Methane and nitrous oxide emissions from conventional and modified rice cultivation systems in South India

Research Paper

Methane and nitrous oxide emissions from conventional and modified rice cultivation systems in South India

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ABSTRACT

Rice (*Oryza sativa* L.) production is facing major challenges, including scarcity of irrigation water and ongoing climate change. Modifications of the current cropping techniques could increase yield, save water, and mitigate greenhouse gas emission. We investigated the effect of planting methods (young seedlings, wide spacing with alternate wetting and drying irrigation [YW-AWD], old seedlings, narrow spacing with continuous flooding [ON-CF], and in-between the two planting methods [IB-AWD]) and rice varieties on methane (CH_4) and (N_2O) emissions during two crop seasons. The results show that CH_4 emission, averaged over rice varieties, reduced for YW-AWD by 41% and 24%, compared with ON-CF, while the reduction in emission for the IB-AWD method was 48% and 26% in summer (dry) and monsoon (wet) season, respectively. However, an increase in N_2O emission was observed for YW-AWD and IB-AWD methods in both seasons. There was no significant difference in CH_4 and N_2O emissions between the tested varieties. The total water saving under YW-AWD and IB-AWD was 47.5% and 49.3% in summer, and 79.4% and 79.8% in monsoon season, respectively, compared with ON-CF. The grain yields of YW-AWD and IB-AWD were comparable with the yield of ON-CF in both seasons. The CO_2-eq emission and yield-scaled CO_2-eq emission from YW-AWD and IB-AWD were significantly lower compared with ON−CF due to low CH_4 emission, while maintaining similar rice yields. This study showed that the YW-AWD and IB-AWD methods are effective in reducing CO_2-eq emission and saving irrigation water, while maintaining the rice yield.

1. Introduction

Agriculture is estimated to account for 10%–20% of anthropogenic greenhouse gas (GHG) emissions worldwide (Smith et al., 2008); in 2005, it accounted for 50% and 60% of the total anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions, respectively. Rice paddies are considered one of the most important sources of CH_4 and N_2O emissions, which have attracted considerable attention due to their contribution to global warming (Harris et al., 1985; Bouwman, 1990). In India, paddy rice cultivation occupies about 44 million ha, the largest rice producing area in Asia, and accounts for 20% of the total rice production worldwide. India would need to produce up to 130 million t

of milled rice by 2030 to meet the growing demands, in contrast with 92 million t in 2005 (Gujja and Thiyagarajan, 2009). To ensure food security for the growing population, expansion of rice-cropped area and continuous intensification of rice cultivation would likely increase greenhouse gas emissions. Data on trade-offs between rice yield increase and reduction in greenhouse gas emissions are urgently needed for innovation in cropping techniques.

Modification of current cropping technique might be a way to reduce greenhouse gas emissions from rice soil. In this respect, a system of rice intensification has been introduced as an efficient, resource saving, and productive strategy to practice rice farming. It involves reduced water application, organic amendments, and transplanting

young single seedling per hill with wide spacing. Studies have reported a positive effect on yield (Gujja and Thiyagarajan, 2009; Jain et al., 2014) and reduction in CH_4 emission under this method (Fazli and Man, 2014). However, some other studies have found no significant effect on grain yield or even a negative effect, with the system of rice intensification (Chapagain et al., 2011; Jain et al., 2014). This might be due to a reduction in the initial population size while transplanting a single seedling per hill. Therefore, another cultivation method was introduced, which was in-between the conventional practice and the system of rice intensification. In this cultivation system, 2–3 seedlings should be planted per hill with wide spacing, to increase the initial population size at transplanting.

One practice that has been shown to reduce the water use in rice systems is alternate wetting and drying irrigation (AWD) (Linquist et al., 2014; Lampayan et al., 2015). It is an approach to increase rice productivity through proper management of resources. This practice is being promoted by the International Rice Research Institute (IRRI) and the national research and extension programs in Bangladesh, India, and other parts of the world, as a water-saving irrigation practice. In Bangladesh, on-farm trials indicated that AWD reduced the irrigation input by 13%–38%, while increasing the yield by 0.4–1.0 t ha^{-1} (Lampayan et al., 2015). Various studies have also reported that AWD irrigation can save irrigation water without losses in rice grain yield (Yao et al., 2012; Belder et al., 2004), while reducing CH_4 emission from the rice soil (Yagi et al., 1996; Ly et al., 2013). However, considerable amounts of N_2O emission could occur in rice fields because of AWD (Xu et al., 2015). In terms of the global warming potential (CO_2-eq emission), the cumulative N_2O emission was lower than that of CH_4 emission from rice soil (Kurosawa et al., 2007). Previous studies also reported that N_2O emissions contribute much less to the global warming potential than CH_4 (Yan et al., 2005; Itoh et al., 2011; Pittelkow et al., 2013; Sander et al., 2015; Tarlera et al., 2016). Therefore, decreasing mainly the CH_4 emissions from rice soil is the most effective way to mitigate total greenhouse gas emission from rice production. However, the effect of AWD management under modified planting techniques on CH_4 emission, and its potential trade-off with increased N_2O emission from rice paddy, has not yet been investigated in South India, where 28% of Indian rice is grown.

Although there are many advantages of using the AWD irrigation practice, it is not easy for practical use by farmers; unless simple irrigation indices are developed, it is difficult for them to decide the best time for irrigating their crop. The International Rice Research Institute (IRRI) and Institute for Agro-Environmental Science (NIAES) developed a set of simplified guidelines for AWD irrigation system, using a field water tube as a tool to monitor the water level below the soil surface (Minamikawa et al., 2015). They used a perforated field water tube so that the water table is easily visible. Irrigation is applied when the perched water table falls to 15 cm below the soil surface. The threshold of 15 cm is called "safe AWD" as this does not cause any decline in the yield. However, the performance of safe AWD technology under modified planting method has not yet been evaluated in South India, where double cropping of paddy rice is practiced per year. In Tamil Nadu, the sixth largest rice-producing state in India, 89% of about 2 M ha paddy area is under irrigated conditions, of which, 54% of the paddy rice is irrigated by pumping of underground water; thus, AWD would allow farmers to control their irrigation during the two rice crop seasons in a year. There is a huge potential to reduce the irrigation water use and mitigate greenhouse gas emissions from paddy rice fields by practicing modified cultivation systems in Tamil Nadu, South India. Therefore, this experiment was conducted to (i) assess the effects of modified rice cultivation systems on water usage, crop yield, and methane and nitrous oxide emissions, (ii) compare rice varieties in terms of rice yield and GHG emissions, and (iii) evaluate global warming mitigation potential of modified cultivation systems for a sustainable rice production in both summer (dry) and monsoon (wet) seasons in Tamil Nadu, South India.
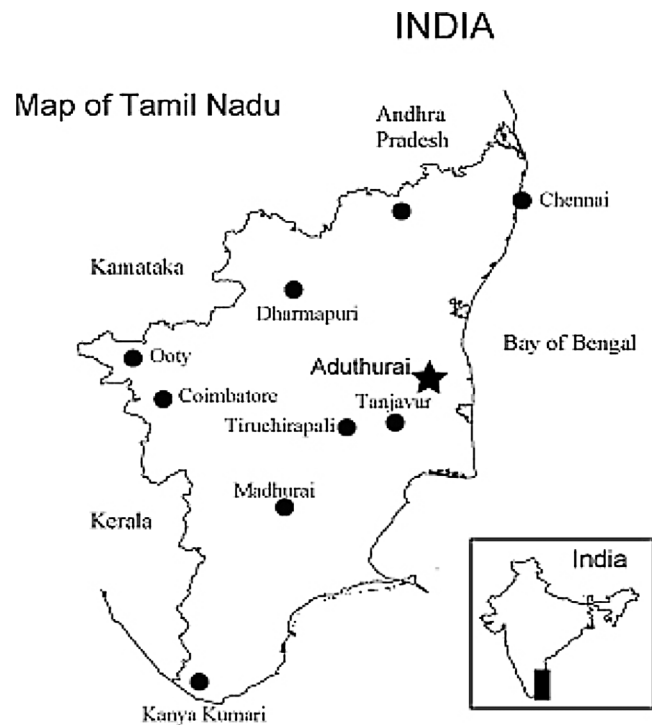

