

Pattern of methane emission and water productivity under different methods of rice crop establishment

Priyanka Suryavanshi · Y. V. Singh ·
R. Prasanna · Arti Bhatia · Y. S. Shivay

Received: 13 September 2011/Revised: 24 January 2012/Accepted: 23 March 2012/Published online: 12 April 2012
© Springer-Verlag 2012

Abstract Methane (CH₄) emission and water productivity were estimated in an experiment conducted during wet (rainy) season of 2010 at the research farm of Indian Agricultural Research Institute, New Delhi, India. Treatments comprising three methods of crop establishment viz., conventional transplanting (CT), system of rice intensification (SRI) and double transplanting (DT) were laid out in randomized block design with four replications. Scented rice (*Oryza sativa* L) variety ‘Pusa Basmati 1401’ was transplanted in puddle field. In CT and SRI 21 and 12-day-old seedlings, respectively, were transplanted while in DT overall 45-day-old seedlings were transplanted. In CT and DT flooded conditions while in SRI saturated conditions were maintained. Results indicated that among the methods of crop establishment, CT had maximum cumulative CH₄ emission (32.33 kg ha⁻¹) followed by DT (29.30 kg ha⁻¹) and SRI (19.93 kg ha⁻¹). Temporal CH₄ flux fluctuated between 79.7 and 482.0 mg m⁻² day⁻¹ under CT; 46.0 and 315.0 mg m⁻² day⁻¹ in SRI and 86.7 and 467.3 mg m⁻² day⁻¹ in DT. Considerable temporal variations in the individual CH₄ fluxes were observed. Flux of CH₄ was generally higher in early stage of crop and peaked about 21 days after transplanting coinciding with tillering stage of crop. CH₄ flux declined gradually from

75 days after transplanting and stabilized at the harvest stage of rice in all the three methods of transplanting. Global warming potential was highest in CT (807.4 kg CO₂ ha⁻¹) and lowest in SRI (498.25 kg CO₂ ha⁻¹). However, a reverse trend was observed with carbon efficiency ratio. The water savings to the extent of six irrigations was recorded in SRI over CT. A saving of 27.4 % irrigation water and 18.5 % total water was recorded in SRI over CT while the corresponding values of DT over CT were 14.5 and 9.8 %. Water productivity of SRI (3.56 kg/ha mm) was significantly higher as compared to DT (2.87 kg/ha mm) and CT (2.61 kg/ha mm).

Keywords Methane emission · Water productivity · Global warming potential · Rice fields · System of rice intensification (SRI) · Double transplanting · Carbon efficiency ratio

Introduction

Methane (CH₄) and nitrous oxide (N₂O) are the two important greenhouse gases contributing 15 and 5 %, respectively, of the enhanced greenhouse effect globally. Agricultural and associated sectors produce about 50 and 70 %, respectively, of the total anthropogenic emissions of these gases (IPCC 1995; Bhatia et al. 2005a). CH₄ is produced by methanogens during organic matter decomposition, under an environment where the oxygen (O₂) and sulphate (SO₄²⁻) are scarce (Cicerone and Oremland 1988; Bouman 2007) and is present at about 1,774 ± 1.8 ppb in the atmosphere (IPCC 2007).

Paddy fields are considered as a significant source of CH₄ and N₂O emissions, which have attracted considerable attention due to their contribution to global warming (Adhya et al. 2000; Bouman 2007; Hadi et al. 2010). Paddy

P. Suryavanshi · Y. S. Shivay
Agronomy, Indian Agricultural Research Institute,
New Delhi 110012, India

Y. V. Singh (✉) · R. Prasanna
CCUBGA, Indian Agricultural Research Institute,
New Delhi 110012, India
e-mail: yvsingh63@yahoo.co.in

A. Bhatia
Environmental Science, Indian Agricultural Research Institute,
New Delhi 110012, India

cultivation occupies about 44 million ha in the Indian subcontinent, the largest in Asia, and is one of the major sources of CH₄ emission. Indian rice fields are often blamed to be major contributors of atmospheric CH₄ (Bhatia et al. 2005a). Rice paddies are one of the major anthropogenic sources of atmospheric CH₄ (IPCC 2007). CH₄ emissions are controlled by various factors under field conditions, including the type and amount of fertilizer application (Cai et al. 2007), the water regime (Yan et al. 2009; Zou et al. 2005), the soil characteristics (Yan et al. 2005; Xiong et al. 2007) and the weather conditions (Yang and Chang 1998; Khalil et al. 2008).

In permanent flooded fields, CH₄ emissions are much higher than those in mid-season drained fields (Cai et al. 2003; Mosier et al. 2004). Cai et al. (2000) attributed high CH₄ emissions from some types of rice fields in China to the flooding of those rice fields in the winter season as well as the water regime during rice growing season. However, global predictions of CH₄ emissions from rice fields are complex to predict, because of differences in water regime, fertilizers, organic matter amendment make it (Cai et al. 2007; Khalil et al. 2008).

The agriculture sector contributed over 80 % of all-India CH₄ emissions in 1995, including 42 % from livestock-related activities, 23 % from rice paddy cultivation and 16 % from biomass consumption (Bhattacharya and Mitra 1998). The development of efficient irrigation water management minimizes the emission of these gases from paddy soil (Boundia et al. 1996; Hadi et al. 2010). Intermittent drainage has been proposed as a recommended water management to reduce CH₄ emission from paddy soil (Boundia et al. 1996; Hadi et al. 2010). However, Nugroho et al. (1994) reported that intermittent drainage did not affect CH₄ emission or, inversely, some time emitted more CH₄ compared to continuously flooded soils.

