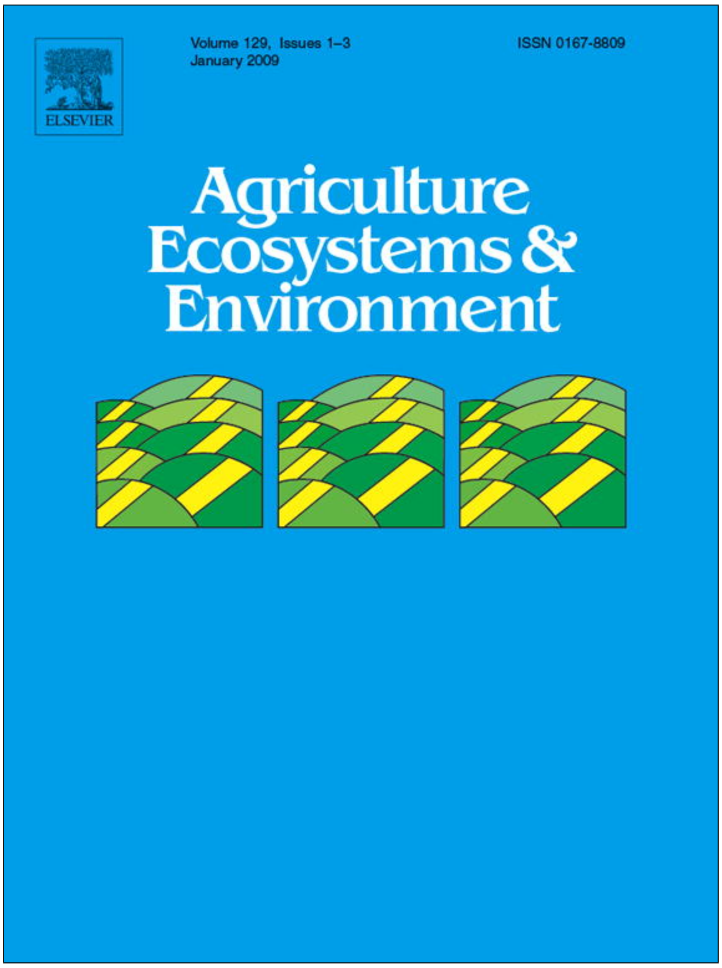

Volume 129, Issues 1–3
January 2009
ISSN 0167-8809
ELSEVIER

Agriculture Ecosystems & Environment

Agriculture, Ecosystems and Environment 129 (2009) 228–237

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Methane and nitrous oxide emissions from an integrated rainfed rice–fish farming system of Eastern India

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ARTICLE INFO

Article history:
Received 15 March 2008
Received in revised form 31 August 2008
Accepted 5 September 2008
Available online 17 October 2008

Keywords:
Methane emission
Nitrous oxide emission
Rice–fish farming system
Sustainable agriculture
Global warming potential
C-credit compliance

ABSTRACT

Integration of fish stocking with rice (*Oryza sativa* L.) cultivation promises an ecologically sound and environmentally viable management of flooded ecosystem. Rice agriculture contributes to the emission of greenhouse gases CH_4 and N_2O, but little is known on the effect of fish rearing in fields planted to rice on the emission of these two greenhouse gases. In a field study, CH_4 and N_2O fluxes were measured from a sub-humid tropical rice field of Cuttack, eastern India, as affected by integrated rice–fish farming under rainfed lowland conditions. Three Indian major carps, *Catla catla* H., *Labeo rohita* H. and *Cirrhinus mrigala* H., and *Puntius gonionotus* B. were stocked in rice fields planted to two rice cultivars in a split-plot design with no fish and fish as the main treatments and two rice varieties as sub-treatments with three replicates each. Fish rearing increased CH_4 emission from field plots planted to both the rice cultivars with 112% increase in CH_4 emission in *cv.* Varshadhan and 74% in case of *cv.* Durga. On the contrary, fish stocking reduced N_2O emission from field plots planted to both the rice varieties. Movement of fish and associated bioturbation coupled with higher dissolved organic-C and CH_4 contents, and lower dissolved oxygen could be the reasons for release of larger quantities of CH_4 from rice + fish plots, while higher dissolved oxygen content might have influenced release of more N_2O from the rice alone treatment. The total greenhouse gas emission, expressed as CO_2 equivalent global warming potential (GWP), was considerably higher from rice + fish plots with CH_4 contributing a larger share (91%) as compared to rice alone plots (78–81%). On the contrary, N_2O had a comparatively lesser contribution with 19–22% share in rice alone plots that was further reduced to 9% in rice + fish plots. However, considering the profit-loss analysis based on the market price of the produce, rice–fish system provided a net profit of \$453.36 ha^{-1} over rice alone system in spite of higher carbon credit compliance of a rice–fish ecosystem due to larger cumulative GWP.

1. Introduction

Flooded fields planted to rice (*Oryza sativa* L.) are important anthropogenic sources of atmospheric methane (CH_4) and nitrous oxide (N_2O), two potent greenhouse gases with relative global warming potentials of 25 and 298 times that of carbon dioxide (CO_2) over a time horizon of 100 years (IPCC, 2007). Biogenic CH_4 is produced in the anoxic environments of submerged soils and sediments including rice paddies during anaerobic degradation of organic-C compounds and enters the atmosphere at or near the earth's surface after escaping from the methanogenic habitats (Conrad, 1996). Rice paddies contribute approximately 10–13% to the global CH_4 emission (Crutzen and Lelieveld, 2001). The most crucial process for CH_4 emission from flooded paddy is its production which is influenced by a number of soil processes as well as common cultivation practices including rice variety (Satpathy et al., 1998) grown, while the plant-mediated transport of produced CH_4 is important for its release to the atmosphere (Wassmann and Aulakh, 2000). On the contrary, while earlier reports indicated negligible N_2O emission from flooded paddy fields (Smith et al., 1982), some of the later studies suggest that rice cultivation might be a significant anthropogenic source of N_2O (Cai et al., 1997). N_2O emission from paddy fields is affected by soil processes including nitrification–denitrification, climate and soil type and most importantly, form and mode of application of fertilizer-N (Cai et al., 1997; Akiyama et al., 2005). Such variability in the production and emission of CH_4 and N_2O is further compounded with a large degree of spatial and temporal

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doi:10.1016/j.agee.2008.09.003

(interannual and interseasonal) variations. Thus, there is large uncertainty in the estimated values for total CH_4 and N_2O emission from rice paddies of the world. While global estimates on CH_4 emission from rice paddies show an average of 20–150 Tg $year^{-1}$ (Mosier et al., 1998), estimated whole-year background emission of N_2O from flooded paddy amounts to ~0.28 Tg $year^{-1}$ (Akiyama et al., 2005). In order to increase the accuracy in the estimation of CH_4 and N_2O emission from rice cultivation and to predict the future CH_4 and N_2O emission as well as to develop desired mitigation options, intensive monitoring of CH_4 and N_2O emission from rice paddy is highly imperative. Rice cultivation contributes a large part to the tropical food production, especially in Asia covering about 154 million ha with more than 65% area located in south and south-east Asia. Projected increase in rice production during the coming decades (Maclean et al., 2002) is anticipated to result in a further increase in CH_4 and N_2O fluxes to the atmosphere due to intensification of the prevalent cultivation practices.

