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Methane and nitrous oxide emissions from rice and maize production in diversified rice cropping systems

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Abstract Traditional irrigated double-rice cropping systems have to cope with reduced water availability due to changes of climate and economic conditions. To quantify the shift in CH_4 and N_2O emissions when changing from traditional to diversified double cropping-systems, an experiment including flooded rice, non-flooded "aerobic" rice and maize was conducted during the dry season (February–June 2012) in the Philippines. Two automated static chamber–GC systems were used to continuously measure CH_4 and N_2O emissions in the three cropping systems of which each included three different nitrogen fertilization regimes. Turning away from flooded cropping systems leads to shifts in greenhouse gas emissions from CH_4 under wet soil to N_2O emissions under drier soil conditions. The global warming potential (GWP) of the non-flooded crops was lower compared to flooded rice, whereas high CH_4 emissions under flooded conditions still override enhanced N_2O emissions in the upland systems. The yield-scaled GWP favored maize over aerobic rice, due to lower yields of aerobic rice. However, the lower GHG emissions of upland systems are only beneficial if they are not overwhelmed by enhanced losses of soil organic carbon.

Keywords Methane · Nitrous oxide · Aerobic rice · Maize · Yield-scaled GWP

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Abbreviations

DAS	Days after seeding
GHG	Greenhouse gas
GWP	Global warming potential
GY	Grain yield
SOC	Soil organic carbon

Introduction

Arable soils are an important source, both for atmospheric nitrous oxide (N_2O) and methane (CH_4) which currently contribute about 6 and 20 %, respectively to the overall global increase in radiative forcing

(Houghton et al. 1996; WMO 2006; IPCC 2013). Nitrous oxide emissions are mainly related to increased nitrogen inputs by mineral and organic fertilizers in upland systems, whereas CH_4 emissions mainly stem from flooded rice cultivation (Neue and Sass 1998; Yan et al. 2009; IPCC 2013) contributing currently with 9–19 % to global CH_4 emissions (Denman et al. 2007). In contrast to CH_4 emissions, N_2O emissions from paddy rice fields are mostly negligible since anaerobic soil conditions shift the end product of denitrification towards N_2, and are unfavorable for nitrification, thus limiting substrate (i.e. nitrate) availability for denitrification (Cai et al. 1997; Zou et al. 2005). In tropical upland systems like aerobic rice or maize, low redox potentials which favor the production and emission of CH_4 are rarely present. However, alternating moist–dry soil conditions after irrigation or heavy rainfall events are stimulating nitrification–denitrification processes and thus promoting N_2O production and emission (Zheng et al. 2000).

Rice (*Oryza sativa* L.), the staple food of more than three billion people, is generally cultivated under flooded conditions demanding up to one-third of the World's freshwater resources (Bouman et al. 2007). Growing water demands in municipal and industrial sectors and increasing climatic variability requires adaptation of irrigated rice production to future changes in the availability of water resources. Particularly in Asia, where 89 % of the world's rice paddies are located (FAOSTAT 2012), physical water scarcity will influence 2 Mha of irrigated dry season rice and 13 Mha of irrigated wet season rice due to lack of irrigation water (Tuong and Bouman 2003). Bouman et al. (2005) assume that another 22 Mha of irrigated dry season rice in South and Southeast Asia will be confronted with economic water scarcity when rising costs, e.g. fuel for pumps, will make intensive irrigation unaffordable for farmers. Therefore, rice farmers in Asia will be forced to avoid intensive rice irrigation in periods with low water availability (i.e. dry season) or diversify their cropping systems by switching to upland crops like maize. The decline in available irrigation water and simultaneous increasing demand of maize for poultry and biofuel production is currently driving the change from rice–rice (wet–dry season) systems to rice–maize cropping systems across tropical and subtropical Asia. Such rice–maize systems already cover a total area of over 1.3 Mha

(Timsina et al. 2010). Another option of adapting to insufficient water resources in lowland rice environments is the cultivation of ''aerobic'' rice varieties (Bouman 2001; Bouman et al. 2005), where irrigation aims at keeping soils at field capacity rather than flooded or saturated (Belder et al. 2005). Although a lot of effort was put into development of nutrient-responsive aerobic rice cultivars (Bouman 2001; Lafitte et al. 2002), yields are still lower compared to flooded rice cultivars. In an experiment conducted by Belder et al. (2005) an aerobic rice system produced 15–39 % lower yields than a flooded system. Changes from rice cultivation under puddled and submerged soils to water-saving practices or diversified cropping systems with pronounced aerobic soil conditions will not only affect yields but also soil carbon (C) and nitrogen (N) turnover (Bronson et al. 1997a, b; Abao et al. 2000; Wassmann et al. 2000) and associated emissions of greenhouse gases (GHG) such as CH_4, N_2O and CO_2. Changes from paddy rice to upland rice and soybean/wheat cultivation under temperate climate in Japan, revealed significant increase in net global warming potential (GWP) by increased N_2O emission, but also reduced CH_4 emissions from paddy soils with preceding upland crop cultivation which lead to reduced combined GWP (Nishimura et al. 2005, 2011).

The main objective of our study was to investigate and compare differences in N_2O and CH_4 emissions and resulting GWPs (CO_2-eq) from traditional paddy rice, "aerobic rice" and maize cultivation in the dry season under subtropical climate conditions. We hypothesize that the conversion of flooded to non-flooded cropping systems will lead to "pollution swapping" with CH_4 emissions dominating under wet soil and N_2O emissions dominating under drier soil conditions. The dry season conversion towards upland agriculture will lead to an overall increase of the greenhouse gas effect (expressed in GWPs) due to disproportionally high increase of N_2O emissions under subtropical climate conditions.

Materials and methods

Site description

The field study was established at the Experimental Station of the International Rice Research Institute

(IRRI), Los Baños, Philippines, about 66 km south of Manila. The study site (14°09′45″N, 121°15′35″E, 21 m a.s.l.) was historically cropped with paddy rice in both wet and dry seasons prior to the experimental set-up for over two decades. The long-term yearly (1979–2011) average sum of rainfall at this site is 2,006 mm, with annual mean, maximum and minimum temperatures of 27.1, 30.7, and 23.5 °C, respectively (IRRI Climate Unit 2011). Rainfall is unevenly distributed over the year with a long-term average sum of rainfall of 300 mm in the dry season (January–May) and 1,706 mm in the wet season (June–December). Total amount of rainfall during the sampling period (dry season 2012) was 310.4 mm, with monthly totals of 111, 35 and 170.9 mm for March, April and May. Mean monthly air temperature over the sampling period was 27.9 °C, with mean monthly air temperatures of 26.4, 28.3 and 29 °C for March, April and May (Fig. 3d). The soil is classified as *"Andaqueptic Haplaquoll"* (USDA classification) with clay dominated soil texture (54.2 % clay, 32.8 % silt, 13 % sand). The topsoil (0–0.1 m) has a bulk density of 1.0 kg dm^{-3}, a pH of 6.1 (1:1 soil/water suspension) and an organic carbon content of 1.8 %.

