Agriculture, Ecosystems and Environment 239 (2017) 143–153

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

How does burning of rice straw affect CH_4 and N_2O emissions? A comparative experiment of different on-field straw management practices

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ARTICLE INFO

Article history:
Received 12 August 2016
Received in revised form 28 December 2016
Accepted 30 December 2016
Available online 24 January 2017

Keywords:
Emission factors
Rice straw burning
Straw management practices
GHG emissions
GWP

ABSTRACT

Open-burning of rice straw residues pollutes the air and contributes to global warming through emissions of greenhouse gases (GHGs). Although burning of straw residues emits large amounts of CO_2, this component of the smoke is not considered as net GHG emissions and only concludes the annual carbon cycle that has started with photosynthesis. Hence, we focused on emissions of CH_4 and N_2O from open-field burning against a baseline of straw incorporation. The experimental approach combined a newly designed combustion chamber for the collection of smoke followed by chemical analysis (Exp. A) as well as field observations of soil-borne emissions for different straw treatments (Exp. B). At constant straw moisture of 10%, the mass-scaled Emission Factors (EF_m) were 4.51 g CH_4 and 0.069 g N_2O per kg dry weight (kg^{-1}_{dw}) of straw. In Exp. B, we conducted field trials over two seasons with the following straw management practices: SRt – straw retained including stubbles and incorporated, PSRm – partial straw removal only stubbles incorporated, CSRm – complete straw removal including removal of stubbles, and SB – straw burned followed by incorporation of ash and unburned residues. Soil-borne emissions were recorded with a closed chamber approach whereas straw burning was computed indirectly using the EF from Exp. A. As metrics for comparison, we have used the GWP contributions of CH_4 and N_2O for the different straw management practices over two cropping seasons in the field. On an annual basis, SRt had the highest total GWP (8023 kg CO_2eq ha^{-1}). SB entailed a GWP of 4913 kg CO_2eq ha^{-1} that was almost identical to the GWP of PSRm (4531 kg CO_2eq ha^{-1}). CSRm had the lowest GWP (3470 kg CO_2eq ha^{-1}) that was significantly lower than that of SRt. However, full GHG accounting of straw removed from the field will depend on the ensuing utilization of straw and the off-field emissions involved – which was outside of the boundaries of this study. The quantification of open field burning in this study can be instrumental for diverse purposes by providing data of an important component in emission inventories and carbon footprint analysis of rice.

1. Introduction

Rice is a widely grown crop that leaves a substantial quantity of plant residues in the field such as roots, stubbles, and straw. After harvest, rice straw is either scattered in the field, accumulated in piles, or baled and sold for other purposes such as for mushroom production, fuel for cooking, ruminant fodder, stable bedding, and paper making. It is estimated that 242, 97, 22, and 11 Mt of rice straw residues are produced per year in China, India, Thailand, and the Philippines, respectively (Liu et al., 2011; Gadde et al., 2009). These residues are often burned in the field, which is a cost-effective method widely practiced, especially in Asia. In the Philippines, 95% of these residues undergo open-field burning (Gadde et al., 2009).

Rice straw burning has advantages in terms of farm operations but disadvantages from an environmental perspective. The

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http://dx.doi.org/10.1016/j.agee.2016.12.042

burning process eliminates many pathogens and the practice is less laborious than straw incorporation (Kutcher and Malhi, 2010; Mendoza and Samson, 1999). Burning allows for rapid and complete residue removal, especially for those practicing double or triple cropping (Singh et al., 2008), but it could result in the loss of major nutrients (Dobermann and Fairhurst, 2002). Additionally, biomass burning is the second-largest source of trace gases and the largest source of primary fine carbonaceous particles in the global troposphere (Launio et al., 2013; Akagi et al., 2011; Zhang et al., 2008). Open-burning of rice straw in the field is of incomplete combustion in nature; hence, a large amount of pollutants are emitted such as SO_2, NOx, including toxic gases such as carbon monoxide (CO), dioxins and furans, volatile organic compounds (VOC), carcinogenic polycyclic aromatic hydrocarbons (PAH), as well as fine inhalable particles (Oanh et al., 2011; Jenkins et al., 2003). Intensive burning of agricultural wastes in many Asian countries may substantially contribute to the formation of Atmospheric Brown Cloud (ABC) that affects local air quality, atmospheric visibility, and Earth's climate (Kanokkanjana et al., 2011; Tipayarom and Oanh, 2007; Torigoe et al., 2000). Open-burning of straw residues also contributes to global warming through emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (IPCC, 2013; Gadde et al., 2009; Gupta et al., 2004). However, CO_2 coming from biomass burning is not considered as a net GHG emission since the carbon released is assumed to be reabsorbed by the vegetation during the next growing season (IPCC, 2006). According to Miura and Kanno (1997), the carbon (C) and nitrogen (N) in the burned straw are emitted as CO_2-C (57–81%), CO-C (5–9%), CH_4-C (0.43–0.90%), and N_2O-N (1.16–1.50%).

The combustion process in vegetation encompasses ignition, flaming and smoldering stages. Crop biomass consists of cellulose and hemicelluloses (typically 50–70% dry matter), lignin (15–35%), amino acids, and proteins, including volatile substances. It also contains minerals (up to 10%) and water (up to 60%) (Andreae and Merlet, 2001). During combustion, thermal degradation begins with a drying/distillation step, in which volatiles and water are released. It is followed by pyrolysis, in which thermal cracking of the biomass molecules occurs, which results in the formation of char, tar, and flammable white smoke (Lobert and Warnatz, 1993). Glowing combustion begins when the temperature reaches 800 K, which releases a complex mixture of tar and gas products and forms a flammable mixture when diluted with air. Flaming combustion occurs when this mixture ignites, which converts the reduced substances emitted during pyrolysis to simple molecules, particularly CO_2, N_2O, N_2, NO, SO_2, and H_2O. At this stage, intermediate products such as CO, CH_4, C_2H_2, C_2H_4, H_2, and PAH, and soot particles, are also released. Flaming combustion ceases when most volatiles have been released and thus smoldering begins. At temperatures usually <850 K, large amounts of CO are emitted (Lobert et al., 1990).

Several attributes could influence straw burning and its emissions. Water content or moisture in plants can either prevent a fire completely or slow down the burning process and eventually terminate the fire. Density and structure of biomass are other characteristics to be considered for combustion properties. Higher density will increase temperatures in the fuel and will extend the burning period. Another critical attribute is fuel size because smaller particles are capable of sustaining flaming combustion, which will in turn support the burning of larger particles (Lobert and Warnatz, 1993).

A majority of the existing publications assessing emissions from straw burning are based on estimation using Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines and U.S. EPA 1995 values (Vibol and Towprayoon, 2010; Gadde et al., 2009; Yang et al., 2008; Cao et al., 2005; Streets et al., 2003). There are only a few studies in Southeast Asia in which measurements are conducted in order to obtain actual Emission Factors (Arai et al., 2015; Kanokkanjana et al., 2011; Oanh et al., 2011) given that this region regularly experiences extended fires in harvested rice fields. Many studies on the impact of straw incorporation on GHG emissions from paddy fields have already been carried out and are available in literature. However, only limited information exists on the effect of incorporating burned straw and other straw residue management practices during fallow on the emissions of CH_4 and N_2O during the subsequent cropping season (Liu et al., 2016; Sander et al., 2014). This study was therefore undertaken (1) to calculate the actual Emission Factors of CH_4 and N_2O during rice straw burning process using a combustion chamber (Exp. A) and (2) to conduct inter-comparison of the CH_4 and N_2O emissions of straw burning with other straw management practices during a full cropping cycle of 2 consecutive seasons (Exp. B).

