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Introduction

Mangroves play an important role in supporting coastal food webs and nutrient cycles in the adjacent coastal ecosystems (Mumby et al., 2004). An ecosystem service that has recently received increased scientific attention is the high carbon (C) sequestration capacity of mangroves (Howard et al., 2014). Mangroves contain on average 1.023 Mg C/ha, predominantly due to belowground carbon storage, which makes them one of the most carbon rich forest types (Donato et al., 2011). However, globally, agricultural soils have the potential to sequester approximately 5500–6000 Mt CO_2-eq. yr^{-1} by 2030 due to their current low level of OC (Zhang et al., 2018). Mangroves can accumulate large amounts of peat and other forms of mangrove-derived carbon making them very efficient coastal C-sinks (Bouillon et al. 2008; Ezcurra et al., 2016). Despite their role as important carbon-sinks and the worldwide efforts to reduce carbon emissions, mangroves are threatened globally. The major threats come from deforestation and conversion of mangroves to aquaculture and agriculture (Atwood et al., 2017).

Mangrove and rice systems act as a source as well as a sink for greenhouse gases (GHGs), particularly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Mukhopadhyay et al., 2002). The CO_2, CH_4 and N_2O are the major GHGs which responsible for global warming. Mangrove and rice are typically providing passage to GHGs emission, mainly methane (CH_4) and nitrous oxide (N_2O) from soil to the atmosphere through pneumatophore and rice-aerenchyma columns, respectively (Bhattacharyya et al., 2019, 2020; Padhy et al., 2021). Mainly emissions take place through three modes of transport in mangrove, such as (i) the aerenchyma of pneumatophores (negatively geotropic breathing roots of mangrove); (ii) diffusion from the soil through ebullition (through the bubble, soil-water inter-phase) and (iii) diffusion through water (either dissolved in stagnant or tidewater) (Purvaja et al., 2004; Dutta et al., 2015). Whereas, in rice the emission only takes place through rice-aerenchyma from soil to atmosphere. Apart from this, tidal fluctuation, seasonal temperature variation, and intermittent water stagnation also play a crucial role in regulating GHGs emissions in mangrove. Hence, seasonal variation (winter, summer, pre-monsoon and monsoon) is one of the important factors for GHGs emissions in the mangrove (Chowdhury et al., 2016; Padhy et al., 2020).

In Indian Sundarban region, the 10.5% of the mangrove has lost its greenery during 1930 to 2013 due to extreme events like sea level rise, cyclone, flood, etc, and anthropogenic activities (Padhy et al., 2020; 2021). In Sundarban, the mangroves are primarily converted to agriculture, mainly rice and rice-based system. In this region, the mangrove and rice ecologies present adjacent to each other that creates a unique interphase. As both the mangrove and rice systems are the source of GHGs emissions, therefore there is a need to quantify the seasonal GHGs emissions in the Sundarban eco-reg.

2. Importance of the work

- Spatial accounting of greenhouse gases fluxes of mangrove-rice systems in Sundarban have a great importance in the climate change scenario.
- Both site specific and seasonal distribution of GHGs indicate the status of mangrove degradation as well as the conversion of mangrove to rice or rice-based cropping system.
- Geospatial maps of GHGs fluxes in mangrove-rice systems in Sundarban would provide a ready-made information for policy makers to chalk out climate change mitigation work keeping in mind the recent commitment of India to have zero net emission on or before 2070.
- Accounting the spatial and temporal GHGs emission from mangrove ecosystems is important not only for regional and national emissions inventories but also for management and mitigation of these gases.

3. Research Gaps

- Lack of GHGs emissions data in the coastal belt Sundarban, apart from few specific sites.
- Few reports on the spatiotemporal variations of three major GHGs like methane, nitrous oxide, and carbon dioxide in mangrove-rice systems in Sundarban, India
- GHGs emission maps are not well documented in Sundarban.
- There are only few reports in which emission from undisturbed mangroves along with emission from adjoining rice areas have been reported. Since the influx of nutrient enriched water from rice fields enter the mangrove forests hence there is chances of changes in the emission of GHGs from mangrove due to this. Similarly, the brackish water entry into non-mangrove areas and within mangrove system also affects the GHGs emission and it is important from ecological point of view to account and document this variation in GHGs emission.

4. Site Description

The Indian Sundarban mangroves ecosystem is present in the state of West Bengal, India. It lies between 21° 27′ 30″ to 22° 30′ 00″ N (latitude) and 89° 02′ 00″ to 90° 00′ 00″ E (longitude). Sundarban is the part of different islands which are presents in the delta of three big rivers (Ganga- Meghna-Brahmaputra). Three representative degraded mangrove sites and adjacent rice systems were selected for our study based on remote sensing data and maps developed by NRSC, Hyderabad, India in respect of 1930 and 2013-year period (Padhy et al., 2020; 2021). In Sundarban, the mangrove area decreased from 2387 km^2 to 2136 km^2 from 1930 to 2013. The mangrove has been lost globally mainly because of human interferences (e.g., agriculture, aquaculture, shoreline development) and also due to sea-level rise. Based on this, three different locations were selected namely, Sadhupur (22.12 N, 88.86 E), Dayapur (22.14 N, 88.84 E) and Pakhiralaya (22.14 N, 88.84 E) (Figure 1). The GHGs (CH_4, CO_2, and N_2O) fluxes were estimated at three different sites (Sadhupur, Dayapur and Pakhiralaya) of Sundarban-India during four seasons (winter, summer, pre-monsoon, and monsoon) in both degraded mangrove and rice systems. The spatial details of study area are presented in Figure 1.