Field experimental design

As preparation phase, all plots were cropped with flooded rice under identical conventional N fertilization in the previous wet season (June–December 2011). Rice straw from the harvest of the former paddy rice cultivation was removed, and stubbles were incorporated during the land preparation for the dry season cultivation in December 2011. Automated greenhouse gas exchange measurements were conducted in three different cropping systems: traditional flooded rice (fRice), diversified systems of aerobic rice (aRice) (*O. sativa* L.) and maize (maize) (*Zea mays* L.). Furthermore, each cropping system underwent three different treatments of N fertilization rates. Cropping systems and fertilizer treatments were replicated three times which lead to a total of 27 measuring plots (3 reps × 3 crops × 3 fertilizations) arranged in a split-block design on nine field sections. The nine field sections (528 m^2), homogenously cultivated with one crop type and water regime (i.e. 3 × flooded, 3 × aerobic rice and 3 × maize), were separated from each other by earthen dams reinforced with plastic sheets to protect dry fields from water

infiltration of flooded fields. The entire nine field sections were further subdivided into three sub-plots each (app. 180 m^2), receiving different rates of N fertilizations which included zero-N, site specific and conventional (Fig. 1; Table 1). Irrigation was done by a hydrant system which supplied water from a nearby reservoir.

Flooded and aerobic rice were planted by direct seeding with 60 kg seed ha^{-1} and 20 cm row spacing on February 1 and 10, respectively. The high yielding irrigated lowland variety NSIC Rc222 (Tubigan 18) was used for flooded rice and the rainfed lowland variety NSIC Rc192 (Sahod Ulan 1), which is adapted to short-term drought, was used for aerobic rice cultivation (PhilRice 2010). Basal fertilization with Solophos and Muriate of potash were applied at rates of 30 kg P$_2$O$_5$ ha^{-1} and 60 kg K$_2$O ha^{-1} between planting rows before seeding. Field sections with flooded rice systems were kept under traditional irrigation management, maintaining water saturated soil conditions after seeding and a water level of about
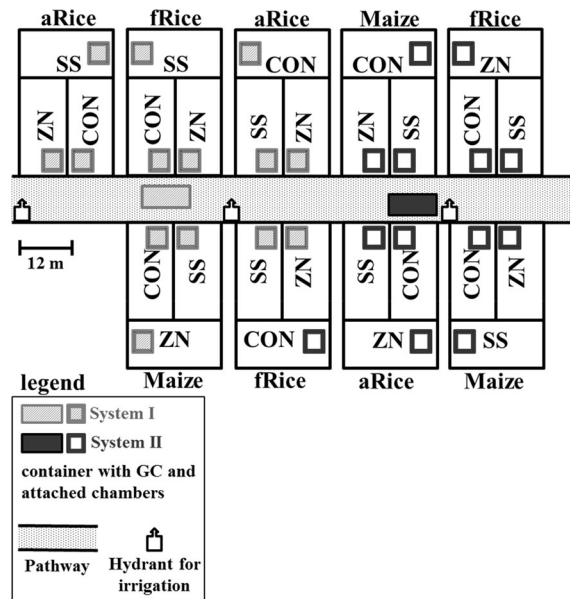

Fig. 1 *Outline* of the split-block design used in this study. Flooded rice (fRice), aerobic rice (aRice) and maize (Maize) fields are split into three fertilizer management plots: zero-N (ZN), conventional (CON), site-specific (SS) and replicated three times. One automated chamber is positioned on each plot and connected to a GC situated in one of the two containers on-site. Due to the large number of chambers (n = 27), sampling is split into two systems to obtain six measurements per day and chamber

Table 1 Total and split nitrogen application rates in kilogram nitrogen per hectare (source: urea) for the three cropping systems (flooded rice, aerobic rice, maize) under three different fertilizer treatments [zero-N (ZN, not shown—no N application), conventional (CON) and site-specific (SS)]

Fertilizer treatment	Flooded rice		Aerobic rice		Maize	
	CON	SS	CON	SS	CON	SS
Total N (kg N ha^{-1})	130	180	130	180	130	190
Split rates (kg N ha^{-1})	30/50/50	45/60/75	30/50/50	45/60/75	30/50/50	60/60/70
Split dates (dd.mm)	16.02/01.03/28.03		08.03/16.03/28.03		29.02/25.03/15.04	
Seeding date (dd.mm)	01.02		10.02		24.02	
Harvest date (dd.mm)	24.05		28.05		13.06	
Cropping period (d)	114		109		111	
Covered by sampling period (d)	83		87		87	

Dates of fertilization, seeding and harvest for each crop are presented in the same column. Sampling period (03.03–28.05.2012) did not cover complete cropping periods

5 cm from 31 days after seeding (DAS) until approximately 95–100 DAS. For fields with aerobic rice, water was applied by flush irrigation maintaining soil water contents at field capacity. Maize was planted on February 24 using the Pioneer hybrid variety 30T80. Planting distances were 25 and 50 cm seed spacing in rows and across rows, respectively. Maize crops received basal fertilization of 50 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1} at seeding and were sporadically hose irrigated during periods of low soil moisture conditions. Site-specific and conventional nitrogen treatments of flooded and aerobic rice were fertilized in three split applications with a total of 180 and 130 kg N ha^{-1} urea and maize with 190 and 130 kg N ha^{-1} urea, respectively (Table 1). Total amounts for conventional fertilization were based on local farmers' practice while leaf color charts were used to compute N fertilization rates for site-specific management. Zero-N plots received no nitrogen at any time.

Greenhouse gas measuring system

CH_4 and N_2O emissions were measured at 27 plots by automatic static chambers (Fig. 1). Chambers, made of transparent acryl glass, were installed immediately after seeding and stayed in place for the whole duration of the measuring campaign. Chambers were fixed to stainless steel frames driven approximately 10–20 cm into the soil. The frames in flooded fields had two holes (5 cm diameter each) allowing identical field water level dynamics inside measuring chambers.

Flooded rice chambers covered a basal area of 1 × 1 m, whereas basal area of aerobic rice and maize chambers was 0.5 × 0.5 m. Rice was grown inside the chambers with chamber heights at 1.2 m for flooded rice and flexible chamber heights (ranging between 0.20 and 0.80 m) for aerobic rice, being adjusted to plant heights with intersection pieces. Maize chambers representatively covered row and interrow areas, with two maize plants being seeded and grown inside chambers until they exceeded the chamber height (0.30 m). Thereafter stems of maize plants were clamped airtight by a flexible sealing into a special chamber centerpiece covering the section between the two closing chamber lids (Fig. 2). Rice chambers were fertilized evenly and maize chambers along plant rows by hand according to field application rates and respective chamber areas. Chamber lids were equipped with pneumatic cylinders with two chambers at a time being automatically operated during one measurement cycle lasting 24 min. For homogenous air mixture all chambers were equiped with fans. To prevent distinct heat stress and to avoid loss of precipitation during chamber closure times, thresholds were set to a chamber temperature of 45 °C and a precipitation of 0.1 mm precipitation per hour. If either of both thresholds was exceeded chamber lids automatically opened. Chambers were connected via stainless steel tubes to one of two automatic valve systems (with system 1 consisting of 13 chambers and and system 2 consisting of 14 chambers) transfering gas samples to two separate gas chromatographs, operated in air conditioned containers on-site (Fig. 1).