2. Materials and methods

2.1. Experiment A: straw burning experiment using a combustion chamber

2.1.1. Collection of crop residues and preparation of moisture level treatment

Rice straw residues of cultivar NSIC Rc222 were collected after the dry season of 2016 from within the Experiment Station of the International Rice Research Institute (IRRI) in Los Baños, Laguna, Philippines. All crop residues were air-dried indoors and leftover grains were removed to reduce the variability in terms of weight. Sub-samples were analyzed for total C and N in the IRRI Analytical Services Laboratory (ASL).

To impose a fixed moisture level of 10% on the air-dried samples, straw bundles with a weight of 600 g each were evenly laid on a clean plastic sheet and misted with the necessary amount of distilled water using an ordinary spray bottle. They were then placed in sampling bags, tightly sealed, and stored for 48 h to ensure that the moisture would not only stay on the surface of the sample but would also penetrate within the cell walls of the rice straw. Right before the straw burning measurement, we took a sub-sample (100 g) to determine the actual moisture content by drying in the oven at 70 °C, and then measured the weight loss after 48 h.

2.1.2. Rice straw combustion set-up

The combustion set-up consisted of three major parts: the combustion chamber, condenser, and outlet (Fig. 1). The combustion chamber where the rice straw samples were burned had a dimension of 1.0 m × 1.0 m × 1.0 m. Inside the chamber, a small sheet of galvanized iron was placed under a cylindrical mesh. The cylindrical mesh served as the container for the rice straw samples and ensured that they had similar density or compaction while the galvanized iron sheet received the finer ash particles after burning. Located on the two sides of the chamber were two inlets to provide air during burning. The O_2 supply ranged from 18.3–20.9%, which allowed oxic conditions throughout the combustion process. The smoke passed through a chimney consisting of (i) an L-shaped pipe mounted on top of the combustion chamber enclosed in a cylindrical base, (ii) a condenser that cooled down the smoke and fumes to 30–40 °C, and (iii) an exhaust with the outlet (Fig. 1). The exhaust pipe was approximately 1.3 m long and facilitated the collection of smoke samples from the outlet using syringes. Temperature (°C), O_2 (%), and air velocity (m/s) were measured at the outlet using RASI 700, a portable emission/combustion analyzer (Eurotron Instruments UK Ltd).

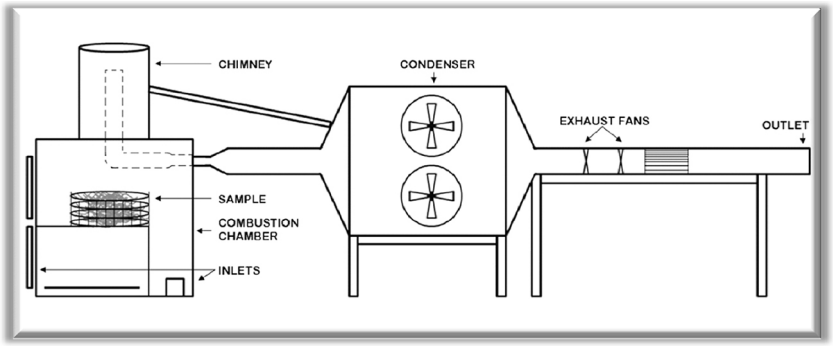

Fig. 1. Schematic set-up of combustion chamber.

2.1.3. Gas sampling and analysis

Sampling started from ignition until there was no smoke coming out of the hood anymore. The gas samples were manually collected at 30-s intervals using 60-mL syringes with 22G needles and 0.2-μm thick PTFE filter membranes. These filter membranes made sure that no soot or tar was included to avoid any contamination or harm to the instrument during analysis of the samples. The filter lasted for 10–20 samples depending on the moisture level of the straw being burned. The gas samples were injected into 30-mL glass vials previously evacuated using a vacuum system and then brought into the lab. To facilitate dilution (1:2) of samples prior to analysis, a 30-mL gas sample was injected into another 30-mL pre-evacuated glass vial followed by the addition of 30-mL high-purity N_2 gas (99.99%). A gas chromatograph (SRI GC-8610C) equipped with flame-ionization detector (FID) and electron-capture detector (ECD) was used for the analysis of CH_4 and N_2O, respectively. The temperature of the FID was 330 °C and that of the ECD was 350 °C, while the column temperature was set at 70 °C. For both the ECD and FID, the carrier gas used was nitrogen (N_2). The packing material of the columns for CH_4 and N_2O analysis was Porapak Q (50–80 mesh) and the length of the columns was 3 m each. Personnel involved during the burning activity wore proper personal protective equipment (PPE) to ensure their safety and precautionary measures were observed during sampling.

2.1.4. Ash collection

After every burning activity, ash samples and unburned residues were carefully separated and placed in paper bags. Finer ash particles that adhered to the galvanized iron sheet were also collected using an ordinary paint brush. The ash samples were properly labeled and sent to the IRRI-ASL for analysis of total C and N.

2.1.5. Estimation of emission factors

The Emission Factors from biomass burning through controlled measurements were determined using the following equation developed for combustion experiments (França et al., 2012):

$$EF_x = \frac{V_{\text{Total chimney}}}{M_{\text{fuel (dry basis)}}} * \frac{[X]M_x}{V_{X\ (1\ \text{mol at 1 atm and 0°C})}} \quad (1)$$

where (EFx) is the mass-based Emission Factor in g kg^{-1} (grams of species X per kg of burned dried biomass); VTotal chimney is the total volume of gas flow through the chimney during the experiment (m^3); [X] is species X concentration (molar fraction); M_X is species X molecular weight (g mol^{-1}); M fuel (dry basis) is the amount of dry fuel consumed (kg); and V_X is the molar volume of gas at standard temperature and pressure (STP) (=0.0224 m^3). Volume correction at 0 °C and subtraction of ambient air concentration were also included for the calculation of emissions.

For the sake of consistency, we refer to the EFx values from our measurements as mass-scaled Emission Factors, EF_m CH_4 and EF_m N_2O, respectively. This terminology allows a clear distinction from area-scaled emissions, E_a CH_4 and E_a N_2O, which are given per ha (see 2.2.3).

2.2. Experiment B: field experiment on straw incorporation

2.2.1. Site characteristics, treatment, and experimental design

The study site is a 1-ha field in the Experiment Station of IRRI (14.148° N, 121.267° E) with an elevation of 27 m above mean sea level. The soil has a pH of 7.1, 1.33% total C, 0.13% total N, 1.45 $cmol_c\ kg^{-1}$ exch K, and 29.2 $cmol_c\ kg^{-1}$ cation exchange capacity. The IRRI weather station database (1979–2015) had recorded an average annual precipitation (± standard deviation) of 2115 ± 402 mm and an average annual mean air temperature of 27.4 ± 0.36 °C. The study site was previously used for certified seed production, for which it had been uniformly cultivated and fertilized. All straw residues were ground-cut and hauled at the end of each growing season, so there was minimal C input into the soil prior to the set-up of this experiment. The study was done during the 2015WS (wet season) and the 2016DS (dry season). For 2015WS, land preparation was from 4 to 17 June 2015 (−14 to −1 days after transplanting, DAT); growth period from 18 June to 20 Oct 2015 (0–124 DAT); and fallow period from 21 Oct to 25 Nov 2015 (125–160 DAT). For 2016DS, land preparation was from 26 Nov to 21 Dec 2015 (−26 to −1 DAT); growth period from 22 Dec 2015 to 12 Apr 2016 (0–112 DAT); and fallow period from 13 to 26 Apr 2016 (113–148 DAT).

