

Greenhouse gas emissions and energy exchange in wet and dry season rice: eddy covariance-based approach

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Abstract Lowland tropical rice-rice system has a unique micrometeorological characteristic that affects both energy component and net ecosystem energy. Periodic and seasonal variations of methane (CH₄), carbon dioxide (CO₂), and energy exchange from irrigated lowland rice-rice ecosystem were studied using open-path eddy covariance (EC) system during the dry (DS) and wet (WS) seasons in

2015. Concurrently, the manual chamber method was employed in nitrous oxide (N₂O) measurement efflux. Cumulative net ecosystem carbon exchange (NEE) was observed highest (−232.55 g C m^{−2}) during the WS and lowest (−14.81 g C m^{−2}) during wet fallow (WF). Similarly, the cumulative net ecosystem methane exchange (NEME) was found highest (13,456.5 mg CH₄ m^{−2}) during the WS and lowest (2014.3 mg CH₄ m^{−2}) during the WF. Surface energy fluxes, i.e., sensible (Hs) and latent heat (LE) fluxes, showed a similar trend. With the advancement of time, the ratio of ecosystem respiration (Re) and gross primary production (GPP) increased. The cumulative global warming potential (GWP) for the two cropping seasons including two fallows was 13,224.1 kg CO₂ equivalent ha^{−1}. The GWP and NEME showed a similar trend as soil enzymes and labile carbon pools in both seasons (except GWP at the harvesting stage in the wet season). The mean NEE exhibited a more negative value with decrease in labile pools from panicle initiation to harvesting stage in the WS. Soil labile C and soil enzymes can be used as an indicator of NEE, NEME, and GWP in lowland rice ecology.

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Climate change

Introduction

Eddy covariance (EC) measures the fluxes of greenhouse gas (GHG) that exchange in between the rice-

rice ecosystem and atmosphere (Baldocchi 2003). The net ecosystem exchange (NEE) of carbon dioxide (CO_2) of the rice-rice system can be measured using the EC data over a large area (Chapin et al. 2006). Carbon dioxide is an important driver controlling carbon cycle. The carbon cycle is governed by photosynthetic fixation of atmospheric CO_2 and its release by autotrophic and heterotrophic respiration. Basically, NEE is influenced by several factors like soil organic carbon (SOC) content, plant water supply, leaf area index, type of crop, and management practices (Smith et al. 2010; Reichstein et al. 2005). The SOC accumulates in flooded rice soil due to the oxygen deficiency limited by slow diffusion in flooding water. Thus, waterlogged rice soil acts as a store house of carbon (Joosten and Clarke 2002). During the fallow period, the stored carbon in soil may be oxidized by microorganism (Maljanen et al. 2001). Emission of methane (CH_4) from the rice field is gaining attention globally as it is the second largest radiative forcing GHG after CO_2 (Forster et al. 2007). Irrigated lowland rice paddies are one of the principal anthropogenic sources of CH_4 , representing approximately 5–10% of the worldwide CH_4 source (Kirk and Bickert 2004; Matthews et al. 2000). In lowland irrigated rice, flooding creates anaerobic soil condition which helps CH_4 production from the decomposition of both native and externally added organic materials (Neue 1993; Wassmann et al. 2000). In an estimate, it was observed that methane emission was 500–600 Tg CH_4 year⁻¹ globally (Dlugokencky et al. 2011). Therefore, diminishment of the global CH_4 sources offers possibilities for curtailing the rising trend in the global warming at a short time (Dlugokencky et al. 2011). Also, nitrous oxide (N_2O) has higher global warming potential. Nitrogenous fertilizer applied to crops is the predominant source of N_2O emission that accounts for approximately 75% of direct emission from agricultural soil (Zheng et al. 2004).

Eddy covariance techniques can be used to measure various components of energy balance like latent heat flux (LE), sensible heat flux (Hs), soil heat flux (G), net radiation (NR), etc. (Kristensen et al. 1997). Because of standing water, the lowland rice field is different from other aerobic crops. Substantial effect of energy partitioning into Hs and LE was noted in rice; for instance, in standing water, LE is around 65–79% of net radiation (NR), while Hs is about 8% of NR (Masseroni et al. 2015). Photosynthetically active radiation (PAR) is mainly the solar radiation energy in between 400 and 700 nm wavelength which is used by plants for

photosynthesis (Mitchell et al. 1998; Sinclair and Muchow 1999). The crop duration, growth, and some agronomic characters of rice are influenced by inadequate PAR. For example, prolonged period of low light exposure increases plant height and growth and enlarges the leaf surface (Ren et al. 2002; Liu et al. 2009).

About 90% of the global rice production is contributed by the Asian countries (Masseroni et al. 2015) like India, China, the Philippines, Japan, Bangladesh, etc. In India, rice is grown in 43.95 M-ha areas with an annual production of 106.54 Mt (GOI 2014). Rice-rice cropping system is the dominant system followed in the coastal region of eastern India. This system largely contributes in GHG production which is influenced by various edaphic conditions, agricultural management practices, and soil properties (soil enzymes and carbon pools). For understanding the dynamics of CO_2 and CH_4 in rice paddies, knowledge of soil enzymes and labile pool of carbon are required to draw a meaningful interrelation of gaseous emission with the chemical and microbiological properties of soil (Ling et al. 2011). For instance, the enzymes like dehydrogenase and β -glucosidase are involved in carbon cycling and reflect the microbial activity in soil organic matter decomposition (Das and Varma 2011). Similarly, fluorescein diacetate activity indicates the active microflora which is involved in producing extracellular enzymes (Adam and Duncan 2001).

For several decades, climate change studies using eddy covariance data focused only on the exchange of carbon dioxide (Alberto et al. 2009; Bhattacharyya et al. 2014), methane (Alberto et al. 2014; Detto et al. 2011), surface energy fluxes, and balance (Masseroni et al. 2015; Tsai et al. 2007) under flooded and aerobic rice ecology throughout the world. All these studies have explained the component of mass and/or energy exchange using eddy covariance, but limited information is available on the factors affecting gaseous exchange and GWP in tropical paddy.

In the earlier work from India, it was demonstrated how NEE, GPP, and RE were governed by net radiation, vapor pressure deficit, soil moisture, soil temperature, soil heat flux, and air temperature (Bhattacharyya et al. 2013a). Seasonal carbon balance was also determined using the data of CO_2 and CH_4 obtained from EC (Bhattacharyya et al. 2014; Swain et al. 2016). Keeping the above facts in mind, the current study was conducted (i) to study the daily, seasonal, and annual variations in energy component and mass exchange in rice-rice ecology and (ii) to understand the effect of environmental (e.g., Hs, LE, PAR, NR)

and biological (e.g., soil enzymes and LC pools) factors on the gaseous exchange and GWP in rice soil.