Fig. 2 Maize chamber used in the experimental set-up: maize stems are clamped airtight into a special chamber centerpiece with flexible sealing after the plants exceeded chamber height. Chamber base area is covering seeding row and interrow representatively

Gas chromatographs were equipped with a flame ionization detector (FID) and an electron capture detector (ECD) for online detection of CH_4 and N_2O concentrations, respectively. An ascarite column was used in front of the ECD to avoid bias caused by CO_2 in sample air (Zheng et al. 2008). Determination of CH_4 and N_2O fluxes was based on changes in concentrations over time represented by four chamber air samples taken at 6 min intervals during one measuring cycle. The sampling design resulted in a total number of six flux rates per day per chamber. Each measuring cycle was complemented by analysing two samples of a defined standard gas mixture. Fluxes were calculated by linear regression procedures and were corrected by chamber temperature, atmospheric pressure and chamber volume. The minimum detection limit computed according to Parkin et al. (2003) considering specific chamber heights was 4.3, 4.3–17.1, 25.7 µg N_2O–N m^{-2} h^{-1} and 13.4, 13.4–53.6, 80.4 µg CH_4–C m^{-2} h^{-1} for maize, aerobic rice (min and max chamber height) and flooded

rice measurements, respectively. CH_4 and N_2O fluxes were measured over a 3 months period lasting from March 3 until May 28. Daily fluxes of any combined crop and fertilization treatment were calculated by arithmetic means of sub daily fluxes using three replicated chambers.

Logistic problems delayed the experimental set-up and flux measurements started at 31, 22 and 8 DAS for flooded rice, aerobic rice and maize, respectively (27, 20 and 8 % of cropping period). For all crops measurement lasted until harvest. The different seeding and harvest dates led to a total sampling period of 83 days for flooded rice and 87 days for aerobic rice and maize (Table 1). Due to delayed start of measurements the first fertilizer event in flooded rice was not captured. Furthermore malfunction of detectors led to an interruption of N_2O measurements between March 15 and 21 (6 % of cropping period for all crops). For the computation of total emissions covering the whole cropping season (109–114 days), missing fluxes were gap-filled by linear interpolation or LandscapeDNDC model simulations as presented by Kraus et al. (2014).

For direct comparison, we calculated the GWP of total seasonal emissions of N_2O and CH_4. For this respective fluxes of N_2O and CH_4 were converted into CO_2 equivalents taking into account the specific radiative forcing potential relative to CO_2 of 298 for N_2O and 25 for CH_4 for a 100 years time horizon (IPCC 2007). As suggested by Linquist et al. (2012), GWP of the sum of N_2O and CH_4 emissions were scaled with crop grain yields (yield-scaled GWP) to assess how different fertilizer management strategies affect product-related GHG fluxes. Direct N_2O emission factors (EF$_d$ %) of applied N fertilizer (kg N ha^{-1}) were calculated by using the following equation:

$$EF_d \% = 100 \, (E_F - E_0) \, / \, N \qquad (1)$$

where E_F (kg N ha^{-1}) is the cumulative N_2O flux from the N-fertilized treatment, and E_0 (kg N ha^{-1}) is the cumulative N_2O flux from the unfertilized treatment (zero-N).

Auxiliary data

Weather data such as precipitation and air temperature was acquired from data sets provided by the IRRI Climate Unit from weather stations in close vicinity

(<500 m) to the investigated field site. Soil moisture at 5 cm soil depth was recorded since April 2012 in 10 min intervals using ECH2O 5TM sensors (DECA-GON, Pullman, Washington, USA).

Grain yield (GY) expressed in kg dry matter ha^{-1} was measured at two randomly selected areas in each of the 27 plots. Total harvest sample area was 5.76 m^2 in flooded and aerobic rice plots and 4 m^2 in maize plots. GY of the nine different treatments (three crops × three fertilizer treatments) were calculated by using the arithmetic mean of the three plot replicates.

Statistical analyses

All statistical analyses were performed with SPSS 21.0 (SPSS, Inc., USA). The assumptions for normality and homogeneity of variance were preliminarily verified graphically by residual versus fitted values, box plots, and steam leaf plots. Since greenhouse gas fluxes did not show normal distribution, they were log-transformed before parametric statistics were applied. An analysis of variance (ANOVA) was used to compare N$_2$O and CH$_4$ flux data, grain yield and yield-scaled GWP among different crops and fertilizer treatments. Whenever the ANOVA indicated significant differences ($p < 0.05$), a pairwise comparison of means was undertaken using the Tukey HSD test. In addition, we employed OriginPro 8.6 (Origin Lab Corporation, USA) for figure preparation.

Results

CH$_4$ and N$_2$O emissions

Flooded rice

Seasonal CH$_4$ emissions of the different fertilizer treatments decreased with increasing N input. CH$_4$ emissions of the zero N fertilization treatment (121 kg CH$_4$–C ha^{-1} season^{-1}) were about one-third higher ($p < 0.01$) than those of the N fertilization treatments. Seasonal CH$_4$ emissions for site-specific fertilizer treatment (80 kg CH$_4$–C ha^{-1} season^{-1}), which received highest N inputs of 180 kg N ha^{-1}, were about 7.5 % lower than CH$_4$ emissions from the conventional fertilization (130 kg N ha^{-1}) treatment (Table 2), but the difference was not significant ($p = 0.138$). Temporal progression of mean daily

CH$_4$-fluxes of all fertilization treatments ranged between 0.9 ± 0.9 and 23.4 ± 14.3 mg CH$_4$–C m^{-2} h^{-1} (Fig. 3a). Generally, CH$_4$ fluxes were low until the end of panicle initiation (55 DAS, March 27). Thereafter, CH$_4$ fluxes continuously increased until May 13–16. Following the last irrigation on May 7, several rainfall events lead to slowly declining water levels since plots were not yet drained. Between May 13 and 16, CH$_4$ emissions of all fertilization treatments decreased except for peak emissions on May 20 (109 DAS) when maximum CH$_4$ fluxes of up to 80 mg CH$_4$-C m^{-2} h^{-1} could be detected within a time-window of 8–12 h. In the zero-N and site-specific fertilizer treatments, this "hot moment" significantly contributed (6 and 16 %) to total seasonal emissions. This effect was of minor importance in the conventional fertilization treatment. Thereafter, emissions decreased to values below 3 mg CH$_4$–C m^{-2} h^{-1} before harvest on May 24 (113 DAS).

Seasonal N$_2$O emissions of the flooded rice cropping systems significantly ($p < 0.001$) increased with increasing rates of N fertilization from 0.42 up to 1.61 kg N$_2$O–N ha^{-1} season^{-1} (Table 3). Mean daily N$_2$O emissions ranged from −0.04 ± 0.02 to 0.26 ± 0.12 mg N$_2$O–N m^{-2} h^{-1}, exceeding 0.15 mg N$_2$O–N m^{-2} h^{-1} only on days following N fertilization (Fig. 3a). Mean daily N$_2$O emissions of zero-N plots ranged between −0.04 ± 0.2 and 0.07 ± 0.09 mg N$_2$O–N m^{-2} h^{-1} where the maximum flux occurred after drying and rewetting of the fields on May 20. Mean daily emissions of fertilized plots were much higher and ranged from −0.03 ± 0.2 to 0.26 ± 0.12 mg N$_2$O–N m^{-2} h^{-1} with maximum daily fluxes of 0.13 ± 0.05 and 0.26 ± 0.12 mg N$_2$O–N m^{-2} h^{-1} occurring about 1 week after the second fertilization event. Emissions during the first week following fertilization events accounted for about 43 % of the total seasonal N$_2$O emissions.