The experiment was laid out in a completely randomized design with four straw management treatments and three replications with a plot size of about 500 m^2 each. The four straw management treatments comprised of (1) Straw Retained (SRt) – after combine harvesting, straw residues were distributed evenly in the plot; (2) Partial Straw Removal (PSRm) – after combine harvesting, straw was gathered by the baler and removed from the plot leaving only 35-cm stubbles; (3) Complete Straw Removal (CSRm) – after combine harvesting and baling, the remaining straw on the ground was completely removed by manually cutting the stubbles; and (4) Straw Burned (SB) – all straw residues were burned in the plot one day before land preparation.

At the start of each season, land preparation started with dry cultivation using a disc plow, followed by land soaking, plowing, harrowing, and leveling using a two-wheel tractor with wooden planks, which incorporated the respective straw amounts in all management treatments. For the 2015 wet season, fourteen-day-old NSIC Rc18 rice seedlings were manually transplanted with a spacing of 20 cm × 20 cm on 18 June 2015 and were manually harvested on 20 October 2015. Basal fertilizers (32 kg N ha^{-1}, 14 kg P ha^{-1}, and 27 kg K ha^{-1}) were applied and an additional

41 kg N ha^{-1} urea fertilizer was broadcast in two splits. For the 2016 dry season, fourteen-day-old NSIC Rc18 rice seedlings were manually transplanted with a spacing of 20 cm × 20 cm on 22 December 2015 and were harvested on 12 April 2016 using a combine harvester. Basal fertilizers (35 kg N ha^{-1}, 15 kg P ha^{-1}, and 29 kg K ha^{-1}) were applied and an additional 110 kg N ha^{-1} urea fertilizer was broadcast in two splits. The soil was kept saturated with no standing water in the early vegetative stage from 0 to 7 days after transplanting (DAT) to allow the seedlings to recover from transplanting shock and to prevent golden apple snails from damaging the crops. Then a 3–5-cm depth floodwater was maintained in the field until 7–10 days before harvest. The plots were drained before harvest to allow the grains to fully ripen and to dry the fields for easy operation of the combine harvester and baler.

2.2.2. Soil-borne emissions

Gas measurements were done starting from land preparation, growth, and fallow periods. Fluxes of nitrous oxide and methane were determined using the static chamber method as described by Sander et al. (2014) every week starting at around 0930H. Additionally, after each N application, gas measurements were conducted daily for five days.

The anchor used for each chamber was a stainless steel metal base (40 cm length × 22 cm width × 12 cm height). It was inserted into the soil at about 10-cm depth and included two rice hills inside the chamber. To allow stabilization, the anchors were placed in the plots before the first gas sampling and remained in the field throughout the season. At each sampling time, the water depth inside the metal base and the base height were likewise measured.

The gas collection chambers, made from a plastic box (40 cm length × 22 cm width), were used with variable heights (11, 42, and 81 cm) to accommodate the height of the growing plants inside the chamber. The chambers included a vent to allow equilibration of the pressure, a thermometer, and a sampling port. A 12 V battery-operated computer fan was installed in the tall chambers (42 and 81 cm height) to ensure well-mixed air during sampling while a sampling syringe was used to mix the air in the small chambers right before taking the sample.

During sampling, the gas collection chambers were placed on the trough of the metal bases with a water seal. Gas samples inside the chambers were collected at 0, 10, 20, and 30 min after the chamber closure using a 60-mL syringe fitted with a stopcock. Then, the samples were immediately injected into an evacuated 30-mL vial equipped with a gray butyl rubber septum and analyzed by the SRI GC-8610C gas chromatograph (GC) within one week. The details of the GC analysis are discussed in Section 2.1.3, Gas sampling and analysis. The applied method follows requirements for soil emission measurements as described by Butterbach-Bahl et al. (2016).

Linear regression of the four measurement points (0, 10, 20, and 30 min) was used to calculate the hourly flux rates based on the ideal gas law, using the chamber air temperature values measured at the time of sampling. The hourly fluxes of CH_4 (mg CH_4 m^{-2} h^{-1}) and N_2O (μg N_2O m^{-2} h^{-1}) were calculated as follows (Minamikawa et al., 2015):

$$\mathrm{Flux}_{CH4} = \frac{\Delta C}{\Delta t} * \frac{V}{A} * \rho * \frac{273}{273 + T} \quad (2)$$

$$\mathrm{Flux}_{N2O} \frac{\Delta C}{\Delta t} * \frac{V}{A} * \rho * \frac{273}{273 + T} \quad (3)$$

where $\Delta C/\Delta t$ is the concentration change over time (ppm-CH_4 or ppb-N_2O h^{-1}); V is chamber volume (m^3); A is chamber area (footprint; m^2); ρ is gas density (0.717 kg m^{-3} for CH_4 and 1.977 kg m^{-3} for N_2O at 0 °C); and T is the mean air temperature inside the chamber (°C).

To calculate the total amounts of CH_4 and N_2O emitted for a sampling interval, the trapezoidal integration method (i.e., linear interpolation and numerical integration between sampling times) was used following these steps as described by Minamikawa et al. (2015). First, the daily gas flux was calculated by multiplying the daily mean hourly gas flux by 24. Second, the emission between every two consecutive measurements was calculated using linear interpolation. We virtually set the fluxes to zero at the start of the land preparation for 2015WS and at the end of the fallow period of 2016DS. Then the daily gas fluxes were summed up to calculate the seasonal emissions. To calculate GWP, radiative forcing potentials (relative to CO_2, for a 100-year time horizon) of 265 and 28 were used for N_2O and CH_4, respectively (IPCC, 2013).

2.2.3. Emissions during straw burning

Methodological constraints impaired a direct measurement of the *in situ* emissions during open-field burning, so a mass balance approach was used to quantify emissions in the straw burning. The Emission Factors (EF_m) for CH_4 and N_2O at 10% moisture content obtained in Exp. A were used to estimate the amount of area-scaled emissions (E_a) for CH_4 and N_2O, respectively, during straw burning following these equations:

$$E_aCH_4(\mathrm{kg\ CH_4 ha^{-1}}) = \frac{EF_m(\mathrm{g\ CH_4 kg^{-1}_{dw}}) * \mathrm{straw\ burned(kg_{dw} ha^{-1})}}{1000} \quad (4)$$

$$E_aN_2O\ (\mathrm{kg N_2O ha^{-1}}) = \frac{EF_m(\mathrm{g\ N_2O\ kg^{-1}_{dw}}) * \mathrm{straw\ burned(kg_{dw} ha^{-1})}}{1000} \quad (5)$$

To calculate GWP, radiative forcing potentials (relative to CO_2, for a 100-year time horizon) of 265 and 28 were used for N_2O and CH_4, respectively (IPCC, 2013).

2.3. Statistical analysis

Analysis of variance (ANOVA) was performed on GWP CH_4, GWP N_2O, and total GWP during the different growth stages (land preparation, growth, and fallow) as well as on seasonal and annual values using PROC MIXED in SAS® version 9.3 (SAS Institute Inc., 2011). Likewise, analysis of variance was also done on seasonal grain yield, yield-scaled GWP and emissions of CH_4 and N_2O. Straw treatment mean comparisons were done using Tukey-Kramer test at the 5% level. The ANOVA of emissions of CH_4 and N_2O during each sampling time was done with statistical tool for agriculture, STAR 1.0 (http://bbi.irri.org/). Differences among treatment means were analyzed by the least significant difference (LSD) at 5% level.