Rice–fish systems co-evolved alongside wet rice cultivation in southeast Asia over 6000 years ago (Ruddle, 1982) and are a sustainable form of agriculture (Heckman, 1979; Kurihara, 1989) providing invaluable protein, especially for subsistence farmers managing marginal farming systems of rainfed lowland ecology. Traditional rainfed lowlands, flood-prone (deep water) and irrigated rice agro-ecosystems lend themselves for fish culture when the whole rice field has a water depth of 0.3–1.0 m. Rice–fish farming has been recorded in tropical and subtropical Asia over the past 150 years. Its combined production has been propagated most intensely over the past 15–20 years, coinciding with the international emphasis on food production and nutritional security for a rapidly growing human population (Fernando, 1993). While a total of ~1.08 million ha currently being used for rice–fish farming, there is a potential of 10.2 million ha of rice area being brought under this system of cultivation (Lightfoot et al., 1992). Transformation of wetlands and rice fields for rice–fish production tends to directly benefit food production and income, as well as farm integration (Lightfoot et al., 1993). A rich variety of direct and mainly indirect beneficial effects emanate from the interactions between rice and fish (Koohafkan and Furtado, 2004).

Rice–fish farming systems are globally important in terms of three environmental issues, *viz.* climate change, shared water and biodiversity. CH_4 and N_2O are the major greenhouse gases emitted from rice fields, but the impact of integration of fish in rice cultivation on the emission of these two greenhouse gases are not known. As a result, it is not easy either to apply appropriate mitigation measures or to design trade-offs between mitigation measures and rice and fish production (Ranganathan et al., 1995). One of the possibilities is the application of global environmental subsidies (carbon credit) where national developing economies are unable to allocate them the desired priority. There are also innovative agricultural systems with a variety of local designs adapted to, *viz.* cultural attributes, appropriate rice and fish species for husbandry, different kinds of water resource availability, timing and drainage, natural and artificial nutrient inputs for growth, the biological and chemical control of pests and diseases, and edaphic conditions. It is essential to understand the impact of such agricultural interventions on the emission of CH_4 and N_2O from this economically important farming system.

Oxygen deficiency and reducing conditions are characteristics of flooded rice soils (Ponnamperuma, 1972; Liesack et al., 2000). Such reducing conditions often provide a congenial environment for CH_4 production (Kruger et al., 2001). It was previously considered that fish might aerate the paddy soil by burrowing into the soil for searching food (Lightfoot et al., 1992a). This would prevent a drop in the redox potential and lower CH_4 emission and by default would increase N_2O emission. However, in a field experiment, Frei et al. (2007) reported an increase in CH_4 emission in rice–fish treatment that resulted from the bioturbation effect created by the movement of fish. Our objectives in the present study were: (1) to investigate the effect of fish growing on CH_4 and N_2O emission from an integrated rice–fish farming system of eastern India under rainfed lowland conditions; (2) to scrutinize the dynamics of total organic carbon (C_{TOC}) and total N (N_{TOTAL}) contents of the soil and the changes in select physico-chemical properties of soil and water in relation to CH_4 and N_2O emission in an integrated rainfed rice–fish farming system; and (3) to assess the environmental impact of the rice–fish system *vis-á-vis* its economic benefit for the farmers and contribution to the food and nutritional security in rainfed lowland agro-ecologies.

2. Materials and methods

2.1. Field experiment

A field experiment was carried out during the wet cropping season (June–December) of 2005 at the experimental farm of the Central Rice Research Institute (CRRI), Cuttack, India (85°55′E, 20°25′N; elevation 24 m). Annual precipitation is ~1500 mm $year^{-1}$, of which ~75% occurs during June–September. Mean seasonal maximum and minimum temperatures during the wet season of 2005 was 39.2 and 22.5 °C, respectively and the mean seasonal ambient temperature was 27.7 °C. The soil was an Aeric Endoaquept with sandy clay loam texture (25.9% clay, 21.6% silt, 52.5% sand), bulk density 1.40 Mg m^{-3} and percolation rate < 10 mm day^{-1}. Soil collected from the plough layer (0–15 cm) had pH (H_2O) 6.16, cation exchange capacity 15 mEquiv. 100 g^{-1}, electrical conductivity 0.5 dS m^{-1}, total C 0.66% and total N 0.08%, exchangeable K 120 kg ha^{-1}.

The field plot had a natural gradient of 0.08 cm m^{-1} from west to east and a refuge pond of 10.0 m width and 1.75 m depth was constructed at the eastern end of the field for gathering the field water during the post-monsoonal period and also acted as a sanctuary for the fish. A peripheral trench (3.0 m width and 1.0 m depth) was excavated around the rice growing area which was blocked at the western end and connected to the mainland for easy access to the rice plot. The field was prepared by raising the levees and providing trenches for fish movement. The field was ploughed several times, larger clods broken and leveled on the third week of May 2005. The field was divided in 10 m × 10 m plots. Two promising lowland rice cultivars, *cv.* Varshadhan and Durga were dry-seeded with 80 kg seed ha^{-1} in rows 20 cm apart on May 31, 2005. A fertilizer schedule of 40 kg N ha^{-1} as urea and 20 kg each of P and K ha^{-1} as P_2O_5 (as single superphosphate) and K_2O (as muriate of potash) was applied at the time of sowing and covered with a thin layer of soil. The weeds germinated along with rice and remained in the field till accumulation of rain water. Subsequently, most of the terrestrial weeds perished with the increase in the water level and the aquatic weed population gradually built up. After sufficient water accumulation in the refuge system and in the field, fish fingerlings of 8–10 cm size and average weight of 8 ± 2 g, were released during the first week of August at a stocking density of 6000 fingerlings ha^{-1}. The fish species stocked belonged to three Indian major carps, *viz.* catla (*Catla catla* H.), rohu (*Labeo rohita* H.) and mrigal (*Cirrhinus mrigala* H.) and *Puntius gonionotus* B. at a ratio of 30, 25, 30 and 15 (on a percentage basis), respectively. Fish stock was regularly fed with a mixture of oil cake and rice bran or polish (1:1) at 2% of total biomass applied daily in feeding trays in the refuge tank. No plant protection or weed control measures were undertaken.

The experiment was laid out in a split-plot design with the two treatments, no fish and fish as the main treatments and two rice varieties as sub-treatments with three replications each.

The treatments thus included (i) *cv.* Varshadan without fish, (ii) *cv.* Varshadhan with fish, (iii) *cv.* Durga without fish, and (iv) *cv.* Durga with fish. The field plots without any fish were barricaded properly with bamboo cage to prevent the movement of fish inside the barricade without blocking the movement of water. With the onset of monsoon, rainwater gathered in the field plots and reached to a maximum level of 53 cm. The crop was grown and was harvested at maturity on January 10, 2006, at 224 days after sowing.