Aerobic rice

CH$_4$ emissions for all aerobic rice fertilizer treatments showed similar temporal development (Fig. 3b) and seasonal emissions (4.94–5.41 kg CH$_4$–C ha^{-1} season^{-1}) were not different between fertilization treatments ($p = 0.267$, Table 2). Mean daily CH$_4$ fluxes varied between −0.04 ± 0.3 and 8.9 ± 10.5 mg CH$_4$–C m^{-2} h^{-1}. CH$_4$ fluxes continuously increased after the beginning of

Table 2 Seasonal CH_4–C emissons (±standard error) computed from mean fluxes for the sampling period (SP 83–87 days) and the cropping period (CP 109–114 days, including simulated emission data)

Crop	Zero-N (kg CH_4–C ha^{-1} season^{-})	Conventional (kg CH_4–C ha^{-1} season^{-})	Site-specific (kg CH_4–C ha^{-1} season^{-})	p^a
Fertilizer treatment				
Flooded rice				
SP (83 d)	113.78 ± 3.01 Aa	75.55 ± 1.85 Ab	72.63 ± 1.63 Ab	***
CP (114 d)	121.92 ± 6.26 Aa	86.81 ± 4.76 Ab	80.27 ± 4.02 Ab	***
Aerobic rice				
SP (87 d)	4.66 ± 0.22 B	4.84 ± 0.24 B	5.20 ± 0.26 B	ns
CP (109 d)	4.94 ± 0.44 B	5.41 ± 0.52 B	5.28 ± 0.48 B	ns
Maize				
SP (87 d)	1.01 ± 0.06 C	0.70 ± 0.05 C	0.87 ± 0.08 C	ns
CP (111 d)	0.96 ± 0.09 C	0.71 ± 0.09 C	0.85 ± 0.14 C	ns
p^b	*	*	*	
	*	*	*	

Analysis of variance (ANOVA) for seasonal CH_4 emissions between crops (aerobic rice, flooded rice and maize) and fertilizer treatments (conventional, site-specific and zero-N) was performed for SP and CP, results are presented in their respective rows and columns. Seasonal flux of CP was used to compute GWP

Values in each row ($^a p$ in lowercase letters) and column ($^b p$ in capital letters) followed by the same letter do not differ significantly at $p < 0.05$. (*ns* not significant * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$)

measurements and rose sharply after panicle initiation on April 5. Average total water input from irrigation and rainfall was highest in April with about 238 ± 48 mm where daily emissions for all fertilization treatments more than doubled within this period, with highest emissions occurring between April 21 and 23. After irrigation was stopped (May 1), mean daily emissions varied between 0.2 and 0.6 mg CH_4–C m^{-2} h^{-1}, with periods of increasing emissions following rainfall events.

Seasonal N_2O emissions of aerobic rice cropping systems increased with increasing rates of N fertilization (0.66–2.27 kg N_2O–N ha^{-1} season^{-1}), showing significant differences between fertilized and zero-N treatments ($p < 0.001$, Table 3). Mean daily N_2O emissions ranged from −0.02 ± 0.01 to 0.68 ± 0.48 mg N_2O–N m^{-2} h^{-1} and only exceeded 0.2 mg N_2O–N m^{-2} h^{-1} on days following fertilization events (Fig. 3b). Highest N_2O fluxes were measured following the first fertilization event at March 8. On March 8 and 9 aerobic rice plots were irrigated with a total of 54 mm resulting in up to a 30-fold increase of N_2O emissions from 0.02 to 0.68 (conventional) and 0.52 (site specific) mg N_2O–N m^{-2} h^{-1} in the following 4–5 days in the two fertilizer treatments. Consecutive rainfall events (total > 20 mm) combined with the third fertilization

event on March 28 lead to elevated N_2O emissions of about 0.3 mg N_2O–N m^{-2} h^{-1} in both fertilized plots from March 24 to April 3. N_2O emissions started to decrease to background levels after April 3 in the fertilized treatments. The zero-N treatment of aerobic rice showed only a small increase in N_2O emissions after rainfall events mainly at the beginning of the cropping period. After the first week of April until end of May, N_2O fluxes of all treatments were low (>0.05 mg N_2O–N m^{-2} h^{-1}) and showed little temporal variability except minor sporadic increases mainly in the site specific treatment.

Maize

CH_4 emissions of all maize fertilizer treatments were low without showing any strong temporal dynamics over the whole measuring period (Fig. 3c). Since uptake of atmospheric CH_4 was hardly observed upland Maize fields were weak sources of CH_4. Seasonal emissions of the different treatments ranged between 0.71 and 0.96 kg CH_4–C ha^{-1} season^{-1} and were not significantly different ($p = 0.241$, Table 2). Mean daily CH_4-fluxes ranged from 0.05 ± 0.01 to 0.34 ± 0.49 mg CH_4–C m^{-2} h^{-1} and only exceeded

Fig. 3 Mean daily fluxes (*lines* and *symbols*) of methane [with volumetric water content at 5 cm soil depth (*lines*)] and nitrous oxide [with irrigation (*bars*) and fertilization events (*arrows*)] for the three fertilizer treatments from flooded rice (**a**), aerobic rice (**b**) and maize (**c**) over their respective cropping periods from seeding to harvest (109–114 days). Gaps in the sampling period were filled with simulated emission data to compute seasonal flux and GWP (areas with *gray shading*). *Error bars* (SD_{Median} = 50–100 % of fluxes) are not included to enhance visibility. Climate data (mean daily air temperature and total daily rainfall) is presented in (**d**)
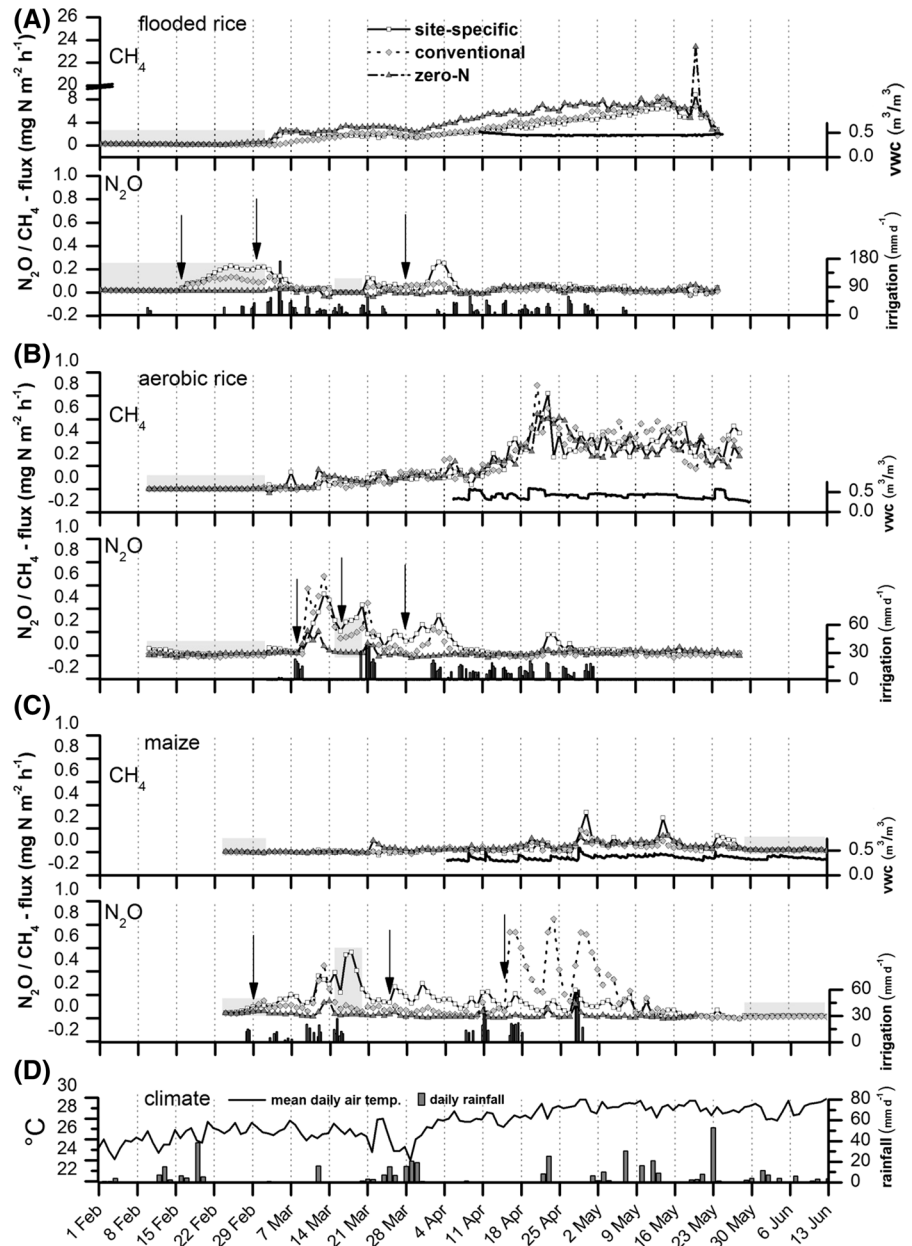
0.1 mg CH_4–C m^{-2} h^{-1} following pronounced irrigation or rainfall events. Until March 21 mean daily fluxes of all treatments varied around 0.01 mg CH_4–C m^{-2} h^{-1}. On March 15 and 16 maize fields were irrigated, with zero-N plots receiving almost twice the amount of water than the fertilized treatments. After three consecutive days of rainfall from March 20 to 22, CH_4-emissions in zero-N plots increased to 0.1 ± 0.17 mg CH_4–C m^{-2} h^{-1} and slowly decreased

