15 and 25% of annual emissions during the first and second cropping cycle, respectively, while at higher N rates (N_{140}, N_{200}, N_{260}), seasonal emissions accounted for an average of 61 and 58% of annual emissions during the first and second cropping cycle, respectively (Table 2). On an annual basis, mean N_2O emissions for N_0, N_{80}, and N_{140} were similar, whereas N_{200} and N_{260} were 166 and 318% greater than N_0, respectively. Fertilizer-induced N_2O emission factors increased with N rate in both seasons, ranging from 0% (N_{80} in 2011) to 0.39% (N_{260} in 2010) (Fig. 2). As N_2O emissions were similar across N rates during fallow periods, there were no differences between seasonal and annual fertilizer-induced emission factors.

Soil DOC concentrations steadily increased during the growing season under flooded conditions each year, but decreased to pre-season values when fields were drained prior to harvest (Fig. 3a and b). Soil DOC tended to be higher for N_{140} than N_0 for much of the growing season in 2010, but when analyzed over the entire growing season there were no significant differences between treatments in 2010 or 2011. Soil NH_4-N contents were greater in N_{140} than N_0 following N application in both years as would be expected, but NH_4-N concentrations of the N_{140} treatment decreased rapidly during rice tillering in June and values remained low in both treatments for the remainder of the growing season (Fig. 3c and d). Soil NO_3-N was present prior to fertilizer addition and flooding for seeding both years, but decreased rapidly following flooding and remained very low throughout the flooded period (Fig. 3e and f). Nitrate contents were not affected by N rate.

Dissolved CH_4 concentrations were higher with fertilizer N addition (N_{140}, N_{260}) compared to N_0 during grain filling in 2011 (Fig. 4a). Across N rates, dissolved CH_4 values decreased rapidly after water had drained from the field starting on September 12. In contrast, CH_4 emissions steadily declined during grain filling in August and early September, with higher fluxes occurring in N_{140} compared to N_0 and N_{260} prior to the drain (Fig. 4b). However, when floodwater levels dropped to zero on September 12 and dissolved CH_4 concentrations decreased, a corresponding spike in methane flux was observed that was similar in magnitude across N rates.

3.3. GWP, yield, and yield-scaled GWP

Mean GWP during the growing season generally increased with N addition but was inconsistent during fallow periods (Table 3). The contribution of CH_4 to total GWP was always much greater than N_2O, averaging 96% across N rates during the growing season and 90% during the fallow period. Annually, there was a significant effect of N rate on mean GWP, with an average increase of 37% for N_{140}, N_{200}, and N_{260} as compared to N_0 (Table 3). In both years, there was a strong response of rice yield to N rate (Table 4). Mean yield increases of 4.3 and 7.4 Mg ha^{-1} were observed for N_{80} and N_{140}, but no further yield gains were achieved at N_{200} or N_{260} compared to N_{140}. Maximum yields occurred between N_{140} and N_{200}, while yields plateaued or decreased at N_{260}. Mean seasonal and annual yield-scaled GWP decreased as N rate increased (Table 4). Mean annual yield-scaled GWP estimates for N_{140}, N_{200}, and

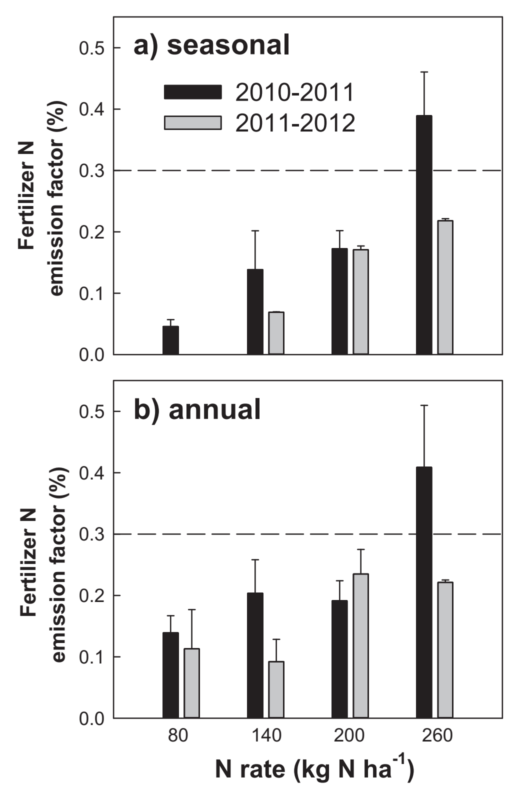

Fig. 2. Fertilizer N-induced N_2O emission factors calculated for (a) seasonal and (b) annual emissions. Error bars represent the standard error of three replicates. The direct N_2O emission factor adopted by the IPCC for rice systems is indicated with a dashed line at 0.3% (IPCC, 2006).

