Indian Journal of Geo-Marine Sciences
Vol. 43(6), June 2014, pp. 1007-1019

Source-sink inventory of greenhouse gases from Indian mangroves: a review

Kakolee Banerjee, Dipnarayan Ganguly, Paneer Selvam A., Purvaja Ramachandran & Ramesh R.*

National Centre for Sustainable Coastal Management, Anna Univeristy, Chennai 600 025, India

* [E-mail: rramesh_au@yahoo.com]

Received 17 December 2012; revised 1 May 2014

Present study inventorises quantitative evaluation of greenhouse gas (GHG) emissions from various mangrove ecosystems distributed along the Indian coast. Inconsistency in terms of methodological aspects of GHG flux estimations from Indian mangrove ecosystems along with the variation in space and time, has been tried to be pointed out in this present paper. Inventorization of existing resources available from mangrove ecosystems along the east and west coast of India, would be useful for estimating the future potential ecosystem capacities for fluxes of CO_2, CH_4 and N_2O. This review further confirms the potential role of Indian mangrove waters and sediments as perinial source for GHGs, whereas the canopy (vegetation) particularly acts as a CO_2 sink.

[Keywords: Greenhouse gases, Source, Sink, Inventory, Indian mangroves]

Introduction

The Global Warming Potential (GWP), which is a measure of the contribution of a given mass of greenhouse gas (GHG) to global warming over a specific time interval, is used to convert CH_4 and N_2O emissions from mangrove ecosystems in India to their CO_2-equivalent for comparing their GHG impacts. The GWP for CH_4 is 25, while for N_2O it is 298[1] over 100 years. These GWP values are used to express the CH_4 and N_2O flux to the atmosphere in terms of their CO_2 equivalence amount[2]. Several studies showed that coastal ecosystems, such as estuaries, mangrove waters, salt marsh waters and coral reefs are assumed to be a net source of greenhouse gases especially CO_2[3,4], CH_4[5] and N_2O[5], because they receive massive inputs of organic matter, which is decomposed in the coastal ocean and releases carbon dioxide (CO_2)[6,7]. Soil anoxicity in the presence of high organic carbon could stimulate the anaerobic process like denitrification, sulphate reduction, methanogenesis, which can ultimately lead to the release of N_2O[5] (also a byproduct of nitrification), H_2S and CH_4 to the atmosphere. Borges *et al*.[8] reported oversaturation of CO_2 in different mangrove forest surrounding waters, suggesting that this surface water can be a significant source of CO_2 to the atmosphere, though the entire ecosystems (sediment, water and vegetation) are probably sinks. The direction and magnitude of air-water CO_2 exchanges strongly depends on the type of ecosystem at the coast (healthy/degraded)[7], the ocean currents dominating at a respective coast (e.g. whether tide dominated or wind dominated)[9] and the geographical latitude (temperate, tropical, subtropical)[7,9]. Mangrove waters are also rich in nutrients and tend to have higher rates of primary productivity[10], which in turn leads to more organic material falling to the depth, depleting the oxygen levels and creating favorable conditions for methane-producing bacteria-methanogens[11,12]. Under anaerobic conditions mangrove sediments (in the presence of

*Corresponding author

the substrates and methanogens) produce methane (CH_4), which is then transferred from *sediments* into the overlying *waters* (sediment to water flux). The CH_4 that escapes both aerobic and anaerobic CH_4 oxidizers (both in sediment and water) ultimately enters the atmosphere, contributing to the greenhouse effect.[13,14,15]. Increased nitrogen input to mangrove sediments due to rising anthropogenic activities, along with the periodic tidal flooding creates anoxic sediment conditions, thereby enhances anaerobic microbial nitrogen metabolism (denitrification)[17,18,19]. This process along with nitrification (oxidation of ammonia to nitrate in the oxic environment) together significantly contributes to nitrous oxide (N_2O) formation in the system.

In this present review, three major greenhouse gases (CO_2, CH_4 and N_2O) from the mangrove ecosystems along the Indian coast were selected. Mangrove wetlands are well known as a significant natural source/sink of these greenhouse gases. Measurements of these gas emissions are relatively sparse from both Indian mangrove forest sediment and surrounding waters. One of the key objectives of this paper is to identify the major gaps in GHG flux studies of Indian mangroves, based on which future studies can be directed to get a more comprehensive understanding.

Synthesis

Mangrove forests consist of a consortium of tree and shrub species that inhabit at the confluence of land and sea, and can withstand very hostile and inhospitable conditions (like: higher salinity, tidal extremes, wind velocity, high temperature and muddy anaerobic soil conditions)[20]. Globally, mangroves are estimated to cover 137,760 km^2 (based on satellite image analysis) in 118 countries and territories in the tropical and subtropical regions of the world[21]. Indian mangroves are distributed in about 4,956 km^2 (Fig. 1), which constituted about 3.6% of the world's mangroves[22]. In the Country's total area under the mangrove vegetation, 57% is recorded on the east coast and 23% on the west coast. Bay islands (Andaman and Nicobar) account for 20% of the country's total mangrove area. Sundarbans is the largest mangrove forest in the world, located in India and Bangladesh. Mangroves have a vast existence on the east coast of India due to the nutrient-rich alluvial soil formed by the rivers - Ganges, Brahmaputra, Mahanadi, Godavari, Krishna and Cauvery and perennial supply of freshwater along the deltaic coast. However, mangroves on the west coast are of peculiarly bedrock valley type, scattered, comparatively smaller than the east coast[22].