Fig. 1. Location of the experimental site in Aduthurai, Tamil Nadu, India. The site is characterized flat terrain in the Kaveri river system. ArcGIS 10.1, ESRI, Redland.CA. https://www.esrij.com/products/arcgis-for-desktop. GADM: Global Administrative Areas (2012). GADM database of Global Administrative Areas, version 2.0 [online] URL:gadm.org.

2. Materials and methods

2.1. Experimental site and design

The field experiments were carried out from May 2016 until January 2017, during two rice growing seasons, at the Tamil Nadu Rice Research Institute (TRRI), Aduthurai, Thanjavur District, Tamil Nadu (11°0′N, 79°30′E, 19.4 m MSL), South India (Fig. 1). The agro-ecological conditions in the area were: a tropical wet and dry/savanna climate with a pronounced dry season in the high-sun months, and no cold or wet seasons (monsoon season) in the low-sun months, with an annual precipitation of 1292 mm in 2015. The rainfall, and minimum and maximum temperatures during the experimental period, as recorded at the meteorological observatory of TRRI, are shown in Fig. 2. The soil was classified as Alluvial clay (United States Department of Agriculture, USDA classification). A rice–rice (*Oryza sativa* L. ssp. *indica*)-black gram (*Vigna mungo*) cropping rotation system is the typical practice in this area. The experimental soil was composed of: 1.1 g kg^{-1} total nitrogen (N), 19.6 g kg^{-1} total carbon (C), pH 7.5 (1:5H$_2$O) and EC 11.6 mS m^{-1}, 13.6% sand, 61.2% silt, and 25.3% clay (Inubushi et al., 2017).

There were two crop seasons, summer – hot and dry season (local name – Kuruvai season; from May to September) and monsoon – wet season (local name – Thaladi season; from September to January) in this experiment. The experiment was laid out in a split plot design with three replications. The two set of factors included in this experiment were as follows: three different planting methods, i.e., i) transplanting old seedlings with narrow spacing with continuous flooding (ON-CF), ii) transplanting young seedlings, wide spacing with alternate wetting and drying irrigation (YW-AWD), and iii) in-between conventional practice and YW-AWD (IB-AWD) as main plots, and two currently grown rice varieties, i.e., variety ADT 43 and CO 51 in summer season and variety ADT 46 and TKM 13 in monsoon season, as sub plots. Each experimental plot measured 7 m × 5 m. To prevent lateral seepage, we
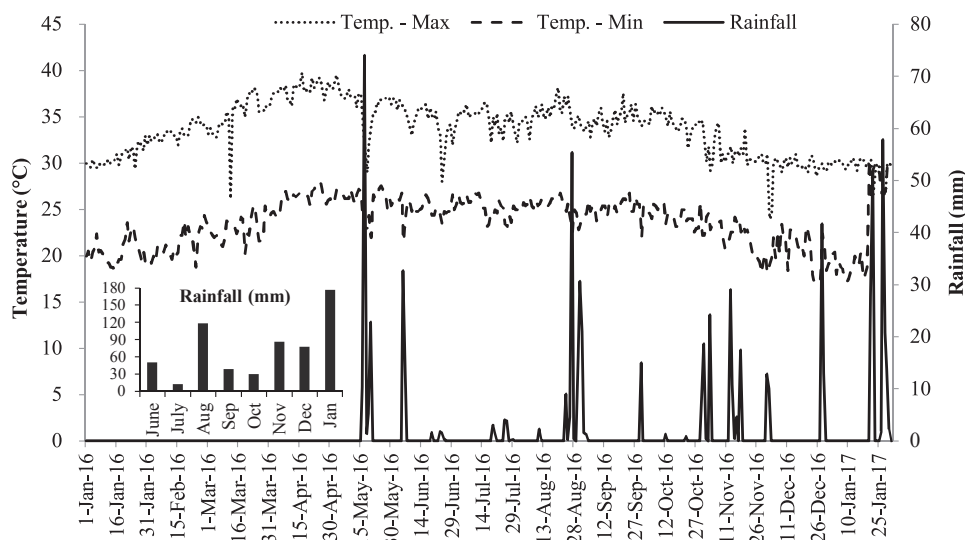
Fig. 2. Daily average rainfall, maximum and minimum temperatures from January 2016 until January 2017 as measured at experimental site of Tamil Nadu Rice Research Institute, Aduthurai, Tamil Nadu, India. Insert shows the monthly accumulated rainfall.

used triple bunds and maintained the main plots 2.5 m apart from each other.

In the summer season, 12-day old seedlings were transplanted on 2nd June 2016, with one seedling per hill in a puddled field at 25 cm × 25 cm spacing in the YW-AWD practice. To avoid damage to the young and tender single seedlings during transplanting, 16-day old seedlings were transplanted with 2–3 seedlings per hill at 25 cm × 25 cm spacing in the IB-AWD practice, on 6th June 2016. In the ON-CF practice, 25-day old seedlings were transplanted on 15th June 2016 with 2–3 seedlings per hill at 10 cm × 15 cm spacing. For monsoon season, 8-, 15-, and 25-day old seedlings were transplanted on 29th September, and 5th and 15th October 2016 for the YW-AWD, IB-AWD, and ON-CF methods, respectively, with the same spacing and seedling number as in the previous crop.

The field was flooded 15 days before puddling on 15th May 2016, in the summer season, and for 7 days before puddling on 23rd September 2016, in the monsoon season. In both the crop seasons, the puddling was conducted using cattle. After transplanting, the water level was maintained at a height of 2–3 cm above the soil surface for the first two weeks for all planting methods. In the ON-CF practice, at two weeks after transplanting, continuous flooding was done with a water depth of 5 cm throughout the rice–growing season until the final drying period before harvest. For alternate wetting and drying irrigation in YN-AWD and IB-AWD methods, a perforated, 25-cm long field water tube was used in this experiment. Bottom 15 cm of the tube was perforated with multiple holes on all sides. The tube was placed 15 cm deep into the soil. Two weeks after transplanting in the YN-AWD and IB-AWD methods, the AWD cycle was started and it continued until 14 days before harvest. After irrigation, the water depth gradually decreased. When the water level had dropped to about 15 cm below the soil surface, irrigation was applied to re-flood the field to a depth of about 3–5 cm. Irrigation was done by pumping underground water.