within the next 5 days. In all treatments CH_4-emissions were highest (up to 0.29 ± 0.15 mg CH_4–C m^{-2} h^{-1}) after 64 mm irrigation at April 28 and 29 and increased again in mid and end of May following periods of heavy rainfall.

Seasonal N_2O emissions differed significantly between fertilized and non-fertilized treatments ($p < 0.01$) and were about five to six times higher in fertilized plots (3.22 and 3.95 kg N_2O–N ha^{-1} season^{-1}) compared to the

Table 3 Seasonal N_2O–N emissons (±standard error) computed from mean fluxes for the sampling period SP (SP 83–87 days) and the cropping period (CP 109–114 days, including simulated emission data)

Crop	Zero-N (kg N_2O–N ha^{-1} season^{-1})	Conventional (kg N_2O–N ha^{-1} season^{-1})	EF$_d$ (%)	Site-specific (kg N_2O–N ha^{-1} season^{-1})	EF$_d$ (%)	p[a]
Fertilizer treatment						
Flooded rice						
SP (83 d)	0.39 ± 0.03 c	0.64 ± 0.04 Bb		1.20 ± 0.08 Ca		***
CP (114 d)	0.42 ± 0.05 c	0.99 ± 0.09 Bb	0.44	1.61 ± 0.17 Ba	0.66	***
Aerobic rice						
SP (87 d)	0.57 ± 0.04 c	1.04 ± 0.09 Bb		1.82 ± 0.08 Ba		***
CP (109 d)	0.66 ± 0.09 b	1.51 ± 0.31 Ba	0.66	2.27 ± 0.28 Ba	0.89	**
Maize						
SP (87 d)	0.41 ± 0.03 c	3.92 ± 0.23 Aa		2.60 ± 0.08 Ab		***
CP (111 d)	0.63 ± 0.06 b	3.95 ± 0.27 Aa	2.55	3.22 ± 0.49 Aa	1.36	**
p[b]	ns	***		***		
	ns	**		**		

Direct N_2O emission factor (EF$_d$) was computed for CP. Analysis of variance (ANOVA) for seasonal N_2O emissions between crops (aerobic rice, flooded rice and maize) and fertilizer treatments (conventional, site-specific and zero-N) was performed for SP and CP, results are presented in their respective rows and columns. Seasonal flux of CP was used to compute GWP

Values in each row ([a]p in lowercase letters) and column ([b]p in capital letters) followed by the same letter do not differ significantly at $p < 0.05$ (*ns* not significant ** $p < 0.01$; *** $p < 0.001$)

zero-N treatment (0.63 kg N_2O–N ha^{-1} season^{-1}, Table 3). Although conventional treatments received lower rates of N fertilization mean seasonal N_2O emissions exceeded emissions of the site-specific treatment. However, it should be noted that this was mainly caused by exceptional high N_2O emissions from one single chamber after the third fertilization event (April 15). Mean daily N_2O emissions showed high temporal dynamics in both fertilized treatments and ranged between $-0.01 ± 0.01$ and $0.85 ± 0.78$ mg N_2O–N m^{-2} h^{-1} (Fig. 3c). After the first fertilization event on February 29 and irrigation on March 3–4, N_2O emissions in both fertilization treatments slightly increased until March 7 and decreased without further water inputs in the following days. Between March 10 and 12, all maize plots were irrigated with 22 mm which resulted in an increase of four to ten times higher N_2O values with the conventional treatment showing the highest mean daily flux of $0.45 ± 0.19$ mg N_2O–N m^{-2} h^{-1} on March 13. Similarly, N_2O emissions increased after the second fertilization event on March 25 following irrigation and/or rainfall events. In this period daily N_2O emission of the site-specific treatment were two to three times higher than emissions of the conventional plots with maximum emissions of up to $0.3 ± 0.18$ mg N_2O–N m^{-2} h^{-1}

(March 31). This was opposite after the third fertilization (April 15) event when N_2O emissions of the conventional treatment were much higher with maximum mean daily flux rates exceeding 0.8 mg N_2O–N m^{-2} h^{-1} following increase of soil moisture either by rainfall or irrigation events. At the end of April mean daily N_2O fluxes of both fertilizer treatments decreased to flux rates around 0 mg N_2O–N m^{-2} h^{-1}.

Comparison of mean seasonal CH$_4$ and N_2O emissions between different cropping systems

Mean seasonal CH$_4$ fluxes were highest in flooded rice (>80 kg CH$_4$–C ha^{-1} season^{-1}) followed by 90 % lower fluxes of about 5 kg CH$_4$–C ha^{-1} season^{-1} in aerobic rice and lowest fluxes in the maize system (<1 kg CH$_4$–C ha^{-1} season^{-1}) with differences being statistically significant ($p < 0.05$). This trend and magnitude of fluxes was the same in all of the three fertilization treatments demonstrating that CH$_4$ emissions were mainly depending on soil wetness (flooded rice ≫ irrigated rice ≫ maize) rather than nitrogen fertilization (Table 2). In contrast, mean seasonal N_2O emissions of zero-N treatments did not differ across

different cropping systems. Under fertilization, highest ($p < 0.01$) mean seasonal N_2O emissions exceeding 3 kg N_2O–N ha^{-1} $season^{-1}$ were observed in the maize system. N_2O emissions of the flooded and aerobic rice systems were significantly lower (0.99–2.27 kg N_2O–N ha^{-1} $season^{-1}$). Although N_2O emissions of aerobic rice were about 1.5 times greater than flooded rice, differences were not significant (Table 3).