Materials and methods

Location for measurement

The study site is located in the farm of the National Rice Research Institute (NRRI) Cuttack, Odisha, India (20° 27' 6" N latitude, 85° 56' 25" E longitude and 24 m above mean sea level). The yearly mean temperature was 27.7 °C and mean annual rainfall was 1300 mm during the period of experimentation. The study site soil is sandy clay loam in texture (24.5% clay, 22.4% silt, 53.1% sand) and characterized as Aeric Endoaquept with bulk density 1.39 Mg m⁻³, pH (1:2.5 soil:solution ratio) 6.19, electrical conductivity 0.40 dS m⁻¹, total C 11.0 g kg⁻¹, and total N 0.78 g kg⁻¹.

Establishment of crop

Rice was grown in the dry season (DS) and wet season (WS) of 2015 followed by two fallow periods (dry fallow, DF and wet fallow, WF). Twenty-one-day-old rice seedlings (cv. Naveen in DS and cv. Swarna-Sub 1 in WS) were transplanted to a puddled soil with 20 cm × 15 cm spacing. Transplanting was done on the 2nd week of July in WS and 1st week of January of DS and harvested in November and last week of May, respectively. Nitrogen (N) was applied through urea in three equal splits at the basal, maximum tillering (MT), and panicle initiation (PI) stages. About 80 and 100 kg N ha⁻¹ were applied in the WS and DS, respectively. Phosphorus (P) and potassium (K) were added at the rate 40 kg ha⁻¹ each at basal during land preparation in both seasons. However, the observation site was kept flooded with 6 ± 2 cm standing water throughout the crop growth and drained out 15 days before the harvest.

Observation site for CO₂ and CH₄ flux

The EC was installed at the center of a lowland flooded rice field covering a fetch area of 2 ha. The main components of the EC system were a sonic anemometer (CSAT3, M/s Campbell Scientific Corp.) for 3D wind speed and sonic temperature and an open-path infrared gas analyzer (LI-7500A, M/s LICOR Inc.) for flux of CO₂ and water vapor. A data logger (CR3000, M/s Campbell Scientific Corp.) was used to record the flux data. The infrared gas analyzer and sonic anemometer were installed on a tripod

aluminum mast at the height of 1.5 m. The LI-7500A was sloped 15° of the head portion from the vertical direction to minimize the entering of precipitation inside the window. The LI-7500A and CSAT3 were directed to the prevalent southwest wind direction (Campbell Scientific, Inc 2009; LICOR, Inc 2011). The NEE was calculated by cumulating the CO₂ flux (flux of CO₂, F_c) and CO₂ storage change (F_s). The F_s was ignored due to the low height of the rice canopy. The mean vertical flux density of CO₂ was obtained by using the formula (Webb et al. 1980; Baldocchi 2003):

$$F_z = \rho_a \overline{\omega' C'} \tag{1}$$

Where F_z is the mean vertical flux density of CO₂, ρ_a is the density of air (kg m⁻³), ω' is the 30-min covariance between vertical fluctuations in wind speed, and C' is the CO₂ mixing ratio; time averaging was denoted by overbars, whereas the primes presented as fluctuations of mean value. A positive value of the covariance indicated net transfer of CO₂ to the atmosphere, while a negative value signified net absorption of CO₂ by the photosynthetic flora. Seasonal net exchange was calculated from the half an hour mean NEE data (Tanner and Thurtell 1969). Methane flux was measured using an open-path CH₄ analyzer (LI-7700, M/s LICOR Inc., USA) installed at a height of 1.5 m above the soil surface. This sensor contained a diode laser in an open Herriott cell configuration using wavelength modulation spectroscopy (McDermitt et al. 2011; Alberto et al. 2014). Output of the methane sensor was logged into a CR3000 data logger (M/s Campbell Scientific Corp., Canada).

Measurements of heat fluxes and temperature

The H_s and LE were measured by the EC system employing three-axes sonic anemometer and open-path CO₂ and H₂O infrared gas analyzer. Turbulent fluxes of H_s and LE were calculated from covariance between a respective scalar and the vertical wind (w) as (Aubinet et al. 2000):

$$H_s = \rho_a C_{pa} \overline{T' w'} \tag{2}$$

$$LE = L \rho_a \overline{q' w'} \tag{3}$$

where ρ_a (kg m⁻³) is the density of air, C_{pa} = (1004 J kg⁻¹ K⁻¹) is the specific heat of air at constant pressure,

and $L = (2.256 \times 10^6 \text{ J kg}^{-1})$ is the latent heat of vaporization of water. The w' , T' , and q' are the deviations from time means of vertical wind speed (ms^{-1}), virtual temperature (K), and the water vapor mixing ratio (mmol mol^{-1}), respectively.

The 4-component radiation sensor (CNR4, KIPP, and ZONEN, M/s Campbell Scientific Corp.) was used to take reading of NR. Simultaneously, a soil temperature probe (107 B, Campbell Scientific Corp.) was used to measure soil temperature at a depth of 5 cm.

Quality control, gap filling, and processing of flux data

The raw data collected from EC were checked for quality (Mauder and Foken 2011). The raw flux data was cleaned by removing the spikes (Vickers and Mahrt 1997). All the corrections like planar fit coordinate rotation, conversion of buoyancy, high-frequency response losses, and density fluctuations were done (Wilczak et al. 2001; Liu et al. 2001; Webb et al. 1980; Aubinet et al. 2000). After this, the data were processed using the EdiRe software (University of Edinburgh). The U^* filtering method was employed for removal of spikes that arise due to unsuitable environmental conditions (Reichstein et al. 2005; Papale and Valentini 2003; Bhattacharyya et al. 2014). The “look-up” table approach was used for gap filling of lost and discarded data (Falge et al. 2001).

Flux partitioning of NEE

The NEE denotes the net gain or loss of carbon of an ecosystem and it is determined by deducting the loss of carbon by autotrophic (R_a) and heterotrophic (R_h) respiration from GPP of autotrophic organisms. The rectangular hyperbola (Ruimy et al. 1995) method was used for flux partitioning of NEE into GPP and R_e :

$$NEE_{\text{night+day}} = -[(\alpha\beta Q/\alpha Q + \beta)] + \gamma \quad (4)$$

Where α is the apparent ecosystem quantum yield, β is the hypothetical maximum GPP uptake, γ is the estimated R_e , and Q is the PAR ($\mu\text{mol m}^{-2} \text{ s}^{-2}$). The GPP was calculated by using the equation:

$$NEE = \text{GPP} - R_e \quad (5)$$

Nitrous oxide measurement

The EC system used in this study had no separate sensor for measuring N_2O ; hence, the N_2O flux was measured by the manual closed chamber method near the eddy fetch area throughout the year by following the standard procedure (Bhattacharyya et al. 2012; Datta et al. 2009; Chatterjee et al. 2018). Measurements were initiated at the start of the season and continued until the end of whole cropping season including both the fallows. The flux data were taken every 3–7-day intervals; however, during fertilizer application, data were collected 1 day before and 1 day after the fertilizer application. The N_2O concentration was measured in a gas chromatograph (Chemito 2000, M/s Thermo Scientific) furnished with an electron capture detector (ECD). The linear interpolation technique was used to fill the gap (Datta et al. 2009). Subsequently, the cumulative and seasonal mean N_2O emission was figured graphically.