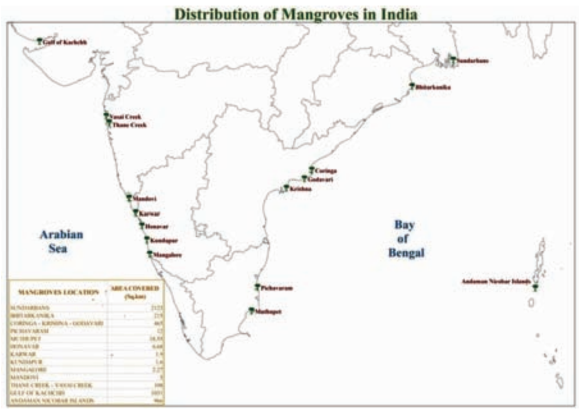

Fig. 1–Map showing the distribution of mangrove along the Indian coast

GHG emission data from Indian mangroves were gathered from published literatures and available unpublished theses. Current data status shows mangroves only from the east coast of India have been studied in details. Whereas, west coast of India has significant areas of mangrove coverage, which is not studied in the same frequency. Three types of fluxes of CO_2, CH_4 and N_2O have been considered for inventorization, a) Air-water flux; b) sediment-air flux; and c) canopy-air/biosphere-atmosphere flux, and shown in Tables 1, 2 and 3, respectively.

Discussions

Mangrove sediments are well known as a natural sources of greenhouse gases[23], whereas the entire ecosystems (sediment, water and vegetation) are probably sinks for atmospheric CO_2[8]. Fluxes from the coastal waters including mangrove wetlands and estuaries often play a significant role in GHG emissions to the atmosphere[24]. Air-water as well as biosphere-atmosphere interactions often can control the atmospheric trace gas composition at a regional

Table 1–Air-water fluxes of CO_2, CH_4 and N_2O from Indian mangroves

	Name	State	Area	WATER-AIR Flux					
				CO_2		CH_4		N_2O	
			(Km²)	Method	Flux mmol Mol C m^{-2} yr^{-1}	Method	Flux mmol C m^{-2} yr^{-1}	Method	Flux mmol C m^{-2} yr^{-1}
1	SUNDARBANS	WEST BENGAL	2123	Indirect Flux[59]	*1.10* [34]	Indirect Flux[59]	*0.027*[34]	No available	
				Indirect Flux[59]	*20.70* [52,53]				
				Indirect Flux[59]	*30.66*[54]	Indirect Flux[60]	*29.2*[54]		
				Direct Flux (Floating Chamber)	*20.91*[54]	Direct Flux (Floating Chamber)	*16.79*[54]		
				Indirect Flux (Micrometeorological Method)	0.11[30]	Indirect Flux[61]	0.7 - 49.1[30]		
				Indirect Flux (Micrometeorological Method)	(-)2358 - 24655[32] -	Indirect Flux (Micro meteoro logical Method)	(-) 8928 – 17502[32]		
				No available Data		Indirect Flux (Micrometeorological Method)	2.6 to 20.7[36]		
2	PICHAVARAM	TAMIL NADU	12	Indirect Flux[59]	27.01[34]	Indirect Flux Calc[59]	0.19[34]	Direct Flux Calc (Floating Chamber)	11.4[56]
				Direct Flux Calc (Floating Chamber)	92.0 - 160.3[55]	Direct Flux Calc (Floating Chamber)	3.7 - 11.4[55]	Direct Flux Calc (Floating Chamber)	1.1 - 1.3[56]
3	MUTHUPET		18.55	No available Data					

4		ANDAMAN & NICOBAR	966	Indirect Flux Calc[59]	33.58[34]	Indirect Flux Calc[59]	0.22[34]	No available Data	
				Direct Flux Calc (Floating Chamber)	27.38[34]	Direct Flux Calc (Floating Chamber)	0.20[34]		
						Indirect Flux Calc[62]	201.4 - 210.2[14]	Indirect Flux Calc[62]	2.0 - 2.1[14]
						Direct Flux Calc (Floating Chamber)	*302.2*[14]	Direct Flux Calc (Floating Chamber)	11.4[14]
								Indirect Flux Calc (Air-Sea gas exchange model)	2.0 - 2.1[56]
								Direct Flux Calc (Floating Chamber)	10.5[56]

Table 2–Sediment-air fluxes of CO_2, CH_4 and N_2O from Indian mangroves

					SEDIMENT-AIR Flux				
	Name	State	Area (Km^2)	Method	CO_2 Flux Mol C $m^{-2}yr^{-1}$	Method	CH_4 Flux mmol C m^{-2} yr^{-1}	N_2O Method	Flux mmol N m^{-2} yr^{-1}
1	SUNDARBANS	WEST BENGAL	2123	No available Data		Static chambers	280.3[15]	Static Chamber Static chambers	4734 –0.2[56] 19173[36]
2	BHITARKANIKA	ODISHA	215	No available Data		Chamber method; flux through pneumato-phores	50 – 1768[43]	Static Chamber	1.8 – 41[43]
3	CORINGA	ANDHRA PRADESH	465	No available Data		Chamber method	2008 – 8098[57]	Static Chamber	
4	PICHAVARAM	TAMIL NADU	12	No available Data		Close Chamber Technique	3.5 - 3.8[56]	Static Chamber	14585[58]
						Static	184 - 586.9[41]	Static	9.9 - 14.0[55]

					chambers		Chamber	
					Close Chamber Technique	341.6 - 543.1[55]	Static Chamber	
5	MUTHUPET		18.55	No available Data	Static chambers	551.9[15]	Static Chamber	1.4 - 2.6[56]
					Chambers method; flux through pneumato-phores	431 – 855[19]	Static Chamber	13.1[14]
							Static Chamber	3.6 - 6.7[19]
6	ADYAR ESTUARY MANGROVE		0.48	No available Data	Close Chamber Technique	30353[58]	No available Data	
7	ENNORE CREEK		0.7		Close Chamber Technique	9894[58]		
8	ANDAMAN & NICOBAR		966	No available Data	Static chambers	155.9 - 252.3[14]	Static chambers	1.1 - 1.8[14]

Table 3–Canopy-air / biosphere-atmosphere fluxes of CO_2, CH_4 and N_2O from Indian mangroves