System of rice intensification (SRI) has been proposed as a strategy which is more efficient, resource-saving and productive way to practice rice farming. SRI, developed in Madagascar with the help of Malagasy farmers, involves reduced water application, including adoption of alternate wet and dry irrigation (AWDI) as a part of a new strategy of rice intensification, i.e. growing rice under mostly aerobic soil conditions. Double transplanting (DT) has been reported as promising method of transplanting, especially under contingent conditions (Aker et al. 2008; Rautray 2006); however, it has not been evaluated in terms of greenhouse gas emission potential.

Various crop-management practices, especially water management are known to play a major role in the CH₄ emission (Mosier et al. 1998; Pathak et al. 2003). However, comparative analyses of the CH₄ emissions from paddy fields under different methods of crop establishment are lacking. Numerous studies conducted on the manipulation of depth and intervals of irrigation intended to save water have demonstrated that continuous submergence is not essential

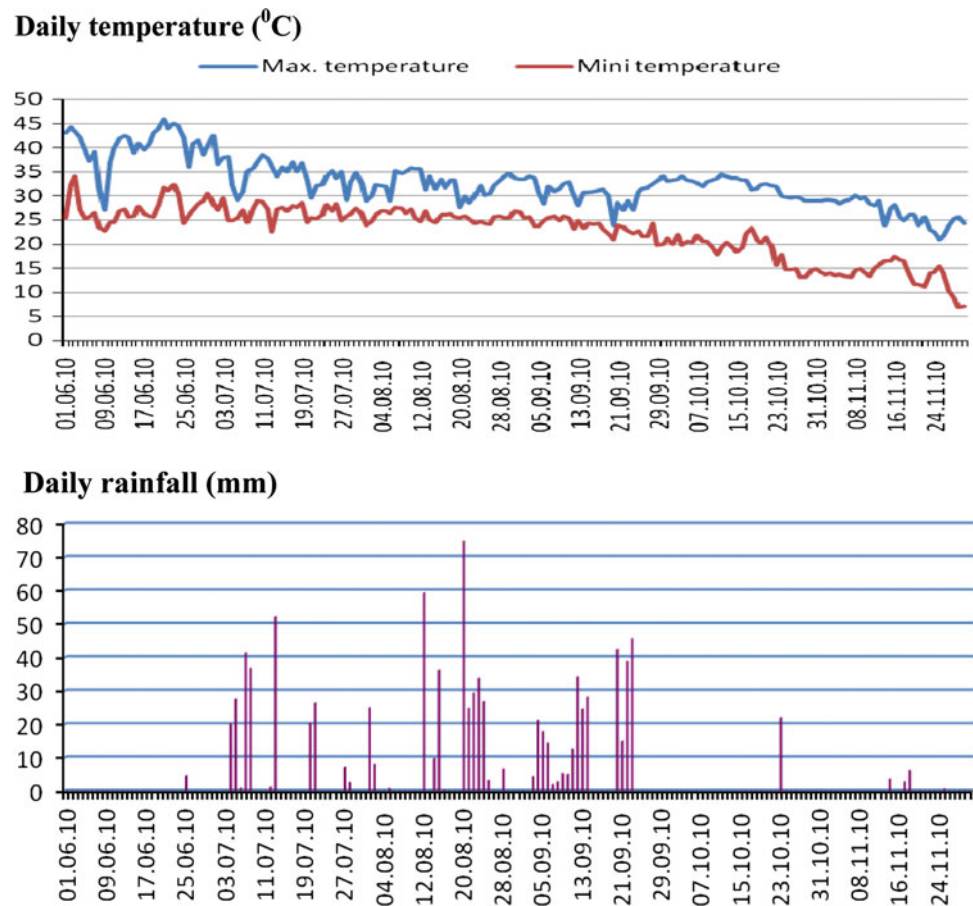
for obtaining high rice yields (Guerra et al. 1998). Bhuiyan and Tuong (1995) after conducting research over several years concluded that maintaining a significant depth of water throughout the season is not needed for high rice yields. About 40–45 % of the water normally used in irrigating the rice crop in the dry season can be saved by applying water in small quantities, only enough to keep the soil saturated throughout the growing season, without sacrificing rice yield. Similar result was reported by Sato and Uphoff (2007) for AWDI under SRI management in Eastern Indonesia. Similarly, Tabbal et al. (1992) and Singh et al. (1996) have reported that maintaining a very thin water layer, at saturated soil condition, or alternate wetting and drying, can reduce water applied to the field by about 40–70 % compared with the traditional practice of continuous shallow submergence, without a significant yield loss. Keisuke et al. (2007) and Davids (1998) also reported the reduction of irrigation water requirement for non-flooded rice by 20–50 % compared to flooded rice, with the difference being strongly dependent on soil type, rainfall and water management practices. Davids (1998), however, reported that rice yields under non-flooded conditions decreased proportionally with reduced water application due to increased water stress. With this background, an experiment was conducted to estimate the CH₄ emission, global warming potential (GWP) and water productivity under different methods of rice crop establishment.