3. Results and discussion

3.1. Experiment A. rice straw residue burning using combustion chamber

3.1.1. Combustion efficiency

Table 1 summarizes the conditions of the rice straw samples during the burning experiment. The initial weights of the straw samples subjected to burning were 444.1 g dry matter (DM) for a constant moisture level of 10%. The combustion period lasted for 14.5 min with only small amounts of unburned residues of approximately 1% of the dry weight left corresponding to an efficiency of 98.7%.

Table 1
Experimental and derived parameters (incl. Emission Factors) of burning of rice straw with moisture content of 10%; uncertainty values denote standard deviation.

Experimental Parameter			
Replication	5	Unburned residue (g DM)	5.9 ± 3.0
Initial residue (g DM)	444.1 ± 2.2	Combustion efficiency (%)	98.7 ± 0.7
Combustion time (min)	14.5 ± 0.0		

Derived Parameter				
	CH_4		N_2O	
	Acronym/unit	Value	Acronym/unit	Value
Mass-scaled EF	EF_m_CH_4 ($g\,CH_4\,kg^{-1}{}_{dw}$)	4.51 ± 0.36	EF_m_N_2O ($g\,N_2O\,kg^{-1}{}_{dw}$)	0.069 ± 0.012
Fraction of element per straw burned	Fraction of C (%)	90.44 ± 0.26	Fraction of N (%)	85.01 ± 0.41
Fraction of C and N released as GHG	C as CH_4-C (%)	1.05 ± 0.08	N as N_2O-N (%)	0.29 ± 0.05
Area-scaled emissions	EF_a_CH_4 ($kg\,CH_4\,ha^{-1}$)	10.04 ± 0.12	EF_a_N_2O ($kg\,N_2O\,ha^{-1}$)	0.154 ± 0.002

Note:
$$\text{Fraction of element per straw burned} = \frac{\text{Straw(C or N)} - \text{‴}\sigma\eta\text{(C or N)}}{\text{Straw(C or N)}} * 100$$
$$\text{Fraction of C and N released as GHG} = \frac{\text{Amount of}(CH_4\text{–C or } N_2O - \text{N})}{\text{Straw(C or N)}} * 100$$

3.1.2. CH_4 and N_2O emission factors

Fig. 2 shows the temporal patterns of CH_4 and N_2O oxide emissions during the straw residue burning. The typical pattern of the combustion comprised the ignition, flaming, and smoldering phase followed by extinction. Fig. 2 shows that the initial two minutes consisted of a rapid increase in CH_4 and N_2O emissions. This strongly suggests that the ignition process was quickly followed by simultaneous occurrence of smoldering and flaming phases in which CH_4 and N_2O were formed, respectively. The smoldering phase began to dominate the next two minutes, which showed a steep decrease in N_2O emissions. CH_4 also had a decreasing trend, most probably because a greater concentration had been generated in the earlier smoldering phase.

Table 1 shows the mass-scaled Emission Factors ($g\,kg^{-1}{}_{dw}$) for CH_4 and N_2O as well as the total straw-C and straw-N lost (%) during straw burning. EF_m for CH_4 was 4.51 $g\,kg^{-1}{}_{dw}$ and for N_2O was 0.069 $g\,kg^{-1}{}_{dw}$. This corresponds to 1.05% and 0.29% of the total C and N released from straw burning, respectively. We also computed the subsequent area-scaled emissions (E_a) that were 10.04 $kg\,CH_4\,ha^{-1}$ and 0.154 $kg\,N_2O\,ha^{-1}$ as averages for both seasons.

3.1.3. Comparison with other studies

Table 2 presents a list of mass-scaled Emission Factors from this experiment in comparison with other relevant studies, namely, those that used straw with similar moisture content as in our study. Our EF_m for CH_4 was higher than the values reported by EPA U.S. (1995), Miura and Kanno (1997), and Hayashi et al. (2014), but was only half of the value reported by Arai et al. (2015). These differences in values could be attributed to the different combustion conditions set prior to burning (i.e. density and compaction of straw materials) and the different infrastructure of the combustion chambers used. As for N_2O, our value was in a similar range as most other values except the EF value reported by Arai et al. (2015) that was almost four times higher. In comparison to the IPCC default value (IPCC, 2006), the Emission Factors from this study are twice as high for CH_4 and almost identical for N_2O (Table 2). However, it should be noted that mass-scaled Emission Factors have been reported to increase at higher moisture contents which is an aspect that will be addressed in a follow-up study.

3.2. Experiment B. GHG emissions from straw burning and other straw management practices

3.2.1. Amount of rice straw residues incorporated, grain yields of rice and yield-scaled GWP

Table 3 shows the amount of dry straw residues incorporated in the different straw treatments, the corresponding grain yields of NSIC Rc18, and the yield-scaled GWP. Based on the total fresh weight, we estimated the dry weight of straw by considering the general moisture conditions in the field that varied by the straw volume and seasons. We also applied a decomposition rate of 25% given that the straw residues were left on the field for more than a month before incorporation. This decomposition rate was based on field observations and resulting estimates by expert scientists. Following the equation by Yadvinder-Singh et al. (2004) the

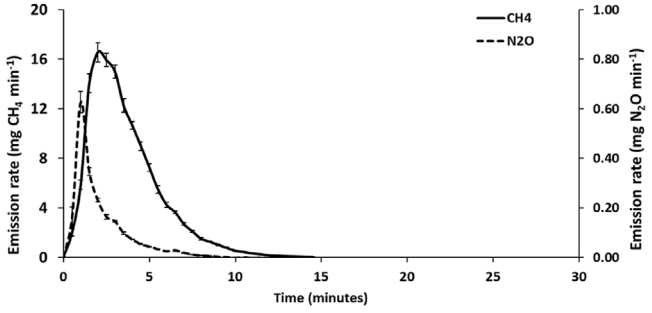

Fig. 2. Temporal patterns of CH_4 and N_2O oxide emissions during straw residue burning at 10% moisture content. Values represent the mean of five replicates ± standard error (SE).

Table 2
Comparison of published mass-scaled Emission Factors for CH_4 and N_2O during burning of rice straw with moisture content of 10–15%.

Moisture content (%)	Emission Factor ($g\,kg^{-1}{}_{dw}$)		Source
	CH_4	N_2O	
15.0	1.20	–	U.S. EPA (1995)
10.6	2.10	0.067	Miura and Kanno (1997)
14.2	4.10	0.083	Miura and Kanno (1997)
10.6	0.70	0.033	Hayashi et al. (2014)
15.0	9.60	0.264	Arai et al. (2015)
10.0	4.51	0.069	This study
Unknown	2.16	0.056	IPCC (2006)[a]

[a] Calculated using given algorithm for biomass burning, Emission Factors of CH_4/N_2O for burning of agricultural residues (Tab. 2.5), and combustion factor of rice (Tab. 2.6).

Table 3
Amount of dry straw residues incorporated, grain yields of cultivar NSIC Rc18, and yield-scaled global warming potential (GWP) in the different straw management treatments.