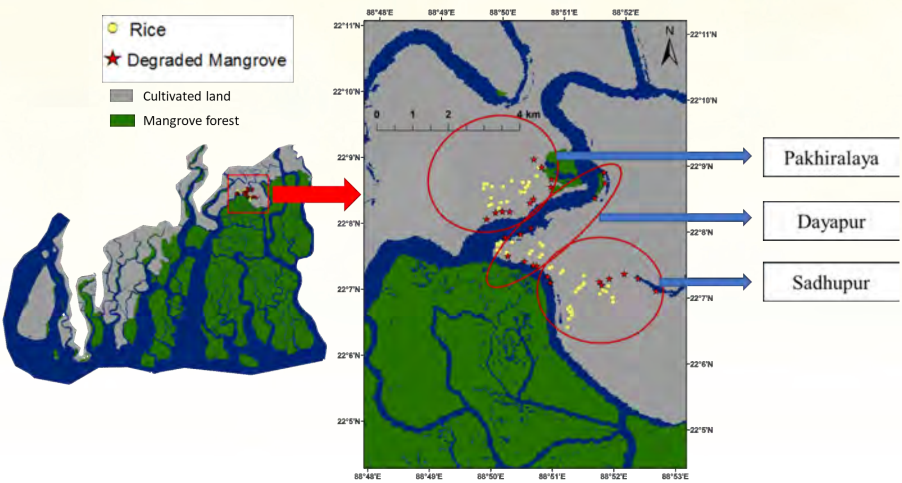

Figure 1: Study sites of mangrove-rice systems in Sundarban, India.

5. Sample collection and geospatial maps generation

5.1 Greenhouse gases collection and analysis

The gas and water samples were collected from three different locations on monthly basis with three replications for the estimation of GHGs emissions. The geolocations of each sample sites were recorded, and the sites were revisited over the different seasons as per the need of the study. The gas samples were collected both by the 'manual chamber method' and by the 'bubble collection chamber' to capture the seasonal fluxes from soil/sediments surface as well as from gas-water interphase, respectively (Figure 2, 3). The liquid samples were used to estimate dissolved GHGs concentration. Based on the variation in temperature and rainfall pattern in Sundarban, four distinct seasons were selected [winter (November, December, and January), summer (February, March, and April), pre-monsoon (May and June) and monsoon (July, August, September, and October)] for the study (Chowdhury et al., 2016; Padhy et al., 2020).

Figure 2: Greenhouse gas collection from mangrove-rice systems by using "manual close chamber" in Sundarban-India.

Figure 3: Greenhouse gas sampling by using "bubble collection chamber" for capturing the GHGs fluxes through ebullition from mangrove-rice systems in Sundarban, India

5.2 Preparation of geospatial maps

Land use land cover classification using satellite imagery was done for mapping of mangrove forests, agricultural land, water bodies. The GHGs emission were interpolated using inverse distance weighing. The brief description of the methodologies is presented below.

5.2.1 Mapping of mangrove forest and agricultural land

Multitemporal and multispectral Landsat 8 Operational Land Imager (OLI) data for the year 2017 were used for Land Use Land Cover (LULC) classification which included mangrove forests, rice/ cultivated lands, orchards, barren land, wetland and water bodies. Landsat OLI data were downloaded from the USGS archives (http://earthexplorer.usgs.gov) Satellite data were geo-referenced and a hybrid classification technique in combination with Normalized Difference vegetation Index (NDVI), image segmentation and visual interpretation were adopted to map the LULC. Detailed methodology of the LULC classification is provided by Reddy et al. (2018).

5.2.2 Interpolation of sampled GHGs emission

The latitude and longitude of the GHGs sampling points were recorded using a GPS (Global positioning system) device. The prediction for unsampled location in the buffer zone was done using Inverse distance weighted (IDW) interpolation. Inverse distance weighted interpolation assumes that the attribute value of an unsampled point is the weighted average of known values within the neighbourhood, and the weights are inversely related to the distances between the prediction location and the sampled locations. The inverse-distance weight is modified by a constant power or a distance-decay parameter to adjust the diminishing strength in relationship with increasing distance. IDW assumes that each measured point has a local influence that diminishes with distance. It gives greater weights to points closest to the prediction location, and the weights diminish as a function of distance, hence the name inverse distance weighted. Weights are proportional to the inverse of the distance (between the data point and the prediction location) raised to the power value n. As a result, as the distance increases, the weights decrease rapidly. The rate at which the weights decrease is dependent on the value of n. If n = 0, there is no decrease with distance, the prediction will be the mean of all the data values in the search neighbourhood. As n increases, the weights for distant points decrease rapidly. The mathematical expression for the IDW is

$$\hat{Z} = \frac{\sum_{i=1}^{n} \frac{Z_i}{d_i^n}}{\sum_{i=1}^{n} \frac{1}{d_i^n}}$$

where $\hat{Z}$ is the value of the attribute of a point to be estimated; Zi is the value of the attribute at sampling point; di is the Euclidean distance between the sampling point and the point where value is to be estimated; n (88 nos.) is the exponential power exponent. The higher the power is, the smaller the influence of the point estimated from the far reference point and the smoother the final interpolation result.