GWP measurement

The GWP is used to assess a GHG to absorb heat in the atmosphere comparative to CO_2 . Integrated assessment of GHG emissions articulated as GWP was calculated using the formula: $\text{GWP} = 24.5 * \text{CH}_4 + \text{CO}_2 + 320 * \text{N}_2\text{O}$ kg CO_2 equivalent ha^{-1} from CH_4 , CO_2 , and N_2O flux values (Bhattacharyya et al. 2012).

Soil enzymatic activities and soil LC pools

Soil enzymatic activities and LC pools were determined at MT, PI, FL (flowering), and H (harvesting) stages. Soil samples were collected in polythene bags from five random points (0–15 cm depth) using an auger near the fetch area of the EC system. Then, the soil samples were kept in a refrigerator at 4 °C. Dehydrogenase (DHA), fluorescein diacetate (FDA) hydrolysis, and β -glucosidase (β -GLU) activities were determined in the soil samples by the procedure described by Casida et al. (1964), Adam and Duncan (2001), and Eivazi and Tabatabai (1988), respectively. Modified chloroform fumigation-extraction method was used for soil microbial biomass-C (MBC) measurement (Witt et al. 2000). Readily mineralizable carbon (RMC) was extracted by 0.5 M K_2SO_4 followed by estimation using the wet digestion method (Inubushi et al. 1991; Vance et al. 1987).

Results

Daily, seasonal, and annual variations in NEE and NEME

The mean NEE varied from -5.71 to $2.29 \text{ g C m}^{-2} \text{ day}^{-1}$ during the monitoring period covering both crop seasons and fallow periods (Fig. 1a). The mean NEE was lower in the DF ($-1.49 \text{ g C m}^{-2} \text{ day}^{-1}$) than in the WF ($-0.29 \text{ g C m}^{-2} \text{ day}^{-1}$). Contrastingly, mean NEE during the DS ($-1.62 \text{ g C m}^{-2} \text{ day}^{-1}$) was higher than the mean NEE during the WS ($-1.83 \text{ g C m}^{-2} \text{ day}^{-1}$). Annual mean NEE calculated by averaging the crop seasons and fallow periods was recorded $-1.31 \text{ g C m}^{-2} \text{ day}^{-1}$ (Table 1). The mean value of NEE was found negative in all the cases. Cumulative NEE values for the DF and WF were -95.37 and $-14.81 \text{ g C m}^{-2}$, whereas cumulative mean NEE values during the DS and WS were -199.73 and $-232.55 \text{ g C m}^{-2}$, respectively. The annual cumulative NEE was observed $-542.47 \text{ g C m}^{-2}$ (Table 1). It was also observed from our study that the NEE became more negative with the increase of PAR and NR (Table 2).

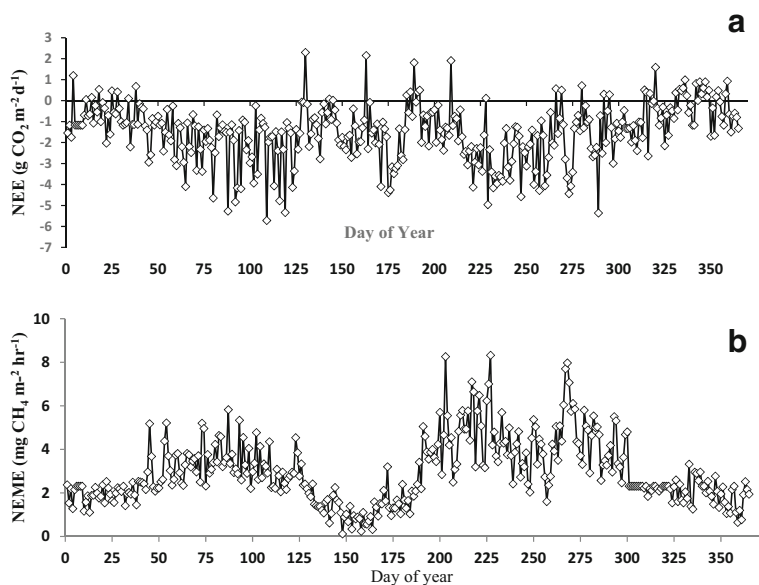
Daily mean NEME varied from 0.12 to $8.85 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ during the study period (Fig. 1b). Mean NEME values recorded during the DF and WF were 1.47 and $1.99 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$, respectively. Mean of NEME was $2.86 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ during the DS and it increased to $4.19 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ during the WS. Annual mean NEME during the study period was 2.62 mg CH_4

$\text{m}^{-2} \text{ h}^{-1}$. The cumulative NEME was $2259.81 \text{ mg CH}_4 \text{ m}^{-2}$ in the DF, while the value was a little higher ($2447.87 \text{ mg CH}_4 \text{ m}^{-2}$) during the WF (Table 1). Cumulative NEME values during the DS and WS were 8434.11 and $12,781.96 \text{ mg CH}_4 \text{ m}^{-2}$, respectively. The annual cumulative NEME values during the study period were $25,923.8 \text{ mg CH}_4 \text{ m}^{-2}$ (Table 1). The highest methane flux in a day ($5.82 \text{ mg m}^{-2} \text{ h}^{-1}$ in the DS and $8.32 \text{ mg m}^{-2} \text{ h}^{-1}$ in the WS) was observed during the MT to PI stages of crop development (Fig. 1b). NEME had significant and positive correlation with LE in both seasons (Table 2).

Daily, seasonal, and annual variations in N_2O efflux

Daily mean N_2O flux varied from 4.17 to $52.96 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ throughout the crop seasons including the two fallow periods (Fig. 2). Mean $\text{N}_2\text{O-N}$ flux values during the fallow periods after the harvest of the crop were $10.06 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ (DF) and $5.37 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ (WF), while the flux values were quite high during the DS ($27.51 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$) and WS ($23.82 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$). Cumulative N_2O fluxes of both fallow (DF and WF) periods were 644.07 and $273.97 \mu\text{g N}_2\text{O-N m}^{-2}$, respectively (Table 1). The annual mean N_2O flux was $16.69 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ (Table 1). Three peaks of $\text{N}_2\text{O-N}$ efflux following the application of urea were observed both in the dry and wet seasons (Fig. 2).