The recommended fertilizers were applied at 150 kg N ha^{-1}, 50 kg P$_2$O$_5$ ha^{-1}, 50 kg K$_2$O ha^{-1}, 25 kg ZnSO$_4$ ha^{-1}, and 500 kg gypsum ha^{-1}. Gypsum and zinc sulfate, and diammonium phosphate (DAP) as a source of phosphorus, were applied as basal fertilizers. Urea as a source of nitrogen, and muriate of potash as a source of potassium, were applied in three equal portions at active tillering, heading, and flowering time. For weed management, a rotary weeder was used in the YN-AWD and IB-AWD methods, whereas, in the ON-CF method, manual hand weeding was done. Crop was harvested at physiological maturity. The harvest dates were 14th September 2016 for summer, and 18th January 2017 for monsoon season.

2.2. Gas sample collection, analysis, and calculation

The samples used to determine CH$_4$ and N$_2$O concentrations were collected using the closed chamber method (Minamikawa et al., 2015). The sampling frequency was once every week. However, air sampling was done twice a week during the early water management period of the summer rice and whenever there was a fertilizer application event, air sampling was done one day after fertilization. The gas samples from all the plots were collected 22 and 20 times during the rice-growing period in summer and monsoon seasons, respectively. Inside the chamber, an electric fan was installed to circulate the air, and a pressure-regulating bag was kept to avoid pressure changes. Gas samples were drawn from the chambers through a three-way stopcock using an airtight 50-mL syringe at 0, 15, and 30 min after closure. The air inside the chamber was thoroughly mixed by flushing the syringe five times before collection of the gas samples. The sample gasses were then transferred to 15-mL vacuum glass vials with rubber stoppers, and kept cool and dark until analysis. The temperature inside the chamber was recorded at the time of sampling using a micro-temperature thermometer (PC-9125, AS ONE Co., Tokyo, Japan). The concentrations of CH$_4$ and N$_2$O were analyzed using a gas chromatograph (GC 2014, Shimadzu Corporation, Kyoto, Japan) equipped with a flame ionization detector (FID) and an electron capture detector (ECD), respectively. All samples were analyzed within one month after collection at the laboratory of Institute for Agro-Environmental Science (NIAES), National Agriculture and Food Research Organization, Tsukuba, Japan. The CH$_4$ and N$_2$O fluxes were calculated by examining the linear increases in CH$_4$ and N$_2$O concentrations in the headspace of the chambers over time. The total seasonal CH$_4$ and N$_2$O emissions from all plots were calculated directly from the fluxes.

2.3. CO$_2$ equivalent emission

The equivalent CO$_2$ (CO$_2$-eq) emission for total CH$_4$ and N$_2$O emissions (greenhouse gas intensity) was calculated using the equation:

$$CO_2\text{-eq} = (TCH_4 \times 34 + TN_2O \times 298)$$

where CO$_2$-eq is the total amount of equivalent CO$_2$ emission (kg CO$_2$-eq ha^{-1}), TCH$_4$ is the total amount of CH$_4$ emission (kg ha^{-1}), TN$_2$O is the total amount of N$_2$O emission (kg ha^{-1}), 34 and 298 are the global warming potentials for CH$_4$ and N$_2$O, respectively, to CO$_2$ over a 100-yr time horizon (IPCC, 2013).

2.4. Water use and productivity

Irrigation depth for all treatments was measured using an ordinary scale meter. In each plot, the depth of water was measured at nine selected spots after each irrigation. The mean depth of irrigation water was calculated for each plot. The other measurements were calculated using the following equations by Suryavanshi et al. (2012):

Irrigation water use (mm) = sum of mean depth of each irrigation

Total water use (mm) = irrigation water use (mm) + rainfall (mm)

Water saving (%) = (water used in ON-CF – water used in YW-AWD or IB-AWD) × 100/water use in ON-CF

2.5. Other data measurements

Soil temperature at a depth of 10 cm was recorded at the time of gas sampling. The redox potential was recorded using a battery-operated Eh meter (YK-23RP, Taiwan) by inserting the platinum electrode into the soil under investigation to a root-zone depth of 5 cm. The daily surface water depth was also recorded. At maturity, the grain yield was determined from a 1-m^2 sampling area at harvest, and was expressed as rough (unhulled) rice at 14% moisture content. The above-ground straw yield was also determined after drying the plant materials at 80 °C for two days.

2.6. Statistical analysis

The effects of the treatment factors (planting methods and rice variety) on CH_4 and N_2O emissions from the rice paddies were examined. The experimental data were analyzed by analysis of variance (ANOVA) using CropStat 7.2 statistical software program (International Rice Research Institute, IRRI, Philippines). The treatment mean comparisons were done at 5% level of probability using the least significant difference (LSD) test. Pearson correlation analysis was done using XLSTAT statistical software program.

3. Results

3.1. Weather conditions and water usage

The total precipitation was 577 mm over the two rice-growing seasons of year 2016–2017 (Fig. 2). The summer rice-growing season experienced 206 mm of rainfall while the monsoon rice season accounted for 210 mm of rainfall. When compared with the monsoon season (878 mm) of year 2015–2016, the monsoon rice season of year 2016–2017 was relatively low in rainfall amount. To meet the plant demand for water during growth and development under low rainfall, the total number of irrigations provided in the ON-CF method was 21 times in summer and 10 times in the monsoon season (Table 1). With

AWD, the number of irrigations was reduced to 11 times in summer and only twice in the monsoon season. Thus, there was a saving of 10 and 8 irrigation times for summer and monsoon seasons, respectively. The total amount of irrigation in the ON-CF method was 930 mm in summer and 526 mm in the monsoon season. In the YN-AWD and IB-AWD methods, it was 488 and 471 mm in summer, and 108 and 106 mm in the monsoon season, respectively. Therefore, 47.5% and 49.3% water saving was observed under YN-AWD and IB-AWD in summer, and 79.4% and 79.8% in the monsoon season, respectively.

3.2. Soil environmental factors

In the summer season, the soil Eh was as low as −150 mV during the first week and then it showed an increasing trend toward the end of growing period (Fig. 3e–f). The conventional method showed mostly lower-than-average soil Eh values than the modified methods in both rice varieties. In the monsoon season, the soil Eh values for all the treatments were generally lower than −100 mV during vegetative growth period (Fig. 4e–f). From the middle growing period, YN-AWD and IB-AWD showed an increasing trend toward the end of growing period, whereas the ON-CF method maintained a lower soil Eh value, except at the harvest time. Large differences in soil surface water depth were observed among the planting methods due to different water management practices throughout the rice growing period (Figs. 3 g–h and 4 g–h).

Soil temperature was high during the early growing period in summer season with the highest value recorded on 20th June (Fig. 3i–j). The soil temperature then decreased and remained less variable until the end of the growing period. In the monsoon season, soil temperature was higher during early and middle growing periods and decreased gradually by the end of the growing period, except on 30th December (Fig. 4i–j). In both rice varieties, the water depth and soil temperature were showed a close association (Figs. 3 g–j and 4 g–j).