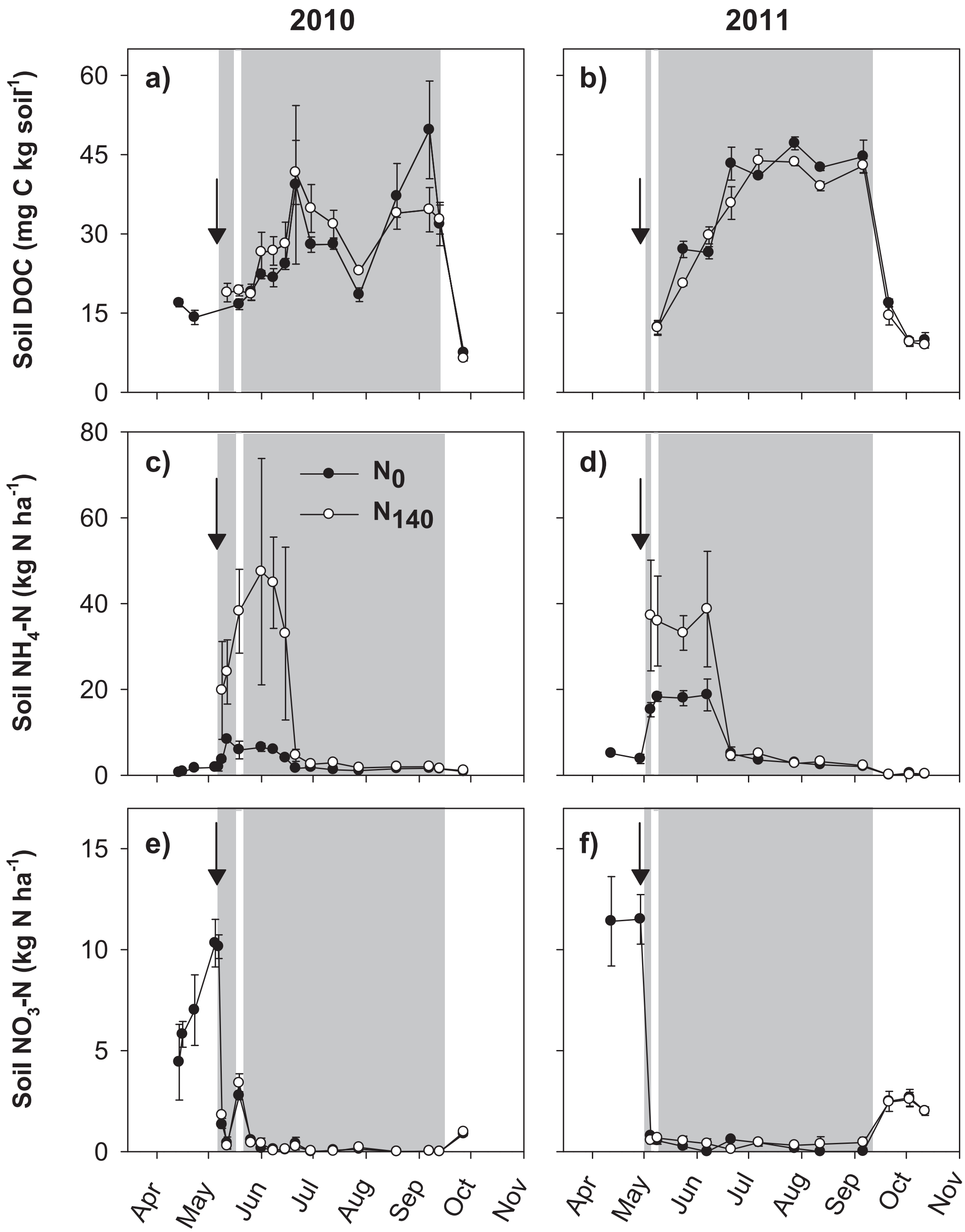

Fig. 3. Soil extractable (a, b) dissolved organic carbon (DOC) concentrations, (c, d) NH_4-N, and (e, f) NO_3-N contents during each rice growing season. Error bars represent the standard error of three replicates. Dates of fertilizer N application and soil submergence are indicated by black arrows and gray shaded areas, respectively.

N_{260} were significantly lower than N_0, with an average reduction of 49% occurring at N_{140} and N_{200} (Fig. 5).

4. Discussion

4.1. Seasonal and annual patterns of CH_4 and N_2O emissions

Few studies have quantified GHG emissions from rice systems on an annual as opposed to seasonal basis, yet our findings indicate that it is important to monitor emissions year-round where possible. For instance, the contribution of each fallow period to annual CH_4 emissions ranged from 10 to 38% across N rates. Therefore, reports based on seasonal emissions may underestimate annual totals when fields are flooded during the fallow period. In a previous study in this region, approximately 55% of annual CH_4 emissions occurred during the fallow period (Fitzgerald et al., 2000). Our range is more similar to that reported by Xu and Hosen (2010) for various rates of straw incorporation (5–35%), and the value of 40% determined by McMillan et al. (2007). When considering N_2O emissions, it is noteworthy that the fallow period was often an equally important source of N_2O as the growing season, with it representing 20–88% of annual N_2O emissions. Previous studies have

Table 3
Estimated global warming potential (GWP) based on CO_2 equivalents of CH_4 and N_2O emissions during each growing season, fallow period, and annual cropping cycle. Within each column and year, values followed by no letter or the same letter are not significantly different at $p < 0.05$.