6. Geospatial maps of GHGs fluxes in mangrove-rice systems

6.1 Seasonal methane (CH_4) fluxes from soil to atmosphere over the selected sites

Both the degraded-mangrove and rice are the source of methane production and emission from soil to the atmosphere through pneumatophore of mangrove and rice-aerenchyma columns, respectively. The CH_4 fluxes were varied both in the different locations and during the seasons in both degraded-mangrove and rice systems. Seasonal variation is one of the important factors for GHGs emissions in the mangrove and rice. In mangrove, the higher CH_4 flux was observed during monsoon season as compared to other (Figure 4, 5). Firstly, monsoon corresponds to the rainfall period with the relatively low-temperature conditions and availability of a sufficient carbon and nitrogen in soil either from mangrove-derived (autochthonous) or transported by river water from different terrestrial habitats (allochthonous). Secondly, the water is less turbid during the monsoon having higher transparency and more nutrient load leads to increase phytoplankton, which enhances CH_4emissions during monsoon as compared to other seasons. Similarly, in rice the higher CH_4 flux was observed during monsoon and summer as compared to winter and pre-monsoon (Figure 4, 5). However, in rice ecology the CH_4 emission were more during summer and monsoon because, at that time the rice was in the panicle initiation and maximum tillering stage. These two stages are the critical growth stages of rice where the soil carbon fractions were more due to higher rhizo-depositions and more root exudates carbon content which leads to more CH_4 emissions as compared to other rice growth stages. When comparing both the systems, higher CH_4 flux was observed in rice as compared to the mangrove. Firstly, frequent anaerobic condition during the rice growing period is the primary reason behind more CH_4 emission from rice as compared to mangrove which prevails periodic changes in the aerobic/anaerobic condition due to tidal intrusion. Secondly, the higher availability of sulphate ions in seawater and their consequent reduction in mangrove sediments which is a dominant anaerobic microbial terminal-electron accepting process in mangrove sediments enhance the sulphur reducing bacterial (SRB) community over methanogens resulting less CH_4 emission from mangrove as compared to rice

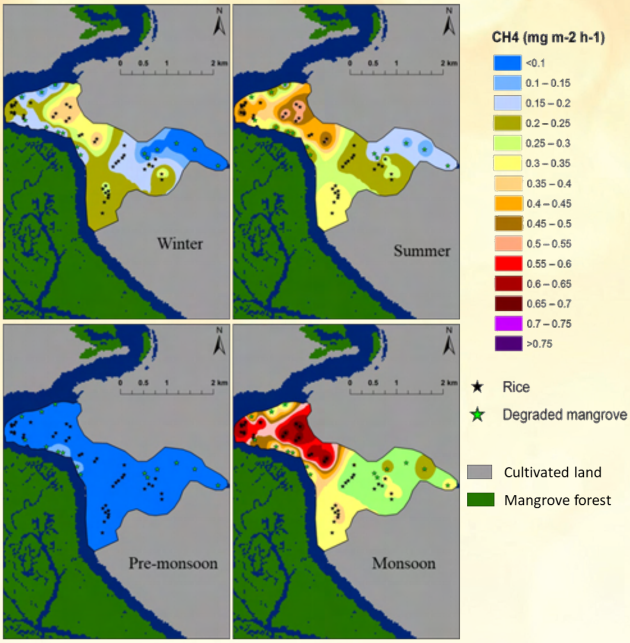

Figure 4: Geospatial maps showing the variations of methane (CH_4) fluxes from soil to atmosphere of mangrove-rice systems during four seasons at Sadhupur and Dayapur sites of Sundarban, India.

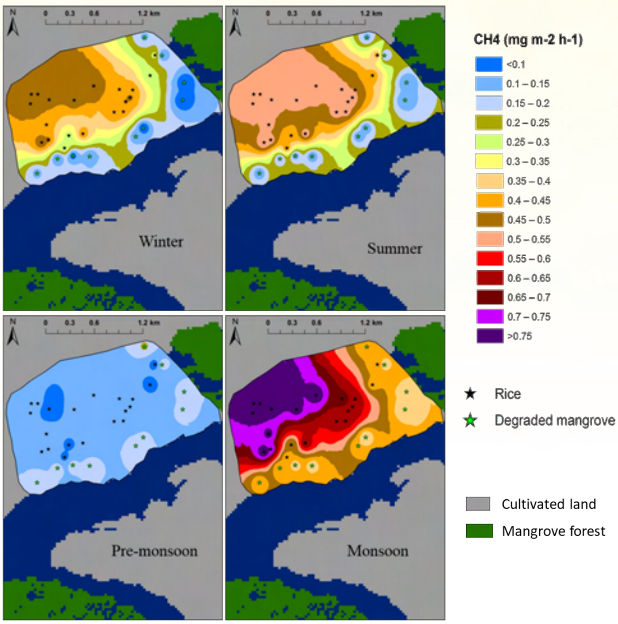

Figure 5: Geospatial maps showing the variations of methane (CH_4) fluxes from soil to atmosphere of mangrove-rice systems during four seasons at Pakhiralaya sites of Sundarban, India.