Materials and methods

Agro-meteorological conditions

The climate of New Delhi, India is of sub-tropical and semi-arid type with hot and dry summer and cold winter and falls under the agro-climatic zone ‘Trans-Gangatic plains’. Summer months, May and June are the hottest with maximum temperature ranging between 41 and 46 °C, while there is a drop in temperature from September onward. January is the coldest month of the year with a minimum temperature ranging from 5 to 7 °C. The mean annual normal rainfall at Delhi is 650 mm, while July and August are the wettest months. The annual mean pan evaporation is about 850 mm. The detailed weather data during crop growing season (June–November) recorded at the meteorological observatory of Indian Agricultural Research Institute; New Delhi, India is depicted in Fig. 1. The year 2010, had more than normal rainfall (929.8 mm during June to November) out of which 237, 339 and 314 mm (95.7 % of total) were received during July, August and September months, respectively. There were 9, 11 and 15 no. of rainy days during July, August and September months, respectively, which was above normal considering the normal rainfall pattern of this area. That

Fig. 1 Daily weather conditions during experimental period



much number of rainy days saved lot of irrigation water. However, much fluctuation was not recorded in other weather parameters like maximum and minimum temperatures over the normal conditions of Delhi.

Site characteristics

The experiment was conducted during wet (*rainy*) season (June–November) of 2010 at the research farm of Indian Agricultural Research Institute, New Delhi, India situated at a latitude of 28°40' N and longitude of 77°12' E, altitude of 228.6 m above the mean sea level (Arabian Sea). The mean annual rainfall of Delhi is 650 mm and more than 80 % generally occurs during the south-west monsoon season (July–September) with mean annual evaporation 850 mm. The soils of experimental field analyzed before the start of experiment had 139.9 kg ha⁻¹ available N, 15.64 kg ha⁻¹ available P, 283.2 kg ha⁻¹ available K and 0.56 % organic carbon and 7.8 pH.

Agronomic management of the experiment

The treatments comprising three methods of crop establishment viz., conventional transplanting (CT), SRI and DT

using rice variety 'Pusa Basmati 1401' were carried out in randomised block design with four replications. In CT, 21-day-old seedlings were transplanted on 7 July in puddled field with 20 × 10 cm spacing and the plots were irrigated to maintain a 3–5 cm depth; hand weeding was done two times; recommended fertilizers were applied at 120 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, and 40 kg K₂O ha⁻¹. The P and K were applied basally, while N was applied in three splits: 30 % basal and 35 % each at active tillering and panicle initiation (PI) stages. In SRI practice, 12-day-old seedlings were transplanted at 25 × 25 cm spacing and 2 cm irrigation water was applied, after hairline cracks appeared in the soil surface up to PI; then after PI, irrigation was given 1 day after disappearance of ponded water. Inter-cultivation was done two times with a rotary weeder at 10-day intervals. The same recommended fertilizer was applied as with conventional practice. In DT 45-day-old seedlings were transplanted at 20 × 10 cm spacing in main field under puddled condition. These seedlings were earlier transplanted in secondary field at a closer spacing (7.5 × 7.5 cm) when they were 21 days old and a starter dose of N and irrigation as and when required were given. In DT method water and nutrient management in main field was done as done in CT. Rotary weeder was used in SRI for weed management and interculture while in CT

and DT manual hand weeding was done. The gross plot size was 5.0×3.0 m for each treatment. Crop was harvested at the physiological maturity in the first fortnight of October.

CH₄ gas sample collection and analysis

Collection of gas samples for CH₄ was carried out by the closed-chamber technique using the chambers of $50 \times 30 \times 100$ cm (length \times width \times height) (Pathak et al. 2002). First sample was taken on 14 July (7 DAT) and it was followed by sampling at 14, 21, 30, 45, 60, 75, 90 and 105 DAT in CT and SRI. In DT, first sampling was done with the third sampling (21 DAT) in other two methods of stand establishment (Fig. 2). This chamber was placed between the rows of the plants and one hill was kept inside the chamber under SRI but in conventional and double transplanted rice, four hills could be accommodated. One fan was installed in this box for homogenization of gas in the chamber. One aluminium metal platform was inserted in soil to keep the box and water was filled in grooves to prevent the leakage of gas. One hill of rice seedlings was covered in each sampling chamber. Gas samples were drawn with 50 ml syringe with the help of a hypodermic needle (24 gauge) at 0, 15 and 30 min for CH₄. The samples of gases were collected and brought to the laboratory where they were analyzed within 2 h. A gas chromatograph meter fitted with a 6–1/8-ft stainless-steel column (Porapak N; length \times inner diameter: 3 m \times 2 mm) and a flame ionization detector (FID) was used for measuring concentration of CH₄. For determination of CH₄, N₂ (flow rate 330 ml min⁻¹), H₂ (flow rate 30 ml min⁻¹) and zero air (flow rate 400 ml min⁻¹) were used as the carrier, fuel and supporting gas, respectively. Column, injector and detector temperature were set at 55, 100 and 200 °C, respectively. CH₄ standards of 2 and 10 ppmv obtained from Spectra gas (NIST standards) were used for calibration. Samples of three replications were taken from each method of stand establishment and the mean was taken as the representative value for that method.

The gas emission flux was calculated from the difference in gas concentration according to the equation of Zhang et al. (1998)

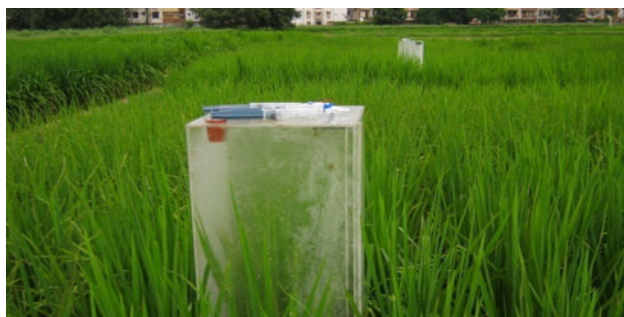


Fig. 2 CH₄ collection chamber installed in rice field

$$F = \rho h \left(\frac{dC}{dt} \right) 273(273 + T)^{-1},$$

where F is the gas emission flux ($\text{mg m}^{-2} \text{h}^{-1}$), ρ is the gas density at the standard state, h is the height of chamber above the soil (m), C is the gas mixing ratio concentration (mg m^{-3}), t is the time intervals of each time (h) and T is the mean air temperature inside the chamber during sampling.