CANOPY-AIR Flux

	Name	State	Area (Km^2)	CO_2 Method	CO_2 Flux Mol C m^{-2} yr^{-1}	CH_4 Method	CH_4 Flux mmol C m^{-2} yr^{-1}	N_2O Method	N_2O Fluxmmol N m^{-2} yr^{-1}
1	SUNDARBANS	WEST BENGAL	2123	Indirect Flux Calc (Micrometeoro logicalMethod)	(-)157.1 - 423.6[51]	No available Data			No available Data
				Indirect Flux Calc (Micrometeoro logicalMethod)	-400.7[49]	Indirect Flux Calc (Micro meteoro logical Method)	2700 – 14369[49]		No available Data
				Indirect Flux Calc(Micro meteorological Method)	0.0004[38]		0.0162[38]		
2	PICHAVARAM	TAMIL NADU	12	No available Data		Chamber, Flux through Pneumato-phores	168.8 - 1453.2[41]		No available Data

scale. Lack in a comprehensive database on GHG emissions from the ecologically important coastal ecosystems in tropical countries is a well established fact[25]. These coastal ecosystems could be of huge potential in terms of their GHG source/sink strength[26]. Among several mangrove ecosystems in India, The Sundarbans is known to be dominated with *Avicennia* sp. followed by other mangrove species like *Ceriops* sp., *Excoecaria* sp.[27]. Pichavaram and Muthupet mangroves are also known to be dominated by *Avicennia* sp., whereas *Rhizophora* is the pioneer species at Wright Myo, Andaman Islands. Difference in species distribution along the coastal waters can change the transfer rate of organic material between various biotic and abiotic compartments, which in turn can alter the emission fluxes of various greenhouse gases from the soil/water/canopy to the atmosphere[28]. Recently, Kathiresan *et al*.[29] extensively studied the net canopy CO_2 flux between two Indian mangrove species (*Rhizophora mucronata* and *Avicennia marina*) and showed 24% higher net canopy photosynthesis by the latter species than the former.

Air-water flux of greenhouse gasses from the mangrove

A large variation of CO_2 emission from Indian mangrove waters has been reported by various research groups. CO_2 fluxes ranged from -2,358 to 24,655 molC m^{-2} yr^{-1} (Fig. 2). Few researchers showed that the mangrove waters can change its nature as a sink or a source along with season[30] and space[31].

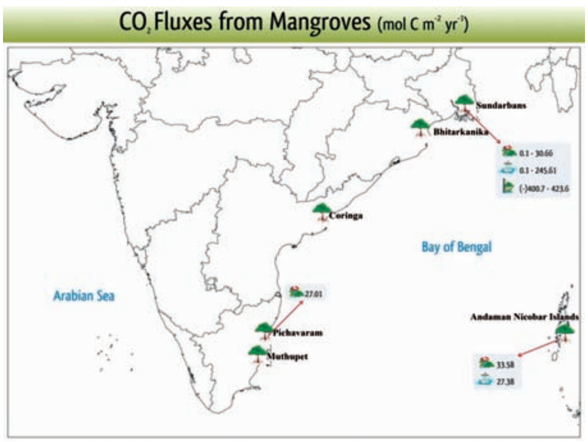

Fig. 2–CO_2 flux from various parts (water/soil/canopy) of mangrove ecosystem

Earlier very high magnitude in source-sink strength was reported from the Sundarbans mangrove ecosystem[32]. More recent studies[31] reported relatively lower emissions from this mangrove waters (i.e. from inner middle and outer part of Sundarbans mangrove waters). Many of these mangroves are in close proximity to the urban areas along the coast (e.g. Impact of Kolkata metropolitan to Sundarbans or Chennai metropolitan over Adyar estuary). Variable human influence, anthropogenic load etc. on these ecosystems often cause the inter-annual variation in CO_2 emission from the mangrove waters. CO_2 flux from the other mangrove dominated rivers of the east coast of India and the Andaman Nicobar Islands were well within a limited (lower) range. Relalively smaller catchment areas with lesser fresh water runoff into these rivers than the Sundarbans water could be responsible for the limited vareation in air water CO_2 fluxes from these mangraves dominated rivers. Large deviation in the CO_2 fluxes reported from the same system by various researchers could be due to the use of various gas transfer velocities considered for its calculation. This gas transfer velocity is often controlled by the combined effect of diffusive and turbulent processes on both sides of the interface that limit the transfer of gas between the bulk water and air phases. Physical forcing for gas transfer is wind stress and buoyancy at the sea surface, Whitecaps/ bubble production and wind/wave interactions and surface lms all play a role in determining the rate of gas transfer [33]. Difference of sampling methodology (depends on the calibration of the sampling/estimation systems and the associated uncertainty of estimation) also can cause a huge difference in the flux calculations. Although, there was a good agreement in CO_2 flux data derived by using the direct and indirect methods[34]. Most of these water bodies remained supersaturated with respect to the CO_2 with occasional under-saturation caused by post-monsoonal phytoplankton bloom. Often these waters reflect the adjacent soil biogeochemistry, which changes in regular basis with time and space. As the organic load in the sediment changes with space (spatial variation in terms of the proximity to the anthopogenic sources, density and type of mangrove etc.) and time (temporal variation in terms of fresh water input, rainfall, supply of mangrove litter), the oxidation reduction state also changes resulting a variation in the greenhouse gas fluxes. Mean of CO_2 flux reported from the Indian mangrove waters along the east coast of India was estimated to be 20.18 molC m^{-2} yr^{-1}(average of all the reported annual mean value) (Figure 2 and Table 1). Mean CO_2 flux from worlds mid-latitude estuaries are 16 ± 11 molC m^{-2} yr^{-1} (between 0 - 23.5°S) and 14±20 molC m^{-2} yr^{-1} (between 0 - 23.5°N)[35], which indicates that Indian mangrove waters as a significant CO_2 source to the atmosphere compare to the global air-water CO_2 flux values from the estuaries. Present study also showed that the Indian mangrove waters contribute higher CO_2 air-water flux relative to the global mean CO_2 flux from the mangrove waters (~ 18 molC m^{-2} yr^{-1}; [8]).

Methane flux from mangrove waters also showed large variations (Fig. 3). Except one report[23], most of the reported value show mangrove waters as a persistent CH_4 source to the atmosphere. Mangrove sediment (with low oxygen) acted as a major source of methane and was indicated by the enriched concentration in the sediment pore water (e.g. pore water was 19 times greater than those of surface water[36]). The Andaman waters, which are relatively free from much human influences showed relatively high air-water methane flux[14]. Most of the cases these trace gases are transferred from sediment to the water column. The concentration of this dissolved gas and their flux to the atmosphere are therefore largely depends on the tidal conditions, mangrove types, soil characters etc. CH_4 flux from the mangrove waters along the east coast of India was ranged between 0.027 and 17,502 mmolC m^{-2} yr^{-1}.