6.2 Seasonal nitrous oxide (N_2O) *fluxes from soil to atmosphere over the selected sites*

Like CH_4 flux, the N_2O fluxes were also higher in rice than the mangrove (Figure 6, 7) due to higher N substrate availability in the rhizosphere through the application of nitrogen fertilizer during the rice growth stages that trigger the N_2O fluxes. More nitrogen contents in the rice soil enhanced the nitrifier and denitrifier communities in rice soil, whereas less communities in mangrove due emit less N_2O. Furthermore, Higher salinity in mangrove soils is the key reason for less N_2O fluxes because higher salinity decreases the rate of nitrification and denitrification by inhibiting the growth of nitrifiers as well as denitrifiers community. In our study higher N_2O fluxes was observed during summer as compared to other seasons in the mangroves (Figure 6, 7). However, in rice the higher N_2O emission was observed during monsoon and summer due to the critical rice growth stages (i.e., panicle initiation and maximum tillering stage, respectively) and the application of nitrogen fertilizer at that time.

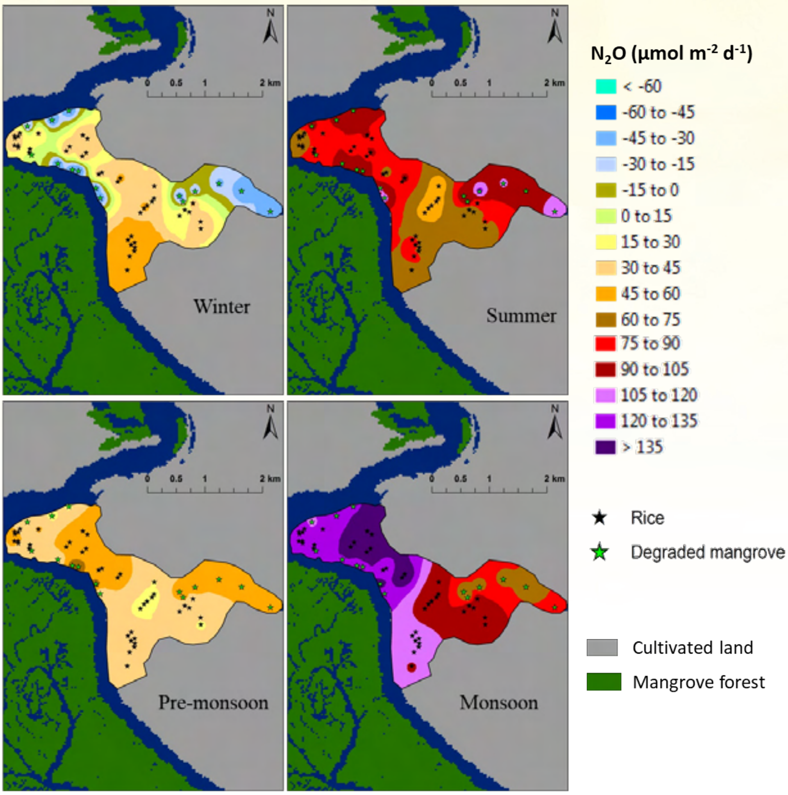

Figure 6: Geospatial maps showing the variations of nitrous oxide (N_2O) fluxes from soil to atmosphere of mangrove-rice systems during four seasons at Sadhupur and Dayapur sites of Sundarban-India.

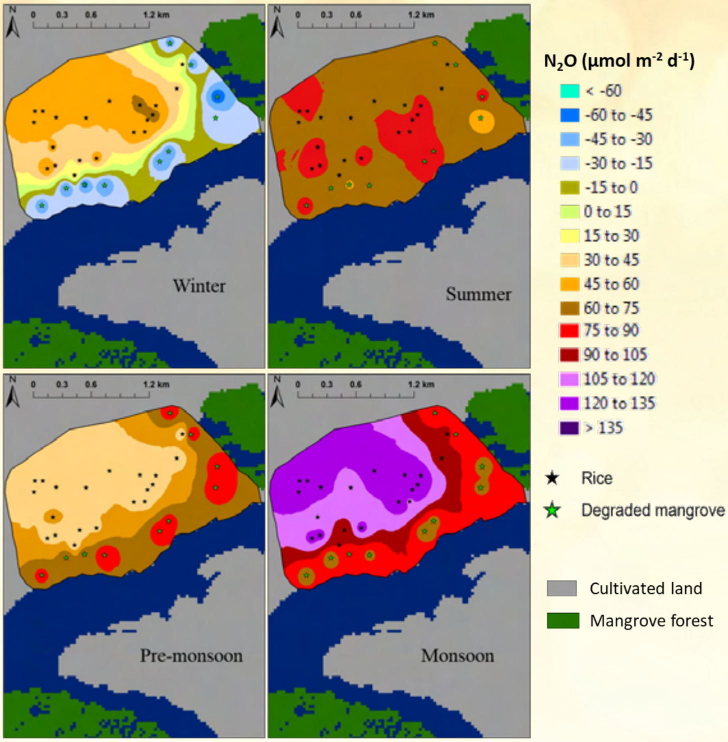

Figure 7: Geospatial maps showing the variations of nitrous oxide (N_2O) fluxes from soil to atmosphere of mangrove-rice systems during four seasons at Pakhiralaya sites of Sundarban-India.