Total gas emissions during the study period were calculated by integrating gas emissions on sampling days and cumulative gas emissions on the sampling days. Cumulative gas emissions were determined according to Singh et al. (1996).

Global warming potential

Based on a 100-year time frame, the GWP coefficient for CH₄ is 25, when the GWP value for CO₂ is taken as 1 (IPCC 2007). The GWP of different treatments were calculated using the following equation (Watson et al. 1996).

$$\text{GWP} = \text{CH}_4 \times 25.$$

Carbon equivalent emissions (CEE)

A CEE was calculated by using the following equation:

$$\text{CEE} = \text{GWP} \times (12/24).$$

Carbon efficiency ratio (CER)

CER was calculated using the following equation:

$$\text{CER} = \text{Grain yield (in term of C)}/\text{CEE}$$

Carbon content of rice was taken as 48 % of total grain yield.

Water productivity

Water management varied in different methods of stand establishment. In CT and DT plots were irrigated up to 5 cm depth immediately after disappearance of water. In SRI, plots were irrigated as per demand of crop and AWDI was maintained with no standing water in the field during the vegetative growth stage; then continuous irrigation with shallow standing water (2 cm) during the reproductive stage and finally draining of the field 7 days before harvest as recommended under SRI practice. In DT, there was saving of two irrigations as compared to CT, due to late planting of seedlings in main field. For maintenance of seedlings in nursery very little water was required due to less area and later those seedlings were transplanted to main field when its total age was 45 days. Each irrigation depth was measured by using an ordinary scale metre,

which had mm and cm mark. In each plot, the depth of water was measured at ten selected spots after each irrigation and on the basis of these observations; the mean depth of irrigation water was calculated for each plot. The other measurements were calculated as given below:

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

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

Water productivity (kg/ha mm) = grain yield (kg/ha) ÷ total water consumed (mm)

Water saving (%) = (water used in CT – water used in SRI or DT) × 100 ÷ water use in CT

Results

CH₄ emission

The dynamics of temporal CH₄ flux from rice grown with different methods of transplanting was analysed by measuring CH₄ at 7, 15, 21, 30, 45, 60, 75, 90 and 105 days after transplanting (Table 1). The CH₄ flux fluctuated between 79.7 and 482.0 mg m⁻² day⁻¹ under CT, 46.0 and 315.0 mg m⁻² day⁻¹ in SRI and 86.7 and 467.3 mg m⁻² day⁻¹ in DT. Considerable temporal variations in the individual CH₄ fluxes were observed. CH₄ fluxes increased sharply to a very high level right after transplanting of rice and peaked within about 3 week in SRI and CT, then decreased gradually to a negligible amount towards harvest. In DT, flux peak was noticed in first observation itself. Results indicated that overall CH₄ emission concentrations were higher at tillering stage of crop. The CH₄ flux peaks were found when observations were taken at 21 and 60 DAT, after application of chemical fertilizer (urea). CH₄ flux came to mean levels, few days after application of fertilizer. The flux of CH₄ was generally higher in early stage of crop and peaked about 1 month after transplanting at a late tillering stage. CH₄ flux declined gradually 75 days after transplanting and stabilized at the harvest stage of rice in all the three methods of transplanting.

Cumulative CH₄ flux was highest in CT throughout followed by DT and SRI.

Global warming potential

Total seasonal CH₄ emission was significantly higher in CT (32.33 kg ha⁻¹ season⁻¹) as compared to DT (29.30 kg ha⁻¹ season⁻¹) and SRI (19.93 kg ha⁻¹ season⁻¹) (Table 2). However, total emission between SRI and DT was statistically *at par*. GWP of CT (807.4 kg CO₂ ha⁻¹) was the significantly higher as compared to DT (732.5 kg CO₂ ha⁻¹) and SRI (498.3 kg CO₂ ha⁻¹). GWP under SRI was significantly less than DT also.

Carbon equivalent emissions

CEE of SRI (135.89 kg C ha⁻¹) was significantly lower as compared to CT (220.22 kg C ha⁻¹) and DT (199.77 kg C ha⁻¹) though it was statistically *at par* between CT and DT (Table 2).

Carbon efficiency ratio

Total carbon fixed under SRI (2,410 kg ha⁻¹) was significantly higher as compared to CT (2,170 kg ha⁻¹) and DT (2,150 kg ha⁻¹) though it was statistically *at par* between CT and DT (Table 2). CER also was the highest (17.73) under SRI and it was significantly higher than DT (10.76) and CT (9.85) (Table 2).