Year	N rate (kg ha^{-1})	GWP (kg CO_2 eq ha^{-1})		
		Growing season	Fallow period	Annual
2010–2011	0	1655	274 c	1929 b
	80	2985	462 bc	3447 a
	140	2760	1259 a	4020 a
	200	2926	981 ab	3907 a
	260	2788	1505 a	4293 a
2011–2012	0	3804 b	2196	6001
	80	4845 a	1286	6131
	140	5289 a	1565	6854
	200	5537 a	1346	6883
	260	4942 a	1778	6720
Mean	0	2729 b	1235	3965 b
	80	3915 a	874	4789 ab
	140	4025 a	1412	5437 a
	200	4231 a	1164	5395 a
	260	3865 a	1641	5507 a

measured N_2O emissions during the fallow period or under crop rotations such as wheat and have also reported that more than 50% of annual N_2O emissions typically occur outside the rice growing season (Liang et al., 2007; Xiong et al., 2002; Yao et al., 2010; Zhao et al., 2011). Perhaps most importantly, in addition to potentially underestimating the GWP of rice systems, our results illustrate that differences between treatments within a growing season do not always translate to differences on an annual basis (Table 2). These results emphasize that a full accounting of GHG emissions is needed, particularly for rice growing areas such as California where climate change policies are beginning to support the development of carbon offset markets in which rice growers can be compensated to adopt GHG mitigation practices (Climate Action Reserve, 2011).

Seasonal CH_4 emissions ranged from 69 to 160 kg CH_4-C ha^{-1} with N addition, which is in agreement with previous work conducted in California water-seeded rice systems (Bossio et al., 1999; Fitzgerald et al., 2000; McMillan et al., 2007). However, annual emissions during the second cropping cycle were approximately twice that of the first (Table 2). Large interannual CH_4 variations at the same site are common, even when crop management and climate are reasonably similar year to year (Corton et al., 2000; Itoh et al., 2011; Sass et al., 2002). Annual differences in our study may be attributed to water management practices during the fallow period (Cai et al., 2003), as the field was not flooded the winter prior to the first growing season but was flooded during subsequent fallow periods. Flooding during the fallow period can enhance emissions during the following rice growing season, primarily due to soils remaining in a reduced condition which promotes early and rapid methanogenesis (Yan et al., 2005; Xu and Hosen, 2010). Consequently, annual CH_4 emissions can be 1.8–2.3 times greater (Zhang et al., 2011). Overall, interannual variations in N_2O emissions were small relative to CH_4, except for N_{260} where emissions during the fall drainage period were greater in 2010 than 2011 (Fig. 1b). This might be attributed to differences in soil moisture or available N, as soil temperatures during this period of each year were similar (Fig. 1c).

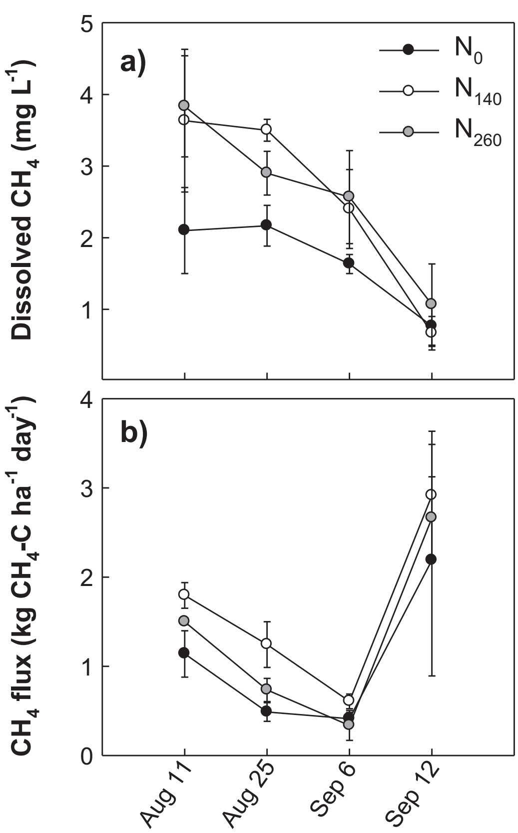

Fig. 4. Dissolved (a) soil CH_4 concentrations and corresponding (b) CH_4 flux during grain filling in 2011. The first day of field drainage prior to harvest was September 12 when no standing floodwater remained on the field. Error bars represent the standard error of three replicates.

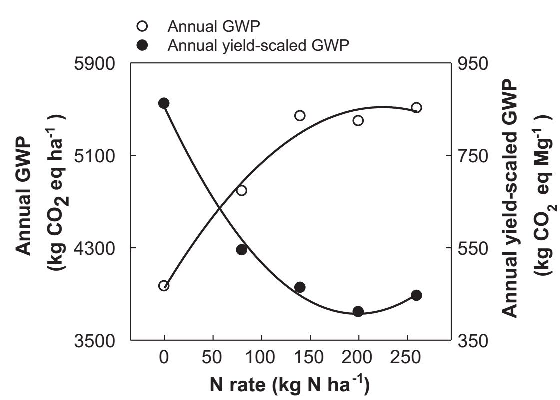

Fig. 5. Two-year mean annual global warming potential (GWP) of CH_4 and N_2O emissions and annual yield-scaled GWP in response to N rate. Maximum yields were obtained between 140 and 200 kg N ha^{-1}. Mean separation groupings for annual GWP and yield-scaled GWP values are indicated in Tables 3 and 4, respectively.

Table 4
Rice grain yield and yield-scaled global warming potential (GWP) calculated on a seasonal and annual basis. Within each column and year, values followed by no letter or the same letter are not significantly different at $p < 0.05$.