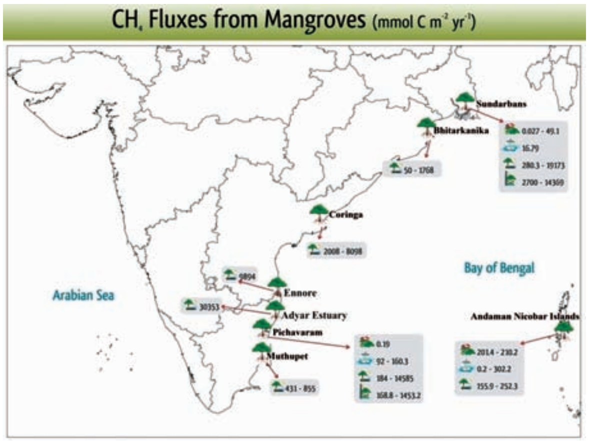

Fig. 3–CH_4 flux from various parts (water/soil/canopy) of mangrove ecosystem

Based on very few N_2O air water flux data, it was observed that N_2O flux along the eastern coast ranged between 1.1 and 11.4 m mol N m^{-2} s^{-1} (Fig. 3). Along the west coast N_2O emission data are still very sparse. Most of these studies were done in very shallow water (<20 m), where the water column never became anoxic. This indicated that N_2O is mostly produced from bottom sediments enriched with organic loads. Most of the published data were considered to determine only the air water flux of N_2O from the mangrove waters of Indian coast and it mean was calculated to be 5.36 mmol N m^{-2} yr^{-1} (Fig. 4). The quantification of individual GHGs in a common

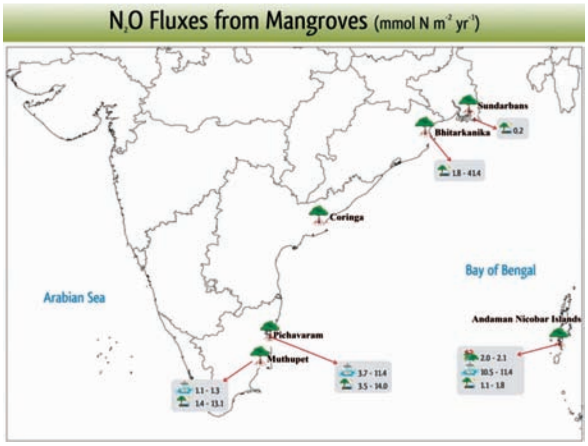

Fig. 4–N_2O flux from various parts (water/soil/canopy) of mangrove ecosystem

scale is based upon their radiative properties, which may be used to estimate the potential future impacts of emissions of those gases into the atmosphere. Standard practice was followed to report GHG emissions in tonnes of CO_2 equivalents (CO_2e) which is a universal unit of measurement used to indicate the GWP of a greenhouse gas, expressed in terms of the global warmingpotential of one unit of carbon dioxide(http://www.defra.gov.uk/environment/economy/reporting/).

In general, not much seasonal trend was reported for either CH_4 or N_2O from most of the undisturbed mangrove areas in India[14]. Mangrove systems largely or moderately influenced by anthopogenic loads often showed some spatial and seasonal trend in terms of the greenhouse gas fluxes, depending on the quality and quantity of the imported material to the mangrove waters[43]. All the mean values of greenhouse gas emissions reported from Indian mangrove waters were converted into their CO_2 equivalent amount and the mean flux is given in Fig. 5a, b and c.

Greenhouse gas fluxes from Sediment

Mangrove sediments are known for its high anoxic nature. Beside allochthonous sources, the sediments receive huge amount of organic carbon in terms of leaf litter on a regular basis. Unfortunately, a very less number of publications are available, which reports direct soil emission of CO_2 from mangrove soils along the Indian coast. For the measurement of the GHG flux, most of the studies in India followed the inexpensive static chamber method to quantify spatial variations between different habitats of the same ecosystem during a relatively short time period[37]. Soil CO_2 efflux from Sundarbans mangroves ranged between 1.21 and 1.78 µmol m^{-2} s^{-1} during the summer months (pre-monsoon) study period (Fig. 2) with a mean of 48.25 ± 5.43 molC m^{-2} yr^{-1} [37]. All these results indicated that mangrove sediments as a persistent source of CO_2 to the atmosphere.

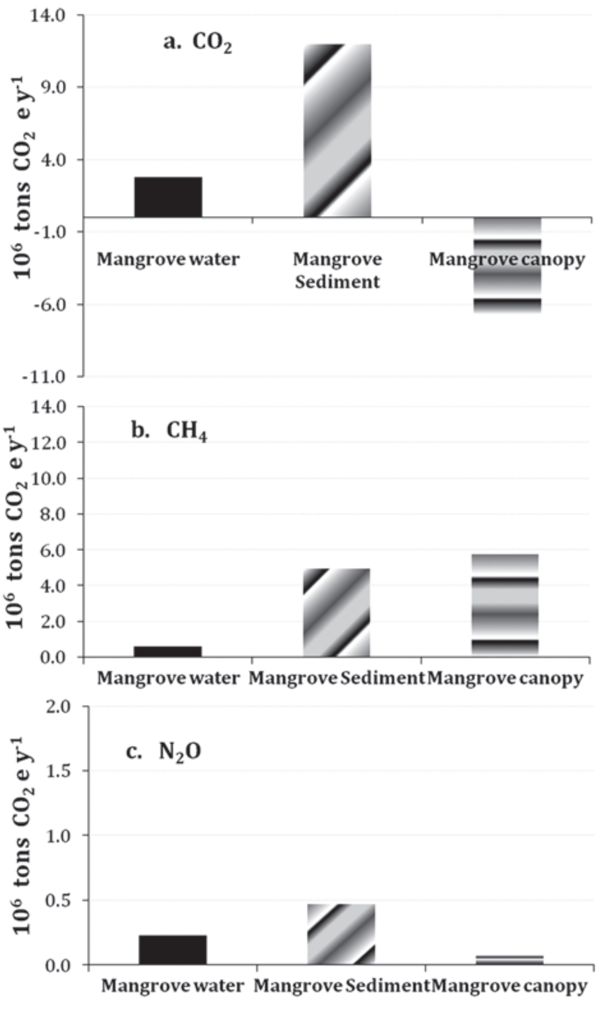

Fig. 5–Net greenhouse gas fluxes from different parts of mangrove ecosystem a. CO_2, b. CH_4, c. N_2O (calculated in terms of CO_2 equivalent for the total mangrove area in India).