3.3. Methane flux

In the summer season, CH_4 flux increased during the early growing period and then gradually decreased toward the end of the growing period (Fig. 3a–b). The CH_4 flux from ON-CF showed two emission peaks, both occurring during the vegetative growing period. In YN-AWD and IB-AWD, a high emission peak was observed when AWD irrigation started. Significant (P < 0.05) differences in the rate of CH_4 emission were observed among the planting methods (Table 2). The highest rate of average CH_4 emission was observed in ON-CF among the three planting methods. There was no significant difference between the YN-AWD and IB-AWD methods. In the monsoon season, CH_4 flux increased from the beginning, and peaked for the first time within two weeks, then showed a decreased emission in both rice varieties (Fig. 4a–b). Thereafter, the CH_4 flux from YN-AWD and IB-AWD increased, peaked for a second time at the middle of the growing period, and then gradually decreased toward the low emission value due to AWD irrigation. The CH_4 flux from ON-CF also showed a high emission peak for the second time and tended to remain high during the middle and later growing periods. In all the planting methods, the CH_4 flux increased again, peaked for the third time at the final stage of growing period and then decreased to the lowest value at harvest time due to dry conditions. Rate of CH_4 emission was significantly higher in ON-CF in comparison with YN-AWD and IB-AWD (Table 2). No significant difference (P > 0.05) in the rate of CH_4 emission was observed between rice varieties in either crop season.

A significant (P < 0.05) difference in the cumulative CH_4 emission was observed among the planting methods (Table 2). In summer season, the highest cumulative CH_4 emission was observed in ON-CF. Compared with ON-CF, YN-AWD and IB-AWD reduced the cumulative CH_4 emissions by 40% and 55% in ADT 43, and by 42% and 43% in CO51, respectively. In the monsoon season, the cumulative CH_4 emissions

Table 1
Water usage influenced by different planting methods in summer and monsoon rice growing seasons.

Season	Treatment	No. of Irrigation	Irrigation water applied (mm)	Rainfall (mm)	Water saving (%)
Summer (June–Sep. 2016)	ON-CF	21	930	206.3	
	YW-AWD	11	488	206.3	47.5
	IB-AWD	11	471	206.3	49.3
Monsoon (Oct. 2016–Jan. 2017)	ON-CF	10	526	210.0	
	YW-AWD	2	108	210.0	79.4
	IB-AWD	2	106	210.0	79.8

ON-CF – old seedlings, narrow spacing with continuous flooding, YW-AWD – young seedlings, wide spacing with alternate wetting and drying irrigation, IB-AWD – in-between the two planting methods.
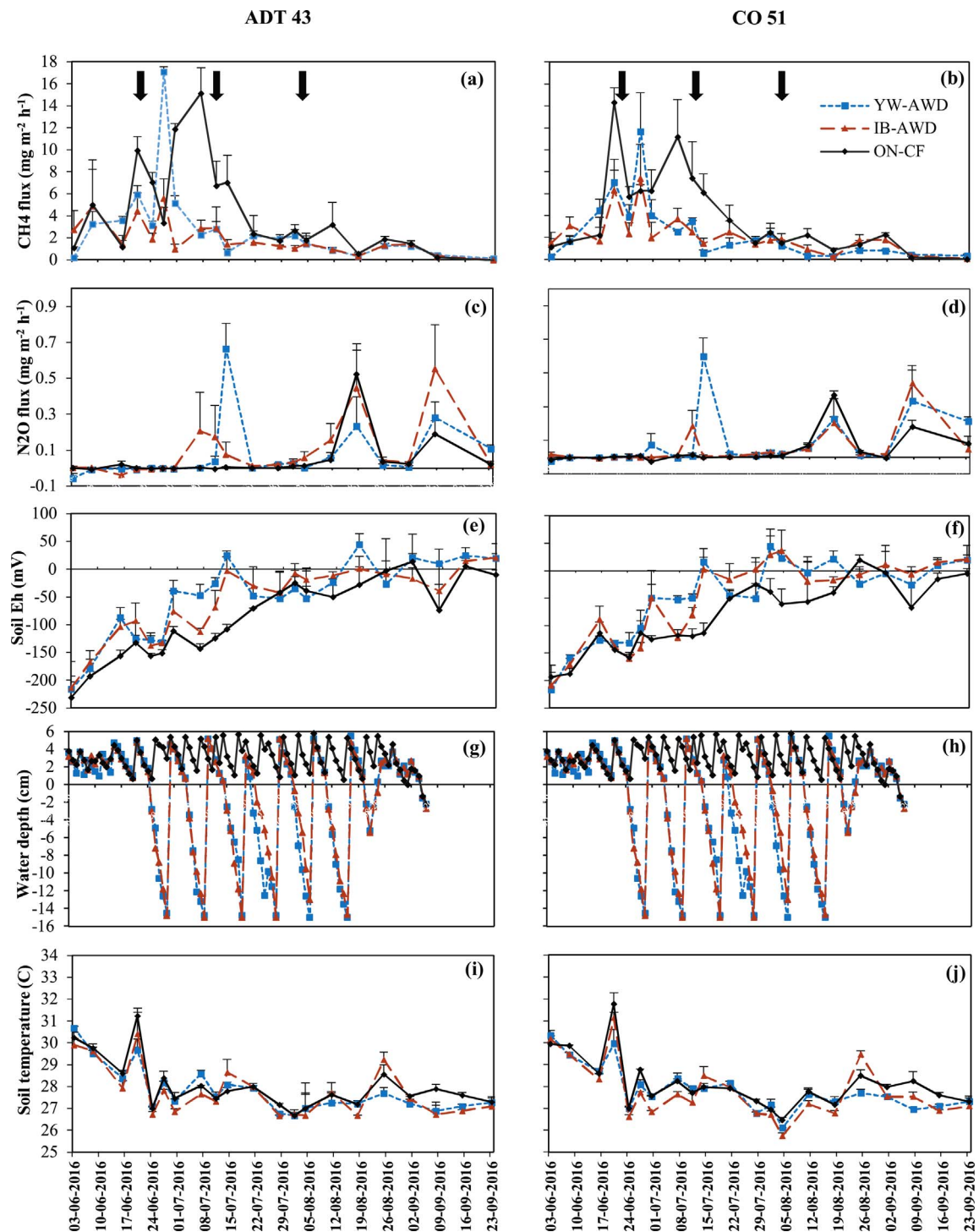
ADT 43

CO 51

Fig. 3. Seasonal variation in CH_4 flux (a, b), N_2O flux, (c, d), redox potential (e, f), water depth (g, h), and soil temperature (i, j) during Kuruvai summer rice growing season for different cropping methods. Error bars indicate standard error of means (n = 3). Arrows indicate, first, second and third split application of fertilizer. ON-CF – old seedlings, narrow spacing with continuous flooding, YW-AWD – young seedlings, wide spacing with alternate wetting and drying irrigation, IB-AWD – in-between the two planting methods.

from YN-AWD and IB-AWD were significantly (P < 0.05) lower compared with ON-CF (Table 2). Compared with ON-CF, the reduction in CH_4 emissions by YN-AWD and IB-AWD were 22% and 31% in ADT 46, and 25% and 20% in TKM 13, respectively. The cumulative emissions of YN-AWD and IB-AWD were statistically similar and no varietal differences were observed in both crop seasons. Between the summer and monsoon seasons, the rate and cumulative CH_4 emissions were higher in the monsoon season (Table 2). Averaged over planting method and rice variety, the summer and monsoon seasons accounted for 33% and

67% of the total emission, respectively, from double-cropping paddy rice.