Year	N rate (kg ha^{-1})	Yield (Mg ha^{-1})	Seasonal yield-scaled GWP (kg CO_2 eq Mg^{-1})	Annual yield-scaled GWP (kg CO_2 eq Mg^{-1})
2010–2011	0	4.3 c	368	433
	80	8.5 b	362	416
	140	12.0 a	230	336
	200	13.1 a	222	298
	260	13.1 a	214	326
2011–2012	0	4.7 c	812 a	1289 b
	80	9.1 b	533 b	672 a
	140	11.7 a	458 bc	590 a
	200	13.1 a	423 c	522 a
	260	12.0 a	418 c	564 a
Mean	0	4.5 c	590 a	861 a
	80	8.8 b	447 ab	544 ab
	140	11.9 a	344 ab	463 b
	200	13.1 a	323 bc	410 b
	260	12.5 a	316 bc	445 b

Considering that maximum CH_4 and N_2O fluxes occurred during event-related peaks, our findings highlight the need to better characterize the short-term temporal variability of GHG emissions in rice systems, particularly during discrete field drainage periods as has been found by others (Denier van der Gon et al., 1996; Liang et al., 2007). For example, individual fall and spring drainage events amounted to up to 40–60% and 16–24% of annual N_2O and CH_4 emissions, respectively, in N_{200} and N_{260}. Similarly, Zhao et al. (2011) reported that 24–42% of annual N_2O emissions from a rice-wheat rotation can occur during the period of field flooding before rice transplanting. Thus, capturing event-related emissions during transition periods will help ensure that accurate data are available to support scaling-up efforts and the development of regional and national GHG inventories.

4.2. *CH_4 emissions and N rate*

Our results for CH_4 emissions along an N gradient suggest that seasonal CH_4 emissions increase in response to N addition in continuously flooded water-seeded rice systems. Mean seasonal emissions for N_{80}, N_{140}, and N_{200} averaged 46% greater than N_0, although N_{260} was not significantly greater than N_0 (Table 2). Findings from two meta-analyses on this topic have shown that lower N rates tend to increase CH_4 emissions, yet high (or excessive) N rates can potentially inhibit CH_4 emissions (Banger et al., 2012; Linquist et al., 2012b). Despite a range of N rates considered in this study, we observed no significant differences in cumulative CH_4 emissions between N rates of 80–260 kg N ha^{-1} during the growing season or fallow period.

Considering that increased rice biomass following N fertilization can enhance soil C availability and thereby CH_4 production (Cai et al., 2007), it was surprising that soil extractable DOC concentrations did not differ between N_{140} and N_0 each growing season (Fig. 3a,b). This was despite a more than a doubling in rice biomass and cumulative differences in mean seasonal CH_4 emissions (Table 2). However, Lu et al. (2000) reported that soil DOC concentrations in the root zone were 3–6 times higher than the non-root zone, indicating that our measurements of bulk soil may not have been sensitive enough to detect differences in available C pools that can be rapidly converted to CH_4. During grain filing in the second growing season, dissolved soil CH_4 concentrations were higher in both N_{260} and N_{140} compared to N_0, yet corresponding CH_4 fluxes for N_{260} were on average 28% lower than N_{140} (Fig. 4a,b). Although not quantified in this study, it is possible that soil NH_4-N concentrations may have been greater in N_{260} compared to N_{140}, which has been shown to stimulate methanotrophic activity and CH_4 oxidation (Bodelier and Laanbroek, 2004; Noll et al., 2008). Of interest is that mean cumulative CH_4 emissions appeared to be more affected by fertilizer N addition during the growing season than the fallow period, even though at higher N rates straw inputs after harvest were much greater and C to N ratios were much smaller than lower N rates (C to N ratios ranged from 44 in N_{260} to 79 in N_{80}). While emissions increased with N rate during the first fallow period, the bulk of emissions in the second fallow period occurred as a single peak following field drainage which was similar in magnitude across N rates (Fig. 1a).

4.3. *N_2O emissions and N rate*

One strategy to limit agricultural N_2O emissions is to synchronize fertilizer N rate with crop N demand, reducing available soil N for microbial N_2O production (Ma et al., 2010; Snyder et al., 2009). Consistent with this theory, a nonlinear response of N_2O emissions to N rate has been observed, with low N_2O fluxes occurring at N rates which are below or match crop N uptake and high N_2O fluxes occurring at fertilizer N rates that exceed crop N demand (Hoben et al., 2011; Kim et al., 2013; McSwiney and Robertson, 2005). Our results demonstrate a clear nonlinear response of N_2O emissions to N rate during the rice growing season (Table 2). While mean seasonal N_2O emissions increased from N_{80} to N_{140}, this also corresponded to significant yield increases. Importantly, the greatest increases in N_2O emissions were observed at fertilizer N rates beyond that required to meet maximum yield (i.e. above N_{140}). These results are in agreement with previous findings and indicate that maximum crop productivity can be achieved with reductions in N_2O emissions when excessive N rates are avoided (Snyder et al., 2009; Van Groenigen et al., 2010).

While CH_4 emissions have been investigated in California rice systems (Bossio et al., 1999; Fitzgerald et al., 2000; Lauren et al., 1994; McMillan et al., 2007), no published data is available for N_2O emissions. In our study, 312 g N ha^{-1} was emitted during the rice growing season on average, which is slightly lower than what has been reported earlier for seasonal N_2O emissions from continuously flooded rice, i.e., 341 g ha^{-1} (Akiyama et al., 2005). Cumulative emissions are generally low for continuously flooded fields because of anaerobic soil conditions, where nitrification is limited to the rhizosphere and denitrification processes typically reduce N_2O to N_2 (Philippot et al., 2009). Of interest is that N_2O emissions did not occur as long as the soil was fully saturated or there was floodwater present, even when the field was drained immediately following seeding and fertilizer N application in early May of each year (Fig. 1b). This is in contrast to previous work where considerable N_2O emissions occurred through the floodwater (Zhao et al., 2011).

