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Exportation of dissolved (inorganic and organic) and particulate carbon from mangroves and its implication to the carbon budget in the Indian Sundarbans

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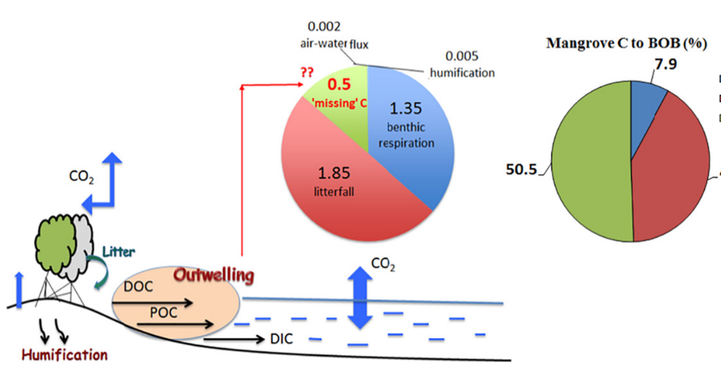
HIGHLIGHTS

- Previous carbon budget of Indian Sundarbans was revisited.
- Riverine and mangrove-derived C export to the BoB were calculated.
- Riverine C export was highest during monsoon with DIC contributed maximum.
- Mangrove-derived C export to the BoB accounted for 7.3 Tg C yr^{-1}.
- Calculation exceeded 'missing C' of 0.5 Tg C yr^{-1} of the previous budget.

GRAPHICAL ABSTRACT



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ABSTRACT

Mangroves are known for exchanging organic and inorganic carbon with estuaries and oceans but studies that have estimated their contribution to the global budget are limited to a few mangrove ecosystems which exclude world's largest the Sundarbans. Here, we worked in the Indian Sundarbans and in the Hooghly river/estuary in May (pre-monsoon) and December (post-monsoon), 2014. Aims were, i) to quantify the riverine export of particulate organic carbon (POC) and dissolved organic and inorganic carbon (DOC, DIC)) of the Hooghly into the Bay of Bengal (BoB), ii) to estimate the C export (DOC, DIC, POC) from the Sundarbans into the BoB by using a simple mixing model, as well as iii) to revise the existing C budget constructed for the mangroves. The riverine exports of POC, DOC and DIC account for 0.07 Tg C yr^{-1}, 0.34 Tg C yr^{-1} and 4.14 Tg C yr^{-1}, respectively, and were largest during the monsoon period. Results revealed that mangrove plant derived organic matter and its subsequent degradation is the primary source of DIC and DOC in the Hooghly estuary whereas POC is linked to soil erosion. Mangroves are identified as a major source of carbon (POC, DOC, DIC) transported from the Sundarbans into the BoB, with export rates of 0.58 Tg C yr^{-1}, 3.03 Tg C yr^{-1}, and 3.69 Tg C yr^{-1} respectively, altogether amounting to 7.3 Tg C yr^{-1}. This C export from the Indian Sundarbans exceeds the 'missing C' of the previous budget, thus necessitating further research to finally resolve the mangrove C budget. However, these first baseline data on C exports from the world's largest deltaic mangrove improves limited global data inventory and signifies the need of acquiring more data from different mangrove settings to reduce uncertainties.

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1. Introduction

Mangroves are highly productive and vital ecological and economical resource, providing varieties of ecosystem services like food and fuel for local inhabitants, nursery grounds for fishes, habitats for mammals and invertebrates (Hogarth, 2007; Nagelkerken et al., 2008), and some protection from waves and currents (Lee et al., 2014). Mangroves are furthermore an important component in the oceanic C cycle (Duarte et al., 2005). Global reports on mangrove C cycling suggest mangrove's potential importance as a C sink having an estimated global primary production of 218 ± 72 Tg C yr^{-1} (Bouillon et al., 2008, Fuentes and Barr, 2015). Above ground and live below ground C stocks in mangroves (956 MgC ha^{-1}) are high compared to salt marshes (593 MgC ha^{-1}), seagrasses (142 MgC ha^{-1}), peatland (408 MgC ha^{-1}) and rain forests (241 MgC ha^{-1}) (Alongi, 2014; Donato et al., 2011; Twilley et al., 1992). Mangroves are also known to export large amounts of particulate and dissolved organic carbon (POC and DOC) into the ocean which is an order of magnitude higher in proportion to their benthic net primary productivity (Kristensen et al., 2008). Alongi (2014) assumed that world mangroves transport 86 Tg C yr^{-1} as dissolved inorganic carbon (DIC) to the adjacent coastal waters, which seemed to be considerably greater than the estimated total export of POC (28 ± 21 Tg C yr^{-1}), DOC (15 ± 13 Tg C yr^{-1}) and the emission of CO_2 from the submerged flood plains within the mangrove ecosystem (42.8 Tg C yr^{-1}). Recently mangroves are recognized to export a substantial amount of exchangeable DOC (EDOC, volatile and semi volatile OC) which corresponds to 60% of the global EDOC flux from the ocean to the atmosphere (Sippo et al., 2017). However, such estimates of mangrove-derived organic and inorganic C are limited to a small number of studies (e.g. Troxler et al., 2015). A large section of mangroves which are not yet studied are nevertheless included in global budgets thus creating and accepting uncertainties due to data upscaling. World's largest mangroves, the Sundarbans, are one of such mangrove systems in the tropics where outwelling of DOC, POC and DIC has so far not been quantified but appear to be very important. In addition, there are some recent and past reports available on the relative distribution and fluxes of inorganic C, suspended sediment and nutrients along the salinity gradient of the Hooghly estuary (Samanta et al., 2015; Mukhopadhyay et al., 2006) but the organic form of carbon (POC, DOC) remains unquantified till date.