7. Spatial distribution of GHGs (CH_4, CO_2 and N_2O) emissions through three different modes in mangrove system

7.1 *Geospatial maps of greenhouse gases fluxes (CH_4, CO_2 and N_2O) from sediment to atmosphere captured through 'manual gas chamber method'*

Among the three modes of GHGs emissions (fluxes through pneumatophores, through ebullition and air-water exchange) in mangrove, GHGs emissions from soil to atmosphere through pneumatophore is more dominant. Pneumatophore, the negatively geotropic breathing roots of mangrove play an important role to transport the GHGs from mangrove sediments to the atmosphere. Considering the season, CH_4 flux was higher during monsoon, followed by pre-monsoon, summer, and winter (Figure 8). The water is less turbid during the monsoon having higher transparency and more nutrient load leads to increase phytoplankton, which enhances CH_4 emissions during monsoon as compared to other seasons. Similarly, among the seasons, the CO_2 fluxes were higher during monsoon and less during winter (Figure 9). However, Higher N_2O fluxes were observed during summer as compared to other seasons (Figure 10).

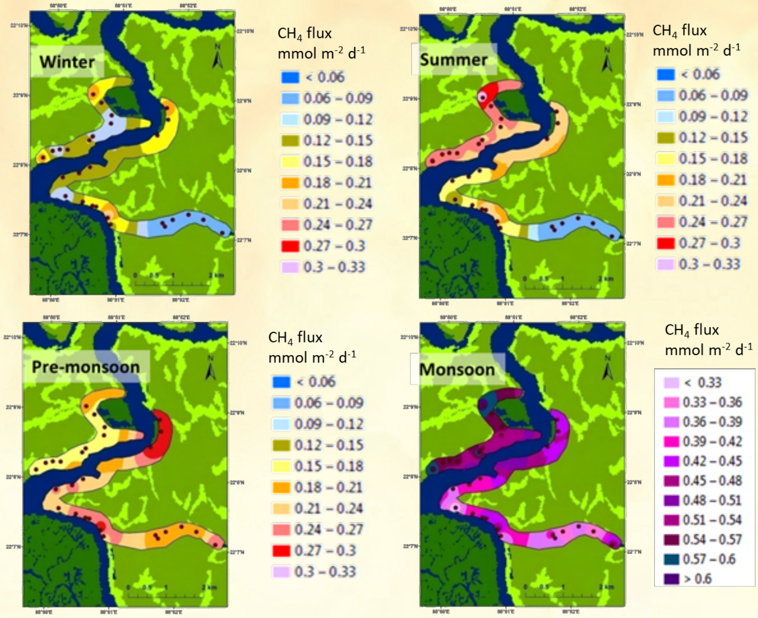

Figure 8: Spatial distribution of methane (CH_4) fluxes from sediment to atmosphere captured through manual close chamber method during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

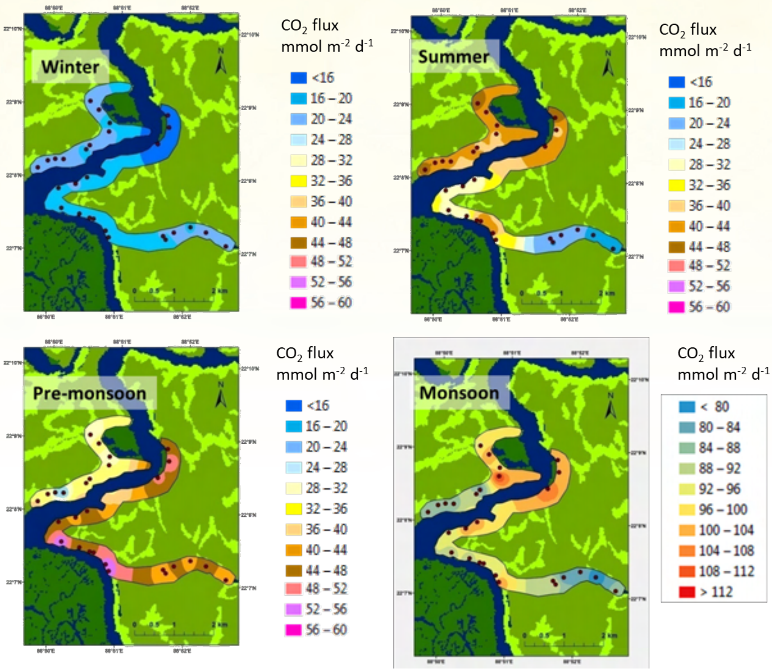

Figure 9: Spatial distribution of carbon dioxide (CO_2) fluxes from sediment to atmosphere captured through manual close chamber method during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