Fig. 1 Daily average of net ecosystem exchange such as a carbon dioxide (NEE) and b methane (NEME) by eddy covariance technique in the year 2015



Seasonal variations in GWP

The cumulative GWP was observed 5803.63 kg CO₂ equivalent ha⁻¹ during the DS, which was less as compared to its value (7213.16 kg CO₂ equivalent ha⁻¹) during the WS (Table 1). The cumulative GWP in DF and WF was 2201.02 and 1264.24 kg CO₂ equivalent ha⁻¹, respectively. The highest GWP (101.96 kg CO₂ equivalent ha⁻¹) was observed on the 109th day of the year during the DS which coincides with the H stage of rice crop, whereas in the WS, the highest GWP (111.98 kg CO₂ equivalent ha⁻¹) was recorded on the 241st day of the year that falls on the FL stage of rice growth (Fig. 3). Mean GWP at the different growing seasons of rice crop (DS and WS) was correlated with NR, PAR, LE, and Hs (Table 2). Mean GWP exhibited a positive and significant correlation ($p < 0.01$) with NR, PAR, and LE during both seasons (DS and WS), while a negative significant correlation ($p < 0.01$) with Hs during the DS (table not shown).

Daily and seasonal variation of NEE, GPP, and Re

Over the season, daily variations of mean NEE varied from 2.21 to -5.51 μmol CO₂ m⁻² s⁻¹ throughout the cropping season, and on the basis of mean diurnal NEE, maximum CO₂ assimilation or uptake by rice crop was found at 12.00 h and maximum emission was observed at 4.30 h (Fig. 4). During the dry season, NEE was lowest (mean -0.63 μmol CO₂ m⁻² s⁻¹) in the vegetative stage, then gradually decreased, i.e., MT to PI stages (mean -1.16 μmol CO₂ m⁻² s⁻¹) and further decreased value (mean -2.04 μmol CO₂ m⁻² s⁻¹) while heading to the FL stage and then it attains its lowest value (mean -2.33 μmol CO₂ m⁻² s⁻¹) during the harvest period (Table 3). The GPP and Re varied from -8.11 to -18.92 and 7.83 to 15.45 μmol m⁻² s⁻¹, respectively, at different growth stages of the DS. The highest GPP (-18.92 μmol m⁻² s⁻¹) and Re (15.45 μmol m⁻² s⁻¹) were recorded at the H stage of the DS. Similarly, during the WS, the GPP and Re varied from -8.1 to -18.92 μmol m⁻² s⁻¹ and 7.83 to 15.45 μmol m⁻² s⁻¹, respectively. The highest GPP (-19.62 μmol m⁻² s⁻¹) at the harvest period and Re (16.70 μmol m⁻² s⁻¹) at the FL stage were recorded during the WS (Table 3). In both crop seasons, the magnitude of Re increased with the advancement of crop growth stages. The GPP was decreased with the advancement of rice growth during

Table 1 Monitoring of net ecosystem carbon dioxide exchange (NEE), net ecosystem methane exchange (NEME), nitrous oxide, and GWP during the crop growth stage including both the dry and wet seasons and fallow period

Season	Net ecosystem carbon dioxide exchange		Net ecosystem methane exchange		Nitrous oxide		Global warming potential (GWP)	
	Mean (g C m ⁻² day ⁻¹)	Cumulative (g C m ⁻²)	Mean (mg CH ₄ m ⁻² h ⁻¹)	Cumulative (mg CH ₄ m ⁻²)	Mean (μg N ₂ O-N m ⁻² h ⁻¹)	Cumulative (μg N ₂ O-N m ⁻² h ⁻¹)	CO ₂ -eq emission (kg CO ₂ ha ⁻¹)	
Dry season	-1.62	-199.74	2.85	8434.11	27.51	3411.97	5803.63	
Dry season (fallow period)	-1.49	-95.37	1.47	2259.81	10.06	644.07	2201.02	
Wet season	-1.83	-232.55	4.19	12,781.96	23.82	3025.74	7213.16	
Wet season (fallow period)	-0.29	-14.81	1.99	2447.87	5.37	273.97	1264.24	
Annual	-1.31	-542.47	2.62	25,923.75	16.69	7355.76	16,482.07	

Table 2 Correlation coefficients between global warming potential (GWP), net radiation (NR), photosynthetic active radiation (PAR), latent heat (LE), and sensible heat flux (Hs)

	NEME	NEE	N ₂ O	LE	Hs	NR	PAR
Dry season 2015							
NEME	1						
NEE	-0.565**	1					
N ₂ O	-0.191*	0.301**	1				
LE	0.427**	-0.483**	-0.590**	1			
Hs	-0.338**	0.336**	0.416**	-0.725**	1		
NR	0.459**	-0.565**	-0.537**	0.876**	-0.500**	1	
PAR	0.399**	-0.517**	-0.509**	0.790**	-0.421**	0.960**	1
Wet season 2015							
NEME	1						
NEE	-0.078	1					
N ₂ O	0.365**	-0.029	1				
LE	0.300**	-0.257**	0.381**	1			
Hs	-0.264**	-0.079	-0.367**	-0.010	1		
NR	0.060	-0.465**	0.008	0.557**	0.399**	1	
PAR	0.101	-0.478**	0.047	0.552**	0.403**	0.989**	1

ns nonsignificant

** Correlation is significant at the 0.01 level (2-tailed); * correlation is significant at the 0.05 level (2-tailed)

both crop seasons. The GPP of the WF is higher than the GPP of the DF and vice versa for Re (Table 3).

Daily, seasonal, and annual variations in Hs, LE, PAR, and NR

The LE was observed as the dominant component of energy balance in the rice-rice ecosystem. Mean daily LE and Hs ranged from 0.13 to 16.65 MJ m⁻² day⁻¹ and from -4.11 to 4.76 MJ m⁻² day⁻¹ during the monitoring period (Fig. 5a, b). The magnitude of mean Hs was in close proximity during the fallow periods (1.45 MJ m⁻² day⁻¹ in the DF and 1.64 MJ m⁻² day⁻¹ in the WF), while the LE during the DF (8.60 MJ m⁻² day⁻¹) was higher than the LE in the WF (2.61 MJ m⁻² day⁻¹) (Table 4). The mean Hs was lower than LE during the DS and WS (Table 4). The

mean PAR during the DS (743.43 μmol m⁻² s⁻¹) was 14.8% higher than the PAR during the WS (647.53 μmol m⁻² s⁻¹), whereas NR in the DS (136.97 W m⁻²) was only 4.6% higher than the mean NR in the WS (130.87 W m⁻²) (Fig. 5c, d). A negative and highly significant correlation of NEE was observed with LE (-0.367), NR (-0.497), and PAR (-0.456), while a significant and positive correlation was observed with Hs (0.133) throughout the year (table not shown).

Soil enzymatic activities and LC pools at different growth stages

Soil enzymes such as FDA, DHA, and β-GLU showed variation in crop growth stages. The FDA was highest at PI (23.84 μg fluorescein g⁻¹ h⁻¹). A

Fig. 2 Daily average nitrous oxide (N₂O-N) flux by the manual chamber method in the year 2015

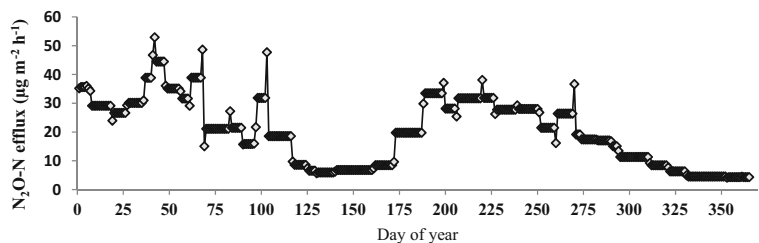
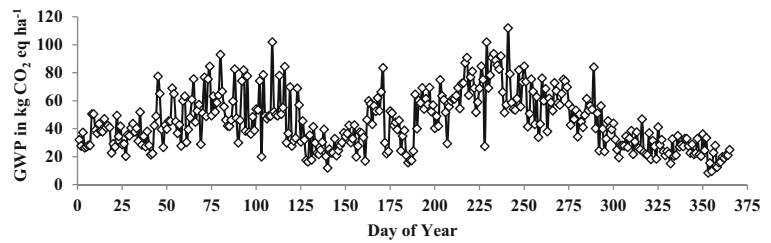


Fig. 3 Global warming potential in CO₂ equivalent emission in the year 2015



similar trend was observed in the case of DHA and β -GLU. DHA and β -GLU were lowest at the MT stage (161.96 $\mu\text{g TPF g}^{-1} \text{ day}^{-1}$ soil, 19.27 $\mu\text{g p-nitrophenol g}^{-1} \text{ day}^{-1}$) followed by the FL (379.57 $\mu\text{g TPF g}^{-1} \text{ day}^{-1}$, 43.38 $\mu\text{g p-nitrophenol g}^{-1} \text{ day}^{-1}$) and PI (478.82 $\mu\text{g TPF g}^{-1} \text{ day}^{-1}$, 60.20 $\mu\text{g p-nitrophenol g}^{-1} \text{ day}^{-1}$) stages (Table 5). Soil labile C pools are represented by MBC and RMC. The RMC was highest in the PI stage (132 $\mu\text{g C g}^{-1}$ during the DS and 79 $\mu\text{g C g}^{-1}$ during the WS) (Table 5). Similarly, the MBC was highest in the PI stage (147.10 $\mu\text{g C}^{-1} \text{ g}^{-1}$).

The GWP and NEME showed a similar trend as soil enzymes and labile carbon pools in both seasons (except GWP at the harvesting stage in the wet season) (Fig. 6a). The N₂O flux during the dry season decreased from the PI to H stages. A similar trend was recorded in soil enzymes and labile carbon pools during those stages. The mean NEE exhibited a more negative value with a decrease in labile pools from the PI to H stages in the wet season (Fig. 6b).

Discussion

NEE as influenced by flooded rice ecology

Positive and negative values of NEE were observed during the study period. A positive value of NEE indicated net CO₂ emission into the atmosphere, while the negative NEE signified the net CO₂ uptake by the rice. During the fallow periods (DF and WF), NEE was slightly higher than the NEE during maturity of crop (Fig. 1a), which indicated slow but steady rates of organic matter decomposition at fallow (McMillan et al. 2007). Once the floodwater receded, the supply of labile fermentation products increased due to the rapid mineralization of leftover organic residues under aerated condition. Higher soil temperatures (as no standing water) during the fallow periods increased in daily CO₂ efflux further (Miyata et al. 2000; McMillan et al. 2007). However, NEE in lowland rice ecology was mainly governed by various physical, physiological, and biological

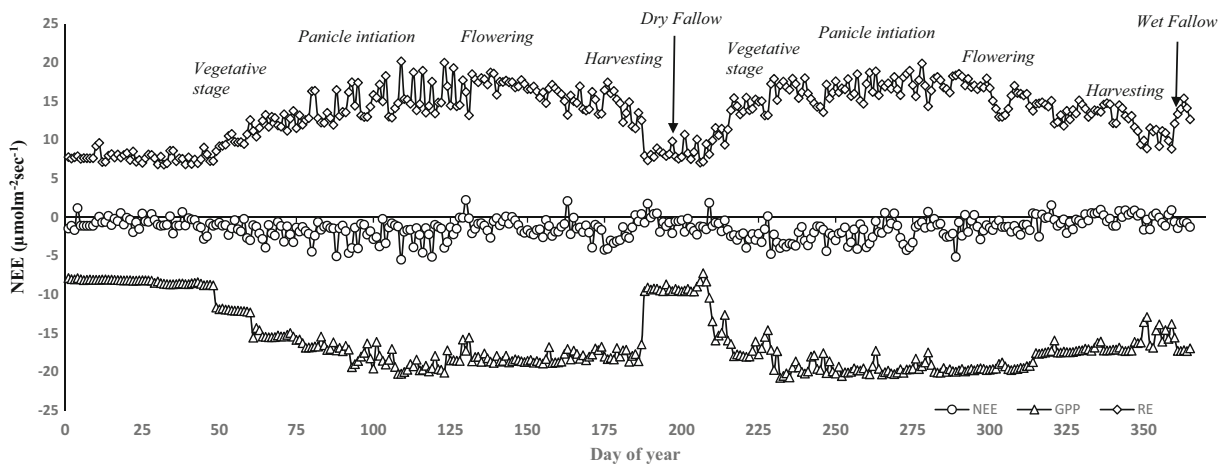


Fig. 4 Partitioning of daily average net ecosystem exchange (NEE), gross primary production (GPP), and respiration (RE) in days of the year 2015

Table 3 Mean NEE, GPP, and Re of the entire crop growing season including the fallow periods

	Stages	NEE ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	GPP ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Re ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
Dry season	Vegetative stage	-0.63	-8.11	7.83
	Panicle initiation	-1.16	-9.90	8.44
	Flowering stage	-2.04	-16.06	12.93
	Harvesting	-2.33	-18.92	15.45
Dry fallow	-	-1.44	-18.07	15.86
Wet season	Vegetative stage	-0.84	-9.17	8.31
	Panicle initiation	-2.36	-17.47	14.48
	Flowering stage	-2.03	-19.60	16.70
	Harvesting	-1.43	-19.62	16.28
Wet fallow	-	-0.28	-16.67	12.84

parameters (Nair et al. 2011; Saito et al. 2005). It was observed from this study that the daily variation in NEE increased with the progress of growth stages and reached its maximum around the PI to FL stages

(Swain et al. 2016). In both the DS and WS, the flooded rice paddy behaved as a net CO₂ sink on a daily basis from vegetative to early maturity stage. During the WS, NEE was lowest at the early

Fig. 5 Daily heat fluxes of different energy balance such as **a** latent heat, **b** sensible heat, **c** photosynthetically active radiation, and **d** net radiation

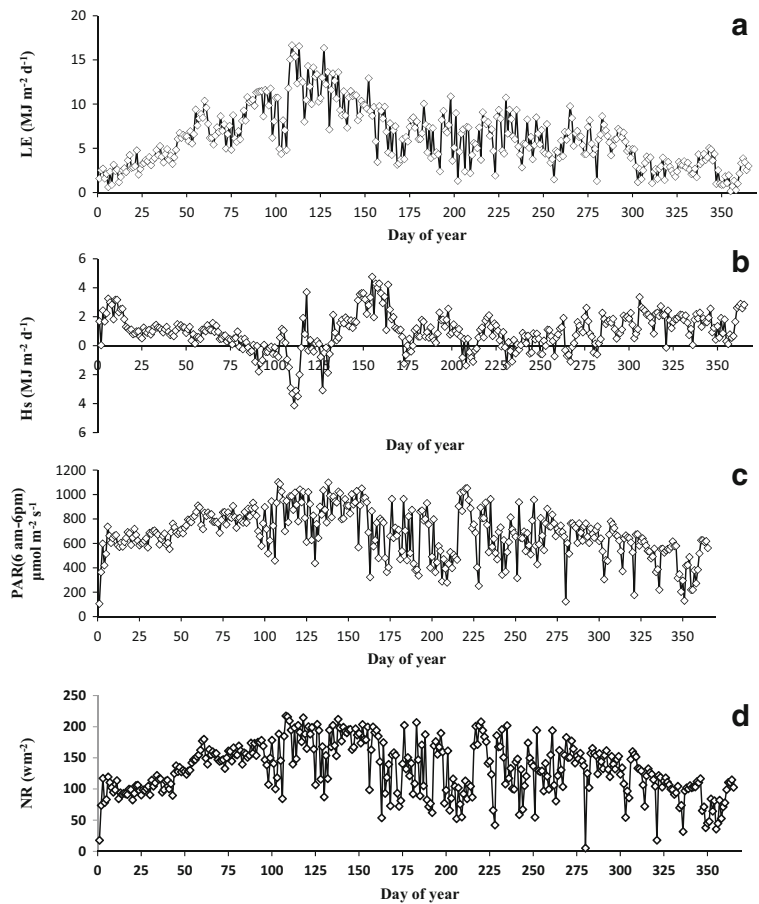


Table 4 Mean and integrated Hs (sensible heat) and LE (latent heat) during the monitoring period including both the dry and wet seasons and fallow period

Season	Sensible heat		Latent heat	
	Average ($\text{MJ m}^{-2} \text{ day}^{-1}$)	Cumulative (MJ m^{-2})	Average ($\text{MJ m}^{-2} \text{ day}^{-1}$)	Cumulative (MJ m^{-2})
Dry season	0.58	70.79	6.95	855.85
Dry season (fallow period)	1.45	92.96	8.60	550.84
Wet season	0.81	103.79	5.61	712.55
wet season (fallow period)	1.64	83.75	2.61	133.39
Annual	4.48	351.29	23.81	2252.44

vegetative stage and shows a peak at the reproductive stage due to greater physiological activity and with elevated photosynthesis rate (Bhattacharyya et al. 2013b). More negative NEE was observed during the day due to higher CO_2 assimilation by photosynthesis (Alberto et al. 2009) which suggested that this was because of gas exchange among the leaves and the pattern of light interception at the canopy level (Nair et al. 2011).

Driving factors of methane exchange under flooding condition of rice ecology

The methanogenesis process in general is influenced by redox potential ($E_h - 200 \text{ mV}$), LC content, pH, moisture content, and temperature (Guo and Zhou 2007). NEME was found to be higher during active tillering (AT) to PI stage of rice crop in both seasons (Fig. 1b) due to higher methanogenic activity and the presence of a higher quantity of substrate particularly labile pools of soil carbon (Tseng et al. 2010). As the soil remained waterlogged during most of the year in the present experiment, the conditions were favorable for methanogenesis. In a water-saturated condition, high methane fluxes were observed, when favorable temperature prevailed and rice rhizosphere was most active and well-developed (Bhattacharyya et al. 2014). Reduction of NEME was observed during the maturity stage, which continued during the fallow period. This may be due to the release of labile substrate by the root that controls CH_4 production up to the flowering of the rice crop and depletes afterwards (Lu et al. 2002). Coupling with less substrate and enhanced CH_4 oxidation at the later growth stages of rice limits the CH_4 emission (McMillan et al. 2007). At same stage of crop growth, methane emission was higher in high-temperature condition. For example, the methane

emission during the PI to FL was higher in the wet season (average methane $4.19 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$, average temperature $32.21 \text{ }^\circ\text{C}$) than the methane emission during the DS (average methane $2.85 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$, average temperature $28.02 \text{ }^\circ\text{C}$). The reason of such trend may be due to an increase in plant-mediated CH_4 transport with increasing temperature. Moreover, the increase in soil temperature also increases molecular diffusion and ebullition of methane (Alberto et al. 2014). It was observed that methane efflux increased with increase in LE with the season in the study which was well supported with the observation reported by Bhattacharyya et al. (2014). The LE might have an influence on daily variation of CH_4 flux in rice paddy because the dissolved CH_4 in soil solution could get released to the atmosphere through transpiration flux (Nisbet et al. 2009).

Daily, seasonal, and annual variations in N_2O efflux

Application of nitrogenous fertilizer such as urea in the present study significantly increased the N_2O flux. The N_2O emission from flooded rice soils is mainly attributed to two major microbial processes, i.e., nitrification and denitrification. Both nitrification and denitrification processes are taking place concurrently in lowland rice soils, although the first is aerobic and another is anaerobic process and are considered as a major source of N_2O emission (Kyaw and Toyota 2007). Extrapolation of daily N_2O -N flux data measured at closed intervals by the manual close chamber method during the entire cropping period was well studied by various researchers (Bhatia et al. 2011; Das et al. 2011; Datta et al. 2009; Bhattacharyya et al. 2012). Emission of N_2O is a microbial-mediated process that depends on available C and N sources which are available to microorganisms (Nayak et al. 2007). Distinctly higher N_2O emissions

Table 5 Soil enzymatic activities with soil carbon showing in different rice crop growth stages in lowland tropical rice

Rice crop stages	Dehydrogenase (DHA) ($\mu\text{g TPF g}^{-1} \text{day}^{-1}$)		Fluorescein diacetate (FDA) ($\mu\text{g fluorescein g}^{-1} \text{h}^{-1}$)		β -glucosidase (β -GLU) ($\mu\text{g p-nitrophenol g}^{-1} \text{day}^{-1}$)		Readily mineralizable carbon (RMC) ($\mu\text{g C g}^{-1}$)		Microbial biomass-C (MBC) ($\mu\text{g C g}^{-1}$)	
	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
Vegetative stage (VS)	161.96	193.52	10.53	13.07	19.27	25.72	79	53	134.02	259.21
Panicle initiation (PI)	498.75	530.32	23.84	26.37	66.59	78.20	132	79	147.10	306.03
Flowering (FL)	379.57	411.13	13.73	16.27	43.38	52.83	110	61	122.58	287.33
Harvesting (H)	272.84	304.40	9.38	11.92	23.41	30.48	49	25	88.26	231.10

were recorded whenever application of urea was done in the field (Fig. 2). Three peaks of N_2O efflux were recorded immediately after urea application in both seasons. It was observed that the amplitude of N_2O flux was more during the dry season as compared to that during the wet season. This may be due to more PAR and NR required during the DS as compared to the WS (Bhatia et al. 2005; Bhattacharyya et al. 2012).

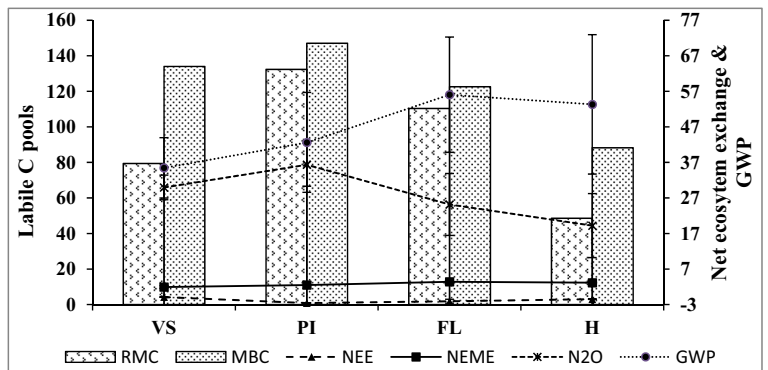
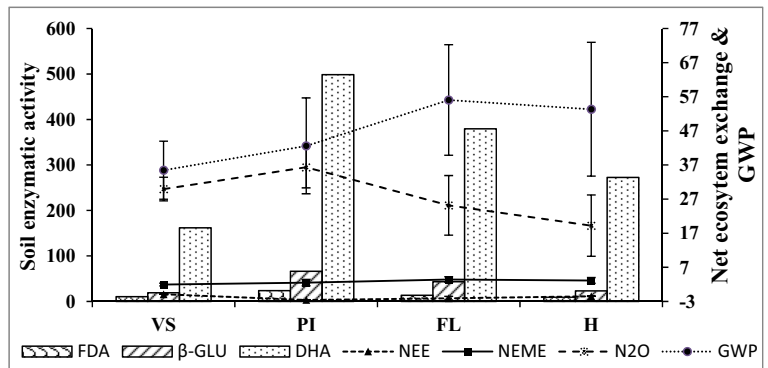
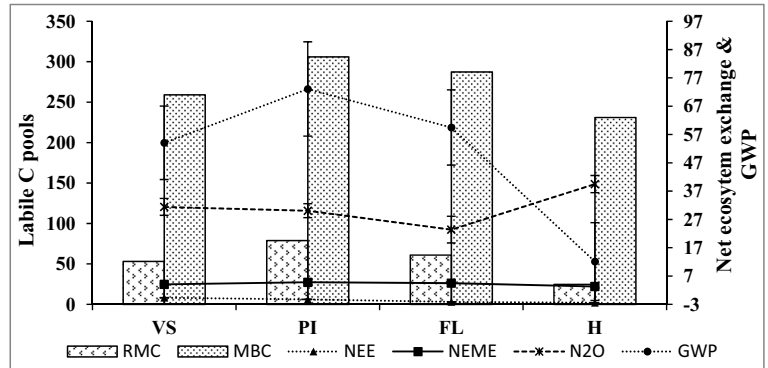
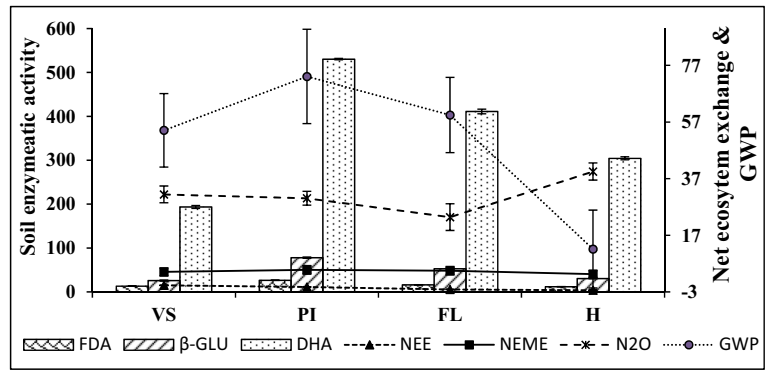
GWP measurement

The GWP was found higher when methane and nitrous oxide emissions recorded higher values. This is evident from the basic calculation of GWP where higher weightage was given to CH_4 and N_2O as compared to CO_2 (IPCC 2007). Application of N fertilizer resulted in enhanced N_2O emission (Fig. 2) which resulted to increased GWP of paddy soil (Fig. 3) (Bhatia et al. 2005). Particularly, the stages of rice crop such as AT to PI where CH_4 emission was more, GWP values also increased (Bhattacharyya et al. 2013a, 2014). The GWP exhibited a positive and significant correlation with NR, PAR, and LE. As NR and PAR increase, the available heat energy helped the soil to warm up which in turn enhanced methanogenic activities which might have favored more decomposition of organic matter in soil and produced more CO_2 and CH_4 that might have increased GWP (Nisbet et al. 2009; Tseng et al. 2010).

Partitioning of NEE into GPP and RE

The GPP and Re which were partitioned from NEE showed a gradual increasing trend from early vegetative to maturity period of the rice crop. Rice behaves as a source of CO_2 during nighttime and as a sink of CO_2 at daytime. It was due to only respiration in the nighttime as photosynthesis is absent and greater Re than the GPP during early morning (Tseng et al. 2010). In the daytime, CO_2 was assimilated by vegetation through photosynthesis and emitted by the soil through microbial respiration (Bhattacharyya et al. 2013b). At nighttime's lowland rice paddy ecosystem, respiration (Re) led to a net efflux of CO_2 to the atmosphere (Swain et al. 2016). Higher GPP during ripening to maturity stage is due to the fact that more CO_2 was assimilated into the plant part which is evident from more negative NEE during that stage. It was also observed that with the increase in temperature, Re also increased. It may be due to the warm temperature which promotes photorespiration, and most crops drop

Fig. 6 Stagewise variation in soil enzymatic activities, LC pools, and gaseous exchange in the **a** wet season and **b** dry season (VS: vegetative stage, PI: panicle initiation, FL: flowering and H: harvesting). Unit for DHA: $\mu\text{g TPF g}^{-1} \text{day}^{-1}$, FDA: $\mu\text{g fluorescein g}^{-1} \text{h}^{-1}$, β -GLU: $\mu\text{g } p\text{-nitrophenol g}^{-1} \text{day}^{-1}$, RMC and MBC: $\mu\text{g C g}^{-1}$, NEE: $\text{g C m}^{-2} \text{day}^{-1}$, NEME: $\text{mg CH}_4 \text{m}^{-2} \text{h}^{-1}$, N_2O : $\mu\text{g N}_2\text{O-N m}^{-2} \text{h}^{-1}$, N_2O : $\mu\text{g N}_2\text{O-N m}^{-2} \text{h}^{-1}$, GWP: $\text{kg CO}_2 \text{ha}^{-1}$



their photosynthetic activities at elevated temperature (Crafts-Brandner and Salvucci 2000).

Sensible heat, latent heat, photosynthetically active radiation, and net radiation as influenced by lowland rice ecology

Because of its unique nature like flooded ecology, energy partitioned into LE is an important factor for rice crop. Except in fallow periods, the LE remained higher than Hs irrespective of the seasons. In lowland rice ecology, the amount of energy used mostly for vaporization of water molecules (LE) outweighed Hs which is required for warming up the ambient air temperature (Alberto et al. 2009). During the fallow season as there were no crops except the rice ratoons of the previous crop, Hs dominated over LE due to very low soil moisture content prevailing in the rice paddy field (Alberto et al. 2011). It was observed that the submerged rice fields had significantly lower Hs than LE during the active crop growing season, because of standing water which reduced the soil as well as canopy air temperature, whereas in fallow periods, Hs increased and LE decreased as the soil surface becomes drier (Alberto et al. 2011). Compared with other crops (e.g., mulberry), rice showed less Hs during sunny days under large NR condition in coastal China (Li et al. 2017). The PAR was higher in mid to end of the dry season (from the PI to H of the rice crop) than in the wet season. Similarly, dry fallow recorded higher PAR compared to the wet fallow. This may be due to clear sky in the dry season and dry fallow which coincide with the summer season, whereas during the wet season and part of the wet fallow, it is less because of the prevalence of cloudy condition due to the commencement of southeast monsoon through that time period (Cruz et al. 2013). A similar phenomenon was observed in case of NR (Santanello and Friedl 2003; Tsai et al. 2007). The NR radiation represents the total available energy that the rice system can use to perform its physiological processes, and it is the difference between incoming and outgoing radiation. A negative correlation of NEE with LE, PAR, and NR was noted. In a water-sufficient system, GPP is positively related to PAR (Alberto et al. 2009), and as a whole, NEE was negative due to enhanced CO₂ uptake during the day through photosynthesis (i.e., increase in GPP). Thus, a negative correlation of NEE with PAR was recorded. Moreover, rice is principally a C₃ crop and CO₂ is assimilated into a 3-

carbon compound by Rubisco, which is a photosynthetic enzyme. The enzyme Rubisco is thermosensitive, which causes photosynthesis to be hampered at higher temperature (Crafts-Brandner and Salvucci 2000). Probably due to the above reasons, a negative correlation of NR with NEE was recorded. As rice has sufficient moisture during its growth stages, the majority of the energy flux is partitioned into LE which is linked to high evaporative flux. This may lead to reduction in CO₂ uptake due to the stomatal closure (Bhattacharyya et al. 2013a).

Soil enzyme activities and LC pools at various crop growing stages

Soil enzyme activities are often used as an indicator of microbial growth and its activity in soils. β-Glucosidase is a carbon-dependent enzyme and its activity increases with the increase in labile C content like RMC and MBC. Fluorescein diacetate is a hydrolytic enzyme which breaks down the organic components in the soil and represents CO₂ evolution as the total microbial activity (Nannipieri et al. 1990). On the other hand, dehydrogenase is considered as the respiratory enzyme where the microbial respiration observed by the CO₂ uptake or evolution took place and can be observed in the form of LC pools. Soluble carbon fraction plays an important role in soil organic matter turnover in agricultural soils like puddled rice soil where it acts as a readily decomposable substrate for microorganisms (García-Orenes et al. 2010). Application of organic manure contributes more labile C which acts as a source of energy and nutrients to the microorganisms (Manna et al. 2007). However, the content of labile pools also varied with stage of the crops. The increase in both soil enzyme activities and LC pools in the PI stage may be due to the release of a higher quantity of carbonaceous root exudates that added to the LC pools and also acted as a substrate for soil enzymes (Win et al. 2012).

Soil LC acts as a food source of soil microbes and increased enzymatic activities indicate the presence of a higher microbial population in soil. The NEME and GWP increased when there is availability of a higher amount of LC (substrate) in soil at the PI stage. However, a clear trend was not recorded for N₂O across the seasons. The NEE was lowest at the early vegetative stage and reached its peak during the

PI to FL due to greater physiological activity and higher photosynthesis CO₂-C uptake. With increased soil enzymatic activities, the NEE becomes less negative which indicates lower assimilation of CO₂ and this can be explained by linking it to the enhanced Re due to the presence of a higher microbial population in soil as indicated by higher enzymatic activities (e.g., β-GLU, FDA, and DHA) (Frankenberger and Dick 1983). Therefore, soil labile C as well as specific soil enzymes could be used as good indicator of NEE, NEME, and GWP in lowland rice ecology.

Conclusion

The NEE and NEME exhibited a clear daily and seasonal pattern throughout the cropping of the rice-rice season. More negative NEE during the ripening stage and higher GPP during the ripening to maturity stage of rice are due to the assimilation of more CO₂ in plant parts. Re increases with temperature rise as warm temperature promotes photorespiration and reduces photosynthetic activities in rice crop. NEME was higher during the AT to PI stages due to higher methanogenesis promoted by the presence of labile substrates (increased RMC and MBC). On the contrary, N₂O flux is controlled by nitrogenous fertilizer (urea) application. The GWP increased with the advancement of crop stages and declined at the end of each season and fallow period. It was also observed that LE dominates over Hs during the cropping season (dry and wet season) and it contributes largely to the NR and energy balance. The PAR, NR, and NEE influence GWP positively. Due to overcast situation during the WS and WF, PAR and NR are less as compared to those during the DS and DF. Soil enzyme activities and LC pools increased with the age of the crop and reached its maximum during the PI stage. The NEME and GWP increased with a higher amount of LC pools in soil at the PI stage. Further investigations are still required to improve our understanding of GHG emissions from different rice-rice ecosystems and their potential response to climate change.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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