3.4. Nitrous oxide flux

In the summer season, N_2O flux peaks were detected after fertilization, and when the soil was drying, they were detected towards crop maturity (Fig. 3c-d). The N_2O fluxes were relatively lower after the first N application than after the second and third N application. Among the

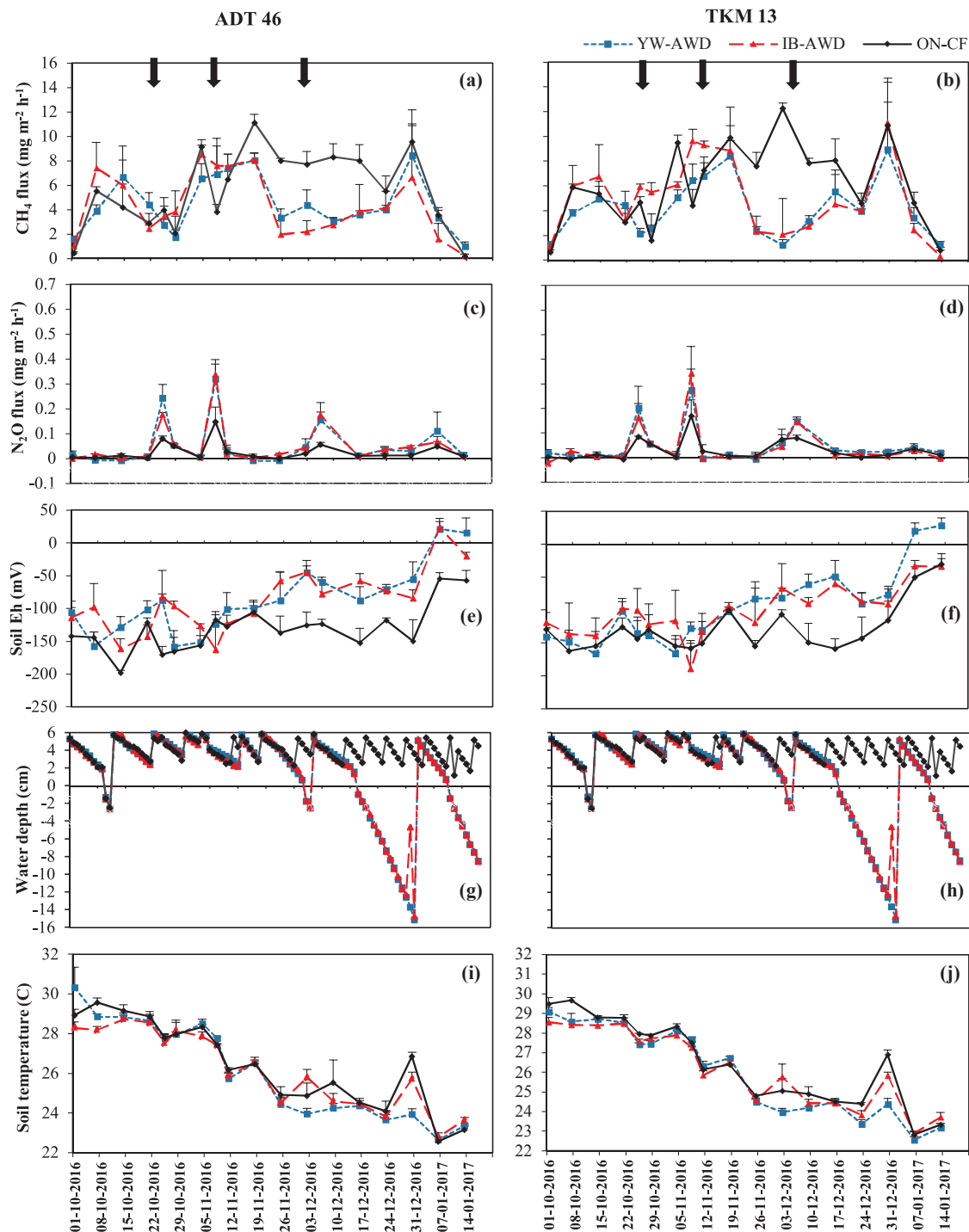**ADT 46**   **TKM 13**

Fig. 4. Same as Fig. 3, but for the Thaladi monsoon rice growing season. Error bars indicate standard error of means (n = 3). Arrows indicate, first, second and third split application of fertilizer. ON-CF – old seedlings, narrow spacing with continuous flooding, YW-AWD – young seedlings, wide spacing with alternate wetting and drying irrigation, IB-AWD – in-between the two planting methods.

planting methods, there was no significant difference (P > 0.05) in the rate of N_2O emission (Table 2). In the monsoon season, N_2O emission peaks were also observed after fertilization and during the drying period for harvest (Fig. 4c-d). The average rate of N_2O emission was significantly different (P < 0.01) among the planting methods (Table 2). For both the seasons, a relatively high rate of N_2O emission was observed from YN-AWD and IB-AWD, compared with ON-CF. There was no significant difference (P > 0.05) in N_2O emission between the rice varieties in either crop season.

In the summer season, there was no significant (P > 0.05)

difference in the cumulative N_2O emission among the planting methods (Table 2). A relatively high cumulative N_2O emission was observed from YW-AWD (1.94 and 2.09 kg ha^{-1}) and IB-AWD (2.69 and 1.53 kg ha^{-1}), compared with ON-CF (1.45 and 1.36 kg ha^{-1} in ADT 43 and CO 51, respectively). Averaged over the rice varieties, the YN-AWD and IB-AWD methods increased the N_2O emission by 28% and 31%, respectively, compared with ON-CF. In the monsoon season, the cumulative N_2O emission from ON-CF (0.61 and 0.73 kg ha^{-1}) was significantly (P < 0.01) lower compared with YN-AWD (1.23 and 1.15 kg ha^{-1}) and IB-AWD (1.22 and 0.96 kg ha^{-1} in ADT 46 and TKM

Table 2

Seasonal average rate and cumulative CH_4 and N_2O emissions, and CO_2-eq emissions in Summer and Monsoon rice growing seasons. Numbers in the table represent means $\pm$ standard deviation (n = 3). *P < 0.05, **P < 0.01, ns = not significance at 0.05 level.