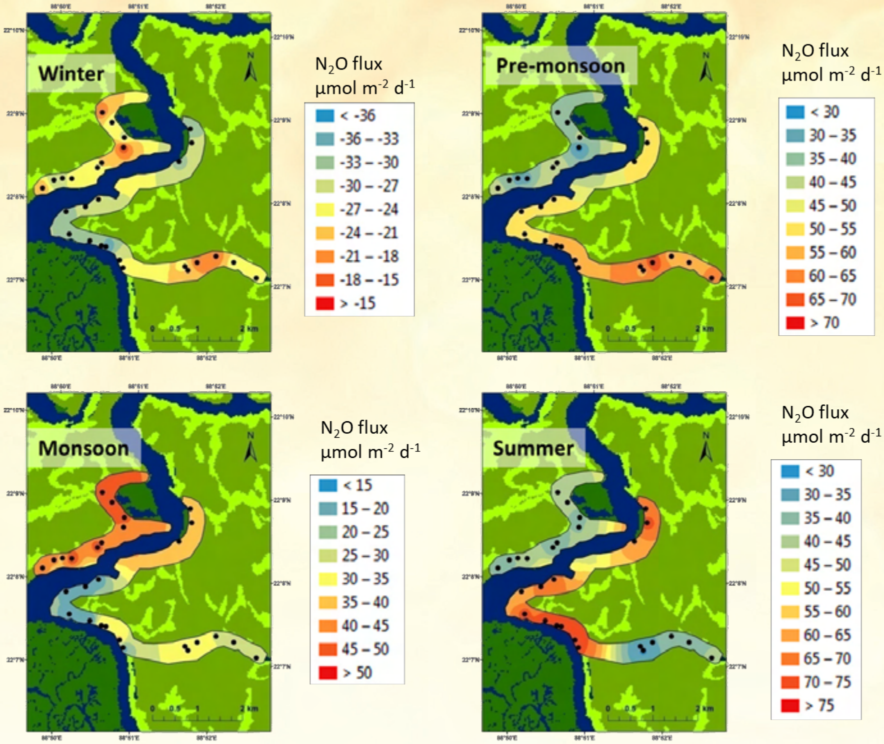

Figure 10: Spatial distribution of nitrous oxide (N_2O) fluxes from sediment to atmosphere captured through manual close chamber method during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

7.2 Geospatial maps of greenhouse gases fluxes (CH_4, CO_2 and N_2O) in mangrove through air-water exchanges

The GHGs fluxes from air-water exchange was play an important role in mangrove due to the regular tidal intrusion and stagnant of sea water in the mangrove sediments. The CH_4 and CO_2 fluxes from air-water exchange was higher during monsoon followed by pre-monsoon, summer, and winter (Figure 11, 12). However, the N_2O fluxes were higher during monsoon and summer as compared to other seasons (Figure 13).

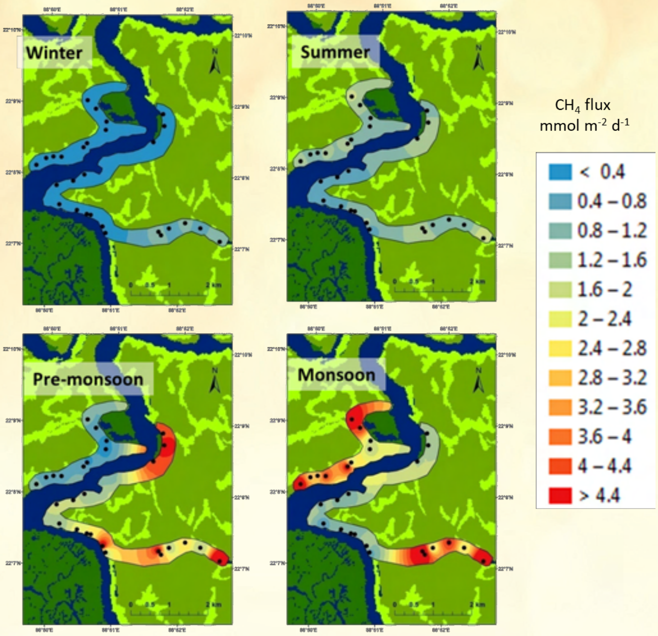

Figure 11: Spatial distribution of methane (CH_4) fluxes through air-water exchanges during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

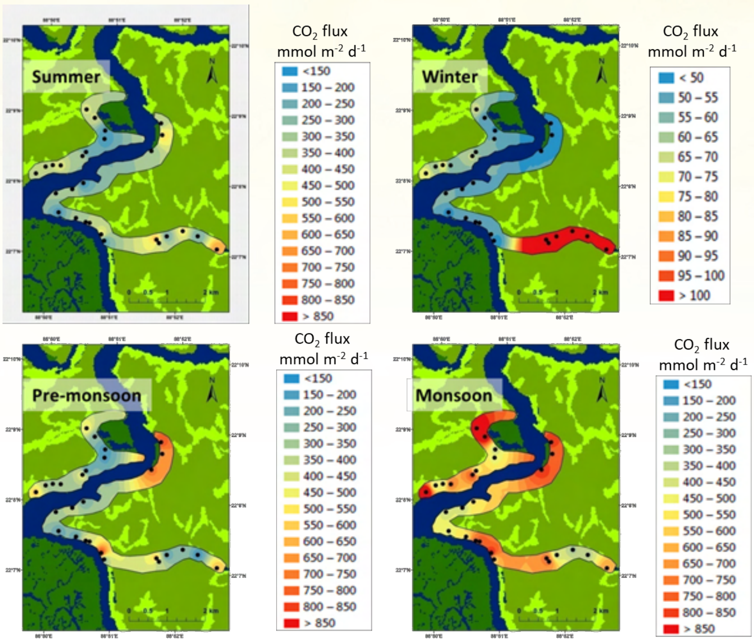

Figure 12: Spatial distribution of carbon dioxide (CO_2) fluxes through air-water exchanges during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