Grain yield

Grain yields of the fertilized treatments were highest (>10 Mg ha^{-1}) in maize, intermediate in flooded (6–7 Mg ha^{-1}) and lowest in aerobic rice (2–3 Mg ha^{-1}). Compared to the flooded rice, mean yields for aerobic rice were about 50–70 % and thus, significantly ($p < 0.05$) lower (Fig. 4b). For both flooded rice and upland maize, grain yields for fertilized treatments were about 3.5 and 10.5 Mg ha^{-1}, and thus significantly higher ($p < 0.01$) than yields of the zero-N treatments. Mean yields of plots under conventional fertilizer treatment were about 7 and 13 % higher than site-specific for maize and flooded rice, but the differences were not significant ($p = 0.959$ and $p = 0.191$ for maize and flooded rice, respectively). For

aerobic rice, grain yields increased with higher N-input but did not differ significantly ($p = 1.28$). The discrepancy between higher fertilizer rates and yields for flooded rice and maize was most likely caused by lodging during storm events with heavy rainfall in May (Fig. 3d). With lower plant height and less panicle weight after grain filling, the aerobic rice variety was less affected.

Global warming potential and yield-scaled global warming potential

For comparing total seasonal N_2O and CH_4 emissions between fertilizer treatments and cropping systems, GWPs expressed in CO_2 equivalents were calculated. The GWP was highest ($p < 0.05$) for flooded rice irrespective of fertilization (Fig. 4a). Overall, GWP of flooded rice cultivation was dominated by high CH_4 emissions. Since CH_4 emission of flooded rice decreased with higher N fertilization rates, maximum GWP of 4.26 ± 0.23 Mg CO_2-eq ha^{-1} $season^{-1}$ was computed for the zero-N treatment which was significantly higher ($p < 0.05$) than the two other fertilizer treatments. Second highest GWPs (1.76–1.54 Mg CO_2-eq ha^{-1} $season^{-1}$) were computed for fertilized
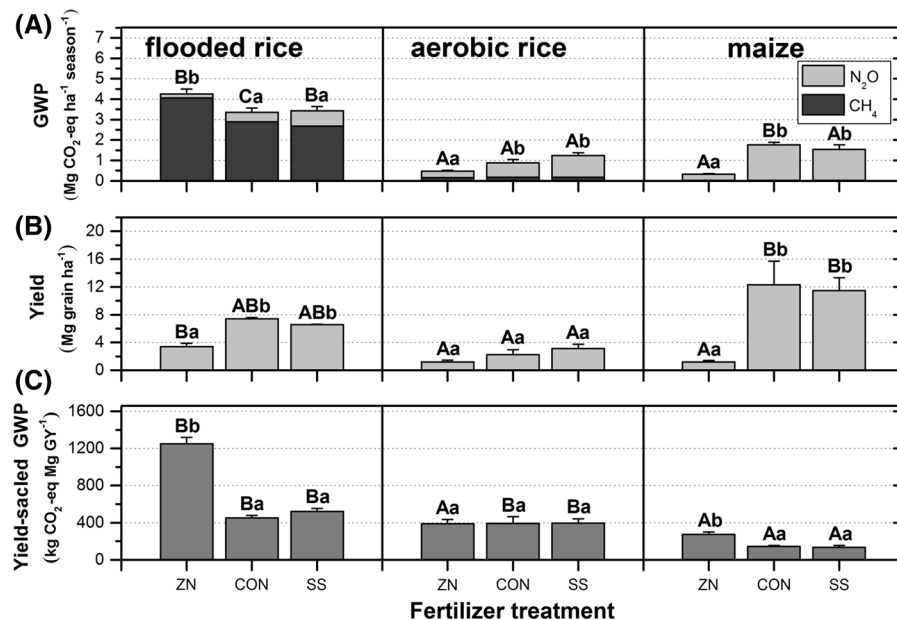

Fig. 4 Mean values of three replicates for **a** combined emissions of N_2O and CH_4 representing GWP in Mg CO_2 equivalent (radiative forcing potential: 298/N_2O; 25/CH_4), **b** yield in Mg grain yield and **c** yield-scaled GWP in kg CO_2 equivalent per Mg grain yield from flooded rice, aerobic rice and maize under three fertilizer regimes [(ZN) zero-N, (CON) conventional, (SS) site-

specific]. Standard errors are represented by *black bars*. Results for analysis of variance (ANOVA) are represented by *capital letters* (between crops with the same fertilizer treatment) and *lowercase letters* (between fertilizer treatments of the same crop) above bars. *Bars* marked with the *same letter* do not differ significantly at $p < 0.05$

maize plots with GWPs being dominated by N_2O emissions. Due to comparable low CH_4 and N_2O emissions, aerobic rice had the lowest GWPs for fertilized plots but the difference was only significant for the conventional treatment ($p < 0.05$). Since CH_4 emissions were nearly equal across the aerobic rice fertilization treatments, GWP increased with increasing rates of N fertilization and N_2O emissions. Minimum GWP was computed for zero-N treatment of the maize system. Relating GWPs to grain yields, fertilized maize treatments showed the lowest ($p < 0.05$) GWP with values less than 300 kg CO_2-eq Mg GY^{-1} (Fig. 4c) mainly due to comparable high yields of over 10 Mg ha^{-1}. Since lower yields from non-flooded rice were accompanied by lower emissions, yield-scaled GWP ranged around 400 kg CO_2-eq Mg GY^{-1}. These values are comparable to the ones of the flooded rice system (450–500 kg CO_2-eq Mg GY^{-1}), linked to higher yields but also higher GHG emissions. High GWP of the flooded rice zero-N treatment combined with low yields resulted in the highest ($p < 0.05$) yield scaled GWP of 1,250 kg CO_2-eq Mg GY^{-1}.

Discussion

CH_4 and N_2O emissions

Highest emissions of CH_4 were measured in the flooded rice system where anaerobic soil conditions with low redox potential favor the reduction of soil organic compounds and the simultaneous production of CH_4 by methanogenic archaea. CH_4 emissions increased over the investigation period, following plant and root development since plant mediated transport is the dominating pathway of CH_4 release into the atmosphere, accounting for up to 90 % of total emissions (Cicerone and Shetter 1981; Holzapfel-Pschorn and Seiler 1986; Whiting and Chanton 1993; Butterbach-Bahl et al. 1997). Slightly elevated CH_4 emissions at the beginning of the sampling period could be caused by a combined effect of available C from remaining plant residue and decreasing oxygen contents in the soil after the fields were flooded to a standing water level of about 5 cm. After irrigation was stopped and fields began to dry, CH_4 emissions decreased, with the exception of a short period in which a maximum release of CH_4 in the flooded rice system occurred. This was most likely caused by release of entrapped CH_4 due to a