Straw treatment	2015WS			2016DS		
	Straw incorporated $kg_{dw}\,ha^{-1}$	Grain yield $Mg\,ha^{-1}$	Yield-scaled GWP $kg\,CO_2eq\,Mg^{-1}$	Straw incorporated $kg_{dw}\,ha^{-1}$	Grain yield $Mg\,ha^{-1}$	Yield-scaled GWP $kg\,CO_2eq\,Mg^{-1}$
SRt	2206	5.73 a	718 a	2234	4.41 a	881 a
PSRm	1299*	6.06 a	446 a	1371*	4.14 a	477 ab
CSRm	0	5.94 a	458 a	0	4.24 a	174 b
SB	2206**	5.76 a	531 a	2244**	4.07 a	453 ab

In a column, numbers followed by same letters are not significantly different by Tukey-Kramer test at 0.05 level.
WS – wet season; SRt – straw retained; PSRm – partial straw removed; CSRm – complete straw removed; SB – straw burned.
* estimated weight of 35-cm stubble incorporated.
** amount of straw burned in the field, ash incorporated.

decomposition rate for 36 days would be 47% under incorporation. It can be assumed, however, that the rate is much lower for straw decomposing on top of the soil which is in agreement with our observations. For the PSRm treatment, in which only the stubbles were incorporated, we applied a stubble:straw weight ratio of 0.59 (based on an ancillary study) to estimate the weight of 35-cm stubble incorporated. As average of two seasons, the amount of dry straw residues used for SRt and for SB was about 1.6–1.7 times higher than those used for PSRm. The different straw treatments did not significantly affect grain yields. The average grain yields during 2016DS (4.22 $Mg\,ha^{-1}$) were lower than in 2015WS (5.87 $Mg\,ha^{-1}$) across all straw treatments because of water stress (brought about by El Niño) that occurred just before flowering. However, the straw treatments significantly affected yield-scaled GWP only during 2016DS. SRt had the highest yield-scaled GWP and was significantly higher than CSRm by about 5 times (Table 3).

3.2.2. Seasonal variations in CH_4 flux

Fig. 3 shows the seasonal variations in CH_4 flux during (a) 2015WS and (b) 2016DS cropping periods. Generally during the

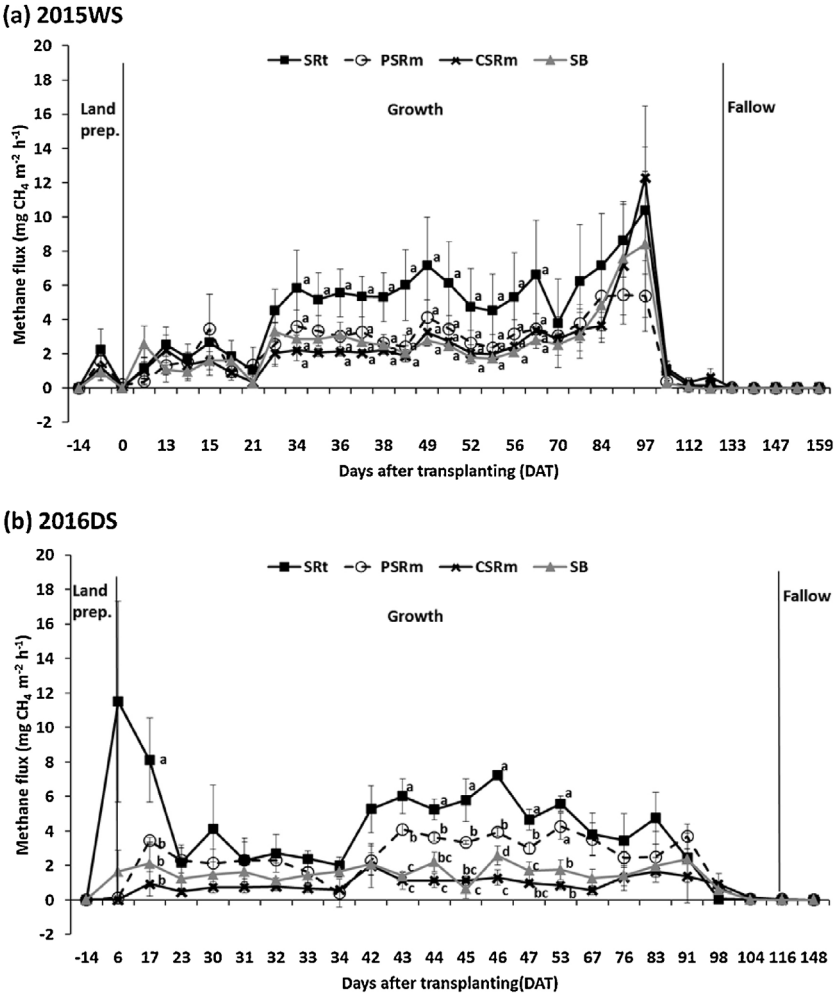

Fig. 3. Seasonal variations in CH_4 flux during (a) 2015WS and (b) 2016DS cropping periods. Values represent the mean of three replicates ± standard error (SE). During each sampling period, the numbers followed by same letters are not significantly different by LSD test at 0.05 level. SRt – straw retained; PSRm – partial straw removal; CSRm – complete straw removal; SB – straw burned.

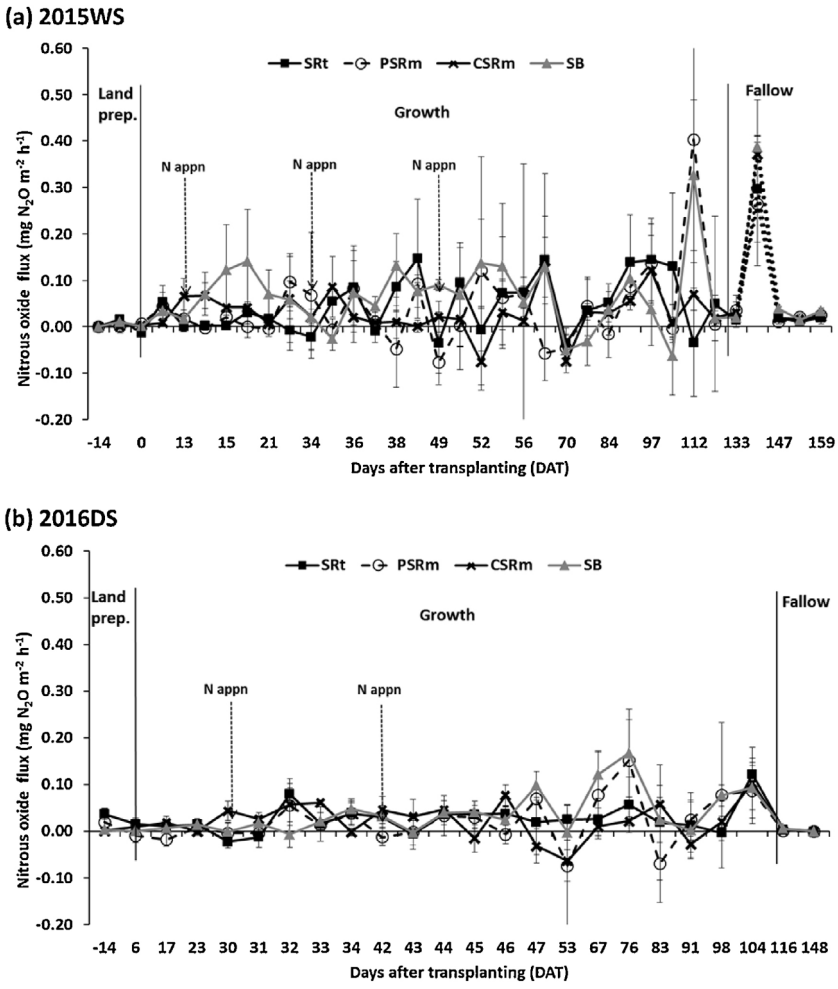

Fig. 4. Seasonal variations in N_2O flux during (a) 2015WS and (b) 2016DS cropping periods. Values represent the mean of three replicates ± standard error (SE). SRt – straw retained; PSRm – partial straw removal; CSRm – complete straw removal; SB – straw burned.