2.2. CH_4 and N_2O emission measurement from flooded paddy and refuge tank

CH_4 and N_2O emission from flooded rice fields and the refuge tank was quantified by manual closed chamber method (Hutchinson and Livingston, 1993; Adhya et al., 1994), at regular intervals from 30 days after sowing (DAS) to 222 DAS. Samplings for CH_4 and N_2O efflux measurement were done in the morning (09.00–09.30) and in the afternoon (15.00–15.30) and the average of morning and afternoon fluxes was used as the flux for the day (Nayak et al., 2006). Sampling for CH_4 and N_2O from the refuge pond and rice field (when water level was higher than 40 cm) was done by floating chamber method, wherein an air-filled rubber tube was fixed at the base of the Perspex chamber to allow it freely float in the water. The floating chamber was kept stranded in the field by fixing four guiding pegs at the four corner of the Perspex box. The changes in the temperature inside the Perspex chamber during the sampling period were recorded using a thermometer placed at the top of the chamber. The effective chamber volume was determined by measuring the height of the water level inside the chamber along with each flux measurement.

Methane concentration in the air samples collected from the crop canopy and the refuge tank were analyzed by gas chromatography in a Varian 3600 gas chromatograph (M/s Varian Instruments Inc., USA) equipped with flame ionization detector (FID) and Porapak N column (2 m length, 1/8 inch OD, 80/100 mesh, stainless steel column). The injector, column and detector were maintained at 80, 70 and 150 °C, respectively. The carrier gas (nitrogen) flow was maintained at 30 ml min^{-1}. The gas chromatograph was calibrated before and after each set of measurements using 5.38, 9.03 and 10.8 μl CH_4 l^{-1} in N_2 (Scotty® II analyzed gases, M/s Altech associates Inc., USA) as primary standard and 1.95 μl l^{-1} in air as secondary standard to provide a standard curve linear over the concentration range used. Under these conditions, the retention time of CH_4 was 0.53 min and the minimum detectable limit was 0.5 μl l^{-1}.

N_2O concentration in the air samples collected in the Tedlar® sampling bags was analyzed in a PerkinElmer ASXL gas chromatograph (M/s PerkinElmer, USA) equipped with ^{63}Ni electron capture detector (ECD) and a Porapak Q column (2 m length, 1/8 in. OD, 80/100 mesh, stainless steel column). The injector, column and detector were maintained at 80, 60 and 350 °C, respectively. The carrier gas (nitrogen) flow was maintained at 20 ml min^{-1}. The gas chromatograph was calibrated before and after each set of measurements using 100 ppb N_2O in N_2 (Scotty® II analyzed gases, M/s Altech Associates Inc., USA) as primary standard and 316 ppb N_2O in N_2 (National Physical Laboratory, New Delhi) as secondary standard. Under these conditions, the retention time of N_2O was 2.20 min and the minimum detectable limit was 100 ppb. Cumulative CH_4 and N_2O emission for the entire cropping period was computed by plotting the flux values against the days of sampling, calculating the area covered under the plot of such relationship and expressed as kg CH_4 or N_2O ha^{-1}.

2.3. Soil and water analyses

The redox potential (Eh) of the soil in the planted field plots was measured with each set of flux measurement. For field measurements, platinum electrodes were placed at a depth of ~10 cm from the surface of the soil. Eh was measured in mV with portable ORP meter (TOA ORP meter RM-12P). Soil Eh was calculated adding the average reading of platinum electrodes against the standard potential (+222 mV) of hydrogen electrode. The soil and water pH was measured with a portable pH meter (Philips model PW 9424) using a combined calomel glass electrode assembly. Water temperature both in the morning and in the afternoon was monitored using a Pt_{100} electrode. Dissolved oxygen (DO) concentration of the floodwater was measured using a portable oxymeter (model Oxi 320, WTW GmbH, Weilheim, Germany) and expressed as mg l^{-1}. The oxymeter was calibrated by inserting the probe in Oxical® SL Beaker and corrected for ambient temperature.

Chlorophyll a was determined according to Vollenweider (1974) by filtering water samples (500 ml) through cellulose nitrate filters (0.45 μm). Chlorophyll was then extracted by immersing the filters in 90% acetone for 3 days at 10 °C. The absorbance of the resultant solution was then measured at 664 nm against acetone blank using a spectrophotometer (Specord 200 UV-Vis Spectrophotometer, Analytik Jena, Germany). Ammonium (NH_4^+-N) in the soil extract (extracted with 2 M KCl) and water samples were estimated by Nesslerization (Jackson, 1973) following precipitation of Fe^{2+}. Dissolved CH_4 content of the floodwater was estimated following the method of Alberto et al. (2000) after correcting for the solubility coefficient (Linke, 1965). The C_{TOC} contents of the soil and the dissolved organic carbon (D_{OC}) contents of the water samples were determined in a TOC analyzer (Micro N/C model HT 1300, Analytic Jena, Germany). The N_{TOTAL} was analyzed by a semi-automated Kjeldahl method (Kjeltech model 2100, Foss Tecator, Sweden).

2.4. Plant parameters

Mean aerial biomass (fresh and dry weights) was measured by harvesting above-ground portions of rice plant, one hill from each replicated plot, on each day of CH_4 sampling as well as at maturity. The aerial biomass values were expressed as g m^{-2} (dry weight basis). Tiller no., grain weight, and grain and straw yields from individual replicated plots were measured at maturity and the harvest index calculated (Bharati et al., 2000). Weed biomass (fresh and dry weights) was measured from individual replicated plots and expressed as Mg ha^{-1}.

2.5. Fish yield

Fish grown in replicated field plots were harvested by repeated netting of refuge tanks, quantified by weighing and expressed as kg fresh biomass ha^{-1}.

2.6. Economic and environmental stability analyses

Production cost covering all the inputs and the market cost of yield were computed at market rates using a high-end value of $ = Rs. 50/- and the net profit analysis was calculated. Integrated evaluation of greenhouse gas emissions from the two farming systems was done and expressed as aggregate CO_2 equivalent (kg ha^{-1}) using an unitary value of CH_4 = 25 CO_2 and N_2O = 298 CO_2 (IPCC, 2007). C-credit compliance was calculated at € 30 = $39 per ton CO_2 as of April 2006 (http://www.emissierechten.nl/marketanalyse.htm).

2.7. Statistical analyses

Individual character datasets were statistically analyzed and the mean comparison between treatments was established by Duncan's multiple range test using statistical package (IRRISTAT, version 3.1, International Rice Research Institute, Philippines). Simple and multiple correlations between soil physico-chemical and biochemical parameters were analyzed using SYSTAT 5.05 (SPSS Inc., 1999) to establish possible statistical relationship.

3. Results

3.1. Methane and nitrous oxide emission from rice–fish fields and refuge tank

CH_4 emission from field plots sown with the two rice cultivars, with or without fish, varied considerably (cv = 17%). CH_4 emission was low in all the plots up to 30 days after sowing (DAS). Measurable CH_4 emission was recorded from 30 DAS onwards which coincided with the moistening of the soil by precipitation followed by germination of the rice crop and stand establishment (Fig. 1). Subsequently, CH_4 emission flux increased concomitant with the increase in plant growth. In general, two emission peaks, one at the flowering stage and the other at the maturity stage, were recorded irrespective of the rice cultivar grown. With the onset of monsoon, water depth in the field plots increased from 12 cm at 30 DAS to a peak of 53 cm at 90 DAS resulting into free movement of fish in the field plots. Presence of fish resulted in an increase in CH_4 emission from both the rice cultivars with two sharp peaks recorded at flowering and maturity stages of the rice crop. The mean CH_4 emission (mg CH_4 m^{-2} h^{-1}) from sowing till harvest followed the order: Varshadhan + fish (2.52) > Durga + fish (2.48) > Durga (1.47) > Varshadhan (1.17). Cumulative CH_4 emission was highest in the treatment Varshadhan + fish (96.33 kg ha^{-1}) while the lowest emission was recorded in field plots planted to *cv.* Varshadhan without fish (45.38 kg ha^{-1}). Thus, percentage increase in CH_4 emission as a result of fish rearing was 112 in case of *cv.* Varshadhan and 74 in case of *cv.* Durga.