In terms of methane flux, the Sundarbans, the largest mangrove of the world, showed an enormous variation in sediment-air values (Table 1). Mukhopadhyay *et al*.[38], observed negative flux of CH_4 in Sundarbans mangrove, which suggested that these mangroves can act as a sink for CH_4, indicating the dominance of methanotrops over methanogenic bacterial activities. However, more recent studies on the Sundarbans reported significant CH_4 flux with a range from 4,734 to 19,173 mmol m^{-2} d^{-1} [36](Fig. 3). Varying degree of fresh water flux along with varying extent of litter supply regulating the availability of the substrate to the mangrove sediment could often controls the balance between the methanogenesis and methanotrophy. These processes along with variation in the soil temperature could cause the interannual variation in CH_4 production/oxidation and its flux to the atmosphere from the mangrove sediment[39] . Exceptionally high CH_4 emission flux was recorded from Adyar Estuary (Fig. 3) with some mangrove patches along the catchment area. These high values were mostly attributed to the high loads of domestic/ industrial sewage coming from adjacent Chennai metropolitan[40] . Seasonally, the variation of CH_4 flux is not consistant from the Indian mangroves. Fresh water flux often enriched the mangrove sediment with organic matter, which often caused higher soil anoxicty which stimulates the CH_4 flux [36]. Bubble ebullition from the sediment caused by the higher water levels in monsoon also can enhance the rate of

CH_4 flux to the atmosphere[41]. In the countrary, few scientists reported, that increased litterfall during non-monsoon months often can increase the soil CO_2 flux to the atmosphere[27].

The static chamber approach was taken in most of these studies of sediment to air N_2O flux measurement in Indian mangrove systems. N_2O flux from mangrove sediments was measured by several researchers and the highest values were obtained from the Bhitarkanika waters. All the results of N_2O flux from sediment to air were within a range of 0.2 to 41.4 mmol m^{-2} d^{-3}. (Fig. 4). Various degrees of sediment denitrification in different mangrove ecosystems results the variation in the N_2O emission to the atmosphere [42]. Several efforts have been made to measure N_2O emission from the Arabian Sea, while almost no data is available from the coastal ecosystems along the west coast of India. Fernandes and Bharathi[42] reported N_2O emission rate from the mangrove sediments while measuring the denitrification rate along the Goa coast and the flux values reached as high as 1.95 nmol N_2O-N g^{-1} h^{-1}. But this reported values were not expressed in terms per unit area.

Majority of the studies reported highest CH_4 and N_2O emissions from mangrove soils in the post-monsoon, when litter fall was maximum enriching the soil organic carbon to a higher degree[43]. Annual litter fall from The Sundarbans mangrove is estimated to be 1,173.85 g dry wt. m^{-2} yr^{-1}, and reported to be the main reason for the enhanced soil anoxicity, which in turn enhance the denitrification and methanogenesis rates in the sediment[27]. Increase in the number of pneumatophores after monsoon, also contribute to plant-mediated emission for greenhouse gas[41]. It was calculated from our study that the mean annual CO_2, CH_4 and N_2O flux in the static chamber method were 1.2 x 10^7, 8.94 x 10^6 and 4.68 x 10^5 tons CO_2 e yr^{-1} respectively (Figure 5a, b, c).

Below-canopy gas exchange

CO_2 in mangrove systems are generated mainly from biogenic respiration processes in the soil and released to the atmosphere. Mangrove vegetations often can play a significant role in capturing the emitted CO_2 gas from the atmosphere by sequestering through the photosynthesis process. Instead of measuring direct CO_2 emission from soil few researchers tried to measure whole ecosystem metabolism in terms of CO_2 flux by using micrometeorological flux calculation method[44]. The basic concept of these micrometeorological methods is that gas transport from the soil surface is accomplished by eddies that displace air parcels from the soil to the measurement height, and that the vertical flux measured at that reference level is identical to the efflux from the soil[45]. Micrometeorological techniques have advantages over chamber systems for do not modifing the micro-environment of the soil surface[45] and can measure soil CO_2 efflux continuously over long time periods. Another advantage can be measured integrate larger surface areas[46,47] which is another advantage of this technique Janssens *et al*[48] clearly depicted that micrometeorological techniques are not suited to estimate soil CO_2 efflux in a forest with undergrowth; however, they do provide valuable information on below-canopy gas exchange.

The canopy-air flux of CO_2 showed large variation from the soil emission flux in the Sundarbans mangrove forest. Previously various researchers[49,51] reported the role of mangrove forest as a net sink of CO_2 from the atmosphere. In the static chamber measurement of soil CO_2 emission the role of mangrove canopy, known for their CO_2 sink nature, was entirely ignored. Sink strength of the mangrove forest reached up to 401 molC m^{-2} yr^{-1} [49]. Earlier Mukhopadhyay *et al*[3] depicted the same mangrove system as a net source of CO_2 to the atmosphere by using identical methodologies. These results indicated that the CO_2 source-sink strength of mangrove forest changes inter-annually depending on rainfall pattern, temperature and other environmental parameters.

In general, at a seasonal scale the magnitute of CO_2 source/sink strength (of the mangrove vegetation) was relatively lower during monsoon comparable to the other seasons[27,49]. Low atmospheric temperature, solar radiation and vapour pressure deficit during the monsoon could be responsible for the lower degree of metabolic processes in the mangrove vegetation compare to the rest of the year. One pilot study had been carried out to get some idea about the carbon sequestration in the mangrove of west coast of India but no data on CO_2 or any other green house gas fluxes were available. Globally, mangroves take up (sequester) approximately 1.5 metric tons ha^{-1} yr^{-1} of carbon or 550 g CO_2 m^{-2} yr^{-1} (mean) from the atmosphere[50]. The mean CO_2 sequestration rate reported from the Sundarbans mangrove systems was ~2.6 times higher (1,469 g CO_2 m^{-2} yr^{-1} [27,49]) than the global mean values.