Water use and productivity

Significantly higher grain yield of rice was recorded in SRI (5,030 kg ha⁻¹) as compared to CT (4,530 kg ha⁻¹) and DT (4,480 kg ha⁻¹) (Tables 3, 4). However, grain yield under CT and DT was statistically *at par*. Variation in water use, water saving and water productivity of rice under different crop establishment methods were recorded (Tables 3, 4). Conventionally transplanted rice required more number of irrigations (18) followed by double transplanted rice (16). Minimum numbers of irrigations (12) were recorded under SRI due to alternate wetting and

Table 1 Effect of methods of crop establishments on temporal CH₄ flux (mg m⁻² day⁻¹)

Treatments	Days after transplanting									
	7	14	21	30	45	60	75	90	105	
Conventional	482.0	340.3	496.0	395.0	336.7	408.0	311.0	209.7	79.7	
SRI	185.7	163.0	313.0	242.3	228.7	245.7	217.7	152.3	46.0	
DT	–	–	463.7	324.3	342.3	401.7	233.3	198.7	86.7	
SEM±	6.20	7.37	18.89	11.86	22.61	7.14	9.01	8.82	2.85	
LSD (<i>P</i> = 0.05)	24.99	29.70	76.14	47.82	91.15	28.79	36.33	35.56	11.47	

Table 2 Seasonal emission of CH₄ and carbon equivalent and their effect on climatic parameters under different methods of crop establishment

Methods of transplanting	CH ₄ emission (kg ha ⁻¹)	GWP (kg CO ₂ ha ⁻¹)	CEEs (kg C ha ⁻¹)	Total C fixed ^a (kg ha ⁻¹)	CER
CT	32.33	807.50	220.22	2,174	9.85
SRI	19.93	498.25	135.89	2,414	17.73
DT	29.30	732.50	199.77	2,150	10.76
SEM±	1.43	17.78	12.32	27	0.13
LSD (<i>P</i> = 0.05)	5.76	71.65	49.65	109	0.52

^a Carbon content of rice was taken as 48 % of total grain yield

drying irrigation. Under SRI, there is a saving of 6 and 4 irrigations over conventional and double transplanted rice. Conventional rice cultivation used highest amount of irrigation water (1,170 mm) which was significantly higher than DT (1,000 mm) and SRI (850 mm). There was a saving of 14.5 % water under DT while in SRI a saving of 27 % water was recorded. Irrigation water productivity was significantly higher under SRI (5.92 kg/ha mm) as compared to DT and CT. However, irrigation water productivity under CT and DT was statistically *at par*. Rainfall recorded under all the three methods of stand establishments was the same as there was no rain between 7 and 27 July. However, total water (rainfall + irrigation) utilized was significantly higher under CT (1,733 mm) as compared to DT (1,563 mm) and SRI (1,413 mm) (Table 4). Thus, there was a saving of 9.8 and 18.5 % water in DT and SRI, respectively. Water productivity of SRI was significantly higher (3.56 kg/ha mm) as compared to DT (2.87 kg/ha mm) and CT (2.61 kg/ha mm). However, water productivity of CT and DT was statistically *at par*.

Discussion

The challenges in maintaining the sustainability of rice farming are increasing with the enhanced scarcity of water and competition for water resources coupled with the stagnant or declining yield levels. This has led to increasing production costs due to higher dependence on agri-inputs (Chapagain and Yamaji 2010). However, despite

these constraints, rice production must increase dramatically over the coming years to meet the world's food needs and especially those of the poor. Hence, producing more rice with less input is a formidable challenge for ensuring the food, economic, social and water security of the Asian countries. SRI is a set of ideas and insights that emphasize the use of younger seedlings (8–15 days), planted singly and at wider spacing, together with the adoption of intermittent irrigation, organic fertilization and active soil aeration to the extent possible (Uphoff 2007; Stoop and Kassam 2002). Our study focused on analyzing the CH₄ flux and water productivity in three different types of crop establishment strategies used for rice cultivation as a mean of identifying the optimal method with reduced CH₄ emission coupled with higher water productivity.

The observations indicated that temporal CH₄ emission fluctuated during the crop cycle. CH₄ flux fluctuated between 79.7 and 482.0 mg m⁻² day⁻¹ under CT, 46.0 and 315.0 mg m⁻² day⁻¹ in SRI and 86.7 and 467.25 mg m⁻² day⁻¹ in DT. Considerable temporal variations in the individual CH₄ fluxes were observed. The CH₄ flux peaks were found when observations were taken after application of chemical fertilizer (urea) which happened at 21 and 60 DAT. Lindau et al. (1991) also showed that urea fertilization increased CH₄ emissions by 86 % with the application of 300 kg N ha⁻¹ when compared with the control plot. Higher emission of CH₄ due to urea application could also be due to the presence of blue green algae biofertilizer, which provided mediation of CH₄ transport from floodwater of rice soil into the atmosphere

Table 3 Effect of methods of crop establishment on irrigation grain yield, water use, irrigation water saving and irrigation water productivity in rice

Method of rice establishment	Grain yield (kg/ha)	No. of irrigation	Irrigation water use (mm)	Irrigation water saving (%)	Irrigation water productivity (kg/ha mm)
Conventional	4,530	18	1,170	–	3.87
SRI	5,030	12	850	27.4	5.92
DT	4,480	16	1,000	14.5	4.48
SEM±	40	0.7	34	2.4	0.23
LSD (<i>P</i> = 0.05)	120	2.8	137	9.6	0.93

Table 4 Effect of methods of crop establishments on total water use, water saving and water productivity in rice

Method of rice establishment	Rainfall (mm)	Total water use (mm)	Grain yield (kg/ha)	Water saving (%)	Water productivity (kg/ha mm)
Conventional	563	1,733	4,530	–	2.61
SRI	563	1,413	5,030	18.5	3.56
DT	563	1,563	4,480	9.8	2.87
SEM±	–	26	40	1.6	0.12
LSD (<i>P</i> = 0.05)	–	104	120	6.4	0.48

