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A system dynamic modeling of carbon cycle from mangrove litter to the adjacent Hooghly estuary, India

Joyita Mukherjee[a], Santanu Ray[a,*], Phani Bhusan Ghosh[b]

[a] Ecological Modelling Laboratory, Department of Zoology, Visva-Bharati University, Santiniketan 731 235, India
[b] Institute of Engineering and Management, Y-12, Sector – V, Salt Lake City, Kolkata 700 091, India

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ABSTRACT

Hooghly-Matla estuarine system receives a major load of carbon from adjacent mangrove forest in the form of litterfall throughout the year. Keeping in view, the crucial role of carbon, a seven compartment model has been proposed to study the dynamics of carbon in this estuarine system. Different forms of carbon present in soil (as soil organic carbon (SOC), soil inorganic carbon (SIC)) and in water (as dissolved inorganic carbon (DIC), dissolved carbon dioxide (DCO_2), dissolved bicarbonate (DBC), dissolved organic carbon (DOC) and particulate organic carbon (POC)) are taken as state variables. Litter biomass, dissolved oxygen, primary productivity, community respiration, temperature of water, pH of water and soil, air–water exchange of carbon dioxide and conversion rates among different forms of carbon are considered as graph time functions. The data used in the present model are collected for over two years from our own field works and experiments. Other sensitive rate parameters which are not possible to collect from survey or experiment, calibrated following standard procedure. Sensitivity analysis is performed along with calibration. Model simulation results are validated with observed data. Results show seasonal variations of litterfall and which is the main source of SOC pool and ultimately transported to the estuary. Other than litterfall, the death of organisms in soil and water enriches the SOC and POC respectively. pH of water is governing factor and depending on this factor, DIC is converted to DCO_2 and DBC, which are taken up by phytoplankton during photosynthesis. Mineralization rate of SOC to SIC and uptake rate of DCO_2 and DBC are the sensitive parameters.

1. Introduction

Mangroves export organic carbon to the adjacent aquatic environment either as leaf litter, particulate or dissolved organic matter. Estuaries are of interest because the most sensitive land–water–atmosphere interactions are pronounced at these regions which are the hosts of major biogeochemical cycles, influence not only the regional ecosystems but also are relevant to global climate system (Zweifel et al., 1995; Wetzel, 2001; He et al., 2010).

Tracking of carbon fluxes and pathways in urban system is also important in regulating anthropogenic carbon emission which is related to global warming. Following NEA based methodology, Chen and Chen (2012) showed that carbon throughflows of an urban system has a pyramidal shaped ecological structure of carbon metabolism.

Cycling of carbon and nutrients in forest ecosystems is dominated by litter decomposition process, which has more influence on litter dynamics and nutrient cycling (Twilley, 1985; Aerts, 2006; Shiels, 2006). Detrital export from mangrove forests is a source of nutrients and energy to nearby estuary and the energetic links between these two systems are intermingled to this detrital export (Alongi, 1990; Fleming et al., 1990; Gong and Ong, 1990; Hemminga et al., 1994; Cifuentes et al., 1996; Twilley et al., 1997; Wafar et al., 1997). Mangrove ecosystems may function as storage of large amounts of organic carbon and important autochthonous carbon sources (Twilley et al., 1992; Lallier-Verges et al., 1998; Matsui, 1998; Fujimoto et al., 1999; Kristensen et al., 2008).

Particulate and dissolved organic matter (POM and DOM) from mangrove wetlands to the estuary can be an important source of energy and nutrition to heterotrophic communities of surrounding estuarine and marine ecosystems and has a pivotal role in the global carbon cycle (Odum and Heald, 1975; Hedges, 1992; Smith and Hollibaugh, 1993). Previous works reveal the immense role of DOC as one of the major components of the food webs (Packard et al., 2000), as a main source of energy for microbial metabolism (Tranvik, 1992), major component of photosynthetic release (Ducklow and Carlson, 1992). Concentration of DOC varies along with magnitude and proportion of autochthonous and allochthonous sources, temperature, depth, seasons (Mantoura and Woodward, 1983; Guo et al., 1995; Zweifel et al., 1995; Ribes

* Corresponding author. Tel.: +91 3463 261 268; fax: +91 3463 261 268/262 672.
E-mail address: sray@visva-bharati.ac.in (S. Ray).

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et al., 1999; Wetzel, 2001; Dafner and Wangersky, 2002; Sugiyama et al., 2004). Fasham et al. (1990) built a model with single compartment for DOM which was simplistic; later DOM has been described as number of separate pools in different models (Billen, 1991; Billen and Becquevort, 1991; Lancelot et al., 1991). Connolly et al. (1992) described carbon utilization of bacteria in natural waters using a model with two separate dynamic DOM pools. Anderson and Williams (1998) constructed a ten compartment detailed model describing the dynamics of DOC and DON by varying C/N ratio. Xinling et al. (2006) proposed a simple coupled pelagic-benthic ecosystem multi-box model. Anderson and Pondaven (2003) used a one dimensional coupled physical biological model to examine the imbalance in the stoichiometry of C and N cycling and dynamics. Anderson and Williams (1999) further used a one-dimensional model by incorporating (DOC) to study the vertical distribution and the downward flux of organic carbon into the water column in the ocean.