CH_4 flux from the mangrove canopy by micrometeorological method was reported only from The Sundarbans[38, 49] ecosystems. Mangrove canopy flux showed a wide range between 0.016 and 14,369 mmol m^{-2} d^{-1} (Fig. 3). Extrapolating the mean flux of CO_2 and CH_4, the mean annual of CO_2 and CH_4 flux from all the Indian mangrove forests by micrometeorological processes were calculated to be -6.7×10^6 and 8.9×10^6 tons CO_2 e yr^{-1}, respectively (Figure 5a and b). These studies indicated that, although mangrove occupies only 0.66% of India's total forest area, the net CO_2 sequestration (considering the emission of CH_4) could reach as high as 1.32% of India's total CO_2 sequestration by all the forest. CO_2 flux data from the forest area has not been collected uniformly using identical methods all over the country. For a more realistic understanding of net ecosystem metabolism, the untouched areas especially the west coast of India should be thoroughly studied.

Conclusion

GHG fluxes (both magnitude and direction) from the water, sediment and canopy showed an interesting nature, which clearly delineated their source-sink nature in terms of emission and sequestrations. Both, mangrove sediment and water acted as a perennial source of these GHGs, where as the vegetation acted as a net sink for CO_2. These results indicated that a change in the surface character (i.e. water/sediment/canopy) can significantly alter the magnitude as well as the direction of trace gas fluxes within the system.

Mangrove canopy can process a large amount of anthopogenically emitted CO_2 by sequestering them in the biomass. Both inter and intra system variability in GHG emission indicate differences in species distribution, rainfall pattern, resource availability within as well as inside them. Mangrove forests account for about 2.4% of tropical forest (www.fao.org/forestry/mangroves), hence accuracy improvement of global carbon sink quantification is essential in the mangrove swamps[39]. Being one of the most carbon-rich forests in the tropics and containing about 2.5 fold greater carbon storage (on average 1,023 Mg C per hectare) relative to Boreal, Temperate and Tropical upland forests[40], mangrove forests could be very useful to play an important role in reducing the rate of atmospheric CO_2 increase. Present review showed that both mangrove waters and the sediment are mostly acting as sources of CO_2 to the atmosphere, whereas the below-canopy gas exchange studies indicated its potential role as a sink of atmospheric CO_2. In addition, variable rates of greenhouse gas emission fluxes from polluted and non- polluted mangrove systems can significantly regulate the regional as well as the global atmospheric gas compositions. Relatively unpolluted /pristine mangrove like Bhitarkanika or Andaman mangrove could be used as reference to delineate the natural and anthropogenic sources of greenhouse gases from the mangrove systems along the Indian coast to the atmosphere.

Acknowledgement

Authors are grateful to Society for Integrated Coastal Management (*SICOM*) for the encouragement and supports. We are also grateful to MoEF, Govt. of India for their uninterrupted support.

References

1 IPCC (Intergovernmental Panel on Climate Change), Atmospheric chemistry and greenhouse gases. The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the IPCC, *Cambridge University Press*, New York, USA, 2007.

2 Ferron, S., Ho, D.T., Zackary, J.I., & Huntley, M.E. Air"Water Fluxes of N_2O and CH_4 during Microalgae (Staurosira sp.) Cultivation in an Open Raceway Pond. *Environ. Sci. Technol.*, 46 (2012) 10842-10848.

3. Borges, A.V., Delille, B. & Frankignoulle, M. Budgeting sinks and sources of CO_2 in the coastal ocean: Diversity of ecosystems counts. *Geophys. Res. Lett.*, 32 (L14601) (2005).

4. Cai, W.J., Dai, M. & Wang, Y.C. Air–sea exchange of carbon dioxide in ocean margins: A province-based synthesis. *Geophys. Res. Lett.*, 33 (12) (2006).

5. Bange, H.W. Nitrous oxide and methane in European coastal waters. *Estuarine Coastal and Shelf Science*, 70 (2006) 361-374.

6. Gattuso, J.P., Frankignoulle, M., & Wollast, R. Carbon and carbonate metabolism in coastal aquatic ecosystems. *Annual Review Ecology Systematics*, 29 (1998) 405-433.

7. Borges, A.V. Do We Have Enough Pieces of the Jigsaw to Integrate CO_2 Fluxes in the Coastal Ocean?. *Estuaries*, 28 (1) (2005) 3-27.

8. Borges, A.V., Djenidi, S., Lacroix, G., The´ate, J., Delille, B., & Frankignoulle, M. Atmospheric CO_2 flux from mangrove surrounding waters. Geophysical Research Letters, 30 (11) (2003) 1558.

9. Borges, A.V. & Frankignoulle, M. Distribution of surface carbon dioxide and air-sea exchange in the English Channel and adjacent areas. *J. Geophy. Res.*, 108 (C5) (2003) 3140.

10. Liu, K.K., Atkinson, L., Chen, C.T.A., Gao, S., Hall, J., Macdonald, R.W., McManus, L.T. & Quiñones, R. Exploring Continental Margin Carbon Fluxes on a Global Scale. *Eos, Transactions, American Geophysical Union*, 81 (2000) 641-644.

11. Morris, J.T. & Bradley, P.M. Effect of nutrient loading on the carbon balance of coastal wetland sediments. *Limnol. Oceanogr.*, 44 (1999) 699-702.

12. Chanton, J.P. & Whiting, G. Trace gas exchange in freshwater and coastal marine systems: ebullition and plant transport, In Methods in Ecology: Biogenic Trace Gases: Measuring Emissions from Soil and Water, Matson, P. & Harriss, R. Eds. *Blackwell Scientific*, (1995) 98-125.

13. Heyer, J. & Berger, U. Methane emission from the coastal area in the southern Baltic Sea. Estuarine. *Coastal and Shelf Science*, 51 (2000) 13-30.