Although N_2O fluxes were shown to increase with N rate when peaks occurred at the end of the growing season, N_2O emissions for N rates < 200 kg N ha^{-1} were likely limited by low soil N availability resulting from rapid fertilizer N uptake and high fertilizer N recovery that is typical in California rice fields (Linquist et al., 2009). For instance, soil NH_4-N and NO_3-N contents for N_{140} remained low during drainage prior to harvest despite this being the period of highest N_2O fluxes each season (Fig. 3c-f). In addition, because the field was flooded for approximately eight months of each year (Xing et al., 2002), annual emissions tended to either be similar (Liang et al., 2007; Xing et al., 2009) or much lower than previous reports (Akiyama et al., 2005; Yao et al., 2010). Interestingly, while N rate had a strong effect on N_2O emission during the growing season, there was no carryover effect of N rate observed during the fallow period. As discussed above, while fallow period N_2O emissions can represent a large proportion of annual emissions, these results suggest that it may not be as critical to account for the effects of N rate during the fallow period in water-seeded rice systems experiencing continuously flooded conditions during the growing season and fallow period.

4.4. GWP, yield, and yield-scaled GWP

When CH_4 and N_2O emissions were expressed as CO_2 equivalents, the major contributor to GWP both during the growing season and fallow period was clearly CH_4 which represented 94% of total GWP across years (Tables 2 and 3). Accordingly, efforts to reduce GWP should focus primarily on CH_4 instead of N_2O in water-seeded rice systems experiencing continuously flooded conditions during the growing season and fallow period. This conclusion is supported by numerous studies on rice production systems differing in fertilizer and water management practices, even though CH_4 mitigation practices can contribute to large increases in N_2O emissions (Yu et al., 2004; Zou et al., 2005). In our study mean seasonal GWP averaged 3753 kg CO_2 eq ha^{-1} across N rates, which is similar to the average of 3757 kg CO_2 eq ha^{-1} determined for rice in a meta-analysis by Linquist et al. (2012a). Consistent with findings of Shang et al. (2011), we observed that mean seasonal and annual GWP increased with N addition compared to the control (Table 3; Fig. 5), with optimal N rates of N_{140} and N_{200} increasing annual GWP by 37% on average. These results suggest that management practices other than N addition should be considered when pursuing GWP mitigation options for water-seeded rice on an area basis.

California rice yields are among the highest in the world and the yield response to fertilizer N can be substantial (Linquist et al., 2009). In our experiment, yields ranged from 4.3 to 13.1 Mg ha^{-1}, which translated to roughly a 40% reduction in mean seasonal yield-scaled GWP across N rates (404 kg CO_2 eq Mg^{-1} instead of 657 kg CO_2 eq Mg^{-1}). The yield-scaled metric is increasingly used to provide a measure of agronomic efficiency that begins to address both climate change and future food supply concerns (Grassini and Cassman, 2012). To our knowledge, these are the first records of GWP and yield-scaled GWP for water-seeded rice systems. Consistent with our hypothesis, these results suggest that optimal N rates can produce maximum yields while reducing annual yield-scaled GWP by 46–52% (Fig. 5). In line with this work, it has been shown using large on-farm datasets that high grain and net energy yields can be achieved with minimal yield-scaled GWP through improved management of inputs, such as fertilizer N, in intensive cereal production systems (Grassini and Cassman, 2012).

5. Conclusions

We quantified the relationship between CH_4, N_2O, and grain yield in response to incremental increases in aqua ammonia N rate in water-seeded rice systems experiencing continuously flooded conditions during the growing season and fallow period. We observed a nonlinear response of seasonal N_2O emissions to N rate and also an increase in mean seasonal CH_4 emissions with fertilizer N addition compared to the control (except at 260 kg N ha^{-1}). While mean annual GWP increased with N rate up to 140 kg N ha^{-1}, a different picture emerged when crop productivity was also considered using the yield-scaled metric. Consistent with our hypothesis, maximum yields were achieved between 140 and 200 kg N ha^{-1}, while mean seasonal and annual yield-scaled GWP decreased by 43–49% at these N rates. Our results suggest that sampling year-round and specifically capturing CH_4 and N_2O fluxes during field drainage periods are critical, as these events contributed substantially to total annual emissions. Since CH_4 was the major contributor to GWP, future work is needed to assess CH_4 mitigation practices that do not compromise yields of water-seeded rice. This might include maintaining non-flooded conditions during the fallow period or reducing C inputs. These results are among the first to report GWP and yield-scaled GWP for rice systems on a seasonal and annual basis and underscore the importance of efficient N management practices to simultaneously achieve high yields with reduced environmental impacts per unit yield.

Acknowledgements

We thank our cooperating rice grower, George Tibbitts, for generously providing support and assistance with all field operations and crop management. We are grateful for the invaluable help provided by Cesar Abrenilla, Chris Mikita, and Timothy Doane in laboratory and field work. The California Rice Research Board and Mars, Inc. provided financial support for this project. We thank the Department of Plant Sciences, UC Davis for supporting C.M. Pittelkow with a graduate student research assistantship. The following persons provided much appreciated assistance: E. Cassiolato, G. Padilla, G. Amalfi, M. Haug, K. Vu, M.C. Andrea, M. Simmonds, M. Lundy, R. Pedroso, T. Shapland, and E. Kirk.