(Ying et al. 2000). In this field blue green algae was applied in previous years and this field is under rice–wheat cropping since last 10 years. One possible reason might be the high redox potential and high pH 7.8 measured in our study. CH₄ production starts at below pH 6.1 and redox potential (Eh) of a soil below –150 mv (Jugsujinda et al. 1996). The Eh of soil gradually decreases after flooding (Takai et al. 1956), which is due to a decrease in the activity of the oxidized phase and increased activity of the reduced phase. Another reason given in literature attributes it to the early nascent stage of crop (Yoshida 1978), as the higher CH₄ emission is correlated with the higher at tillering stage. A higher CH₄ emission at tillering stage is generally due to the lower rhizospheric CH₄ oxidation and more effective transport mediated by rice plants. Flux of CH₄ was generally higher in early stage of crop and peaked about 1 month after transplanting coinciding with active tillering stage of the crop. CH₄ flux declined gradually from 75 days after transplanting and stabilized at the physiological maturity of rice in all the three methods of transplanting. Cumulative CH₄ flux was the highest in CT throughout followed by DT and SRI. Total seasonal CH₄ emission was highest in CT (32.33 kg ha⁻¹) followed by DT (29.30 kg ha⁻¹) and SRI (19.93 kg ha⁻¹). GWP of CT was the highest (807.4 kg CO₂ ha⁻¹) followed by DT (732.5 kg CO₂ ha⁻¹) in and SRI (498.25 kg CO₂ ha⁻¹). The higher CH₄ emission under flooded rice has been reported (Bhatia et al. 2005b). Hadi et al. (2010) suggested that intermittent irrigation and drainage can be a suitable option to reduce greenhouse gas emission from paddy soil in Japan and Indonesia. In SRI, alternate drying and wetting conditions were maintained and these conditions reduced CH₄ emission.

In our study CH₄ emission fluxes peak was recorded at 60 DAT also. It may be possibly due to the fact that rice was at the highest growing stage, the available organic carbon in the form of root exudates increased (Kumaraswamy et al. 2000), which led to an increase in methanogen population. But, at later growth stages of rice, CH₄ emission fluxes decline gradually (Yoshida 1978) and CH₄

was at relatively low levels at physiological maturity of crop. This was due to drainage from the fields as a result there was increase in the activities of the oxidized phase and decreased activity of the reduced phase, leading to a gradual increase in the Eh of soil (Takai et al. 1956). Due to maintenance of aerobic conditions in SRI, the activity of CH₄ producing bacteria was less and thus CH₄ production was much lower under SRI. In DT method, CH₄ emission flux maintained the trend as found in CT, but due to late transplanting in DT by 20 days, total CH₄ emission was low. The variations in CH₄ emission from soils planted with different rice establishment methods are in agreement with the findings reported by other researchers (Kludze et al. 1993). The root exudates have been implicated to be the major source of CH₄ in rice and a considerable variation in the root exudate pattern of different rice varieties exists (Ghosh et al. 1995). Among three methods of stand establishment significant variation in root development was recorded and highest root volume and root dry weight was recorded under SRI followed by CT and DT (unpublished data). The combination of various factors such as the supply of organic matter, size of the root space and oxidation rate in the rhizosphere have been identified to affect the CH₄ emission rates from various rice cultivars (Watanabe and Kimura 1996). In this experiment also methods of stand establishment and water management influenced CH₄ emission. CER of CT was the lowest (9.85) followed by DT (10.76) and SRI (17.73) in increasing order. Bhatia et al. (2005b) found similar trends.

Maximum savings of irrigation water was recorded with SRI (27.4 %), followed by DT (14.4 %) over conventional transplanted rice. Total water saving under SRI was 18.5 %. Impounding of 2–3 cm of irrigation water, after formation of hairline cracks showed considerable water saving besides providing a better root growing environment in SRI. Similar findings were reported by Thiyagarajan et al. (2002). Maximum irrigation water productivity was recorded with SRI (5.92 kg/ha mm), followed by DT and CT methods Anbumozhi et al. (1998) reported increased water productivity in AWDI plot at 9 cm ponding depth compared to continuous flooding. There was a saving of 27.4 % irrigation water in SRI as compared to CT. Mao (1993, 1996) also concluded that in Southern China, AWDI for rice should be more widely used because of its potential for saving water (20–35 %), increasing water productivity (from 0.65–0.82 to 1.18–1.50 kg m⁻³ after the application of AWDI), while also increasing rice yield (15–28 %), and improving the water and soil environment (soil O₂ content was increased by 120–200 %). In our experiment also highest grain yield was obtained in SRI followed by CT and DT. Lower water productivity was recorded in CT (2.61 kg/ha mm) and DT (2.87 kg/ha mm) while SRI gave 3.56 kg/ha mm grain yield for same amount of water.

Chapagain and Yamaji (2010) found 28 % saving of irrigation water, without reducing grain yield by using AWDI practice and recorded better crop growth and reduced disease/pest incidence under these conditions. Sato and Uphoff (2007) reported that continuous submergence is not essential for achieving high rice yields and similar results were found in our study as SRI gave higher productivity as compared to CT and DT.