		CH_4 flux		N_2O flux		CO_2-eq
		Rate (mg m^{-2} h^{-1})	Cumulative (kg ha^{-1})	Rate (mg m^{-2} h^{-1})	Cumulative (kg ha^{-1})	emission (kg CO_2 ha^{-1})
Summer ADT 43	YW-AWD	2.8 ± 0.3	60.0 ± 8.0	0.071 ± 0.040	1.94 ± 0.98	2618 ± 66
	IB-AWD	2.1 ± 1.0	45.1 ± 23.1	0.090 ± 0.062	2.69 ± 1.80	2338 ± 746
	ON-CF	4.5 ± 1.6	99.4 ± 30.5	0.050 ± 0.030	1.45 ± 0.37	3826 ± 946
CO 51	YW-AWD	2.6 ± 0.5	51.7 ± 9.4	0.077 ± 0.020	2.09 ± 0.74	2380 ± 298
	IB-AWD	2.4 ± 0.9	50.8 ± 18.3	0.053 ± 0.030	1.53 ± 0.48	2183 ± 605
	ON-CF	4.1 ± 1.1	88.9 ± 28.2	0.043 ± 0.027	1.36 ± 0.59	3439 ± 876
Monsoon						
ADT 46	YW-AWD	4.5 ± 0.9	119.7 ± 27.7	0.058 ± 0.016	1.23 ± 0.35	4436 ± 841
	IB-AWD	4.4 ± 1.1	114.4 ± 21.4	0.055 ± 0.003	1.22 ± 0.14	4253 ± 722
	ON-CF	5.6 ± 0.5	154.0 ± 15.4	0.027 ± 0.005	0.61 ± 0.09	5419 ± 518
TKM 13	YW-AWD	4.2 ± 1.1	113.5 ± 22.1	0.053 ± 0.002	1.15 ± 0.03	4201 ± 289
	IB-AWD	5.1 ± 0.7	130.2 ± 14.6	0.046 ± 0.003	0.96 ± 0.03	4713 ± 483
	ON-CF	6.0 ± 0.9	164.5 ± 25.7	0.033 ± 0.003	0.73 ± 0.13	5812 ± 892
Analysis of Variance						
Summer	Treat.	*	*	ns	ns	*
	Var.	ns	ns	ns	ns	ns
	Treat. × Var.	ns	ns	ns	ns	ns
Monsoon	Treat.	*	*	**	**	**
	Var.	ns	ns	ns	ns	ns
	Treat. × Var.	ns	ns	ns	ns	ns

ON-CF – old seedlings, narrow spacing with continuous flooding, YW-AWD – young seedlings, wide spacing with alternate wetting and drying irrigation, IB-AWD – in-between the two planting methods.

13, respectively). The cumulative N_2O emission was statistically similar between YN-AWD and IB-AWD. Compared with ON-CF, an increase of 43% and 38% N_2O emission, averaged over rice variety, was observed in YN-AWD and IB-AWD, respectively. There was no significant (P > 0.05) difference in the cumulative N_2O emission between the rice varieties in either crop season.

3.5. Rice productivity and CO_2-eq emission

The methods of planting did not significantly (P > 0.05) affect the grain yield in the summer season (Table 3). However, a marginal increase in grain yield was observed for both the rice varieties in YW-AWD and for variety CO 51 in IB-AWD, compared with ON-CF. A significant (P < 0.01) increase in straw yield was observed for both the rice varieties in YN-AWD and IB-AWD, compared with ON-CF. In the monsoon season, no significant (P > 0.05) differences in grain and straw yield were observed among the planting methods (Table 3). A relative increase in grain yield was observed for variety TKM 13 in YN-

AWD and IB-AWD, compared with ON-CF. A marginal increase in straw yield was observed for both the rice varieties in YN-AWD and IB-AWD, compared with ON-CF. No significant (P > 0.05) differences in grain and straw yield were observed between the rice varieties in either crop season (Table 3).

In the summer season, CO_2-eq emission from ON-CF was significantly (P < 0.05) higher compared with YN-AWD and IB-AWD (Table 2). The CO_2-eq emissions for YN-AWD and IB-AWD were statistically similar. The CO_2-eq emission reduction from YN-AWD and IB-AWD were 32% and 39% in ADT 43, and 31% and 37% in CO 51, respectively, compared with ON-CF. Averaged cross rice varieties, about 76% of the CO_2-eq emission from YW-AWD, 72% from IB-AWD, and 88% from ON-CF during the rice-cropping season resulted from CH_4 emissions in the summer season.

In the monsoon season, a significant (P < 0.01) difference in the CO_2-eq emission was observed among the planting methods (Table 2). The highest CO_2-eq emission was observed in ON-CF compared with YW-AWD and IB-AWD. The reductions in CO_2-eq emission for YN-AWD

Table 3

Effect of planting methods on crop productivity and yield-scaled CO_2-eq emission in Summer and Monsoon rice growing seasons. Numbers in the table represent means $\pm$ standard deviation (n = 3). *P < 0.05, **P < 0.01, ns = not significance at 0.05 level.

	Summer			Monsoon		
	Grain (t ha^{-1})	Straw (t ha^{-1})	Yield-scaled CO_2-eq emission (kg CO_2-eq t^{-1})	Grain (t ha^{-1})	Straw (t ha^{-1})	Yield-scaled CO_2-eq emission (kg CO_2-eq t^{-1})
	ADT 43			ADT 46		
YW-AWD	7.0 ± 0.5	12.4 ± 0.7	394 ± 16	6.4 ± 0.9	13.6 ± 4.5	691 ± 112
IB-AWD	6.5 ± 0.1	11.1 ± 0.5	344 ± 89	6.1 ± 2.1	12.5 ± 2.0	697 ± 314
ON-CF	6.7 ± 0.4	10.6 ± 0.3	558 ± 155	6.4 ± 0.6	11.8 ± 3.0	846 ± 132
	CO 51			TKM 13		
YW-AWD	7.2 ± 0.4	12.3 ± 0.6	366 ± 109	6.8 ± 0.7	12.6 ± 3.7	616 ± 15
IB-AWD	7.3 ± 0.7	11.4 ± 0.4	311 ± 80	7.0 ± 1.0	10.7 ± 0.9	671 ± 41
ON-CF	6.9 ± 1.4	10.3 ± 1.1	466 ± 102	5.3 ± 1.5	10.6 ± 0.5	1098 ± 271
Analysis of Variance						
Treat.	ns	**	*	ns	ns	**
Var.	ns	ns	ns	ns	ns	ns
Treat. x Var.	ns	ns	ns	ns	ns	ns

ON-CF – old seedlings, narrow spacing with continuous flooding, YW-AWD – young seedlings, wide spacing with alternate wetting and drying irrigation, IB-AWD – in-between the two planting methods.

Table 4
Pearson correlation analysis between GHG emissions and soil temperature, soil Eh, straw, and grain yield in summer and monsoon rice growing seasons. *$P < 0.05$, **$P < 0.01$, ns = not significance at 0.05 level.

	Soil temp.	Soil Eh	Grain yield	Straw yield
Summer				
CH_4	0.30**	− 0.45**	0.02[ns]	− 0.33[ns]
N_2O	− 0.24*	0.38**	0.01[ns]	0.48*
Monsoon				
CH_4	0.09[ns]	− 0.36**	− 0.34[ns]	0.01[ns]
N_2O	0.02[ns]	− 0.05[ns]	− 0.02[ns]	0.16[ns]

and IB-AWD were 18% and 22% in ADT 46, and 28% and 19% in TKM 13, respectively, compared with ON-CF. Averaged cross the rice varieties, about 92% of the CO_2-eq emission during the monsoon season from YW-AWD, 93% from IB-AWD, and 96% from ON-CF resulted from CH_4 emission.

Yield-scaled CO_2-eq emission was significantly ($P < 0.05$) affected by the planting methods in the summer season (Table 3). Yield-scaled CO_2-eq emission was higher in the ON-CF method compared with the modified methods because the emission was higher and yield was lower in the ON-CF method. In the monsoon season, yield-scaled CO_2-eq emission from ON-CF was significantly ($P < 0.01$) higher compared with the YN-AWD and IB-AWD methods in both rice varieties. There was no significant ($P > 0.05$) difference in the yield-scaled CO_2-eq emission between the rice varieties and no interaction effects in either crop season.