two cropping seasons across straw treatments, CH_4 fluxes started to increase a few days after soaking the rice field for land preparation. Anaerobic soil condition is attained when the field is flooded. The incorporation of straw residues enhanced the reduced conditions in the soil environment and provided labile C substrates, which are favorable for CH_4 formation and emission (Tokida et al., 2010; Yao and Conrad, 2000; Watanabe et al., 1998). The fluxes during land preparation and the early growth stage are controlled largely by CH_4 production from the anaerobic decomposition of soil organic matter and added rice straw residues (Neue et al., 1994). During the growth period, the observed CH_4 flux rates increased and showed pronounced fluctuations, which coincided with the growth of the rice plants. According to Neue et al. (1997), the high CH_4 production and emissions during the growth period are due to the neutral soil pH and stable low soil redox potential under flooded condition, the increased release of plant-borne C substrates, and the increasing capacity of plant-mediated CH_4 transport. During the fallow

Table 4
Seasonal flux of CH_4 and N_2O in 2015WS and 2016DS as affected by different straw management treatments.

	CH_4 flux		N_2O flux	
2015WS	Ave (mg m^{-2} h^{-1})	Cumulative (kg ha^{-1})	Ave (mg m^{-2} h^{-1})	Cumulative (kg ha^{-1})
SRt	3.09 ± 2.04 a	130 ± 86 a	0.04 ± 0.04 a	1.9 ± 1.5 a
PSRm	1.84 ± 0.80 a	77 ± 34 a	0.04 ± 0.04 a	1.8 ± 1.8 a
CSRm	2.01 ± 0.36 a	84 ± 15 a	0.03 ± 0.02 a	1.4 ± 1.0 a
SB	1.86 ± 0.87 a	88 ± 36 a	0.05 ± 0.01 a	2.3 ± 0.6 a
	CH_4 flux		N_2O flux	
2016DS	Ave (mg m^{-2} h^{-1})	Cumulative (kg ha^{-1})	Ave (mg m^{-2} h^{-1})	Cumulative (kg ha^{-1})
SRt	3.09 ± 1.29 a	130 ± 54 a	0.02 ± 0.02 a	1.0 ± 0.7 a
PSRm	1.45 ± 0.30 ab	61 ± 12 ab	0.02 ± 0.02 a	0.7 ± 0.9 a
CSRm	0.53 ± 0.33 b	22 ± 14 b	0.01 ± 0.01 a	0.5 ± 0.4 a
SB	0.97 ± 0.55 b	51 ± 23 b	0.03 ± 0.01 a	1.5 ± 0.2 a

Within a column, numbers followed by the same letters are not significantly different by Tukey-Kramer test at 0.05 level.

period, the daily CH_4 flux was very low due to its low production rate under aerobic soil condition because the field was kept non-flooded (Alberto et al., 2014, 2015; Zhang et al., 2011).

The effects of different straw treatments on CH_4 flux were quite distinct during both cropping periods. In 2015WS, SRt (straw retained) gave the highest CH_4 flux compared with the other three straw treatments during land preparation, growth, and fallow periods (Fig. 3a). The average seasonal CH_4 flux for SRt was about 63% numerically higher than for PSRm (partial straw removal), CSRm (complete straw removal), and SB (straw burned) but not statistically significant (Table 4). During the second season (2016DS), SRt had the same average seasonal CH_4 flux as in 2015WS but the value was now significantly higher than for SB and CSRm treatments (Table 4). The average seasonal CH_4 flux values decreased for both SB and CSRm compared with the values in 2015WS because of the almost negligible amount of residue incorporated; whereas PSRm still gave a comparable average seasonal CH_4 flux value as in 2015WS (Table 4). Wassmann et al. (2000) reported that removal of plant residues from the field resulted in a 65% reduction in emissions under continuous flooding. It is important to note that the standard error of the CH_4 flux was much higher during 2015WS as compared to 2016DS (see Fig. 3). As a result, we only found significant differences in the cumulative CH_4 emissions among treatments in 2016DS (see Fig. 5).

3.2.3. Seasonal variations in N_2O flux

Fig. 4 shows the seasonal variations in N_2O flux during (a) 2015WS and (b) 2016DS cropping periods. Generally, during the two cropping seasons across straw treatments, N_2O fluxes were low, although N_2O flux peaks were observed when the soil was drying towards crop maturity. There was also a huge N_2O flux during the fallow period in 2015WS (140 DAT, as shown by dotted lines), most probably because of a heavy rainfall (36 mm) before that time (Fig. 4a). However, we think it is reasonable to assume that the N_2O surge did not last for two weeks but was much shorter. Therefore, for the calculation of seasonal N_2O emissions, we assumed a narrower peak lasting for only five days. There were surges of N_2O flux after the application of N fertilizer in some cases but no consistent pattern was observed across straw treatments. A larger seasonal variation in N_2O flux was observed during 2015WS than in 2016DS (Fig. 4a and b). This could be because of the soil moisture condition during the fallow period before the growing season. The fallow period before the 2015WS was drier (with 44.8 mm rainfall) than the fallow period before the 2016DS (with 87.6 mm rainfall). Sander et al. (2014) reported that the dry fallow period has higher values of soil redox potential, which favors N_2O production. Results also showed that negative N_2O fluxes were observed in all treatments. Lardy et al. (2007) and Sander et al. (2014) also observed negative fluxes of N_2O from their field measurements, probably because of the reduction of N_2O to N_2. The average seasonal N_2O fluxes were numerically higher during 2015WS than in 2016DS across all straw treatments, but not statistically significant (Table 4).

3.2.4. GWP contribution of CH_4 and N_2O during different growth periods

Fig. 5a shows the GWP contribution of CH_4 and N_2O during the different growth periods in 2015WS as affected by different straw management treatments. During land preparation, the total GWP was primarily attributed to CH_4 fluxes (90–98%) across all straw treatments (Table 5). SRt had the highest total GWP, followed by PSRm and CSRm while SB had the lowest total GWP. However, during open-field burning of straw residues, the GWP contribution of CH_4 was 279 kg CO_2eq ha^{-1} and that of N_2O was 40 kg CO_2eq ha^{-1} (Table 5). We used the Emission Factors obtained in the straw burning experiment using a combustion chamber (see Table 1) to calculate the GWP contribution of CH_4 and N_2O during the open-field straw burning. During the growth period (Fig. 5a), CH_4 contributed 82–90% to the total GWP across all straw treatments. SRt gave the highest CH_4 flux while SB had the highest N_2O emissions (Table 5). During the fallow period (Fig. 5a), the total GWP was dominated by N_2O (95%), with SB having the highest fluxes across all straw treatments (Table 5). The CH_4 flux was very low because of the aerobic soil condition during fallow.