Conclusions

Among the different methods of rice crop establishment, lowest seasonal CH₄ emission (19.93 kg ha⁻¹) and GWP (498.25 kg CO₂ ha⁻¹) coupled with higher water productivity was recorded with SRI method. The CH₄ flux peaks were found after application of chemical fertilizer (urea). CH₄ flux declined gradually from 75 days after transplanting and stabilized at the physiological maturity of the rice crop in all the three methods of stand establishment. CER of SRI was the highest followed by double and CT. SRI showed 27.4 % water saving over conventional practice and water productivity with this method of rice cultivation was significantly higher over other methods.

References

- Adhya TK, Bharati K, Mohanty SR, Mishra SR, Ramakrishnan B, Rao VR, Sethunathan N (2000) Methane emission from rice fields at Cuttack, India. *Nutr Cycl Agroecosyst* 58:95–105
- Akter MS, Islam MA, Amin HA, Bakul MRA (2008) Comparative efficiency of separated tiller vs bolon practice in aman rice. *Bangladesh Res Publ J* 1:255–263
- Anbumozhi V, Yamaji E, Tabuchi T (1998) Rice crop growth and yield as influenced by changes in ponding water depth, water regime and fertigation level. *Agric Water Manag* 37:241–253
- Bhatia A, Pathak H, Aggarwal PK (2005a) Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. *Curr Sci* 87(3):317–324
- Bhatia A, Pathak H, Jain N, Singh PK, Singh AK (2005b) Global warming potential of manure amended soils under rice-wheat system in the Indo-Gangetic plains. *Atm Environ* 39:6976–6984
- Bhattacharya S, Mitra AP (1998) Greenhouse gas emissions in India for the base year 1990. *Glob Change* 11:30–39
- Bhuiyan SI, Tuong TP (1995) Water use in rice production: issues, research opportunities and policy implications. Paper presented at the inter-center water management workshop, 29–30 September 1995. International Irrigation Management Institute, Colombo
- Bouman BAM (2007) A conceptual framework for the improvement of crop productivity at different spatial scales. *Agric Syst* 93:43–60
- Boundia LV, Neue HU, Wassmann R, Lantin RS, Javellana AM, Arah J, Xu Y, Makarim AK, Corton T, Charoenship N (1996) Understanding the nature of methane emission from rice ecosystem as a basis for mitigation strategies. In: Proceedings of international symposium on maximizing sustainable rice yields through improved soil and environmental management, Khon Kaen, pp. 291–314
- Cai ZS, Tsuruta H, Minami K (2000) Methane emissions from rice field in China: measurement and influencing factors. *J Geophys Res* 105(13):17231–17242
- Cai Z, Sawamoto T, Li C, Kang G, Boonjawat J, Mosier A, Wassmann R, Tsuruta H (2003) Field validation of the DNDC model for greenhouse gas emissions in East Asian cropping systems. *Glob Biogeochem Cycles* 17:1104–1107
- Cai Z, Shan Y, Xu H (2007) Effects of nitrogen fertilization on CH₄ emissions from rice fields. *Soil Sci Plant Nutr* 53:353–361
- Chapagain T, Yamaji E (2010) The effects of irrigation method, age of seedling and spacing on crop performance, productivity and water-wise rice production in Japan. *Paddy Water Environ* 8(1):81–90
- Cicerone RJ, Oremland RS (1988) Biogeochemical aspects of atmospheric methane. *Glob Biochem Cycles* 2:299–327
- Dauids G (1998) Use of the capital intensive irrigation systems in rice. Davids Engineering, Inc. California, USA
- Ghosh S, Jain MC, Sinha S (1995) Estimates of global methane production from rice paddies based on substrate requirement. *Curr Sci* 69:937–939
- Guerra LC, Bhuiyan SI, Tuong TP, Barker R (1998) Producing more rice with less water from irrigated systems. SWIM Paper 5. International Irrigation Management Institute, Colombo
- Hadi A, Inubushi K, Yagi K (2010) Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. *Paddy Water Environ* 8:319–324
- IPCC (1995) Scientific-technical analyses of impacts, adaptations and mitigation of climate change. Report of IPCC Working Group II
- IPCC (2007) Climate change 2007—the physical science basis contribution of working group I to the fourth assessment report of the IPCC. Cambridge University Press, New York
- Jugsujinda A, Delaune RD, Lindau CW, Sulaeman E, Pezeshki SR (1996) Factors controlling carbon dioxide and methane production in acid sulfate soils. *Water Air Soil Pollut* 87:345–355
- Keisuke S, Yamaji E, Sato S, Budhiharto PS, Mizoguchi M (2007) Sustainability of system of rice intensification: benefits of SRI focusing on effects of intermittent irrigation on yield increase and water savings. In: Proceeding of PAWEES 2007 6th international conference on sustainable rural development and management, Seoul National University, Seoul, 18 Oct 2007, pp 25–37
- Khalil MAK, Shearer MJ, Rasmussen RA, Xu L, Liu JL (2008) Methane and nitrous oxide emissions from subtropical rice agriculture in China. *J Geophys Res* 113:G00A05
- Kludze HK, DeLaune RD, Patrick WH (1993) Aerenchyma formation and methane and oxygen exchange in rice. *Soil Sci Soc Am J* 51:386–391
- Kumaraswamy S, Rath AK, Ramakrishnan B, Sethunathan N (2000) Wetland rice soils as sources and sinks of methane: a review and prospects for research. *Biol Fertil Soils* 31(6):449–461
- Lindau CW, Bollich PK, Delaune RD, Patrick WH, Law VJ (1991) Effects of urea fertilizer and environmental factors on CH₄ emissions from Louisiana, USA rice field. *Plant Soil* 136:195–203
- Mao Z (1993) Principle and technique of water saving irrigation for rice. Wuhan University of Hydraulic and Electric Engineering, Wuhan
- Mao Z (1996) Environmental impact of water-saving irrigation for rice. In: Irrigation scheduling: from theory to practice. Proceedings of the ICID/FAO workshop on irrigation scheduling, Rome. FAO, Rome, 12–13 Sept 1995
- Mosier A, Schimel D, Valentine D, Bronson K, Parton W (1998) Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. *Soil Biol Biochem* 30(14):2087–2098