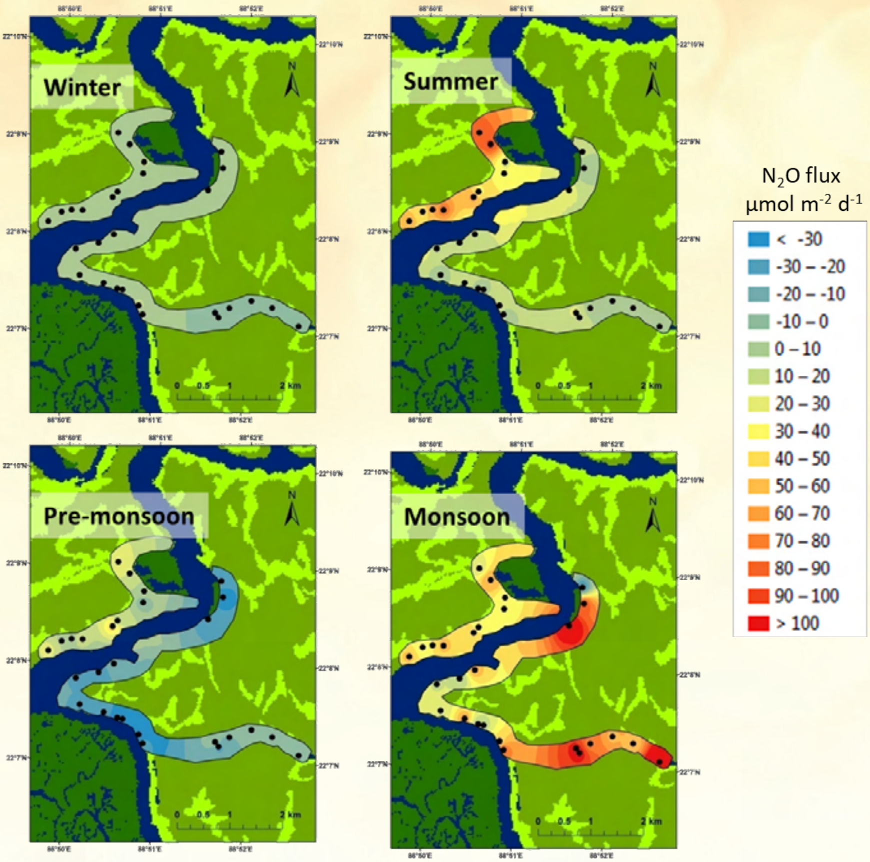

Figure 13: Spatial distribution of nitrous oxide (N_2O) fluxes through air-water exchanges during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

7.3 Geospatial maps of greenhouse gases fluxes (CH_4, CO_2 and N_2O) in mangrove through ebullition

The GHGs fluxes occurred through the ebullition process were estimated for two seasons i.e., pre-monsoon and monsoon in all three sites. The CH_4, CO_2 and N_2O fluxes through ebullition were higher in monsoon compared to pre-monsoon in all the three locations (Figure 14,15,16).

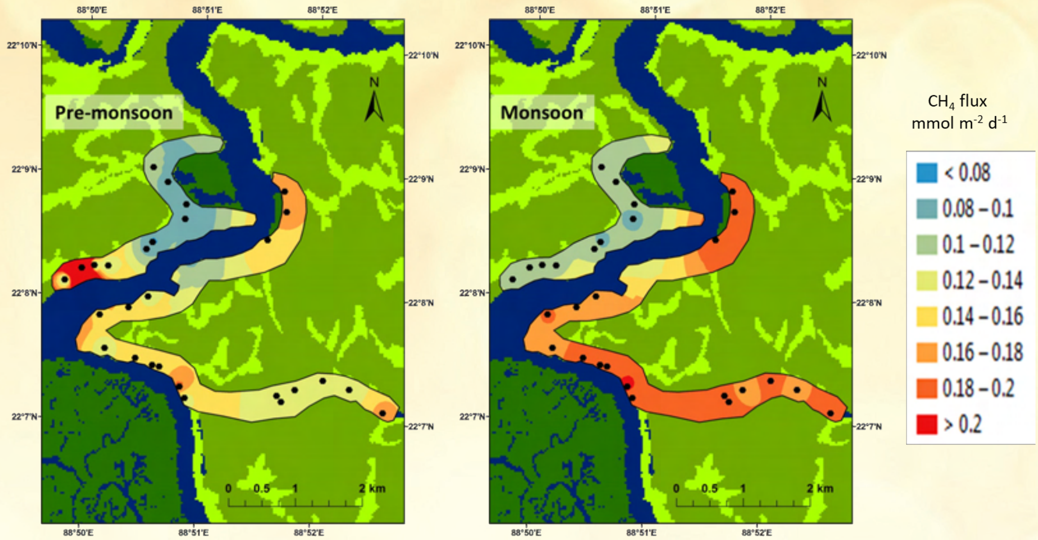

Figure 14: Spatial distribution of methane (CH_4) fluxes from ebullition during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