N_2O emission from all the treatments exhibited significant temporal and spatial variations (cv = 38.2%). Unlike CH_4, N_2O emission flux from rice fields exhibited a peak almost immediately after germination and stand establishment, at 30–36 DAS and declined thereafter (Fig. 2). In general, N_2O fluxes were relatively low during the entire cropping period increasing only towards maturity of the rice crop when the floodwater receded and the field started drying. N_2O emission followed almost similar pattern in both the rice cultivars with two major peaks of N_2O, one at the seedling stage and the other at maturity stage of the crop. Fish movement reduced N_2O emission from both the rice cultivars. Mean N_2O emission (μg N_2O m^{-2} h^{-1}) from sowing till harvest followed the order: Varshadhan (without fish) (36.92) > Durga (without fish) (31.33) > Varshadhan + fish (29.77) > Durga + fish (29.57). Extending the mean emission fluxes to cumulative values (kg N_2O ha^{-1}), N_2O emission followed the order of Varshadhan (without fish) (1.02) > Durga (without fish) (0.92) > Varshadhan + fish (0.75) > Durga + fish (0.72). Percentage decrease in N_2O emission as a result of fish rearing was 29 in case of *cv.* Varshadhan and 22 in case of *cv.* Durga.

CH_4 emission from the refuge pond followed a similar pattern as that from rice fields (Fig. 3). CH_4 emission was very low up to 90 DAS but increased thereafter with larger emission flux till 160 DAS, declining thereafter. Mean CH_4 emission flux from the water surface of the refuge pond measured at 2.47 mg CH_4 m^{-2} h^{-1}. On the contrary, N_2O emission was very low from the surface water of the refuge pond excepting a small peak around 60 DAS with mean N_2O emission flux measuring at 20.44 μg N_2O m^{-2} h^{-1}.

3.2. Floodwater and soil parameters

Floodwater parameters in the present experiment were within a range suitable for fish growing. Mean water temperature increased considerably during the course of the day in all the

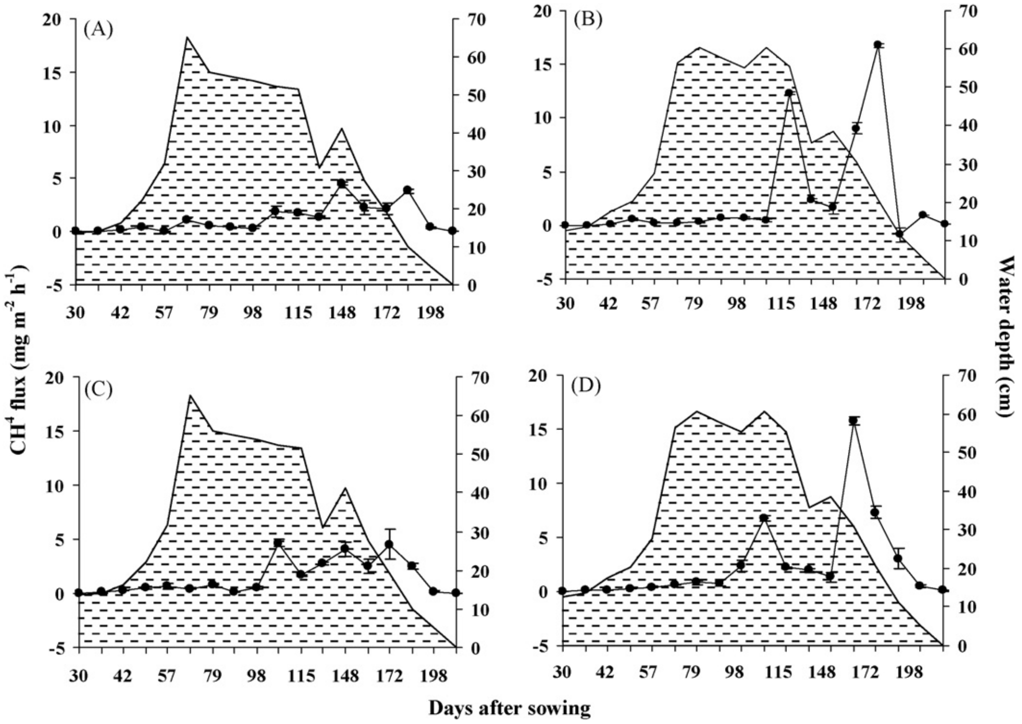

Fig. 1. Seasonal dynamics of CH_4 flux from a flooded field under integrated rainfed rice–fish system and planted to two rice cultivars. Means of four replicate values plotted, bars/half-bars indicate the standard deviation [(A) *cv.* Varshadhan without fish; (B) *cv.* Varshadhan with fish; (C) *cv.* Durga without fish; (D) *cv.* Durga with fish].

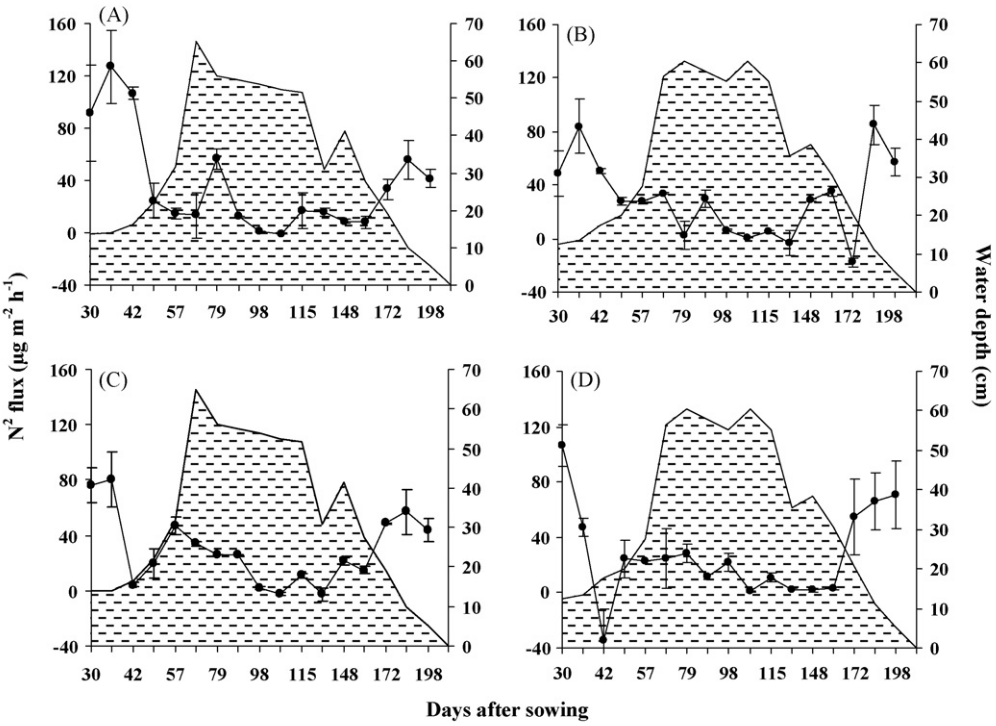

Fig. 2. Seasonal dynamics of N_2O flux from a flooded field under integrated rainfed rice–fish system and planted to two rice cultivars. Means of four replicate values plotted, bars/half-bars indicate the standard deviation [(A) *cv.* Varshadhan without fish; (B) *cv.* Varshadhan with fish; (C) *cv.* Durga without fish; (D) *cv.* Durga with fish].