Fig. 5b shows the GWP contribution of CH_4 and N_2O during the different growth periods in 2016DS as affected by different straw management treatments. During land preparation, the total GWP of SRt was 404 kg CO_2eq ha^{-1} due to large amounts of CH_4 emitted compared with the other three straw treatments, which was most probably because of the fresh rice straw incorporated and the residual effect of the straw incorporated during the previous season (Table 5). SB had the second-highest total GWP (67 kg CO_2eq ha^{-1}). However, during open-field burning of straw residues, the GWP contribution of CH_4 was 283 kg CO_2eq ha^{-1} and that of N_2O was 41 kg CO_2eq ha^{-1} (Table 5). We again used the Emission Factors obtained in the straw burning experiment using a combustion chamber (see Table 1) to calculate the GWP

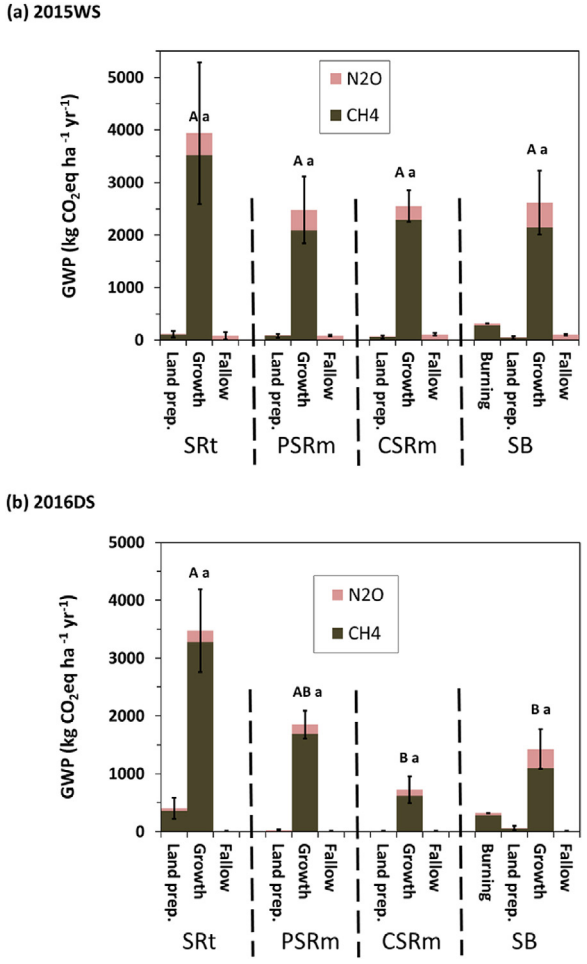

Fig. 5. Total GWP (CH_4 and N_2O) of all straw treatments encompassing land preparation, growth and fallow periods as well as computed GWP of straw burning during (a) 2015WS and (b) 2016DS. Values represent the mean of three replicates ± combined standard error (SE). The different upper case letters reflect a significant difference ($\rho < 0.05$) in GWP CH_4; while different lower case letters reflect a significant difference ($\rho < 0.05$) in GWP N_2O (using Tukey-Kramer test) during the growth period only. SRt – straw retained; PSRm – partial straw removal; CSRm – complete straw removal; SB – straw burned.

Table 5
Global warming potential (GWP) contribution of CH_4 and N_2O during different periods in 2015WS and 2016DS in different straw management treatments.

No. of days	Period	GWP CH_4 (kg CO_2eq ha^{-1})				GWP N_2O (kg CO_2eq ha^{-1})				Total GWP (kg CO_2eq ha^{-1})			
		SRt	PSRm	CSRm	SB	SRt	PSRm	CSRm	SB	SRt	PSRm	CSRm	SB
2015WS													
	Straw burning				279				40				319
14	Land prep.	107[a]	77[a]	58[a]	44[a]	5[a]	2[a]	1[a]	5[a]	111[a]	79[a]	59[a]	49[a]
125	Growth	3525[a]	2088[a]	2290[a]	2141[a]	411[a]	389[a]	262[a]	473[a]	3936[a]	2478[a]	2553[a]	2614[a]
36	Fallow	6[a]	2[a]	12[a]	0[a]	78[a]	82[a]	98[a]	104[a]	85[a]	84[a]	110[a]	104[a]
175	Season	3638[a]	2168[a]	2361[a]	2464[a]	494[a]	473[a]	362[a]	622[a]	4132[a]	2641[a]	2722[a]	3086[a]
2016DS													
	Straw burning				283				41				324
26	Land prep.	355[a]	5[a]	1[a]	51[a]	49[a]	25[a]	11[a]	15[a]	404[a]	30[a]	13[a]	67[a]
113	Growth	3277[a]	1690[ab]	617[b]	1095[b]	199[a]	162[a]	110[a]	332[a]	3476[a]	1852[ab]	727[b]	1427[b]
14	Fallow	2[a]	5[a]	2[a]	0[a]	8[a]	3[a]	6[a]	10[a]	11[a]	8[a]	8[a]	10[a]
175	Season	3634[a]	1700[ab]	620[b]	1430[b]	256[a]	190[a]	128[a]	398[a]	3891[a]	1890[ab]	748[b]	1827[ab]
Annual													
350		7273[a]	3868[b]	2981[b]	3894[b]	750[a]	663[a]	489[a]	1020[a]	8023[a]	4531[ab]	3470[b]	4913[ab]

Within a row and within a parameter, numbers followed by same letters are not significantly different by Tukey-Kramer test at 0.05 level.

contribution of CH_4 and N_2O during the open-field straw burning. PSRm and CSRm had very low total GWP probably because of the negligible amount of straw residue incorporated for two seasons. During the growth period (Fig. 5b), CH_4 also contributed (77–94%) to the total GWP across all straw treatments. Similar to the results in 2015WS, SRt gave the highest CH_4 flux while SB had the highest N_2O emissions (Table 5). During the fallow period (Fig. 5b), the total GWP was lower than in 2015WS across all straw treatments. However, it was also dominated by N_2O (72%), with SB having the highest fluxes across all straw treatments (Table 5).

3.2.5. Annual cycle of GWP of straw burning and straw incorporation

One of the major objectives of this study was an inter-comparison of the CH_4 and N_2O footprint of straw burning with other straw management practices. However, our emissions were only measured on the paddy field; we have not included off-field measurements. Nonetheless, a life cycle assessment of GHG emissions from these different rice straw management practices will be addressed in a follow-up study. We recognize that for the treatments with partial and complete removal of straw, the ultimate GWP will largely depend on the nature of straw use off-field. In case the rice straw is fed to cattle, the overall GWP will be high. Rice straw has low nutritional value and entails high methane emission rates (Malik et al., 2015; Sarnklong et al., 2010; Van Soest, 2006). In the study of Launio et al. (2016), removing rice straw for use as animal feed resulted in a net increase of 13% in total GWP compared to straw burning. Other applications of straw, for example, mushroom production, power generation or bio ethanol production entail lower total GWP (Arai et al., 2015; Cheng and Timilsina, 2011; Delivand et al., 2011; Kim and Dale, 2004). Arai et al. (2015) found that straw-mushroom cultivation had 12.5% lower total GWP than straw burning. Delivand et al. (2011) found that by substituting natural gas or coal fuels with rice straw fuels for power generation would result in a considerable fossil fuel savings and a lower GHG emission. It was estimated that 0.378 t CO_2eq/t straw (db) and 0.683 t CO_2eq/t straw (db) could be avoided if rice straw substitutes natural gas or coal in the power generation sector, respectively. Regarding the use of rice straw for bio ethanol production, a review by Cheng and Timilsina (2011) reported that all advanced bio fuel technologies have the advantage of producing fuels with almost zero or very little net CO_2 emissions to the atmosphere. Given the inherent uncertainties in off-field emissions associated with these two treatments, we have focused our comparative assessment of CH_4 and N_2O footprint on the treatment with complete incorporation of straw as a baseline for straw burning. The results illustrated in Fig. 6a, b showed that burning plays only a fairly minor role within the overall GWP of rice production. The total GWP from burning was about 39% lower than with straw incorporation. Incorporating the straw results in high emissions during the growth period (Fig. 6a) that accounted for >92.4% of the total. Even for the treatment with straw burning, the GWP was dominated by emissions during the growth period (Fig. 6b) that accounted for 82.3%. Burning accounted for only 13.1% of the annual GWP over the entire cropping cycle. Given this relatively small contribution, the mitigation potential of