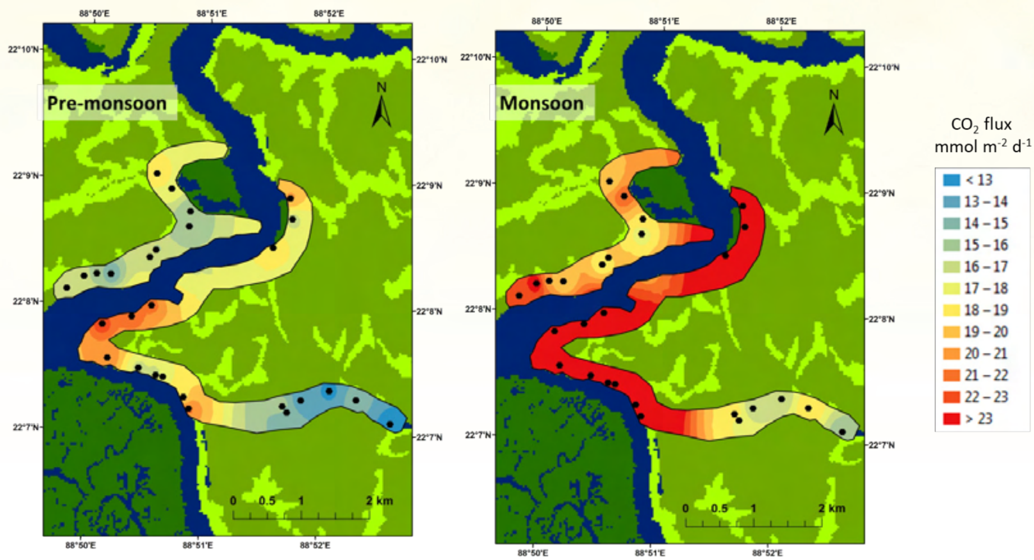

Figure 15: Spatial distribution of carbon dioxide (CO_2) fluxes from ebullition during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

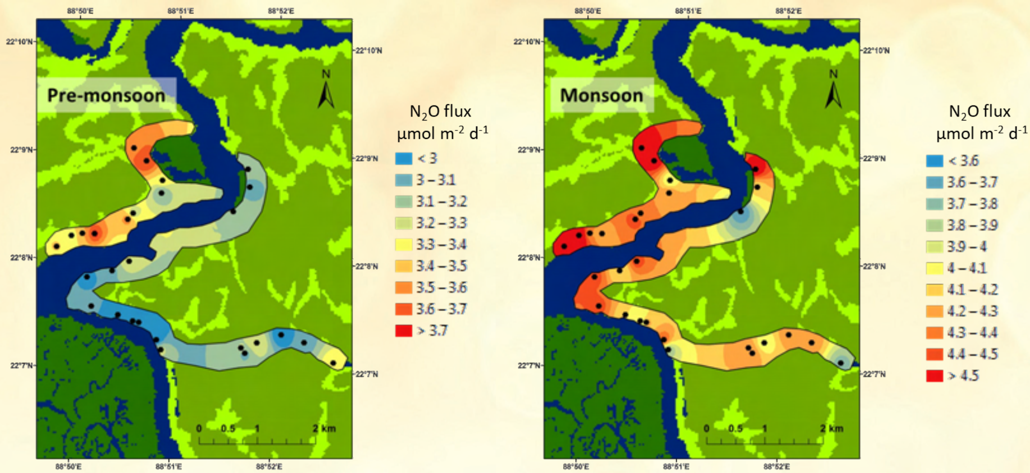

Figure 16: Spatial distribution of nitrous oxide (N_2O) fluxes from ebullition during four seasons (winter, summer, pre-monsoon and monsoon) at the study sites of Sundarban-India.

Conclusion

In the present study we quantified the GHGs (CH_4, CO_2, and N_2O) emissions at three different sites (Sadhupur, Dayapur and Pakhiralaya) of Sundarban-India during four seasons (winter, summer, pre-monsoon, and monsoon) in both mangrove and rice systems. In rice, GHGs fluxes from soil to atmosphere through rice aerenchyma was estimated by using manual close chamber method. Whereas, in mangrove the GHGs fluxes through three modes of transport, such as (i) through the aerenchyma of pneumatophores (ii) diffusion from the soil through ebullition and (iii) GHGs fluxes from air-water interphase were estimated. The CH_4 and CO_2 fluxes through pneumatophore were higher during monsoon, followed by pre-monsoon, summer, and winter, however, higher N_2O fluxes were observed during summer as compared to other seasons. Similar seasonal trend was also found for all the three GHGs in air-water exchange. The methane flux was in the range of 0.058 to 0.278, 0.154 to 0.294, 0.057 to 0.312 and 0.294 to 0.616 mmol m^{-2} d^{-1} during winter, summer, pre-monsoon and monsoon, respectively. Similarly, the CO_2 flux was ranged from 12.41 to 23.38, 24.18 to 56.01, 16.33 to 47.11 and 77.06 to 114.13 mmol m^{-2} d^{-1} during winter, summer, pre-monsoon and monsoon, respectively. Further, the N_2O fluxes was in the range of -14.93 to -38.64, 27.60 to 71.28, 10.82 to 51.58 and

28.32 to 75.52 μmol m^{-2} d^{-1} during winter, summer, pre-monsoon and monsoon, respectively. The GHGs fluxes occurred through the ebullition process were estimated for two seasons i.e., pre-monsoon and monsoon in all three sites. The average CH_4, CO_2 and N_2O fluxes through ebullition were higher in monsoon (0.159 mmol m^{-2} d^{-1}, 22.31 mmol m^{-2} d^{-1} and 4.27 μmol m^{-2} d^{-1}) as compared to pre-monsoon (0.126 mmol m^{-2} d^{-1}, 17.06 mmol m^{-2} d^{-1} and 3.21 μmol m^{-2} d^{-1}), respectively in all the three locations. Apart from this, when comparing both the systems, i.e., mangrove and rice, higher CH_4 and N_2O fluxes were observed in rice as compared to the mangrove system.

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