3.6. Influence of soil environmental factors and crop productivity on GHG emissions

In the summer season, the soil temperature showed a significant positive correlation with CH_4 emission (Table 4). A significant negative correlation between CH_4 emission and soil Eh was also observed. N_2O emission was negatively correlated with the soil temperature and positively correlated with the soil Eh. In the monsoon season, soil temperature showed no significant correlation with CH_4 and N_2O emissions (Table 4). A significant negative correlation between CH_4 emission and soil Eh was also observed. No correlation was observed between gas emission and yield data, except that of straw yield with N_2O emission in the summer season. In the monsoon season, there was no correlation between the yields and greenhouse gas emissions.

4. Discussion

4.1. Effect of planting methods on CH_4 emission

Contrasting seasonal patterns of CH_4 emission were observed during the summer and monsoon seasons (Figs. 3 a–b and 4 a–b). The higher CH_4 emissions during the early growing period of summer rice were attributed to high soil temperature and low soil redox potential during that period. In the monsoon season, the CH_4 flux peaked within two weeks in all planting methods (Fig. 4a-b). High soil temperature, low Eh, and increased availability of substrates favored methanogenic activities to decompose organic matter during the early cropping period (Oo et al., 2013). Among the planting methods, on most days, a higher CH_4 emission was observed from ON-CF, compared with YN-AWD and IB-AWD methods, due to the low soil redox status under flooded condition in ON-CF.

In both crop seasons, the average rate and cumulative emission of CH_4 was significantly ($P < 0.05$) higher in ON-CF compared with YN-AWD and IB-AWD (Table 2). The CH_4 emission during the growing period was not affected by the seedling age in either crop season, although the date of seedlings transplanted varied highly among the planting methods. However, it was significantly affected by the soil

redox status and surface water depth under different irrigation managements. In YN-AWD and IB-AWD, alternate wetting and drying conditions were maintained and these conditions reduced the CH_4 emission in both crop seasons. Yan et al. (2005) reported that the average CH_4 flux from rice fields with single and multiple drainages was 60% and 52% of that from continuously flooded rice fields, respectively. Methane emissions can be reduced by an average of 36.5% with a single drainage and by 43% with multiple aerations (Sander et al., 2015). A recent evaluation carried out in Vietnam revealed that with the system of rice intensification and water management, CH_4 declined significantly by 20%, whereas N_2O emissions increased by 1.5%, both measures calculated in terms of CO_2-eq emissions (Dill et al., 2013). Reductions in the irrigation water volume to the rice paddies led to a lower surface standing water depth (Figs. 3 g–h and 4 g–h), and even no standing water above the surface in AWD irrigation. This increased the oxygen penetration into the soil and led to soil organic C being oxidized to CO_2 instead of CH_4, which ultimately suppressed the CH_4 emissions (Sun et al., 2016). Itoh et al. (2011) tested different water management strategies such as prolonged midseason drainage at nine paddy sites across Japan and observed that the seasonal CH_4 emissions were suppressed by up to 69.5% relative to the conventional methods, while maintaining a similar grain yield. Reducing the amount of irrigation water under YN-AWD and IB-AWD was found to mitigate the CH_4 emissions in both crop seasons. According to the findings from various studies, a possible way of CH_4 mitigation in rice-cultivated paddy wetlands is better management practices in rice production (Yan et al., 2005; Katayanagi et al., 2012; Itoh et al., 2011; Sun et al., 2016). Water management was observed to be the most promising tool for mitigation of CH_4 emissions from paddy rice soil, as a high percentage of reduction has been achieved under different irrigation methods combined with different planting methods (ranging from 22% to 73% mitigation) (Jain et al., 2014; Ly et al., 2013; Katayanagi et al., 2012; Itoh et al., 2011; Sun et al., 2016). Water management practices improved soil permeability and increased the soil redox potential, which reduced methanogenic activities, resulting in the mitigation of CH_4 emission.

Variation in rice planting density, seedlings age, and seedlings per hill might also influence the amount of CH_4 emission from paddy rice fields. Watanabe et al. (2000) reported that a larger number of seedlings per hill or a smaller spacing between hills resulted in smaller CH_4 emissions without decreasing grain yield. Ko and Kang (2000) observed that transplanting 8-day old seedlings showed the highest CH_4 emission, compared with 30-day old seedlings. In this study, transplanting young seedlings with wide spacing in YW-AWD and IB-AWD methods increased the biomass yield and decreased the CH_4 emission, compared with transplanting old seedlings with narrow spacing in ON-CF. Since, no correlation was observed between biomass yield and CH_4 emissions (Table 4) in either of the crop seasons, increase in the plant biomass did not explain the differences in CH_4 emissions among the treatments. Different water-management-related changes (alternate wetting and drying cycles in YW-AWD and IB-AWD, and continuous flooding in ON-CF) in soil redox potential played a critical role in determining the CH_4 emissions from paddy rice soil. Yan et al. (2005) reported that the water regime in the rice-growing season is a main factor controlling the CH_4 emission from rice fields.

Various studies have indicated substantial differences in the rates of CH_4 emission among different rice cultivars (Aulakh et al., 2000; Das and Baruah, 2008; Kumar and Viyol, 2009; Koga and Tajima, 2011; Oo et al., 2016). Varietal differences in CH_4 emission are primarily due to differences in the plant structure, size, number of tillers, metabolism, CH_4 gas transport potential, and root exudates (Setyanto et al., 2004; Jia et al., 2002). Therefore, selection of suitable cultivars might play a major role in the regulation of CH_4 emissions from rice fields. In this study, no significant difference in CH_4 emission was observed between the tested rice varieties in either crop season (Table 2). This was due to similar crop duration, no significant difference in shoot weight and grain yield in these varieties under different planting methods. This

result was also supported by the correlation analysis, which showed that the CH_4 emission was not related with straw or grain yield (Table 4).

The cumulative CH_4 emission in the monsoon season was much higher compared with the summer season, for all planting methods (Table 3). Other studies have also reported that the CH_4 flux from late rice fields is higher than that from early rice fields (Cai et al., 2000; Yang et al., 2010; Oo et al., 2015). The CH_4 flux from a late rice field, preceded by an early rice field, was significantly higher than that preceded by an upland crop (Cai et al., 2000; Oo et al., 2013). They discussed that the water status prior to the rice-growing season is very important for CH_4 emission during the rice-growing season. In this experiment, fresh crop residues from summer rice were incorporated into the soil just after harvesting, which would provide a large addition of organic materials to soil for greater methane production in the monsoon season.

4.2. Effect of planting methods on N_2O emission

In both crop seasons, the peaks in N_2O flux were observed after fertilizer applications (Figs. 3 c–d and 4 c–d). This result was consistent with the observations in previous studies (Zou et al., 2005; Jain et al., 2014), and it was associated with formation of N_2O during nitrification and denitrification of applied nitrogen. Relatively higher N_2O fluxes from YN-AWD and IB-AWD were observed after fertilizer application in both crop seasons. Higher soil redox potential under AWD irrigation favored N_2O formation during the conversion of ammonium, via urea hydrolysis, to nitrate (i.e., nitrification) and subsequent loss of nitrate by denitrification (Sander et al., 2014).