14. Barnes, J., Ramesh, R., Purvaja, R., Nirmal Rajkumar, A., Senthil Kumar, B., Krithika, K., Ravichandran, K., Uher, G., & Upstill-Goddard, R.C. Tidal dynamics and rainfall control N_2O and CH_4 emissions from a pristine mangrove creek. *Geophysical Research Letters*, 33 (15) (2006) L15405.

15. Ramesh, R., Purvaja, R., Neetha, V., Divia, J., Barnes, J., & Upstill-Goddard, R.C. CO_2 and CH_4 emissions from Indian mangroves and its surrounding waters. In: Tateda, Y., Upstill-Goddard, R.C., Goreau, T., Alongi, D., Nose, A., Kristensen, E., & Wattayakorn, G. Greenhouse Gas and Carbon Balances in Mangrove Coastal Ecosystems. Gendai Tosho, Kanagawa, Japan, (2007).

16. Bouillon, S., Borges, A.V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J., Rivera-Monroy, J.H., Smith III, T.J. & Twilley, R.R. Mangrove production and carbon sinks: a revision of global budget estimates. *Global Biogeochemical Cycles*, 22(2) (2008) GB2013.

17. Alongi, D.M., Boto, K.G. & Robertson, A.I. Nitrogen and phosphorus cycles. In Coastal and Estuarine Studies, No. 41: Tropical Mangrove Ecosystems (eds Robertson, A.I. & Alongi, D.M.), *American Geophysical Union*, (1992) 251-292.

18. Corredor, J.E., Morell, J.M. and Bauza, J. Atmospheric Nitrous Oxide Fluxes from Mangrove Sediments. *Marine Pollution Bulletin.* 38 (6) (1999) 473-478.

19. Krithika, K., Purvaja, R. & Ramesh, R. Fluxes of methane and nitrous oxide from an Indian mangrove. *Current Science*, 94 (2) (2008) 218-224.

20. Kathiresan, K. & Ramesh, M.X. Establishment of seedlings of a mangrove. *The Indian For.*, 17 (3) (1991) 93-95.

21. Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., Masek, J. & Duke, N. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, 20 (2010) 154-59.

22. Mangrove cover, India sate of forest report, *Forest survey of India*, Chapter 3 (2009) 27-31.

23. Marinho, C.C., Campos, E.A., Guimaraes, J.R.D. & Esteves, F.A. Effect of sediment composition on methane concentration and production in the transition zone of a mangrove (Sepetiba Bay, Rio de Janeiro, Brazil). *Braz. J. Biol.* 72 (3) (2012) 429-436.

24. Kreuzwieser, J., Buchholz, J., & Rennenberg, H. Emission of Methane and Nitrous Oxide by Australian Mangrove Ecosystems. *JO - Plant Biology*, 5 (4) (2003) 423-431.

25. Murdiyarso, D., Kauffman, J.B., Warren, M., Pramova, E. & Hergoualc2h, K. Tropical wetlands for climate change adaptation and mitigation, Science and policy imperatives with special reference to Indonesia. Working Paper 91. CIFOR, *Bogor*, Indonesia, (2012) 10-14.

26. Mitra, S., Wassmann, R. & Vlek, P.L.G. An appraisal of global wetland area and its organic carbon stock. *Current Science*, 88 (1) (2005) 25-35.

27. Ray, R., Ganguly, D., Chowdhury, C., Dey, M., Das, S., Dutta, M.K., Mandal, S.K., Majumder, N., De, T.K., Mukhopadhyay, S.K. & Jana, T.K. Carbon sequestration and annual increase of carbon stock in a mangrove forest. *Atmospheric Environment*, 45 (28) (2012) 5016-5024.

28. Clough, B.F. Mangrove ecosystems. In: English S, Wilkinson C, Baker V (eds) Survy manual for tropical marine resources, 2nd edn. *Australian Institute of Marine Science Townsville*, (1997) 119-196.

29. Kathiresan, K., Anburaj, R., Gomathi, V. & Saravanakumar, K. Carbon sequestration potential of Rhizophora mucronata and Avicennia marina as influenced by age, season, growth and sediment characteristics in southeast coast of India. *J Coast Conserv*, (2013) doi: 10.1007/s11852-013-0236-5.

30. Biswas, H., Mukhopadhyay, S.K., De, T.K., Sen, S. & Jana, T.K. Biogenic controls on the air-water carbon dioxide exchange in the Sundarban mangrove environment, northeast coast of Bay of Bengal, India. *Limnol. Oceanogr*., 49 (1) (2004) 95-101.

31. Akhand, A., Chanda, A., Dutta, S., Manna, S., Sanyal, P., Hazra, S., Rao, K.H. & Dadhwal, V.K. Dual character of Sundarban estuary as a source and sink of CO_2 during summer: an investigation of spatial dynamics. *Environ Monit Assess*. 185 (8) (2012) 6505-6515.

32. Mukhopadhyay, S.K., Biswas, H., De, T.K., Sen, S. & Jana, T.K. Seasonal effects on the air-water carbon dioxide exchange in the Hooghly estuary, NE coast of Bay of Bengal, India. *J. Environ. Monit*., 4 (2002) 549-552.

33. Wanninkhof, R., Asher, W.E., Ho, D.T., Sweeney, C., & McGillis, W.R. Advances in quantifying air–sea gas exchange and environmental forcing. *Ann. Rev. Marine Sci*., 1 (2009) 213-244.

34. Neetha, V. Dissolved carbon dioxide and methane in estuaries and waters surrounding mangroves on the East coast of India and the Andaman Islands. Ph.D. thesis submitted to Anna University, Chennai, India, (2008).

35. Chen, C.T.A., Huang, T.H., Chen, Y.C., Bai, Y., He, X. & Kang, Y. Review article: Air-sea exchanges of CO_2 in world's coastal seas. *Biogeosciences Discuss*., 10 (2013) 5041-5105 .

36. Biswas, H., Mukhopadhyay, S.K., Sen, S. & Jana, T.K. Spatial and temporal patterns of methane dynamics in the tropical mangrove dominated estuary, NE coast of Bay of Bengal, India. *J. Mar. Syst*., 10 (2007) 1-8.