decrease of hydrostatic pressure with soil drying. These peak emissions contributed by 6–16 % to the total seasonal fluxes which is in good agreement with earlier studies (Wassmann et al. 1994; van der Gon et al. 1996) which found that 10–20 % of the CH_4 emitted during a full rice cropping cycle is released after drying of fields. Total seasonal CH_4 fluxes ranged between 107 and 115 kg CH_4 ha^{-1} $season^{-1}$ for fertilized (conventional and site-specific, respectively) and 162 kg CH_4 ha^{-1} $season^{-1}$ for unfertilized flooded rice plots, which is in the same range than dry season CH_4 emissions reported by Wassmann et al. (2000; 225–8 kg CH_4 ha^{-1}) and Corton et al. (2000; ~100 kg CH_4 ha^{-1}) for comparable cropping systems in the Philippines. Compared to other CH_4 fluxes (mean/median Asia: 217/147 CH_4 ha^{-1}; Indonesia/Philippines: 192/170 CH_4 ha^{-1}) compiled in a review study by Sander et al. (2014), our dry season CH_4 emission rates are much lower. In our study, rice was established by direct seeding, rice straw was removed and incorporation of rice stubbles from the preceding wet rice cultivation was rather early (December 2011). Especially the early incorporation of stubbles and removing of rice straw can explain why CH_4 emissions in the dry season from our study site were lower than averaged emissions for Asia and the Philippines which include flux data from various climatic conditions and management practices, i.e. rice straw incorporation. Moreover, during the dry season, temperatures and evapotranspiration are high while precipitation is generally scarce. Thus, maintenance of continuously flooded field conditions can partly fail (Pampolino et al. 2008). Although we have no documentation of lowered water tables in our study, induced periods of soil aeration, thus reduced methanogenesis, can be a further explanation of lower CH_4 emissions at dry conditions compared to wet season conditions.

In our study we obtained a significant interaction effect ($p < 0.01$, partial eta squared = 0.03) between crop and fertilizer treatment, caused by the effect of fertilization in flooded rice. Under flooded conditions, CH_4 emissions of the zero-N treatment were significantly higher than CH_4 emissions of the fertilized treatments. So far, impacts of N fertilization on CH_4 emissions from rice paddies are controversially discussed in the literature. Our results add to studies where a negative correlation between N fertilization rates and CH_4 emissions was observed. (e.g. Xie et al. 2010; Dong et al. 2011). Xie et al. (2010) reported that addition of

150 kg ha^{-1} urea-N decreased CH$_4$ emissions by 28–30 % (29–34 % in this study) but this effect diminished with higher rates of N fertilization. A meta-analysis of 33 published papers (Banger et al. 2012) revealed that ammonia based fertilization increased CH$_4$ emissions from rice fields in 98 out of 155 paired studies. A decrease in CH$_4$ emissions is explained by stimulating growth and activity of methanotrophs resulting in higher consumption rates of CH$_4$, and leading to lower total CH$_4$ emissions if oxygen is available (Bodelier et al. 2000; Schimel 2000; Kruger and Frenzel 2003; Bodelier and Laanbroek 2004). Stimulation of growth and activity of methanogens and rice plants leading to higher CH$_4$ production rates, due to increased availability of soil organic matter and transport of CH$_4$ into the atmosphere through plant tissue, are stated as reasons for the positive correlation of N fertilization and CH$_4$ emissions (Schimel 2000; Xu et al. 2004). Impacts of N fertilization on CH$_4$ emissions from rice paddies are inconsistently reported in the literature. Nevertheless in our study CH$_4$ emissions in fertilized paddy rice plots decreased significantly. This result points out that under environmental conditions of our study region increasing fertilizer rates in extensive paddy rice systems could be a measure for mitigating CH$_4$ emissions.

CH$_4$ emissions of aerobic rice were similar in all treatments and about 95 % lower than emissions from flooded rice cultivation. CH$_4$ production by methanogenic archaea only occurs under strictly anaerobic conditions (Rothfuss and Conrad 1992), while aerated soil conditions favor CH$_4$ oxidation by methanotrophic bacteria. Therefore, water management is one of the most important factors influencing the magnitude of CH$_4$ emissions in rice production systems (Khalil and Shearer 2006). In our study, soil water content under aerobic rice cultivation was kept at field capacity (Fig. 3b) but allowed to fall dry in the upper soil layer between flush-flooding events, inducing cycles of soil aeration. The resulting oxidized soil conditions inhibited CH$_4$ production and likely enhanced CH$_4$ oxidation, keeping CH$_4$ emissions at much lower levels as compared to the flooded system.

As a result of even drier and well aerated soil conditions, CH$_4$ emissions in the maize system were negligible (only 1 % of flooded rice CH$_4$ emissions). While uptake of atmospheric CH$_4$ only occurred at the beginning of the cropping season, considerable CH$_4$ emissions were observed at wet to saturated soil conditions after pronounced irrigation or strong precipitation events. Physicochemical soil properties in drained paddy fields can differ from upland soils. Due to the hard pan and high clay content, drainage is poor and soil clods tend to be larger (Takahashi et al. 2003), which is presumably suitable for developing anaerobic microsites. Measurements of GHG emissions from tropical maize cropping systems are still rather scarce. Zhou et al. (2013) reported relatively high oxidation rates with seasonal fluxes of −0.7 kg CH$_4$ ha^{-1} for the maize season in a tropical wheat–maize rotation. While more studies identify maize as a sink for atmospheric CH$_4$ (Liebig et al. 2005; Linquist et al. 2012), Lehman and Osborne (2013) found that results from various experiments differ and soils which were previously neutral or sinks of atmospheric CH$_4$ may become net CH$_4$ sources depending on multi-year climatic trends and/or irrigation management. In years with high precipitation their experiment revealed CH$_4$ emissions between 1.2 and 2.13 kg CH$_4$ ha^{-1} from maize cultivation in South Dakota. Also in our study maize fields represented a weak source of CH$_4$ mainly related to CH$_4$ pulse emission after irrigation events.

Following the assumption in our hypothesis N$_2$O emissions did not only increase with higher fertilization rates but also with dryer soil conditions between cropping systems which caused a significant interaction effect ($p < 0.01$, *partial eta squared* = 0.03) between crop and N treatment. Whereas differences in N$_2$O emissions under zero-N fertilization between non-flooded cropping systems were rather small (<3 %), N$_2$O emissions from fertilizer treatments of flooded rice were 50–73 % lower than under maize and about 35 % lower than under aerobic rice cultivation. The anaerobic conditions in flooded systems likely suppressed nitrification thus, limiting the availability of nitrate for denitrification and shifted the end product of denitrification from N$_2$O towards N$_2$ (Cai et al. 1997; Zou et al. 2005). Direct N$_2$O emissions factors (EF$_d$, obtained from seasonal data) for flooded rice were 0.44 and 0.66 %, increasing with N input rates (Table 3). These values are higher than reported by other studies with EF$_d$ of around 0.2–0.3 % (Zou et al. 2005, 2007; Shang et al. 2011) pointing towards sporadic aeration of flooded fields in our study which is in line with Akiyama et al. (2005) who present slightly higher EF$_d$ of 0.37 % for intermittently flooded rice systems. N$_2$O emissions of aerobic rice were higher than flooded rice but 40–70 % lower than N$_2$O emissions from maize. Although

differences in soil water regimes were most likely the main drivers for the differences in N_2O emissions from maize and rice systems it also has to be mentioned that nitrogen placement differed between maize (band) and rice (broadcast) systems. Several studies in upland cropping systems found that band application of nitrogen can increase N_2O emissions when compared to broadcasting (Halvorson and Del Grosso 2013; Engel et al. 2010; Cheng et al. 2006). As indicated by the higher CH_4 emissions, soil water contents (Fig. 3b) were higher in aerobic rice, limiting N_2O and O_2 diffusion into the atmosphere/soil, potentially causing higher N_2 emissions compared to the maize system. In maize, high N_2O emissions were mainly triggered by irrigation or rainfall events after fertilization (Fig. 3c). Seasonal N_2O emissions in maize were 0.63, 3.95 and 3.22 kg N ha^{-1} for fertilizer applications of 0, 130 and 190 kg N ha^{-1}, resulting in EF_d of 2.55 and 1.36 % for conventional and site-specific fertilization treatments, which are much higher than the default EF_d value of 1 % recommended by IPCC (2006). While all chambers showed similar time-response of N_2O pulses after fertilization and irrigation/precipitation, differences in the magnitude of single chamber fluxes was pronounced. The overall higher N_2O emission in the conventional fertilization treatment was mainly caused by one out of three chambers, likely by differences in nitrogen/carbon availability (crop residues, fertilizer placement) causing an emission hot spot. Excluding this data reveals 48 % lower seasonal N_2O emissions in the conventional treatment (2.05 kg N ha^{-1} season^{-1}) resulting in an EF_d of only 1.09 %.