Previous results obtained during a three years study (2009–2011) were used to construct a C budget for the Indian Sundarbans mangroves (Ray et al., 2011, 2013). From the total C budget (Supplementary Fig. 1) it could be deduced that a significant amount of net primary production (NPP 2.79 Tg C yr^{-1}) is lost as litterfall (1.85 Tg C yr^{-1}). A mean benthic respiration rate of 1.35 Tg C yr^{-1} implies that 73% of the C supplied as litter is respired and emitted as CO_2 into the atmosphere. Burial in sediments accounts for 0.005 Tg C yr^{-1} whereas the fate of the remaining C (0.45 Tg C yr^{-1}) is unknown and referred to as the "missing C" in the budget. Since CO_2 emissions from estuaries draining the Sundarbans are relatively low (0.002 Tg C yr^{-1}, Biswas et al., 2004), it is assumed that a large part of the litter C is eroded and leached and subsequently exported via rivers as DOC and POC into the Bay of Bengal (BoB). It is further assumed that besides DOC and POC, OC mineralization and the lateral export of DIC from mangrove sediments to the estuarine waters could also contribute to detect the 'missing C' of the budget (e.g. see papers of Ouyang et al., 2017; Leopold et al., 2015, Lovelock et al., 2015; Chen et al., 2012, Maher et al., 2013).

The main objectives of this study are to provide first base line data on: 1) dissolved (DOC and DIC) and particulate (POC) C fluxes via the Hooghly River into the BoB; 2) the outwelling of POC, DOC, and DIC from the mangroves and 3) revision of the existing C budget constructed for the Indian Sundarbans.

2. Materials and methods

2.1. Site description

The Sundarbans, a UNESCO world heritage site and the largest mangrove ecosystem is situated both in India and Bangladesh at the estuarine phase of the River Ganges- Brahamaputra and the Bay of Bengal (see Fig. 1). The Sundarbans cover a forest area of 10,200 km^2 with a region of 4200 km^2 of reserved forest located in India (Ray et al., 2015). Apart from forest, the biosphere of the Indian Sundarbans (9600 km^2) constitutes 19% of the estuarine waterways such as channels, creeks, and rivers. Starting from the west these rivers are the Hooghly, Saptamukhi, Thakuran, Matla and Gosaba, forming an archipelago of 102 islands out of which 54 are impacted by anthropogenic activities and human inhabitation (Ray et al., 2011 and references therein). The tide is semidiurnal with a significant variation in the tidal range from spring tide (5 m) to neap tide (1.5 m or even less) (Mukhopadhyay et al., 2006, Chatterjee et al., 2013). The average value of Richardson number (Ri) is reported to be <0.14 which indicates unstable conditions in the Hooghly-Sundarban estuarine rivers and supports the intensive vertical mixing with longitudinal dispersion coefficients of 784 $m^2 s^{-1}$ (Goutam et al., 2015, Sadhuram et al., 2005). The climate is characterized by the monsoon (June–September), the post-monsoon (October–January) and the pre-monsoon (February–May). The mean annual rain fall is 1973 mm (Ray et al., 2013) and the annual water discharge from the Hooghly estuary is estimated to be 8.3×10^{10} m^3 yr^{-1} (Samanta et al., 2015).

Station 1 is located in a mangrove creek of Lothian Island (Fig. 1) which is situated at confluence of the Saptamukhi estuary and Bay of Bengal and thus in the buffer zone of the Sundarbans Biosphere Reserve (station 1, 21°32′–21°40′N and 88°05′–89°E). Lothian Island (38 km^2) is occupied by thick dominant mangrove species like, *Avicennia alba*, *Avicennia marina* and *Avicennia officinalis* followed by other mangrove species like *Excoecaria agallocha, Ceriops decandra*, *Aegialitis rotundifolia*, etc. The study sites are dominated by sedimentary environment (alluvial) as a result of extensive fluvio-marine deposits of the river Ganges and the Bay of Bengal. Sediments of the Sundarbans mangrove composed mostly of silt (72 to 87%), 6–16% sand, with 8–14% clay (detail refers to Ray et al., 2014). Tectonic settings, the geographic location and species richness made this island an ideal representative of a more or less pristine mangrove forest within the Sundarbans (discussed in Ray et al., 2015).

The stations 2a–e are located along the Hooghly estuary, the main artery of the Sundarbans, and cover a salinity gradient from 0.8 (stn. 2a) to 22.5 (stn. 2e, Table 1). The fresh water discharge in the river is regulated by the Farrakka dam which is located 285 km upstream from the mouth of the estuary (Mukhopadhyay et al., 2006). A map of the sampling locations is shown in Fig. 1.

2.2. Sample collection and analytical methods

Sampling was performed in May (28–30th) and December (28–31st), 2014 at stations 1 and 2. The pre-monsoon and post-monsoon seasons were selected for sampling when uniform salinity profile with relatively minimum terrestrial inputs were recorded in the Hooghly estuary due to low discharge of the Ganges. The difference in salinity between surface and bottom waters along the Hooghly estuarine stretch varied from 0.5 to 2.2 and was almost negligible in the Saptamukhi estuary (Mukhopadhyay et al., 2006). Maximum Litter fall was recorded in December in contrast to its minimum value during the monsoon (Ray et al., 2011), presumably indicating higher mangrove-derived organic C export from the mangroves. While samples along the salinity gradient of the Hooghly (stns 2a–e) were collected using a boat, the creek in the Lothian Island was sampled from an anchored station over a time period of 20 h. At stn.1 sampling was conducted every 2 h during day time and every 3 h during night covering different tidal