- Mosier A, King J, Palm C (2004) Methane and nitrous oxide fluxes in tropical agricultural soils: sources, sinks and mechanism. *Environ Dev Sustain* 6:11–49
- Nugroho SG, Lumbanraja J, Suprpto H, Kimura M (1994) Effect of intermittent irrigation on methane emission from Indonesian paddy field. *Soil Sci Plant Nutr* 42:609–615
- Pathak H, Bhatia A, Prasad S, Singh S, Kumar S, Jain MC, Kumar U (2002) Emission of nitrous oxide from rice–wheat systems of Indo-Gangetic plains of India. *Environ Monit Assess* 77(2): 163–178
- Pathak H, Prasad S, Bhatia A, Singh S, Kumar S, Singh J, Jain MC (2003) Methane emission from rice-wheat cropping system of India in relation to irrigation, farmyard manure and di-cyandiamide application. *Agric Ecosyst Environ* 97:309–316
- Rautray SK (2006) Yield and economics of promising rice (*Oryza sativa*) hybrids under double transplanting in late spring summer (boro) situation. *Indian J Agric Sci* 76(8):469–471
- Sato S, Uphoff N (2007) A review of on-farm evaluation of system of rice intensification (SRI) methods in eastern Indonesia. CAB Reviews. Commonwealth Agricultural Bureau International, Wallingford, UK, pp 67–87
- Singh JS, Singh S, Raghubanshi AS, Singh S, Kashyap AK (1996) Methane flux from rice/wheat agroecosystem as affected by crop phenology, fertilization and water level. *Plant Soil* 183(2): 323–327
- Stoop WA, Kassam A (2002) A review of agricultural research issue raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving system for resource poor farmers. *Agric Syst* 71:249–274
- Tabbal DF, Lampayan RM, Bhuiyan SI (1992) Water-efficient irrigation technique for rice. In: Murty VVN, Koga K (eds) Soil and water engineering for paddy field management. In: Proceedings of the international workshop on soil and water engineering for paddy field management. Asian Institute of Technology, Bangkok, 28–30 Jan 1992
- Tabbal DF, Bouman BAM, Bhuiyan SI, Sibayan EB, Sattar MA (2002) On-farm strategies for reducing water input in irrigated rice: case studies in the Philippines. *Agric Water Manag* 56:93–112
- Takai Y, Koyoma T, Kamura T (1956) Microbial metabolism in reduction process of paddy soils. *J Soil Plant Food* 2:63–66
- Thiyagarajan TM, Senthikumar K, Sindraban PS, Hengsdijk H, Ramasamy S, Velu V, Durgadevi D, Vogindarajan K, Priyadarshini R, Sudhalakshmi C, Mishra PT, Gayathry G (2002) Crop management options for increasing water productivity in rice. *J Agric Resour* 7(4):169–181
- Uphoff N (2007) Reducing the vulnerability of rural households through agroecological practice: considering the system of rice intensification (SRI). *Mondes Dév* 35:4–8
- Watanabe A, Kimura M (1996) Factors affecting intervarietal variations in methane emission from rice paddies. In: International workshop on paddy fields: sustainable agriculture and control of greenhouse gas emissions, March 7–8, Tsukuba, Japan, pp 77–90
- Watson RT, Zinyowera MC, Moss RH, Dokken DJ (1996) Climate Change impacts, adaptations and mitigation of climate change: scientific-technical analyses, intergovernmental panel on climate change. Cambridge University Press, New York, p 879
- Xiong ZQ, Xing GX, Zhu ZL (2007) Nitrous oxide and methane emissions as affected by water, soil and nitrogen. *Pedosphere* 17:146–155
- Yan X, Yagi K, Akiyama H, Akimoto H (2005) Statistical analysis of the major variables controlling methane emission from rice fields. *Glob Change Biol* 11:55–63
- Yan X, Akiyama H, Yagi K, Akimoto H (2009) Global estimation of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 intergovernmental panel on climate change guidelines. *Glob Biogeochem Cycles* 23:10–20
- Yang S, Chang H (1998) Effect of environmental conditions on methane production and emission from paddy soil. *Agric Ecosyst Environ* 69(1):69–80
- Ying Z, Boecky P, Chen GX, Van Cleemput O (2000) Influence of *Azolla* on methane emission from rice fields. *Nutr Cycl Agroecosyst* 58:321–326
- Yoshida T (1978) Microbial metabolism in rice soils. In: IRRI (ed) Soil and rice. IRRI, Los Banos, pp 445–463
- Zhang L, Yu D, Shi X, Weindorf D, Zhao L, Ding W, Wang H, Pan J, Li CS (1998) Quantifying methane emissions from rice fields in the Taihu Lake region, China by coupling a detailed soil database with biogeochemical model. *Biogeoscience* 6:739–749
- Zou J, Houng Y, Jiang J, Zheng X, Sass RL (2005) 2-Year field measurement of CH₄ and N₂O emissions from rice paddies in China: effects of water regime, crop residue and fertiliser application. *Glob Biogeochem Cycle* 19:2021