Although, no significant differences were observed in the rate and cumulative emissions of N_2O in the summer season, significant differences were observed among the planting methods in the monsoon season (Table 2). In both crop seasons, the rate and cumulative emissions of N_2O from ON-CF were generally low due to continuous flooding during the cropping period. The consistently low soil redox potential under the ON-CF method resulted in more complete denitrification, and consequently, reduced N_2O emission.

Although YN-AWD and IB-AWD significantly mitigated the CH_4 emission in both crop seasons, a trade-off between CH_4 and N_2O emissions resulting from AWD irrigation was observed in this study. YN-AWD and IB-AWD with AWD irrigation increased the N_2O emission by 28% and 31% in summer, and by 43% and 38% in the monsoon season, respectively, compared with ON-CF. An average increase of 23.4% in N_2O-N emission was observed in controlled irrigation over the conventional method (Jain et al., 2014). Reduction in the frequency of rice paddy irrigation subjects the soil to alternating wet/dry conditions, which stimulates the N_2O producers and increases N_2O emissions (Hou et al., 2000). The increased N_2O emissions from YN-AWD and IB-AWD upon fertilization, relative to the ON-CF method, were probably due to the abundant, newly added N and the suitable soil moisture conditions (Zou et al., 2005; Hou et al., 2012). In terms of CO_2-eq emission, the reduction in CH_4 emission was offset by 14.0% and 13.4%, due to an increase in N_2O emission from YN-AWD and IB-AWD, in summer rice, and by 10.7% and 10.0% in the monsoon rice, respectively.

The depth of soil surface water at the time of fertilizer application might play an important role in controlling N_2O emissions (Figs. 3 g–h and 4 g–h). High N_2O emissions from YN-AWD and IB-AWD in both crop seasons might be due to low surface water depth (-15 to +4 cm) compared with ON-CF (+1 to +5 cm). Lower water table position (-11 to 0 cm) is known to enhance N_2O emissions, compared with higher water tables (+2 to +14 cm), in fresh water marsh (Yang et al., 2013). Transition in the soil water regime regulates the soil N_2O emissions, and rice fields are one of the sources of N_2O emission during alternate flooding and drying (Zheng-Qin et al., 2007). The N_2O emission in this study was related to fertilizer applications and soil surface water depth, rather than the rice variety, as no significant difference in N_2O was

observed among the tested varieties in either crop season. As the N_2O flux peaks were detected shortly after fertilization, some emission peaks could be missed due to the low frequency of air sampling soon after N fertilization in this study.

4.3. Water usage, crop productivity, and CO_2-eq emission

Although the date of seedling transplantation varied among the planting methods, there was no effect on water requirement in either crop season. Water use was mainly influenced by different irrigation management practices among the planting methods. Under AWD irrigation, the total water saving from YN-AWD and IB-AWD was 47.5% and 49.3% in summer, and 79.4% and 79.8% in the monsoon season, respectively, compared with ON-CF (Table 1). High water saving in the monsoon season was due to high frequent rainfall occurrences, which coincided with the irrigation time for YN-AWD and IB-AWD. The maximum saving of irrigation water with controlled irrigation under the system of rice intensification was only 27.4%, relative to the continuous flooded rice field, during the wet season in New Delhi (Suryavanshi et al., 2012). A *meta*-analysis conducted by Carrijo et al. (2017) reported that, in cases where AWD is practiced during the wet season, a 25.7% reduction in total water use might translate into an even greater reduction in irrigation water use. The potential for AWD irrigation for rice was also tested in China for saving water (20%–35% compared with the conventional method), while increasing the rice yield (Mao, 1996). In this study, although no significant differences in grain yield were observed in both crop seasons, the grain yield of YN-AWD and IB-AWD with AWD irrigation was comparable with the yield of ON-CF (Table 3). A *meta*-analysis conducted by Carrijo et al. (2017) from 56 studies with 528 side-by-side comparisons of AWD with continuous flooding showed that AWD decreased yields by 5.4%; however, under mild AWD (i.e., when the soil water potential was ≥ -20 kPa or field water level did not drop below 15 cm from the soil surface), the yields were not significantly reduced in most circumstances. In contrast, severe AWD (when soils dried beyond -20 kPa) resulted in yield losses of 22.6% relative to continuous flooding. Although modifications of YW-AWD method, such as transplanting 16-day old seedling with 2–3 seedlings per hill in IB-AWD, were introduced to increase the grain yield in both crop seasons, increase in the rice productivity under IB-AWD depended largely on the rice variety (high yields were observed only in CO 51 and TKM 13 under the IB-AWD method in the summer and monsoon seasons, respectively).

The impact of CH_4 and N_2O emissions, as estimated by the CO_2-eq emission for a 100-yr horizon, was observed among the planting methods. The reduction in CO_2-eq emission during the rice-growing season was primarily attributed to CH_4 emissions (Table 2). The YN-AWD and IB-AWD methods substantially reduced CO_2-eq emission (18%–39%) due to a large reduction in CH_4 emission under the AWD irrigation. This result was consistent with the global warming potential of AWD, resulting from approximately one-third emissions of CH_4 and N_2O compared with the values for continuous flooding (Katayanagi et al., 2012). Even greater CO_2-eq emission reduction, by 45%–90%, was observed in the case of AWD (Linquist et al., 2014) and intermittent irrigation (83% increase) (Peyron et al., 2016) compared with continuous flooding. The decrease in CH_4 emissions in YN-AWD and IB-AWD was the main cause of the effective depression in CO_2-eq emissions, regardless of the rice varieties, in both crop seasons.

The average CO_2-eq emission was higher in monsoon than in the summer season (Table 2). This result suggested that the seasonal variation in CO_2-eq emissions was considerably higher between the rice growing seasons, mainly due to higher CH_4 emissions in the monsoon season. The high cumulative CH_4 emission in monsoon was due to a decrease in the soil redox status and incorporation of fresh crop residues from summer rice.

The yield-scaled metric is increasingly used to provide a measure of agronomic efficiency that begins to address both climate change and

future food supply concerns (Grassini and Cassman, 2012). Results from this study clearly showed that the yield-scaled CO_2-eq emission, which integrates the mitigation of GHG emissions while achieving food security, was the highest in ON-CF, because the emissions were higher, with no significant difference in the grain yield compared with YN-AWD and IB-AWD in either crop season (Table 3). Yield scaled CO_2-eq emission from YN-AWD and IB-AWD was lower due to low CH_4 emissions. Therefore, it is strongly recommended that YN-AWD and IB-AWD methods be adopted for efficient reduction of CO_2-eq emission without reducing grain yield, in comparison with the ON-CF method, regardless of the crop seasons/variety.

5. Conclusion

Alternate wetting and drying irrigation practice reduced the CH_4 emissions from continuous flooding, by introducing periodically aerobic conditions during both rice-growing seasons. Due to the increase in N_2O emissions under AWD practice, it is critical to manage the reduction of both CH_4 and N_2O emissions, while maintaining rice yield. However, in terms of the global warming potential, since the contribution from N_2O emission is lower, decreasing the CH_4 emission is an effective way to mitigate total greenhouse gas emissions from rice fields. The results suggested that the YN-AWD and IB-AWD methods are effective in reducing CO_2-eq emissions and saving irrigation water without affecting the rice yield. In the context of global warming, modified rice cultivation systems are promising ways to ensure food security, while preserving irrigation water and mitigating greenhouse gas emissions.

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