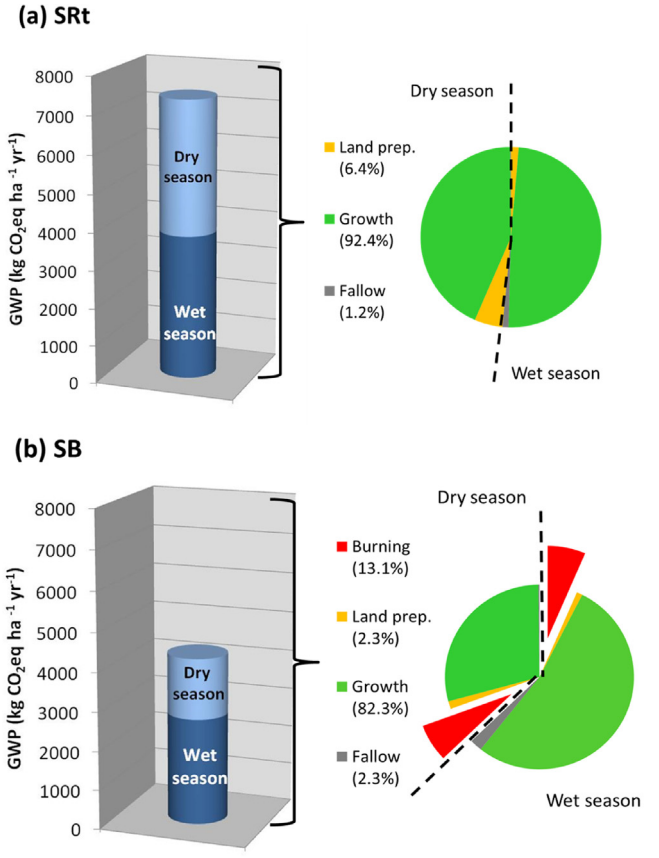

Fig. 6. Annual cycle of GWP of the treatments (a) SRt and (b) SB encompassing land preparation and growth and fallow periods.

alternative straw management will also be fairly constrained as opposed to measures targeting emissions during the growth period. However, improved straw management offers numerous co-benefits and can be applied to almost all rice-growing environments in Asia. In contrast to this almost ubiquitous approach, changes in crop and water management rely on certain pre-requisites that determine their applicability, such as good irrigation facilities for alternate wetting and drying. In turn, alternative straw management could still represent an important component of a wider mitigation program in rice production combining in-depth changes for specific environments and in-width changes across the board.

Although the combustion process during open-field burning is to a certain extent incomplete, the bulk of the biomass is emitted in the form of fully oxidized compounds, namely, CO_2 and NO_2 (Oanh et al., 2011; Jenkins et al., 2003). These emissions are negligible in terms of GWP as CO_2 from agricultural residues does not account for net GHG emissions and NO_2 is not a GHG (disregarding a very small indirect effect through wet deposition and subsequent N_2O emission). However, the CH_4 and N_2O footprint as assessed in our study represents only one aspect of the environmental impacts caused by straw burning. Even if the effect of straw burning is relatively small in terms of GWP, this should by no means be taken as an argument in favor of this practice. Open-burning of rice straw in the field also emits a large amount of pollutants, including toxic gases such as CO, volatile organic compounds, carcinogenic polycyclic aromatic hydrocarbons, as well as fine inhalable particles, aside from the greenhouse gases (Oanh et al., 2011; Jenkins et al., 2003). These emissions cause air pollution that adversely affects human health.

Additionally, rice straw burning causes the loss of major nutrients from the soil – almost complete N loss, P losses of about 25%, K losses of 20%, and S losses of 5–60% (Dobermann and Fairhurst, 2002). On the other hand, the complete removal of stubbles and rice straw residues (CSR), which had the lowest total GWP, may not be beneficial for soil health in the long term. Removal of straw from the field can lead to depletion of K and Si reserves in the paddy (Dobermann and Fairhurst, 2002). However, long-term research at IRRI has shown that, with careful and effective crop and soil management, all straw can be removed from flooded rice fields after harvest without reducing the levels of soil organic matter or soil fertility (Pampolino et al., 2008; Singh et al., 2008). In terms of cost-effectiveness, removal of stubbles and straw from the field entails significant labor-cost (Launio et al., 2016). The use of combine harvesters leave the stubbles standing on the field and the rice straw spread on top of the stubble; so the rice stubbles need to be cut manually to be recovered.

These are some of the important factors to consider (air pollution, nutrient management, and labor-cost) aside from on-field and off-field total GWP contribution; but one has to make careful assessment of the best straw management practice suitable for a specific rice growing system and environment.

4. Conclusions

This study comprises the first GHG measurements from rice straw burning under controlled conditions in the Philippines. Emissions have been assessed during the entire annual cycle (incl. open-field burning) whereas previous studies were limited to the cropping season (land preparation, growth, and fallow) or the burning as such. Straw burning showed lower GWP (−39%) as compared to a baseline of full retention of straw and soil incorporation, though statistically not significant. The GWP contribution of CH_4 and N_2O fluxes during open-field burning collectively corresponded to 13.1% of total emissions. Although this fraction may be regarded as relatively small, mitigation targeting straw burning offers many synergies with other development objectives. Increasing air quality and thus sustainability of rice production could become a major incentive for policies that reduce emissions from straw burning. The Emission Factor of CH_4 obtained with relatively dry straw (10% moisture content) exceeded the IPCC default value by a factor of 2.1. Even though the Emission Factor of N_2O was almost identical to the IPCC value, CH_4 was the main contributor to the total emissions and GWP. This contribution will even be aggravated given the expected increase in CH_4 Emission Factors as a function of moisture contents as reported in other studies. In conclusion, the IPCC estimates seem to considerably underestimate the actual GHG emissions from rice straw burning.

These data should be instrumental in improving national and global emission assessments. Notwithstanding these potential applications of our data, we recognize that further studies for verification are needed, including improvement of the experimental design and consideration of the variability of factors that determine straw burning in time and space.

Acknowledgments

We acknowledge the CGIAR Fund Council, Australia (ACIAR), Irish Aid, European Union, International Fund for Agricultural Development (IFAD), Netherlands, New Zealand, Switzerland, UK, USAID and Thailand for funding to the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS); Engineering and Physical Sciences Research Council (EPSRC); and the IRRI Zeigler Experiment Station. We also thank the German Federal Ministry for Economic Cooperation and Development (BMZ) for its generous funding through the “Scalable straw management options for improved farmer livelihoods, sustainability, and low environmental footprint in rice-based production systems” project (IRRI Ref. No. A-2015-48; Contract No. 81194994).

We express appreciation to Eduardo Secretario for managing the field operations. We also acknowledge the assistance of Angel Bautista, Venjie Carandang, Ryan Sityaro, and Jonathan Escusura for the conduct of the straw burning experiment, and to Feliza Navor for the GC analysis of gas samples.

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