References

Akiyama, H., Yagi, K., Yan, X., 2005. Direct N_2O emissions from rice paddy fields: summary of available data. Global Biogeochem. Cyc. 19, GB1005.

Alberto, M.C.R., Arah, J.R.M., Neue, H.U., Wassmann, R., Lantin, R.S., Aduna, J.B., Bronson, K.F., 2000. A sampling technique for the determination of dissolved methane in soil solution. Chemosphere 2, 57–63.

Banger, K., Tian, H., Lu, C., 2012. Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields? Global Change Biol. 18, 3259–3267.

Becker, M., Asch, F., Maskey, S.L., Pande, K.R., Shah, S.C., Shrestha, S., 2007. Effects of transition season management on soil N dynamics and system N balances in rice–wheat rotations of Nepal. Field Crops Res. 103, 98–108.

Bodelier, P.L., Laanbroek, H.J., 2004. Nitrogen as a regulatory factor of methane oxidation in soils and sediments. FEMS Microbiol. Ecol. 47, 265–277.

Bossio, D.A., Horwath, W.R., Mutters, R.G., Van Kessel, C., 1999. Methane pool and flux dynamics in a rice field following straw incorporation. Soil Biol. Biochem. 31, 1313–1322.

Burney, J.A., Davis, S.J., Lobell, D.B., 2010. Greenhouse gas mitigation by agricultural intensification. Proc. Nat. Acad. Sci. U. S. A. 107, 12052–12057.

Cai, Z., Xing, G., Yan, X., Xu, H., Tsuruta, H., Yagi, K., Minami, K., 1997. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. Plant Soil 196, 7–14.

Cai, Z., Tsuruta, H., Gao, M., Xu, H., Wei, C., 2003. Options for mitigating methane emission from a permanently flooded rice field. Global Change Biol. 9, 37–45.

Cai, Z., Shan, Y., Xu, H., 2007. Effects of nitrogen fertilization on CH_4 emissions from rice fields. Soil Sci. Plant Nutr 53, 353–361.

Climate Action Reserve, 2011. Rice Cultivation Project Protocol. Climate Action Reserve, Los Angeles, CA, Available at: http://www.climateactionreserve.org/how/protocols/rice-cultivation/ [accessed 28.01.12].

Conrad, R., 2002. Control of microbial methane production in wetland rice fields. Nutr. Cycl. Agroecosyst. 64, 59–69.

Corton, T.M., Bajita, J.B., Grospe, F.S., Pamplona, R.R., Asis@@Jr., C.A., Wassmann, R., Lantin, R.S., Buendia, L.V., 2000. Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). Nutr. Cycl. Agroecosyst. 58, 37–53.

Denier van der Gon, H.A.C., van Breemen, N., Neue, H.U., Lantin, R.S., Aduna, J.B., Alberto, M.C.K., Wassmann, R., 1996. Release of entrapped methane from wetland rice fields upon soil drying. Global Biogeochem. Cyc. 10, 1–7.

Doane, T.A., Horwath, W.R., 2003. Spectrophotometric determination of nitrate with a single reagent. Anal. Lett. 36, 2713–2722.

Fischer, A.J., Hill, J.E., 2004. Weed control programs. In: University of California Cooperative Extension and California Rice Research Board (Ed.), Rice Production Workshop. University of California, Division of Agriculture and Natural Resources, Oakland, CA, pp. 9.1–9.10.

Fitzgerald, G.J., Scow, K.M., Hill, J.E., 2000. Fallow season straw and water management effects on methane emissions in California rice. Global Biogeochem. Cyc. 14, 767–776.

Forster, J.C., 1995. Soil nitrogen. In: Alef, K., Nannipieri, P. (Eds.), Methods in Applied Soil Microbiology and Biochemistry. Academic Press, San Diego, CA, USA, pp. 79–87.

Grassini, P., Cassman, K.G., 2012. High-yield maize with large net energy yield and small global warming intensity. Proc. Nat. Acad. Sci. U.S.A. 109, 1074–1079.

Hill, J.E., Williams, J.F., Mutters, R.G., Greer, C.A., 2006. The California rice cropping system: agronomic and natural resource issues for long-term sustainability. Paddy Water Environ. 4, 13–19.

Hoben, J.P., Gehl, R.J., Millar, N., Grace, P.R., Robertson, G.P., 2011. Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. Global Change Biol. 17, 1140–1152.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, 881 pp.

Hutchinson, G.L., Mosier, A.R., 1981. Improved soil cover method for field measurements of nitrous oxide fluxes. Soil Sci. Soc. Am. J. 45, 311–316.

IPCC, 2006. Agriculture, forestry and other land use. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies, Hayama, Japan, 66 pp.

Itoh, M., Sudo, S., Mori, S., Saito, H., Yoshida, T., Shiratori, Y., Suga, S., Yoshikawa, N., Suzue, Y., Mizukami, H., Mochida, T., Yagi, K., 2011. Mitigation of methane emissions from paddy fields by prolonging midseason drainage. Agric. Ecosyst. Environ. 141, 359–372.

Johnson-Beebout, S.E., Angeles, O.R., Alberto, M.C.R., Buresh, R.J., 2009. Simultaneous minimization of nitrous oxide and methane emission from rice paddy soils is improbable due to redox potential changes with depth in a greenhouse experiment without plants. Geoderma 149, 45–53.