plots from an average of 28.51–28.94 °C in the different field plots in the morning (at 9:00 h) to around 32.23–34.63 °C in the afternoon (at 15:00 h) (Table 1). Field plots without fish exhibited significantly higher range of water temperature. The mean pH values also exhibited significant differences ($p < 0.05$) between the treatments in the afternoon but not in the morning. Presence of fish, in fact, tended to increase the pH of water. pH values had negative relationship with both CH_4 and N_2O emission flux (Table 2). Dissolved oxygen content (mg l^{-1}) of the floodwater also increased in the afternoon with the largest increase in the rice alone treatments, the difference being statistically significant (Table 1). Dissolved oxygen contents had significant negative relationship with CH_4 flux value (Table 2). Mean chlorophyll a content (μg l^{-1}) of the floodwater was lower in the rice–fish plots as compared to field plots with rice alone and was negatively correlated with CH_4 flux (Table 2). The highest chlorophyll a content was recorded in field plots grown with rice *cv.* Durga. Dissolved CH_4 content was higher in the rice + fish plots, so also the dissolved organic-C content. For both dissolved CH_4 and dissolved organic-C contents, presence of fish effected significantly higher concentrations as compared to rice alone (Table 1) and had positive correlation with CH_4 efflux (Table 2).

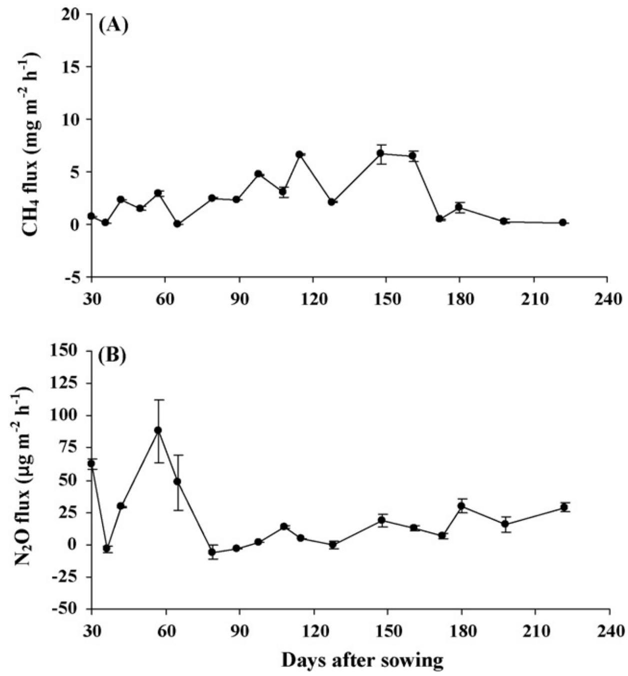

Fig. 3. CH_4 and N_2O emission flux from accumulated water in the refuge pond of the integrated rainfed rice–fish system for the cropping period of wet season, 2005. Means of four replicate values plotted, bars/half-bars indicate the standard deviation [(A) CH_4; (B) N_2O].

Eh of the field plots under various treatments were monitored to establish the relevant effects on CH_4 and N_2O emission measurements. With the accumulation of rainwater (from 30 DAS till 190 DAS), the field plots got flooded and the soil got reduced. The Eh was lowest between 50 and 80 DAS irrespective of treatments and hover around −300 mV. Subsequently, the Eh got stabilized around −140 mV and became aerobic again with the receding of the standing water at maturity of the rice crop (Fig. 4). Mean Eh (mV) values followed the order of Durga + fish (−157) < Varshadhan + fish (−151) < Durga (−132) < Varshadhan (−103). Although the variation in Eh values among the treatments was substantial, no statistically significant differences occurred between the treatments. Eh values of the soil had a significant negative relationship with CH_4 efflux and a significant positive relationship with N_2O efflux (Table 2). The soil pH during the entire experimental period ranged between 6 and 8 (Fig. 4) and did not indicate any statistically significant difference between the treatments. Dissolved oxygen content was significantly higher in the field plots without fish

Table 1

Floodwater characteristics of field plots under rice–fish farming system

Treatment	Rice cultivar	Temperature at 9:00 h (°C)	Temperature at 15:00 h (°C)	pH at 9:00 h	pH at 15:00 h	Dissolved O_2 at 9:00 h ($mg\ l^{-1}$)	Dissolved O_2 at 15:00 h($mg\ l^{-1}$)	Chlorophyll *a* ($\mu g\ ml^{-1}$)	Dissolved CH_4 ($\mu g\ l^{-1}$)	Dissolved organic-C ($\mu g\ l^{-1}$)
Rice	Varshadhan	28.93 ± 2.84a	34.63 ± 1.69b	6.95 ± 0.22a	7.45 ± 0.59a	5.47 ± 1.35b	8.21 ± 0.15c	57.83 ± 50.38c	9.51 ± 0.50a	2.01 ± 0.19a
	Durga	28.94 ± 2.91a	34.51 ± 1.63b	6.93 ± 0.23a	7.44 ± 0.55a	5.58 ± 1.36b	7.96 ± 0.06c	137.99 ± 80.31d	9.78 ± 0.92a	2.20 ± 0.25a
Rice + fish	Varshadhan	28.90 ± 2.26a	32.28 ± 1.72a	7.11 ± 0.61a	7.67 ± 0.38b	3.70 ± 0.89a	5.04 ± 0.04a	7.13 ± 5.21b	14.29 ± 0.93c	4.13 ± 0.14c
	Durga	28.51 ± 2.67a	32.23 ± 1.70a	7.11 ± 0.34a	7.63 ± 0.42b	3.64 ± 0.95a	5.00 ± 0.10a	12.19 ± 11.95b	14.16 ± 1.04c	4.00 ± 0.11c
Refuge tank		28.29 ± 4.0a	33.00 ± 2.02ab	7.23 ± 0.27b	7.45 ± 0.34a	3.13 ± 1.2a	5.29 ± 0.16b	0.12 ± 0.01a	12.84 ± 0.36b	3.33 ± 0.33b

Average of all observations over the whole experimental period ± standard deviation.

In a column, means followed by a common letters are not significantly different ($P < 0.05$) by Duncan's Multiple Range Test (DMRT).