37. Chanda, A., Akhand, A., Dutta, S. & Hazra, S. Summer Fluxes of CO_2 from Soil, in the Coastal Margin of World's Largest Mangrove Patch of Sundarbans - First Report. *J. Basic. Appl. Sci. Res.*, 1(11) (2011) 2137-2141.

38. Mukhopadhyay, S.K., Biswas, H., Das, K.L., De, T.K., & Jana, T.K. Diurnal variation of carbon dioxide and methane exchange above Sundarbans mangrove forest, in NW coast of India. *Indian Journal of Marine Sciences*, 30 (2001) 70-74.

39. Schlesinger & Bernhardt. Wetland Ecosystems, Biogeochemistry, 3rd Edition, An Analysis of Global Change, *Academic Press*, (2013), 233-273.

40. Nirmal Rajkumar, A., Barnes, J., Ramesh, R., Purvaja, R. & Upstill-Goddard, R.C. Methane and nitrous oxide fluxes in the polluted Adyar River and estuary, SE India. *Mar Pollut Bull.*, 56 (12) (2008) 2043-2051.

41. Purvaja, R., Ramesh, R. & Frenzel, P. Plant-mediated methane emission from Indian mangroves. *Global Change Biology*, 10 (2004) 1825-1834.

42. Fernandes, S.O. & Loka Bharathi, P.A. Denitrification: an important pathway for nitrous oxide production in tropical mangrove sediments (Goa, India). *J. Environ. Qual*., 39 (2010) 1507-1516.

43. Chauhan, R, Ramanathan, A.L. & Adhya, T.K. Assessment of methane and nitrous oxide ux from mangroves along Eastern coast of India. *Geofluids*, 8 (2008) 321-332.

44. Barrett, K. Oceanic ammonia emissions in the Europe and their trans boundary fluxes. *Atmospheric Environment*, 32 (3) (1998) 381-391.

45. Mosier, A.R. Gas flux measurement techniques with special reference to techniques suitable for measurements over large ecologically uniform areas. In Soils and the Greenhouse Effect. Eds. Bouwman, A.F. John Wiley & Sons Ltd., Chichester, UK, (1990) 289-301.

46. Dugas, W. Micrometeorological and chamber measurements of CO_2 flux from bare soil. *Agric. For. Meteorol*. 67 (1993) 115-128.

47. Baldocchi, D.D. Flux footprints within and over forest canopies. *Boundary-Layer Meteorol*. 85 (1997) 273-292.

48. Janssens, I.A., Kowalski, A.S., Longdoz, B. & Ceulemans, R. Assessing forest soil CO_2 efflux: an in situ comparison of four Techniques. *Tree Physiology*, 20 (2000) 23-32.

49. Ganguly, D., Dey, M., Mandal, S.K., De, T.K. & Jana, T.K. Energy dynamics and its implication to biosphere–atmosphere exchange of CO_2, H_2O and CH_4 in a tropical mangrove forest canopy. Atmospheric Environment, 42 (2008) 4172-4184.

50. Patil, V., Singh, A., Naik, N., Seem,a U. & Sawant, B. Carbon Sequestration in Mangroves Ecosystems: Review Paper. *Journal of Environmental Research and Development* , 7 (1A) (2012).

51. Chanda, A., Akhand, A., Manna, S., Dutta, S., Das, I. & Hazra, S. Spatial variability of atmosphere-biosphere CO_2

and H_2O exchange in selected sites of Indian Sundarbans during summer. Tropical Ecology, 54 (2) (2013) 167-178.

52. Ghosh, S., Jana, T.K., Singh, B.N. & Choudhury, A. Comparative study of carbon dioxide system in virgin and reclaimed mangrove waters of Sundarbans during freshet. *Mahasagar: Bulletin of the National Institute of Oceanography*, 20 (3) (1987) 155-161.

53. Borges, A.V., Djenidi, S., Lacroix, G., The´ate, J., Delille, B. & Frankignoulle, M. Atmospheric CO_2 flux from mangrove surrounding waters. *Geophysical Research Letters*, 30 (2003) 11-14.

54. Kakolee Banerjee. Biogeochemistry of The Hooghly Estuary And The Adjoining Sundarbans Mangrove, India. Ph.D. thesis submitted to Anna University, Chennai, India, (2012).

55. Senthilkumar, B. Biogeochemical And Biophysical Aspects of Pichavaram Mangrove Ecosystem, South India. Ph.D. thesis submitted to Anna University, Chennai, India, (2007).

56. Purvaja, R., Ramesh, R., Ray, A.K. & Rixen, T. Nitrogen cycling: A review of the processes, transformations and fluxes in coastal ecosystems. *Current Science*, 94 (11) (2008) 1419.

57. Krupadam, R.J., Ahuja, R., Watea, S.R. & Anjaneyulu, Y. Forest bound estuaries are higher methane emitters than paddy fields: A case of Godavari estuary, East Coast of India. *Atmospheric Environment*, 41 (2007) 4819-27.

58. Purvaja, R. & Ramesh, R. Human impacts on methane emission from mangrove ecosystems in India. *Regional Environmental Change*, 1 (2000) 86-97.

59. Borges, A.V., Vanderborght, J.P., Schiettecatte, L.S., Gazeau, F., Ferrón, S., Delille, B. & Frankignoulle, M. Variability of the Gas Transfer Velocity of CO_2 in a Macrotidal Estuary (the Scheldt). Estuaries, 27 (4) (2004) 593-603.

60. Wanninkhof, R. Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res.*, 97 (C5) (1992), 7373-7382.

61. Liss, P.S. & Merlivat, L. Air-sea gas exchange rates: Introduction and synthesis, in The Role of Air-Sea Exchange in Geochemical Cycling, edited by P. Buat-Me´nard, Springer, New York, (1986) 113-127.

62. Clark, J.E, Schlosser, P., Wanninkhof, R., Simpson, H.J., Schuster, W.S.E, & Ho, D.T. Gas transfer velocities for SF, and He in a small pond at low wind speeds. *Geophys. Res. Lett.* 22 (1995) 93-96.