Kim, D.G., Hernandez-Ramirez, G., Giltrap, D., 2013. Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: a meta-analysis. Agric. Ecosyst. Environ. 168, 53–65.

Kreye, C., Dittert, K., Zheng, X., Zhang, X., Lin, S., Tao, H., Sattelmacher, B., 2007. Fluxes of methane and nitrous oxide in water-saving rice production in north China. Nutr. Cycl. Agroecosyst. 77, 293–304.

Lauren, J.G., Pettygrove, G.S., Duxbury, J.M., 1994. Methane emissions associated with a green manure amendment to flooded rice in California. Biogeochemistry 24, 53–65.

Le Mer, J., Roger, P., 2001. Production, oxidation, emission and consumption of methane by soils: a review. Eur. J. Soil Biol. 37, 25–50.

Liang, W., Shi, Y., Zhang, H., Yue, J., Huang, G.H., 2007. Greenhouse gas emissions from northeast China rice fields in fallow season. Pedosphere 17, 630–638.

Lindau, C.W., Bollich, P.K., DeLaune, R.D., Patrick@@Jr., W.H., Law, V.J., 1991. Effect of urea fertilizer and environmental factors on CH_4 emissions from a Louisiana USA rice field. Plant Soil 136, 195–203.

Linquist, B.A., Brouder, S.M., Hill, J.E., 2006. Winter straw and water management effects on soil nitrogen dynamics in California rice systems. Agron. J. 98, 1050–1059.

Linquist, B.A., Hill, J.E., Mutters, R.G., Greer, C.A., Hartley, C., Ruark, M.D., Van Kessel, C., 2009. Assessing the necessity of surface-applied preplant nitrogen fertilizer in rice systems. Agron. J. 101, 906–915.

Linquist, B., Van Groenigen, K.J., Adviento-Borbe, M.A., Pittelkow, C., Van Kessel, C., 2012a. An agronomic assessment of greenhouse gas emissions from major cereal crops. Global Change Biol. 18, 194–209.

Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., Van Kessel, C., Van Groenigen, K.J., 2012b. Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. Field Crops Res. 135, 10–21.

Liu, S., Qin, Y., Zou, J., Liu, Q., 2010. Effects of water regime during rice-growing season on annual direct N_2O emission in a paddy rice–winter wheat rotation system in southeast China. Sci. Total Environ. 408, 906–913.

Lu, Y., Wassmann, R., Neue, H., Huang, C., 2000. Dynamics of dissolved organic carbon and methane emissions in a flooded rice soil. Soil Sci. Soc. Am. J. 64, 2011–2017.

Ma, J., Li, X.L., Xu, H., Han, Y., Cai, Z.C., Yagi, K., 2007. Effects of nitrogen fertiliser and wheat straw application on CH_4 and N_2O emissions from a paddy rice field. Aust. J. Soil Res. 45, 359–367.

Ma, B.L., Wu, T.Y., Tremblay, N., Deen, W., Morrison, M.J., McLaughlin, N.B., Gregorich, E.G., Stewart, G., 2010. Nitrous oxide fluxes from corn fields: on-farm assessment of the amount and timing of nitrogen fertilizer. Global Change Biol. 16, 156–170.

McMillan, M.S., Goulden, M.L., Tyler, S.C., 2007. Stoichiometry of CH_4 and CO_2 flux in a California rice paddy. J. Geophys. Res. 112, G01008.

McSwiney, C.P., Robertson, G.P., 2005. Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize cropping system. Global Change Biol. 11, 1712–1719.

Minamikawa, K., Yagi, K., Tokida, T., Sander, B.O., Wassmann, R., 2012. Appropriate frequency and time of day to measure methane emissions from an irrigated rice paddy in Japan using the manual closed chamber method. Greenhouse Gas Measure. Manage. 2, 118–128.

Mosier, A.R., Halvorson, A.D., Reule, C.A., Liu, X.J., 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. J. Environ. Qual. 35, 1584–1598.

Noll, M., Frenzel, P., Conrad, R., 2008. Selective stimulation of type I methanotrophs in a rice paddy soil by urea fertilization revealed by RNA based stable isotope probing. FEMS Microbiol. Ecol. 65, 125–132.

Parkin, T.B., Venterea, R.T., 2010. Sampling protocols. Chapter 3. In: Follett, R.F. (Ed.), Chamber-Based Trace Gas Flux Measurements. Sampling Protocols. USDA-ARS, Washington, DC, pp. 3-1–3-39.

Philippot, L., Hallin, S., Borjesson, G., Baggs, E.M., 2009. Biochemical cycling in the rhizosphere having an impact on global change. Plant Soil 321, 61–81.

Reddy, K.R., Patrick, W.H., 1978. Residual fertilizer nitrogen in a flooded rice soil. Soil Sci. Soc. Am. J. 42, 316–318.

Rochette, P., Eriksen-Hamel, N.S., 2008. Chamber measurements of soil nitrous oxide flux: are absolute values reliable? Soil Sci. Soc. Am. J. 72, 331–342.

SAS Institute Inc., 2004. SAS/STAT® 9.1 User's Guide. SAS Institute Inc., Cary, NC.