Table 2

Matrix of correlation (r) coefficients between CH_4 and N_2O fluxes and select soil and water parameters in an integrated rainfed rice–fish farming system

Parameter	CH_4 flux	N_2O flux	Eh	pH	Dissolved CH_4-C	Dissolved organic-C	C_{TOC}	Dissolved O_2
N_2O flux	−0.079 (d.f. = 46)							
Eh	−0.266* (d.f. = 46)	0.624* (d.f. = 46)						
pH	−0.492* (d.f. = 46)	−0.606* (d.f. = 46)	−0.541* (d.f. = 46)					
Dissolved CH_4-C	0.917* (d.f. = 14)	−0.019 (d.f. = 14)	0.720* (d.f. = 16)	−0.112 (d.f. = 16)				
Dissolved organic-C	0.797* (d.f. = 14)	0.371 (d.f. = 14)	0.484* (d.f. = 16)	−0.085 (d.f. = 14)	0.923* (d.f. = 14)			
C_{TOC}	0.382 (d.f. = 14)	−0.414 (d.f. = 14)	0.025 (d.f. = 14)	−0.038 (d.f. = 14)	0.382 (d.f. = 14)	0.220 (d.f. = 14)		
Dissolved O_2	−0.263* (d.f. = 46)	−0.018 (d.f. = 46)	−0.222 (d.f. = 14)	−0.011 (d.f. = 14)	0.206 (d.f. = 14)	0.118 (d.f. = 14)	0.152 (d.f. = 14)	
Chlorophyll *a*	−0.370* (d.f. = 46)	0.187 (d.f. = 46)	−0.319 (d.f. = 14)	−0.262 (d.f. = 14)	0.358 (d.f. = 14)	0.403 (d.f. = 14)	−0.516* (d.f. = 14)	0.574* (d.f. = 14)

* Significant at $P < 0.05$.

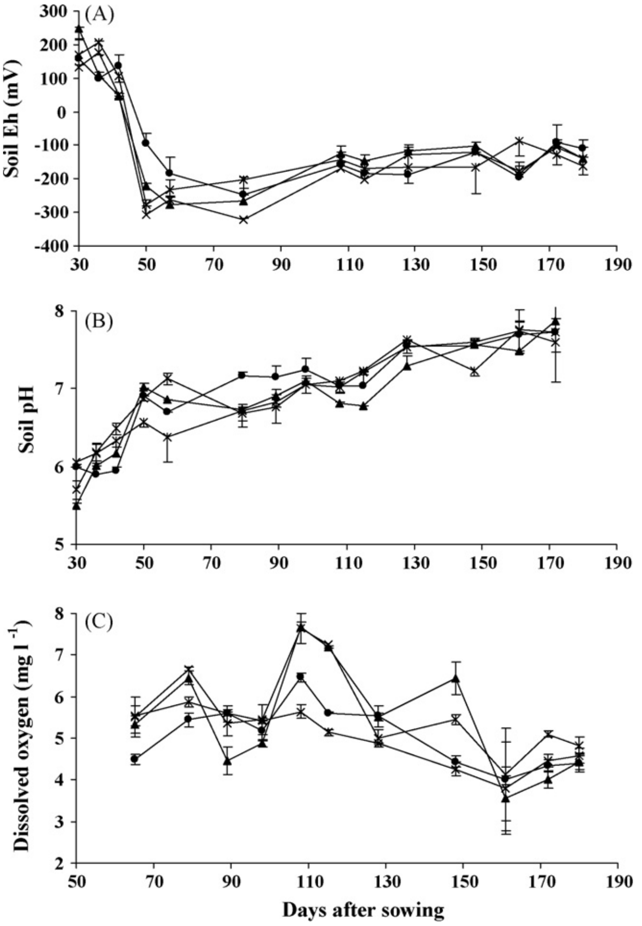

Fig. 4. Seasonal dynamics of changes in (A) redox potential (Eh), (B) pH of the soil and (C) dissolved oxygen concentration of the floodwater from a flooded field under integrated rainfed rice–fish system and planted to two cultivars. Means of duplicate observations plotted, bar/half-bars indicate the standard deviation [(◆) *cv.* Varshadhan without fish; (▲) *cv.* Varshadhan with fish; (*) *cv.* Durga without fish; (×) *cv.* Durga with fish].

than the ones with fish. Dissolved oxygen contents (mg l^{-1}) at the soil–water interface were of the following order Durga (5.58) > Varshadhan (5.47) > Durga + fish (4.94) > Varshadhan + fish (4.88).

Total organic-C (C_{TOC}) and total-N (N_{TOTAL}) contents of the soil was measured at three stages of crop growth (Table 3). Both C_{TOC} and N_{TOTAL} contents were low at the beginning of the experiment but increased with rice plant growth. While C_{TOC} content at panicle initiation stage (115 DAS) did not show any definite trend between the rice + fish and rice alone treatments, N_{TOTAL} contents showed statistically higher values in rice + fish treatments in both the rice cultivars. However, C_{TOC} values were significantly higher in rice alone treatments at a week after harvest (230 DAS). NH_4-N^+ contents of soil and water were measured at four growth stages *viz.* seedling (45 DAS), tillering (65 DAS), flowering (145 DAS) and maturity (215 DAS) (Table 4). Soil NH_4-N^+ contents were always higher in rice alone plots as compared to rice + fish plots at all stages of crop growth. On the contrary, NH_4-N^+ contents of water did not show any specific trend. NH_4-N^+ contents of the refuge pond water were always higher than the field water of any other treatment.

3.3. Yield and yield attributes of rice, weed biomass and fish productivity

Both grain and straw yields varied among the two rice cultivars with the *cv.* Varshadhan yielding significantly higher than *cv.* Durga (Table 5). Growing fish along with rice resulted in an increase in the yields of grain and straw in both the varieties. However, increase in grain yield was statistically significant only in rice + fish plots grown with *cv.* Varshadhan.

Weed biomass (fresh and dry) was higher in rice alone treatments as compared to rice + fish treatments (Table 5). Dry biomass (Mg ha^{-1}) of weeds was highest in *cv.* Varshadhan (0.57) followed by *cv.* Durga (0.50) in respective rice alone treatments. The weed biomass produced was statistically similar in rice + fish treatments of both the two varieties.

Average fish yield was 444 kg fresh fish biomass ha^{-1} calculated on a cumulative basis for the whole cropping period.

3.4. Economic and environmental viability analysis

Table 6 summarizes the integrated evaluation of CH_4 and N_2O emission from the rice + fish farming system *vis-à-vis* rice alone, under rainfed condition. The total emissions from both the systems expressed as aggregated CO_2 equivalent differed significantly between the rice + fish and rice alone systems (Table 6). Calculated on a per hectare basis, the emission of CO_2 equivalent in rice + fish treatment was 82% higher in *cv.* Varshadhan and 83% higher in *cv.* Durga as compared to their respective rice alone treatments. Economic and environmental sustainability analyses (Table 7) indicated that considering the production costs of all major inputs, growing fish with rice resulted in a net profit of $435.36 ha^{-1} from rice + fish treatment as compared to $79.08 ha^{-1} from rice alone

Table 3
Dynamics of total organic-C (C_{TOC}) and total N (N_{TOTAL}) contents[a] of the soil in an integrated rainfed rice–fish farming system