Estuaries are generally considered to be net heterotrophic systems and often act as sources of CO_2 to the Earth's atmosphere (Smith and Hollibaugh, 1993; Frankignoulle et al., 1998). Hooghly estuary is also a heterotrophic system (De et al., 1994; Biswas et al., 2004; Mukhopadhyay et al., 2002a,b). Only few recent studies involving different biogeochemical aspects of this region have been done in this estuarine region. Seasonal variation in the fugacity of CO_2 and its nature of exchange at the air water interface and diurnal and seasonal variation in the mixing ratios of CH_4 and CO_2 in different micrometeorological conditions has been first reported by Mukhopadhyay et al. (2002a,b). Biswas et al. (2004) investigated the driving forces behind the CO_2 exchange from the Sundarban mangrove water. Mukhopadhyay et al. (2006) first examined the annual mass balance for nutrients C, N, P, and Si in the Gangetic delta. Amount of available radiant energy to drive biosphere–atmosphere exchange of CO_2, H_2O, CH_4 and transfer into other energy forms were determined at the land ocean boundary of north east coast of Bay of Bengal by Ganguly et al. (2008). A modeling study has been done by Mandal et al. (2009) to show the nitrogen dynamics in Hooghly-Matla estuarine region.

With the help of the knowledge and information from previous works, own field surveys and experimental works, a seven compartment dynamic model is constructed. The objective of present modeling study is to (1) evaluate and quantify the relationship between the different forms of carbon, (2) their dynamics throughout the seasons, (3) the roles of biological and abiotic factors regarding this process and (4) to recognize the sensitive and key factors for the transformation of different carbons and their dynamics in this estuarine system.

2. Materials and methods

2.1. Study site

Ganges is the largest major river in the India and its first deltaic off shoot is known as Hooghly estuary (21°31′–23°20′N and 87°45′–88°45′E). The Indian Sundarban Mangrove forest (21°32′ and 22°140′N:88°05′ and 89°E) comprises of 9630 km^2; out of which 4264 km^2 is under reserved forest in the estuarine phase of the river Ganges. This estuary has marked its position on the global map due to its unique bioclimatic nature in land ocean boundaries of Bay of Bengal along with the magnificent mangrove. Several numbers of discrete islands constitute Sundarbans. Largest Island in the row, Sagar Island covering an area of about 144.9 km^2 in area, and is surrounded by the River Hooghly on the north and northwest and the River Mooriganga on the east. The island bears a dense network of rivers, canals and creeks. The meso-macrotidal Hooghly estuary has a wide mixing zone extending

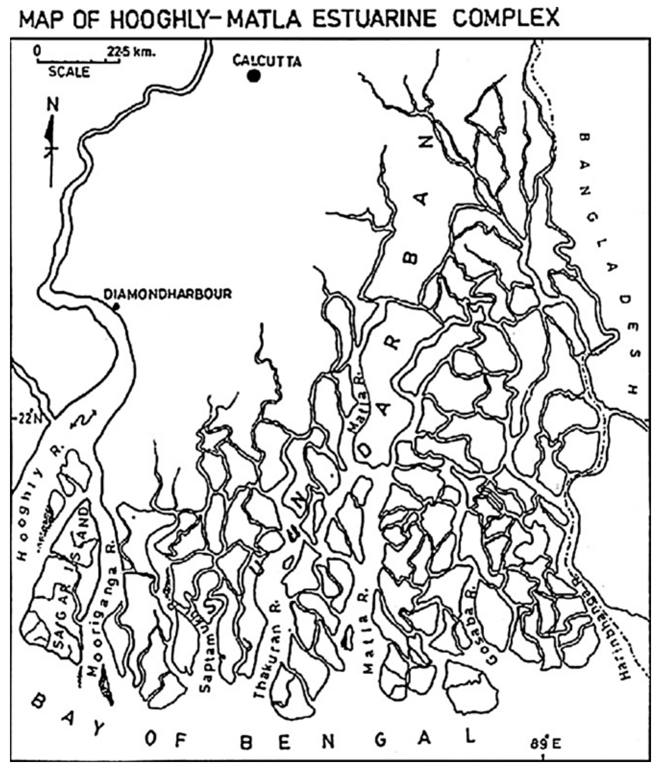

Fig. 1. Study site along with Hooghly-Matla estuarine complex.

from Diamond Harbor to the mouth of the river (Biswas et al., 2010). Sagar Island, located in the western sector of the estuary, is the largest deltaic island in this estuarine complex, lying between 21°56′–21°88′N and 88°08′–88°16′E (Fig. 1). Human activities as well as changes in land use through reclamation for agriculture and aquaculture have altered natural mangrove vegetation cover of this island. This region is in the wet tropical climatic zone with pronounced seasonal climatic changes. The seasons are characterized as premonsoon (March–June) with average high temperature ranging from 25 to 42 °C and minimum precipitation; monsoon (July–October), when 70–80% of annual rainfall occurs, and post-monsoon (November–February), with cold weather (average 25 °C) and negligible rainfall. The monsoon season is generally dominated by southwest winds. *Avicennia marina* is the dominant species among the halophytes of Sagar island. *Avicenna alba*, *Porteresia coarctata*, *Exoecaria agallocha*, *Ceriops decandra*, *Acanthus ilicifolius* and *Derris trifoliate* are also present (Saha and Choudhury, 1995).

2.2. Sampling and experiment

Samples are collected from the mangrove forest floor and the creeks of the of Sagar island. Several experimental and survey works are done over two years in the field to collect data for dissolved and particulate organic carbon (DOC, POC), water temperature, water pH, dissolved oxygen (DO), dissolved carbon dioxide (CO_2(aq)), soil organic carbon (SOC), soil temperature, salinity, etc.

Soil samples are collected from the field stations at a depth of ~8–10 in. (~20–25 cm) in the mangrove forest floor, where tidal flow is encountered at monthly intervals. Soil temperature is measured in the field using a digital thermometer (EUROLAB-ST 9269). Soil samples are further analyzed by measuring organic and inorganic carbon content following standard methods (Greenberg et al., 1992). From a saturated soil–water paste pH is measured monthly (Gupta, 2002). Soil salinity is derived from soil water extracts following the method of Gupta (2002), and calculated by the formula: