Chapter 50
Carbon Dynamics and Greenhouse Gases Emissions in Coastal Agriculture: Mangrove-Rice Ecology in Sundarban, India

Pratap Bhattacharyya, S. R. Padhy, P. K. Dash, and H. Pathak

Abstract Mangrove systems act both as sink and source of GHGs including methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). Mainly, it acts as a sink for CO_2 because of its high biomass production. The higher source of organic carbon and rapid nutrient turnover are the key features of these systems. Mangrove systems facilitate methanogenesis and denitrification processes due to the dominance of anoxic conditions by frequent tidal water intrusions. Apart from these, mangroves provide significant ecological services including maintenance of biodiversity (mammals, birds, fish, algae, microbes), enhancing carbon (C) sequestration, protecting the coastal bank and sustaining economical profits. However, approximately, 40% of tropical mangrove forest was lost in the previous century primarily due to sea level rise, climate change and human-induced activities. About 10.5% of green was lost from Sundarban, India during 1930–2013. Major land use changes were from mangrove to rice and aquaculture-based agriculture. In last three decades, degraded mangrove, rice and aquaculture systems co-exists side by side and represent a typical ecology in Sundarban, India. This ecology has its unique carbon dynamics, GHGs emission pattern, microbial diversities and soil physiochemical dimensions. A distinct variations of the soil bacterial and archaeal diversities related to GHGs emissions and labile C-pools of degraded mangrove-rice system in wetland ecology exist. Soil physico-chemical properties (like high salinity, more available sulphur, sodium, iron) and the related microbial community (methanotrophs, methanogens, SRB) play an important role in carbon dynamics and to mitigate CH_4 emission in the mangrove-rice system. The ratios of methanotrophs: methanogens and sulphur reducing bacteria

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(SRB): methanogens are important indicators to net methane emission. Those are higher in mangrove mean the methane oxidation was dominant over methane production resulting less CH_4 emission from mangrove than rice. Similarly, continuous application of nitrogen fertilizer and more nitrifiers and denitrifiers community in rice, resulting in more N_2O emission as compared to degraded mangrove. Hence, the soil properties and the microbial community make mangrove a green production system as compared to the rice ecology in Sundarban, India. However, recent threats of climate change related issues like sea level rise, soil erosion and coastal bank degradation also make this mangrove-rice system vulnerable. So, soil conservation, mangrove restoration and regeneration and coastal bank protection of this system are the need of the hour.

Keywords Mangrove-rice system · Soil labile carbon pools · GHGs emission · Microbial diversity · Sundarban, India

50.1 Introduction

Mangroves in coastal wetlands are found in the subtropical and tropical region that provide a significant ecological service including maintenance of biodiversity (mammals, birds, fish, algae, microbes), enhancing carbon (C) sequestration, protecting coastal bank and sustaining economical profits (Ray et al. 2011; Chambers et al. 2014; Bhattacharyya et al. 2019). The highest area under mangrove is observed in Asia (42%), then in Africa, followed by North-Central America, Oceania and least in South America (20, 15, 12 and 11%, respectively) (Giri et al. 2011; Padhy et al. 2021). Globally, the characteristics of mangrove ecosystems are primarily driven by tidal behaviour, salinity and temperature. However, at regional level, the biomass and area of mangroves vary in relation to tidal intrusion, sea level rise, waves, rainfall, rivers-flow and anthropogenic activities. Specifically, the stability of mangrove ecosystem is considerably affected by the soil type, soil physico-chemical properties, nutrient status, predation and physiological tolerance to extreme environmental conditions like salinity, temperature and wind tidal intrusion. Mangroves play a key role in maintenance and establishment of coastlines and mediating the carbon (C) cycle and food chain (Marcial Gomes et al. 2008; Giri et al. 2011). However, sea level rise has strongly influenced the mangroves as well as mangrove-agriculture ecologies (Gilman et al. 2008; Day et al. 2008). Mangrove systems act both as sink and source of GHGs (Mukhopadhyay et al. 2002), including methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O). The CH_4, N_2O and CO_2 contribute 20–25%, 5–10% and 40–50%, respectively, towards the warming of the globe. The recent rates of increase of these three GHGs per annum are 0.41, 0.25 and 0.42%, respectively (NOAA 2012; IPCC 2018). Tidal mangrove ecosystems are typical source of CH_4 and N_2O (Chauhan et al. 2008; Chen et al. 2010; Padhy et al. 2020, 2021). Mainly, it acts as a sink for CO_2 because of its high biomass production (Wang et al. 2016). The higher source of organic carbon and rapid nutrient turnover are the key features of these systems. Mangrove systems facilitate methanogenesis and denitrification processes due to the dominance of anoxic conditions by frequent tidal water intrusions (Rennenberg et al. 1992; Krithika et al. 2008; Bhattacharyya et al. 2020a; Padhy et al. 2021). So, eventually, the system function as a good source of N_2O and CH_4.

The world's biggest contiguous mangrove presents in Sundarban situated at the delta of three major rivers, namely the Ganga, Meghna and Brahmaputra. The total area under Sundarban-mangrove is around 10,000 km^2; out of which 38% present in India and the majority of 62% is in Bangladesh (Spalding et al. 2010). The major district in India is "South 24 Parganas" in the state, West Bengal. About 1678 km^2 area under "Reserve Forest" and 2585 km^2 under "Sundarban Tiger Reserve". Approximately, 40% of tropical mangrove forest was lost in previous century primarily due to sea level rise, climate change and human-induced activities. About 10.5% of green was lost from Sundarban, India, during 1930–2013. Major land use changes were from mangrove to rice and aquaculture (Chauhan et al. 2017). In last three decades, degraded mangrove, rice and aquaculture systems co-exist side by side and represent a typical ecology in Sundarban, India. This ecology has its unique carbon dynamics, GHGs emission pattern, microbial diversities and soil physiochemical dimensions. Recent threats of climate change-related issues like sea level rise, soil erosion and coastal-bank degradation also make this mangrove-rice system vulnerable. So, soil conservation, mangrove restoration and regeneration and coastal bank protection of this system are need of the hour.

50.2 Mangrove and Lowland Rice Paddy as an Effective Carbon Sink

Mangroves have higher C production and sequestration capacity (882,200 Mg C km^{-2}) as compared to other forest ecology (102,300 Mg C km^{-2}), globally (Bouillon et al. 2008; Donato et al. 2011). It acts as an effective C sink, thereby sequester higher amount of C (100 t CO_2 ha^{-1} ~ 27 t C ha^{-1}) and also reduce soil erosion. This is the most C-rich vegetation among coastal forests. Both above and below ground C storage capacity of mangroves are significantly higher than other forest in the tropics, hence could be considered as effective C sink. Wetting–drying conditions of the mangrove sediments favour the rapid litter decomposition rate which leads to rapid C influx to sediment and thereby enhancing soil C content. Soil organic C accounted for 49–98% of the total C storage and mostly found at the depth of 0.5 m to more than 3 m (Donato et al. 2011). However, mangrove deforestation emits 0.02–0.12 Pg C $year^{-1}$, which is around 10% of the total global C emissions (Donato et al. 2011). It has also been reported that lowland rice in tropics acts as C sink (0.93 t ha^{-1} $year^{-1}$) (Bhattacharyya et al. 2014), but much lesser quantity than that of pure mangrove ecosystem. Therefore, mangrove-agriculture (specifically rice) in coastal wetland have the potential to sink C provided managed properly.

50.2.1 Soil Labile Carbon Dynamics in Mangrove-Rice Systems

Large amount of soil organic carbon (SOC) is stored in mangrove soil due to higher litre deposition which subsequently sequestered in soil (Kauffman et al. 2013). Tidal pattern in mangrove system causes water stagnation, consequently lowering the rate of SOC decomposition that leads to less CO_2 production and higher C sequestration (Wang et al. 2016). But, small changes in the total organic carbon are difficult to detect as there are high background levels of total carbon in mangrove (Liang et al. 2012). Hence, the labile soil carbon pools are often selected as sensitive indicators to determine the C dynamics in degraded mangrove ecologies (Tian et al. 2013). We know that the labile C pools are significantly related to GHGs emission and nutrient dynamics in mangrove soils and a small change of which can be noticed precisely (Wohlfart et al. 2012). Similarly, in the rice rhizosphere, the soil labile fractions of C play a crucial role for regulating microbial metabolic activities. Soil labile C pools such as readily mineralizable C (RMC), microbial biomass C (MBC), water soluble carbon (WSC), potassium permanganate oxidizable C (KMnO4-C) and dissolved organic carbon (DOC) are considered as soil quality indicators in mangrove as well as rice ecologies (Wohlfart et al. 2012; Bhattacharyya et al. 2013; Padhy et al. 2020).

In a recent study, the soil labile C fractions of soils, viz., MBC, RMC and $KMnO_4$–C were recorded in mangrove-rice ecology, at three different sites (Sadhupur: 22.12 N, 88.86 E; Dayapur: 22.14 N, 88.84 E and Pakhiralaya: 22.14 N, 88.84 E) in Gosaba block of Sundarban, India during four seasons, i.e., winter, summer, pre-monsoon and monsoon. The labile carbon fractions were significantly higher during summer compared to other seasons. The RMC varied from 326.2 to 434.3; 307.0 to 446.6 and 333.3 to 409.3 μg carbon g^{-1} in soils at Pakhiralaya, Sadhupur and Dayapur, respectively (Table 50.1). The MBCs were also significantly higher in summer like RMC. The lowest MBC was found during monsoon (Table 50.1). Similar to RMC and MBC, the $KMnO_4$–C contents were also more in summer followed by winter, pre-monsoon and monsoon. Those were in the range of 795.8–1275.9; 847.9–1318.3 and 779.1–1263.8 μg C g^{-1} in soils at Pakhiralaya, Sadhupur and Dayapur, respectively (Table 50.1).

However, the labile C pools in rice soil were higher in monsoon season as compared to other seasons (Table 50.1). The RMC and MBC contents ranged from 255.8 to 316.4 μg C g^{-1} and 684.6 to 723.8 μg C g^{-1} during monsoon in all the sites (Table 50.1). Similarly, the $KMnO_4$–C was in the range of 1159.9–1308.0 μg C g^{-1} during monsoon which was higher followed by summer (1021.5–1234.7 μg C g^{-1}), winter (660.1–1197.0 μg C g^{-1}) and pre-monsoon (562.5–580.5 μg C g^{-1}), respectively (Table 50.1). So overall, the average labile C pools contents were higher in mangrove as compared to rice.

Table 50.1 Soil labile carbon pool dynamics mangrove-rice systems during four seasons in three locations of Sundarban, India

Location	Season	Readily mineralizable carbon (µg C g^{-1} soil)		Microbial biomass carbon (µg C g^{-1} soil)		$KMnO_4$ oxidizable Carbon (µg C g^{-1} soil)	
		Mangrove	Rice	Mangrove	Rice	Mangrove	Rice
Sadhupur	Winter	361.3 ± 16.3	171.9 ± 9.6	1051.6 ± 15.9	541.9 ± 17.7	1155.0 ± 12.5	916.3 ± 9.4
	Summer	444.6 ± 9.4	175.7 ± 11.8	1111.7 ± 20.6	387.4 ± 25.8	1318.3 ± 18.3	1066.7 ± 20.0
	Pre-monsoon	349.5 ± 9.7	126.4 ± 9.3	793.5 ± 18.2	223.2 ± 14.9	1013.1 ± 17.0	566.4 ± 15.5
	Monsoon	307.0 ± 9.3	255.8 ± 10.3	736.9 ± 17.4	723.8 ± 19.0	847.9 ± 16.5	1164.9 ± 18.5
Pakhiralaya	Winter	333.3 ± 11.7	139.3 ± 13.3	1165.1 ± 10.5	660.1 ± 19.8	1097.4 ± 15.8	660.1 ± 13.2
	Summer	434.3 ± 10.2	174.2 ± 11.4	1178.822.5	379.8 ± 24.6	1275.9 ± 14.2	1021.5 ± 12.9
	Pre-monsoon	348.4 ± 10.5	126.8 ± 9.6	774.7 ± 19.1	224.8 ± 15.3	939.4 ± 17.5	562.5 ± 33.0
	Monsoon	326.2 ± 10.5	286.6 ± 10.1	746.9 ± 17.0	705.6 ± 18.6	795.8 ± 19.6	1159.9 ± 20.0
Dayapur	Winter	266.0 ± 13.4	177.8 ± 13.9	979.2 ± 17.5	653.5 ± 9.4	1246.1 ± 12.5	1197.0 ± 12.6
	Summer	409.3 ± 9.3	172.4 ± 11.6	1027.4 ± 6.2	387.4 ± 19.4	1263.8 ± 18.9	1234.7 ± 18.2
	Pre-monsoon	329.8 ± 8.5	138.4 ± 8.1	785.0 ± 18.4	230.0 ± 17.9	896.6 ± 16.6	580.5 ± 18.9
	Monsoon	333.3 ± 11.0	316.4 ± 11.4	737.2 ± 27.7	684.6 ± 18.5	779.1 ± 22.7	1308.0 ± 20.6

Source Padhy et al. (2020)

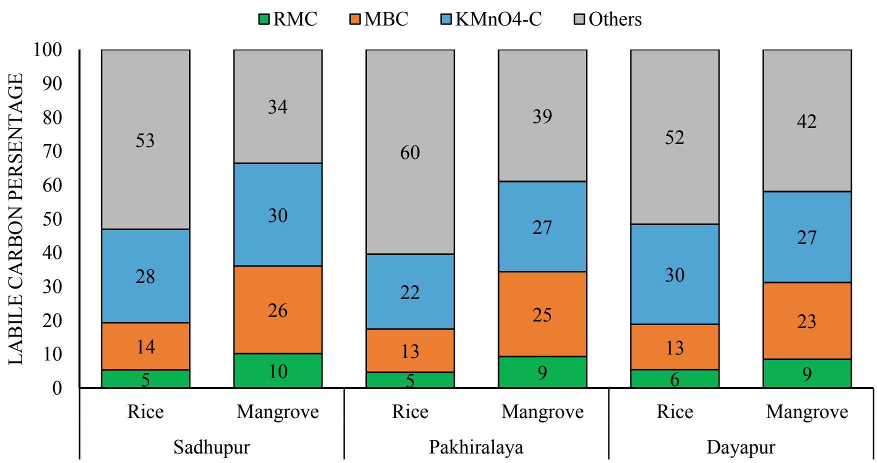

Fig. 50.1 Relative percent distribution of soil labile C pools under mangrove and adjacent rice ecology at three different sites of Sundarban, India. *Source* Dash et al. (2020)

50.2.2 Soil Labile Carbon Distribution in Mangrove-Rice Systems

The percentage of soil labile C pools distribution were estimated in mangrove and rice soil. Among the three labile C pools, $KMnO_4$–C percentage was higher (between 22 and 30%), followed by RMC and MBC (Fig. 50.1). The remaining portion of other labile C pools (considering 40% of TOC), which were not estimated in this study may include water-soluble C, dissolved organic C, etc. The $KMnO_4$ oxidizable carbon are labile in nature; this fraction also includes readily decomposable humic-material and few polysaccharides (Blair et al. 1995; Jiang and Xu 2006).

50.3 Greenhouse Gas Emission from Mangrove-Rice Systems

The GHGs emissions from sediments to the atmosphere in the mangrove ecology occur through three different pathways. Majority of emissions are taken place through the aerenchyma of mangrove-pneumatophores (it is the negatively geotropic breathing-roots of mangrove); diffusion through the sediments/soil by ebullition (as bubble, in soil water interphase) and exchanges through air–water interphases (as dissolved GHGs in stagnant or tidewater) in mangrove (Purvaja et al. 2004; Dutta et al. 2015). While, in rice ecology, emission takes place mainly through the aerenchyma of rice plant from soil to atmosphere and very negligible amount of gas emitted through other sources (10–15%) (Bhattacharyya et al. 2019, 2020b, 2020c).

50.3.1 *Greenhouse Gases Fluxes from Sundarbans' Mangrove: Captured by Manual Chamber*

The GHGs (CH_4, CO_2 and N_2O) fluxes were quantified in mangrove-rice system from soil to atmosphere by manual gas chamber method for four seasons in all the three sites. Seasonal methane flux was higher during monsoon (0.235 ± 0.04 mg m^{-2} h^{-1}), followed by pre-monsoon (0.089 ± 0.02 mg m^{-2} h^{-1}), summer and winter (Fig. 50.2a). During monsoon, CH_4 fluxes were higher in pneumatophore as compared to sediments that did not have pneumatophore (0.254 ± 0.05, 0.377 ± 0.04, 0.269 ± 0.07 mg m^{-2} h^{-1} and 0.164 ± 0.02, 0.120 ± 0.01, 0.228 ± 0.02 mg m^{-2} h^{-1} in pneumatophore and without pneumatophore at Sadhupur, Pakhiralaya and Dayapur, respectively). However, higher N_2O fluxes were observed during

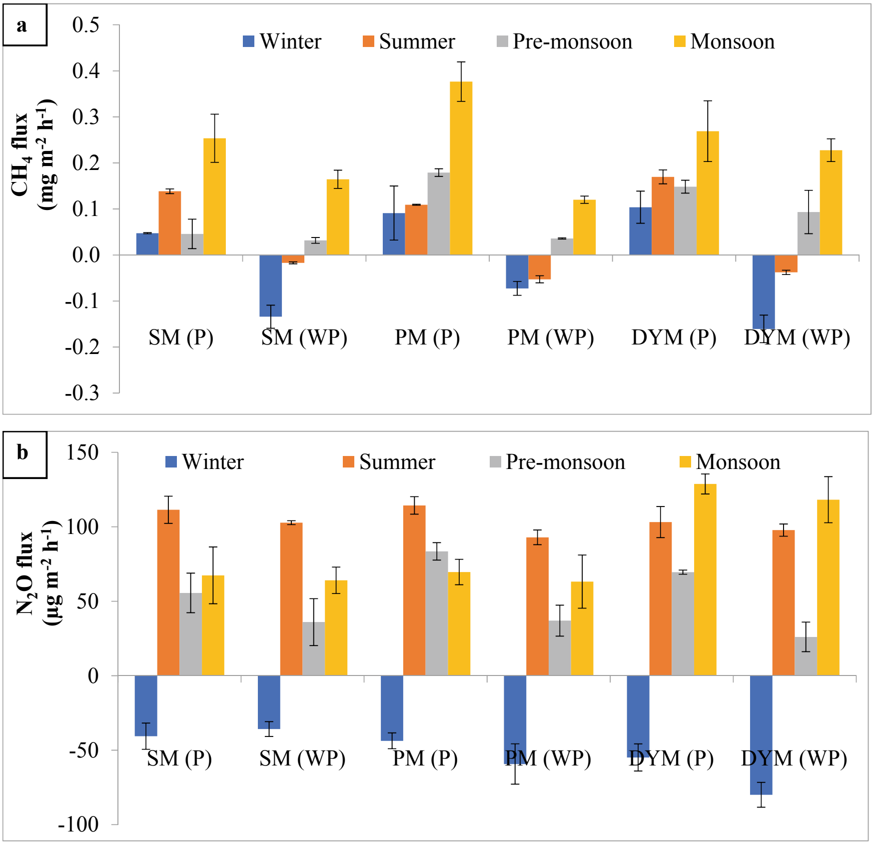

Fig. 50.2 (**a**) Methane and (**b**) Nitrous oxide fluxes estimation in three locations of mangrove (Sadhupur: SM; Pakhiralaya: PM and Dayapur: DYM) during four seasons (winter, summer, pre-monsoon and monsoon) from mangrove sediments. P: in the presence of pneumatophore; WP: without pneumatophore. *Source* Padhy et al. (2020)

summer (103.7 ± 6.0 μg m^{-2} h^{-1}) followed by monsoon (85.2 ± 12.8 μg m^{-2} h^{-1}) and pre-monsoon (51.3 ± 9.4 μg m^{-2} h^{-1}) (Fig. 50.2b). In nut shell, higher GHGs fluxes were recorded in the presence of pneumatophore compared to without pneumatophore (Padhy et al. 2020).

50.3.2 GHGs Fluxes in Ebullition Process

The GHGs fluxes in ebullition were higher "during the time of tide" than "before tide" (Fig. 50.3a, b). The CH_4 and N_2O fluxes were ranged from 0.021 ± 0.005

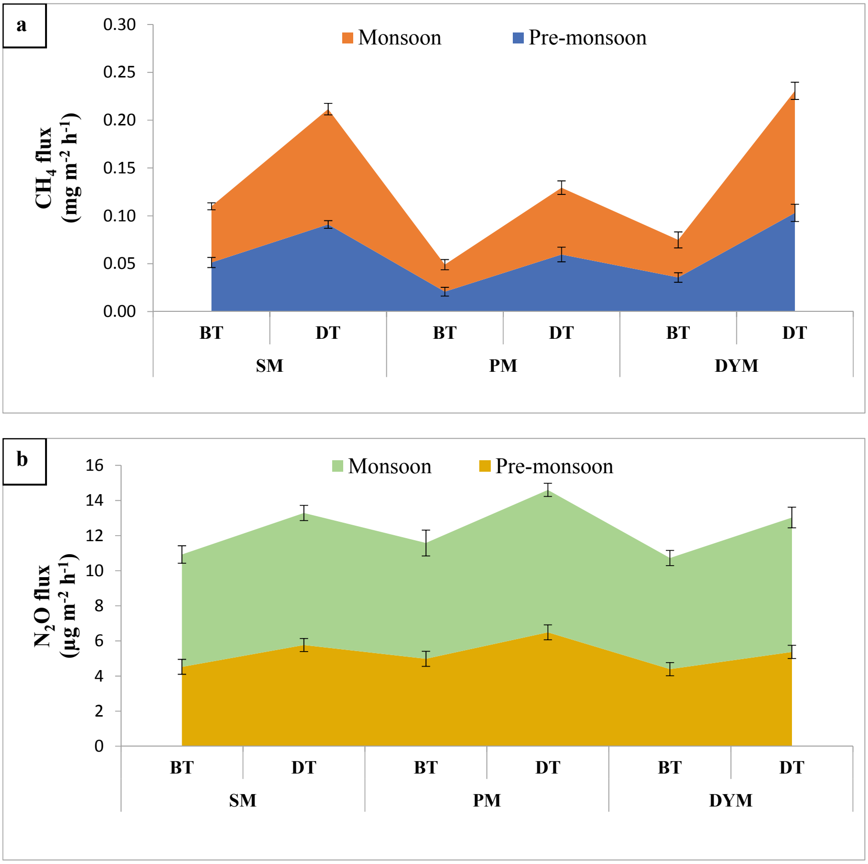

Fig. 50.3 (**a**) Methane and (**b**) Nitrous oxide emission through ebullition in three locations (Sadhupur: SM; Pakhiralya: PM and Dayapur:DYM) during two seasons (pre-monsoon and monsoon) from mangrove sediments. BT: before tide; DT: during tide. *Source* Padhy et al. (2020)

to 0.103 ± 0.009 mg m^{-2} h^{-1}, and 4.39 ± 0.37–6.49 ± 0.43 μg m^{-2} h^{-1} in pre-monsoon and 0.028 ± 0.005 to 0.128 ± 0.009 mg m^{-2} $h^{-1}$and 6.34 ± 0.43 to 8.12 ± 0.38 μg m^{-2} h^{-1} in monsoon at Sadhupur, Pakhiralaya and Dayapur, respectively (Padhy et al. 2020).

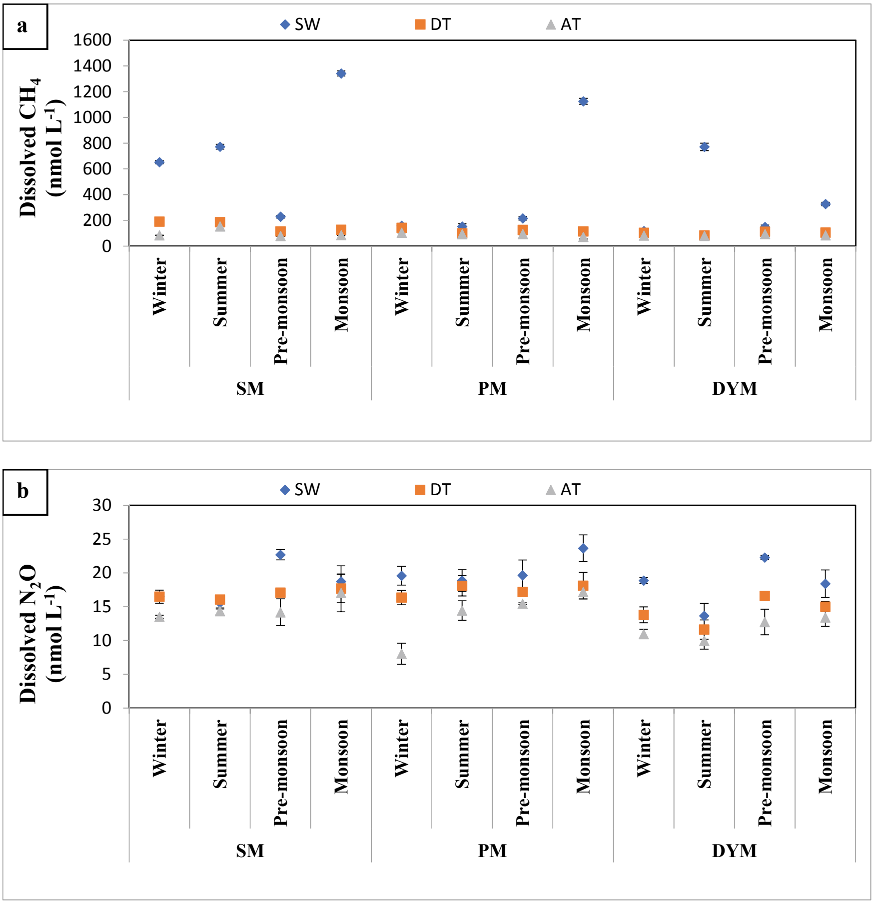

Fig. 50.4 (**a**) Methane and (**b**) Nitrous oxide concentration of surface water in three locations (Sadhupur: SM; Pakhiralya: PM and Dayapur: DYM) during four seasons (winter, summer, pre-monsoon and monsoon) from mangrove. SW: stagnant tide water; DT: during water and AT: after tide water. *Source* Padhy et al. (2020)

50.3.3 Dissolved GHGs Concentration in Surface Water in Mangrove

Tide plays the key role in regulating dissolved GHGs concentration in surface water. The dissolved GHGs concentrations were more in "stagnant-water" as compared to "during tide-water" and "after tide-water". Dissolved CH_4 concentration was more during monsoon than other season irrespective of sites and time of collection of surface water (Fig. 50.4a). Dissolved CH_4 concentrations were higher in "stagnant-water" (1341.2 ± 19.7, 1125.4 ± 23.0 and 327.2 ± 13.3 nmol L^{-1}) (nanomoles per litre) as compared to "during tide-water" (126.9 ± 12.1, 114.6 ± 5.5 and 105.7 ± 13.1 nmol L^{-1}) and "after tide-water" (85.7 ± 2.1, 71.7 ± 16.4 and 83.8 ± 3.9 nmol L^{-1}) during monsoon at Sadhupur, Pakhiralaya and Dayapur, respectively. However, the seasons had no significant effect on the dissolved N_2O concentration in surface water, and these were ranged from 8.0 ± 1.6 to 19.6 ± 1.4 nmol L^{-1}; 10.0 ± 1.3 to 18.9 ± 1.6 nmol L^{-1}; 12.7 ± 1.9 to 22.7 ± 0.8 nmol L^{-1} and 13.4 ± 1.3 to 23.6 ± 2.0 nmol L^{-1} during winter, summer, pre-monsoon and monsoon, respectively (Fig. 50.4b) (Padhy et al. 2020).

50.3.4 Greenhouse Gases Fluxes Through Rice Aerenchyma

The CH_4 and N_2O emission in rice was more during monsoon followed by summer, winter and pre-monsoon (Fig. 50.5a). In the monsoon season, CH_4 and N_2O fluxes were ranged from 0.313 to 0.663 mg m^{-2} h^{-1} and 103.0 to 134.7 μg m^{-2} h^{-1} in all the sites. Higher CH_4 and N_2O emission during monsoon and summer is due to the vegetative/flowering crop growth stages of rice.

50.4 Drivers of GHGs Emission from Mangrove-Rice System

50.4.1 Soil Physico-Chemical Properties

The bacterial and archaeal community structure responsible for GHGs production and emissions is primarily driven by the capability of microbes to withstand the prevalent environmental conditions like oxic/anoxic states of soil, soil texture, active salinity, nutrient dynamics and dominant plant type (Ikenaga et al. 2010; Padhy et al. 2020). The degraded mangrove and lowland rice situated side by side in Sundarban, India, representing a unique ecology with respect to salinity, nutrient dynamics, carbon pools, tidal pattern and oxic/anoxic conditions (Padhy et al. 2021). These

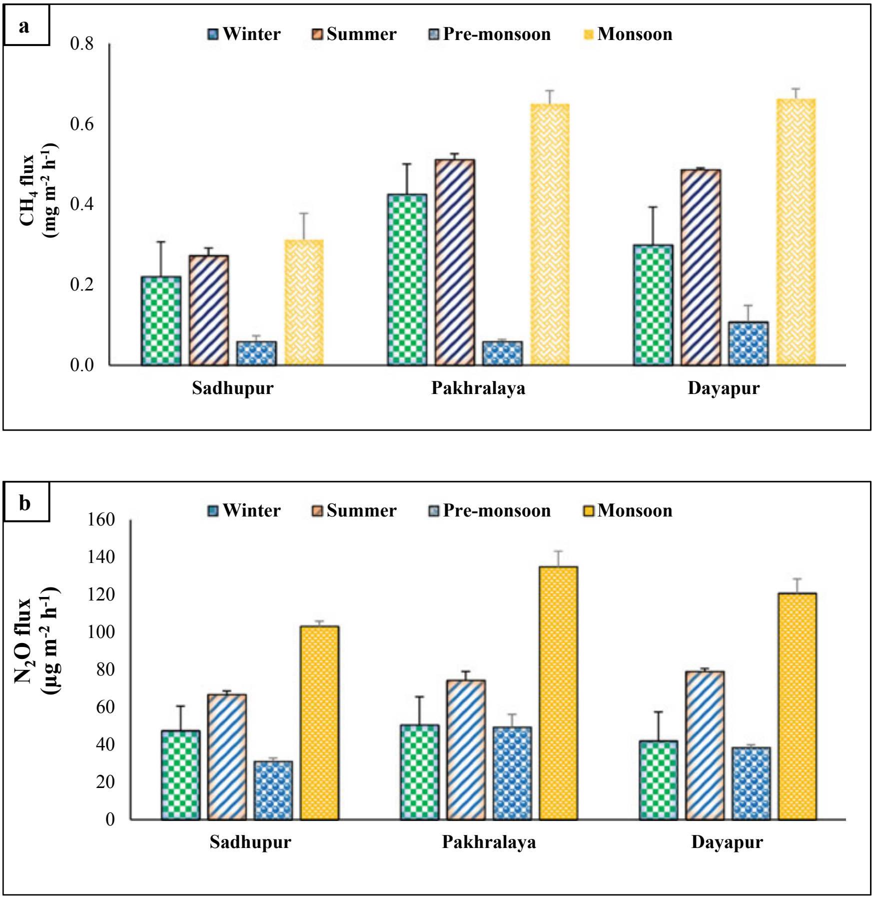

Fig. 50.5 (**a**) Methane and (**b**) Nitrous oxide fluxes estimation in three locations of rice system (Sadhupur: SM; Pakhiralya: PM and Dayapur: DYM) during four seasons (winter, summer, pre-monsoon and monsoon) in Sundarban, India

features have considerable impacts on the microbial community structures and functions. Lower CH_4 emission from mangrove than rice systems is generally due to higher salinity and greater availability of sulphate ions in the mangrove to that of rice (Padhy et al. 2021). While, higher N_2O emission was noticed from rice as compared to mangrove. In rice soils, the higher nitrogen substrate availability in the rhizosphere because of application of nitrogenous fertilizer can favours the N_2O emission. Also, the ammonium oxidizers, nitrifiers and denitrifiers abundance were higher in rice systems. Significant positive correlations existed among ammonium oxidizers, nitrifier and denitrifier that indicated that both nitrification and denitrification processes occurred simultaneously in degraded mangrove-rice ecology that triggers N_2O flux (Bhattacharyya et al. 2013; Padhy et al. 2021). However, Chauhan et al. (2017) reported that the average N_2O emission from the mangrove sediment was significantly higher than the rice paddy soil.

50.4.2 Methanotrophs, Methanogens and Sulphur Reducing Bacterial Community and Their Ratios

The relative methanogen population was found higher in rice compared to mangrove causing less CH_4 emission from mangrove. Further, in rice soil, *Methanosarcina* was identified as the dominant genus that is the specific methanogens which could produce CH_4 by all the three major metabolic pathways of methanogenesis (i.e., acetoclastic, hydrogenotrophic, methylotrophic) (Jing et al. 2016; Bhattacharyya et al. 2016, 2017). The ratios of methanotrophs: methanogens and sulphur reducing bacterial (SRB): methanogens were higher in degraded-mangroves that causes less CH_4 emission in mangrove. These two ratios were relatively less in rice, suggesting the methanogens were dominant over SRB and methanotrophs. Therefore, CH_4 emission was relatively more in rice compared to degraded mangrove in studied area of Sundarban. Sulphur reducing bacteria were predominant in mangrove. It plays a primary role in mineralization and decomposition of organic sulphur in mangrove ecology (Zhuang et al. 2020). The predominance of SRB in degraded mangrove suggested the potential resiliency and bioremediation of the system (Jing et al. 2016). Further, the AMO (ammonia monooxygenase) + nitrifier and denitrifiers ratio were higher in mangrove, resulting in less N_2O emission than that of rice. Though nitrifiers: denitrifiers ratios were higher in mangrove, but both the bacterial communities were significantly higher in rice compared to mangrove. This resulting in more nitrate production as well as higher N_2O emission from rice than that of mangrove.

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