Treatment	Rice cultivar	Days after sowing					
		0		115		230	
		C_{TOC}	N_{TOTAL}	C_{TOC}	N_{TOTAL}	C_{TOC}	N_{TOTAL}
Rice	Varshadhan	0.76 ± 0.07a	0.09 ± 0b	1.02 ± 0.04b (29.1%)	0.07 ± 0a (−22.2%)	1.02 ± 0.02b (29.1%)	0.09 ± 0a (0%)
	Durga	0.76 ± 0.07a	0.09 ± 0b	0.94 ± 0.04ab (18.9%)	0.08 ± 0.01ab (−11.1%)	1.08 ± 0.04b (36.7%)	0.10 ± 0a (42.8%)
Rice + fish	Varshadhan	0.75 ± 0.06a	0.08 ± 0.01ab	0.86 ± 0a (14.6%)	0.09 ± 0b (12.5%)	0.92 ± 0.01a (22.6%)	0.09 ± 0a (12.5%)
	Durga	0.75 ± 0.06a	0.07 ± 0.01a	1.01 ± 0.06b (34.6%)	0.11 ± 0c (57.1%)	1.01 ± 0.01b 34.6%)	0.10 ± 0a (42.8%)
CV (%)		5.0	5.4				
LSD (5%)		0.08	0.01				
LSD (1%)		0.11	0.01				

In a column, means followed by a common letters are not significantly different ($P < 0.05$) by Duncan's Multiple Range Test (DMRT).
Values in parenthesis indicate percent increase over 0 days after sowing.
CV: coefficient of variation; LSD: least significant difference.

[a] Mean of three replicate observations ± standard deviation.

Table 4
NH_4^+-N concentration[a] in soil and water at different growth stages of rice crop in an integrated rainfed rice–fish farming system

Treatment	Rice cultivar	Soil NH_4^+-N (μg g^{-1} soil)				Water NH_4^+-N (μg ml^{-1} water)			
		Crop growth stage				Crop growth stage			
		Seedling (45 DAS)	Tillering (65 DAS)	Flowering (145 DAS)	Maturity (215 DAS)	Seedling (45 DAS)	Tillering (65 DAS)	Flowering (145 DAS)	Maturity (215 DAS)
Rice	Varshadhan	58.73 ± 2.19b	72.93 ± 3.37c	126.84 ± 0.78d	90.19 ± 3.14b	2.40 ± 0.06 a	5.62 ± 0.13ab	4.31 ± 1.94a	4.00 ± 1.64a
	Durga	72.04 ± 1.07d	79.00 ± 3.94d	109.82 ± 0.25c	83.39 ± 6.67b	2.35 ± 0.02a	4.40 ± 0.40a	2.91 ± 0.79a	5.49 ± 1.26a
Rice + fish	Varshadhan	66.92 ± 0.99c	47.15 ± 1.78a	51.09 ± 0.10a	60.41 ± 4.00a	1.25 ± 0.03a	4.50 ± 0.85a	9.55 ± 1.31b	11.39 ± 1.13b
	Durga	50.42 ± 10.53a	54.85 ± 10.44b	68.36 ± 0.66b	60.96 ± 0.57a	0.54 ± 0.02a	6.94 ±± 1.03b	13.90 ± 1.33c	13.87 ± 1.35c
Refuge tank		–	–	–	–	1.73 ± 0.12a	9.76 ± 0.28c	28.07 ± 1.55d	33.02 ± 2.77d
CV (%)		4.9				14.1			
LSD (5%)		5.92				1.93			
LSD (1%)		8.02				2.59			

In a column, means followed by a common letters are not significantly different ($P < 0.05$) by Duncan's Multiple Range Test (DMRT).
DAS: days after sowing; CV: coefficient of variation; LSD: least significant difference.

[a] Mean of three replicate observations ± standard deviation.

Table 5
Yield and yield attributes[a] of rice, weed biomass, and CH_4 and N_2O emission in an integrated rainfed rice–fish farming system

Treatment	Rice cultivar	Grain yield (Mg ha^{-1})	Straw yield (Mg ha^{-1})	Harvest index (%)	Weed biomass (Mg ha^{-1})		CH_4 (kg) Mg^{-1} grain yield	N_2O (kg) Mg^{-1} grain yield
					Fresh biomass	Dry weight		
Rice	Varshadhan	3.93 ± 0.15b	12.40 ± 0.17b	24.08	6.50 ± 1.00c	0.57 ± 0.11a	11.54	0.26
	Durga	3.00 ± 0.10a	5.90 ± 0.36a	33.71	5.25 ± 1.75b	0.50 ± 0a	17.11	0.31
Rice + fish	Varshadhan	4.47 ± 0.25c	13.40 ± 0.62b	25.00	4.63 ± 0.77a	0.42 ± 0.08b	21.57 (86.91)	0.17 (−34.61)
	Durga	3.33 ± 0.29a	6.53 ± 0.15a	33.78	3.67 ± 0.28a	0.30 ± 0.13b	26.75 (56.34)	0.22 (−29.03)
CV (%)		5.8	4.0		10.3	25.3		
LSD (5%)		0.69	2.38		1.04	0.12		
LSD (1%)		1.00	3.47		1.51	0.14		

In a column, means followed by a common letters are not significantly different ($P < 0.05$) by Duncan's Multiple Range Test (DMRT).
Values in parenthesis indicate percent increase/decrease over rice alone.
CV: coefficient of variation; LSD: least significant difference, ns: not significant.

[a] Mean of three replicate observations ± standard deviation.

resulting into a 450% increase in net profit. Converting the aggregate CO_2 equivalent emissions from the two farming systems into C-credit compliance, rice + fish system yielded a value of \$106.80 ha^{-1} with an average increase of 82.56% over rice alone.

4. Discussion

Rice cultivation is an important anthropogenic source of atmospheric CH_4 and N_2O. Apart from different country-specific measurements, quantification of CH_4 emission from rice fields in Asia under different ecologies including irrigated, rainfed and deepwater rice has been made (Wassmann et al., 2000). Emission flux of CH_4 from rainfed lowland paddy as observed in the present study is comparable to values reported in the literature (Adhya et al., 2000; Wassmann et al., 2000). Although transformation of wetlands and rice fields for rice–fish production appears to directly benefit food production and supplement income, information on the impact of integration of fish in rice cultivation on the emission of CH_4 and N_2O are not widely available (Frei and Becker, 2005; Frei et al., 2007). In the present study, fish rearing resulted in an increase in CH_4 emission from both the rice varieties although the extent of emission varied. DO levels in the present study were

Table 6
Global warming potential (GWP)[a] of an integrated rainfed rice–fish farming system

Treatment	Rice cultivar	Cumulative CH_4 emission (kg ha^{-1})	Cumulative N_2O emission (kg ha^{-1})	GWP[b] (Total CO_2 equivalent kg ha^{-1})
Rice	Varshadhan	45.38 ± 1.23a	1.02 ± 0.10b	1438 ± 60
	Durga	51.33 ± 3.86b	0.92 ± 0.11b	1557 ± 129
Rice + fish	Varshadhan	96.33 ± 1.14d	0.75 ± 0.06a	2631 ± 46 (81.67)
	Durga	89.15 ± 1.56c	0.72 ± 0.17a	2846 ± 90 (82.79)
CV (%)		3.20	13.7	
LSD 5%		4.24	0.22	
LSD 1%		6.16	0.32	

Values in parenthesis indicate per cent increase over corresponding rice alone treatment.
In a column, means followed by a common letters are not significantly different ($P < 0.05$) by Duncan's Multiple Range Test (DMRT).
CV: coefficient of variation; LSD: least significant difference.