Sass, R.L., Andrews, J.A., Ding, A., Fisher@@Jr., F.M., 2002. Spatial and temporal variability in methane emissions from rice paddies: implications for assessing regional methane budgets. Nutr. Cycl. Agroecosyst. 64, 3–7.

Schimel, J., 2000. Rice, microbes and methane. Nature 403, 375–377.

Shang, Q., Yang, X., Gao, C., Wu, P., Liu, J., Xu, Y., Shen, Q., Zou, J., Guo, S., 2011. Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments. Global Change Biol. 17, 2196–2210.

Singh, S., Singh, J.S., Kashyap, A.K., 1999. Methane flux from irrigated rice fields in relation to crop growth and N fertilization. Soil Biol. Biochem. 31, 1219–1228.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., 2007. Agriculture. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 497–540.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ. 133, 247–266.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Nat. Acad. Sci. U. S. A. 108, 20260–20264.

Van Groenigen, J.W., Velthof, G.L., Oenema, O., Van Groenigen, K.J., Van Kessel, C., 2010. Towards an agronomic assessment of N_2O emissions: a case study for arable crops. Eur. J. Soil Sci. 61, 903–913.

Verdouw, H., van Echteld, C.J.A., Dekkers, E.M.J., 1978. Ammonia determination based on indophenol formation with sodium salicylate. Water Res. 12, 399–402.

Wang, J.Y., Jia, J.X., Xiong, Z.Q., Khalil, M.A.K., Xing, G.X., 2011. Water regime-nitrogen fertilizer-straw incorporation interaction: field study on nitrous oxide emissions from a rice agroecosystem in Nanjing. China. Agric. Ecosyst. Environ. 141, 437–446.

Wassmann, R., Aulakh, M.S., 2000. The role of rice plants in regulating mechanisms of methane missions. Biol. Fert. Soils 31, 20–29.

Williams, J.F., 2010. Rice Nutrient Management in California. Publication 3516. University of California, Division of Agriculture and Natural Resources, Oakland, CA.

Xie, B., Zheng, X., Zhou, Z., Gu, J., Zhu, B., Chen, X., Shi, Y., Wang, Y., Zhao, Z., Liu, C., Yao, Z., Zhu, J., 2010. Effects of nitrogen fertilizer on CH_4 emission from rice fields: multi-site field observations. Plant Soil 326, 393–401.

Xing, G.X., Shi, S.L., Shen, G.Y., Du, L.J., Xiong, Z.Q., 2002. Nitrous oxide emissions from paddy soil in three rice-based cropping systems in China. Nutr. Cycl. Agroecosyst. 64, 135–143.

Xing, G., Zhao, X., Xiong, Z., Yan, X., Xu, H., Xie, Y., Shi, S., 2009. Nitrous oxide emission from paddy fields in China. Acta Ecol. Sin. 29, 45–50.

Xiong, Z.Q., Xing, G.X., Tsuruta, H., Shen, G.Y., Shi, S.L., Du, L.J., 2002. Measurement of nitrous oxide emissions from two rice-based cropping systems in China. Nutr. Cycl. Agroecosyst. 64, 125–133.

Xu, H., Hosen, Y., 2010. Effects of soil water content and rice straw incorporation in the fallow season on CH_4 emissions during fallow and the following rice-cropping seasons. Plant Soil 335, 373–383.

Yao, Z., Zhou, Z., Zheng, X., Xie, B., Mei, B., Wang, R., Butterbach-Bahl, K., Zhu, J., 2010. Effects of organic matter incorporation on nitrous oxide emissions from rice–wheat rotation ecosystems in China. Plant Soil 327, 315–330.

Yao, Z., Zheng, X., Dong, H., Wang, R., Mei, B., Zhu, J., 2012. A 3-year record of N_2O and CH_4 emissions from a sandy loam paddy during rice seasons as affected by different nitrogen application rates. Agric. Ecosyst. Environ. 152, 1–9.

Yan, X., Yagi, K., Akiyama, H., Akimoto, H., 2005. Statistical analysis of the major variables controlling methane emission from rice fields. Global Change Biol. 11, 1131–1141.

Yan, X., Akiyama, H., Yagi, K., Akimoto, H., 2009. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. Global Biogeochem. Cyc. 23, GB2002.

Yu, K., Chen, G., Patrick@@Jr., W.H., 2004. Reduction of global warming potential contribution from a rice field by irrigation, organic matter, and fertilizer management. Global Biogeochem. Cyc. 18, GB3018.

Zhang, G., Zhang, X., Ma, J., Xu, H., Cai, Z., 2011. Effect of drainage in the fallow season on reduction of CH_4 production and emission from permanently flooded rice fields. Nutr. Cycl. Agroecosyst. 89, 81–91.

Zhao, X., Min, J., Wang, S., Shi, W., Xing, G., 2011. Further understanding of nitrous oxide emission from paddy fields under rice/wheat rotation in south China. J. Geophys. Res. 116, G02016.

Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. Global Biogeochem. Cyc. 19, GB2021.

Zou, J., Huang, Y., Zheng, X., Wang, Y., 2007. Quantifying direct N_2O emissions in paddy fields during rice growing season in mainland China: dependence on water regime. Atmos. Environ. 41, 8030–8042.

Zou, J., Huang, Y., Qin, Y., Liu, S., Shen, Q., Pan, G., Lu, Y., Liu, Q., 2009. Changes in fertilizer-induced direct N_2O emissions from paddy fields during rice-growing season in China between 1950 and 1990. Global Change Biol. 15, 229–242.