Global warming potential and yield

In this study GWP of the flooded rice system was much (2–13 times) higher than the GWP of the upland crops, in particular the zero-N treatments. The hypothesized pollution swapping from CH_4 to N_2O emissions was evident however, reductions in CH_4 were more significant than the increase of N_2O emissions (Fig. 4a). Overall, the increase of N_2O emissions in the non-flooded systems did not offset CH_4 emissions from the flooded rice system. Thus, our hypothesis that the introduction of upland crops instead of flooded rice in the dry season will lead to an increase of the total GWP was not confirmed. Our findings are therefore in line with studies under temperate climate conditions like Minamikawa et al.

(2010) who also report lower combined soil emissions of CH_4 and N_2O from upland rice and soybean/wheat compared to paddy rice in Japan. The highest GWP for all crops and treatments was calculated for the zero-N treatment of flooded rice. This could imply a potential GHG mitigation option for low N-input flooded rice systems, if higher N-fertilization rates in such systems can (1) decrease CH_4 emissions, as observed in our study, and at the same time (2) increase yields. For the Philippines, low N fertilizer rates of about 30–60 kg N ha^{-1} are common (Cassman et al. 1996; Angulo et al. 2012; FAOSTAT 2012; IFA 2012) and possible yield increases of up to 6–7 Mg ha^{-1} by improved agricultural management are reported by Angulo et al. (2012).

Aerobic rice showed the lowest GWP (Fig. 4a). However, calculated GWPs do not include CO_2 emissions, thus potential losses of soil organic carbon (SOC) caused by higher soil aeration may significantly increase the GWP of the non-flooded systems. Under comparable soil conditions, shifting to a rice–maize rotation caused a 15 % decline in SOC relative to the flooded rice–rice cropping systems (Pampolino et al. 2006). This is equivalent to a loss rate of about 1.5 Mg CO_2-eq per ha^{-1} year^{-1} thus, GWPs of upland systems would almost increase towards GWPs of the flooded rice system (Fig. 4a). Due to wetter soil conditions in the irrigated aerobic rice system the SOC loss rate might be lower than in the rice–maize rotation (Alberto et al. 2013).

Driven by the increasing demand of agricultural products caused by growth of the world population, more and more studies are relating GWPs not only to area but also to yields. In our study, grain yields from (fertilized) aerobic rice were 2–3 Mg ha^{-1} and thus more than 50 % lower than yields of the flooded rice variety. Relating GWPs to yields instead of area significantly reduced the differences between the two rice production systems (Fig. 4c). However, other studies at IRRI using different aerobic rice varieties reported higher grain yields of 4–6 Mg ha^{-1} under comparable N fertilization rates (Belder et al. 2005; Bouman et al. 2005; Alberto et al. 2013) which would restore the beneficial impact of aerobic rice cultivation on GWPs, if SOC losses are not offsetting the decrease in CH_4 emissions. In a meta-analysis of 62 study sites, Linquist et al. (2012) reported 657 ± 233 kg CO_2-eq Mg^{-1} GY for flooded rice which is much higher than our values of around 400 kg CO_2-eq Mg^{-1} GY. However, as already mentioned, CH_4 emissions in our

study were comparably low while rice yields were above average. In our study, fertilized flooded rice treatments showed significantly lower CH_4 emissions with significantly higher grain yields which lead to a decrease in the yield-scaled GWP by about 60 % compared to zero-N fertilization treatments. Thus, sufficient N fertilization could imply a potential GHG mitigation option for flooded rice systems with low N inputs which is still quite common in e.g. the Philippines (Cassman et al. 1996; Angulo et al. 2012).

As a C4 plant, maize has a higher photosynthetic capacity than rice, resulting in higher grain yields and thus lower yield-scaled GWP of 134 and 143 kg CO_2-eq Mg^{-1} GY for the fertilized treatments. These results are in good agreement with Linquist et al. (2012) who report 140 kg CO_2-eq Mg^{-1} GY for maize. Lowest yield scaled GWPs of maize would suggest favoring an establishment of flooded rice–maize rotations rather than flooded rice–aerobic rice rotations. However, yield-scaled GWPs of maize are not directly comparable with aerobic and flooded rice production systems. In addition to the potentially substantial SOC losses, maize grain has different nutrition values. Moreover, maize is less important as staple food since only 19 % of the total global maize production is directly consumed by humans, in contrast to 85 % of rice (Maclean et al. 2002). In South Asia the magnitude of maize production depends mainly on the socio-economic circumstances of farmers, demand of maize by livestock (especially poultry), and domestic and international markets of maize for food, feed and fuel industries (Timsina et al. 2010). One considerable asset of maize production is that maize straw can also be used as animal feed. Rice straw in contrast has high contents of silica and can cause additional emissions as post-harvest practices involve burning or incorporation into paddy soils (Yoshinori and Kanno 1997; Naser et al. 2007). Our results indicate that CH_4 emissions from maize–rice systems are lower when compared to traditionally rice–rice systems. However, as long losses in SOC are not quantified it is uncertain if maize production in the dry season can reduce the total annual GWP.

Conclusions

Changing from flooded to aerobic rice or maize cultivation in the dry season caused pollution swapping,

i.e. shifting dominance of CH_4 towards N_2O emissions. Although N_2O has a much higher GWP than CH_4, increased N_2O emissions in non-flooded systems did not surpass the high level of CH_4 emissions from the flooded system. Irrigated aerobic rice showed the lowest GWP and although aerobic rice yields were below average, yield-scaled GWPs were still lower than for the flooded rice system. Considering potential yield increases of aerobic rice implies further GHG mitigation potentials for this cropping system. Higher yields would also make this system attractive to farmers in situations of water scarcity, when intensive irrigation is either not possible or too expensive. High yields resulted in the lowest yield-scaled GWP for the maize system however, differences in nutrition values, energy contents, and social acceptance, as compared to rice, need to be considered. Lower GWPs of the upland systems are only related to CH_4 and N_2O emissions, however enhanced losses of SOC may significantly increase the GWPs of these systems. Therefore, in addition to GHG exchange measurements, further studies should also include simultaneous monitoring of changes in SOC. Compared to zero-N treatments, fertilized flooded rice system showed lower CH_4 emissions and higher yields, with significant benefits on yield-scaled GWP. However, the discussion of this topic in the scientific literature is still diverse and further studies are still necessary to clarify if N application can be an effective tool to mitigate GWP of flooded rice production systems with low N-input.

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