[a] Mean of three replicate observations ± standard deviation.

[b] GWP was calculated with unitary value of CH_4 = 25.0 CO_2 and N_2O = 298 CO_2 (IPCC, 2007).

Table 7
Economic[a] and environmental viability analysis of an integrated rainfed rice–fish farming system

Treatment	Production cost ($)						Market cost of yield ($)			Net profit ($)	C-credit compliance[b] ($)
	Rice seed	Fertilizer	Fingerling	Fish feed	Labor	Total	Rice	Fish	Total		
Rice	8.48	5.20	–	–	274.00	287.68	366.76	–	366.76	79.08	58.50
Rice + fish	8.48	5.20	60.00	85.00	290.00	448.68	413.40	470.64	884.04 (141.04)	435.36 (450.53)	106.80 (82.56)

Values in parenthesis indicate percent increase over rice alone.

[a] All the costs are calculated at market rates ($ per ton): rice = 106.00; fish = 1060.00.

[b] C-credit compliance is calculated at (per ton CO_2): €30 = $39 (as of April 2006: http://www.emissierechten.nl/marketanalyse.htm).

significantly higher in the field plots containing rice alone as compared to rice + fish plots. Frei et al. (2007) reported higher values of CH_4 emission from rice–fish systems from Bangladesh that was attributed to a drop in the DO level. Thus, the most likely reason of high CH_4 emission as observed in the present study could be due to higher methanogenesis in an environment containing comparatively lower dissolved oxygen concentration as well as fish movement and associated bioturbation that would have caused release of the entrapped CH_4. Strong disturbance of the upper soil layers caused by fish movement resulting into increased water turbidity was reported earlier (Chapman and Fernando, 1994; Frei and Becker, 2005a).

The carp species grown in the present experiment feeds on planktons, algae and aquatic weeds (Vromant et al., 2002) and could be the reason for lower chlorophyll *a* content and lower weed biomass. Increase in floodwater turbidity due to the bottom feeding habit of the carps, especially *C. mrigala*, may additionally have hampered photosynthetic activity of the floodwater (Chapman and Fernando, 1994). However, release of fish excreta and the digested/semi-digested organic residues would have caused higher availability of dissolved organic-C that would have influenced higher CH_4 production and its subsequent emission. Dissolved organic-C had a significantly positive correlation with CH_4 emission ($r = 0.79^*$, $n = 15$). Even the dissolved CH_4 content was also higher in rice + fish plots and had statistically significant positive relationship with CH_4 emission ($r = 0.917^*$, $n = 15$).

Emission of N_2O, however, presented a completely different picture. N_2O emission from flooded fields planted to rice exhibited a much lower flux as compared to CH_4. N_2O emission fluxes from rice fields have been measured for different countries (Akiyama et al., 2005) and the values reported in the present study (0.72–1.02 kg N_2O ha^{-1}) remains within the reported range. Interestingly, fish growing resulted in a marginal reduction in the N_2O emission flux. Initial flux of N_2O could be due to higher atmospheric temperature and low water level in the field (Silvola et al., 1996) as well as high available N in the form of fertilizer. Increased N_2O emission at maturity stage in all the treatments may be due to increased N mineralization (Adhya et al., 1996; Arnold et al., 2005). Higher dissolved oxygen content in the rice alone treatment might have influenced nitrification resulting into release of more N_2O.

Lightfoot et al. (1993) demonstrated that stocking of fish in rice fields may contribute to the general fertility status of the rice field. The enhancing effect of fish rearing on physicochemical characteristics of soil and floodwater has been reported by a number of researchers (Cagauan, 1995; Vromant and Chau, 2005). The nutrient dynamics in the floodwater and the soil interstitial water are very similar which is not surprising as the rice field floodwater and the soil form a continuum (Watanabe and Furusaka, 1980). In the present study, soil NH_4^+-N contents were high in the rice alone plot compared with rice + fish plots at all stages of crop growth although NH_4^+-N contents of water did not exhibit any specific trend. Fish perturbation of the soil–water interface might make the soil porous for nutrients to be readily absorbed by the rice roots (Vromant and Chau, 2005).

The impact of fish growing in rice fields is visible in the increase in grain yield of rice in rice + fish plots, although it varied depending on the rice cultivar grown and only in case of *cv.* Varshadhan, the increase in grain yield was statistically significant (Table 5). Increase in soil fertility due to fish rearing has been reported earlier and was attributed to either (1) additional nutrients from decomposing dead fish and from fish faeces, (2) fish perturbation of the soil-water interface leading to release of fixed nutrients, and (3) fish grazing on the photosynthetic aquatic biomass aiding in nutrient recycling and decreasing N losses (Cagauan, 1995). It is possible all these eventualities, either alone or in combination might have resulted into an increase in grain yield in rice.

Considering the results of the integrated evaluation of greenhouse gas emissions from the rice–fish ecosystem, it provide insights into the main sources of greenhouse gas emissions and their contribution to the total atmospheric loading, expressed as aggregate CO_2 equivalent global warming potential (GWP). The total emission from rice + fish plots was considerably higher with CH_4 contributing a larger share (91%) as compared to rice alone plots (78–81%). On the contrary, N_2O had a comparatively lesser contribution with 19–22% share in rice alone plots that was reduced further to 9% in rice + fish plots. Flooded rice fields are established CH_4 source and also contribute to N_2O especially in intensive rice farming system. Intensive rice cropping under irrigated condition with optimum nutrient management can emit CH_4 flux in the range of >175 kg CH_4 ha^{-1} (Setyanto et al., 2000), as compared to the present study where fish stocking resulted in CH_4 efflux in the range of 89–96 kg CH_4 ha^{-1}. Transforming the GWP value to C-credit compliance (http://www.emissierechten.nl/marketanalyze.htm, Gilbert et al., 2004), rice–fish system contributes to a value which is 68.17% higher than rice alone under rainfed conditions. However, considering the profit-loss analysis based on the market cost of yield, rice–fish system provides a net profit of $356.28 ha^{-1} over rice alone system. Thus, considering the higher profit potential, rice–fish system presents an economically sound agricultural system in spite of higher GWP and related C-credit compliance.

5. Conclusions

Integration of rice and fish cultivation promises ecologically sound and economically successful management of flooded ecosystems. In the present study, rearing fish in paddy fields resulted in an increased emission of CH_4 and decreased release of N_2O. However, considering the attendant economic benefits of growing fish in rice fields, rice–fish ecosystem can be an important crop management system. This is evident from the additional fish output, an important source of protein to the marginal farmers and higher net profit that underwrites the increased carbon credit compliance of a rice–fish ecosystem due to larger cumulative GWP calculated as total CO_2 equivalent emission from such ecosystem.

Acknowledgements

We thank the Director, Central Rice Research Institute, Cuttack for permission to publish the results. A. Datta was supported by a fellowship from the SAC-CRRI Collaborative project granted to the corresponding author (Grant no. SAC/RSAM/EIAA/WP/01/03). D.R. Nayak was supported by a fellowship from the Council of Scientific and Industrial Research, New Delhi.

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