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Can seaweed be a potential sink of carbon?

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Abstract: We estimated stored carbon in three dominant seaweed species Enteromorpha intestinalis, Ulva lactuca and Catenella repens in three different seasons (premonsoon, monsoon and postmonsoon) from four sampling stations in the deltaic ecosystem of Indian Sundarbans (21°40' N to 22°40'N and 88°03'E to 89°07'E) during 2015. The average stored carbon content varied from 921.05 g m^{-2} (during monsoon) to 1163.02 g m^{-2} (during premonsoon) in E. intestinalis. In U. lactuca, the stored carbon ranged from 26.10 g m^{-2} (during postmonsoon) to 250.50 g m^{-2} (during premonsoon). In case of C. repens, the range of stored carbon is 9.11 g m^{-2} (during postmonsoon) to 76.89 g m^{-2} (during premonsoon). Amongst selected seaweed species, E. intestinalis showed uniformity in biomass between sectors ($p_{cal} = 1.59 < p_{crit} = 18.51$) and seasons ($p_{cal} = 2.03 < p_{crit} = 4.14$), which implies tolerance of the species to variable salinity and also potential of the species in the vertical of carbon sequestration.
Keywords: Seaweeds, stored carbon, seasonal variation, Indian Sundarbans

I. INTRODUCTION

Seaweeds or benthic macroalgae, being important members in the blue carbon domain, are thallophytes containing photosynthetic pigments that live either in marine or brackish water environs. Like their terrestrial counterpart, the seaweeds can prepare their own food with the help of sunlight and nutrient present in the seawater. They occupy the intertidal zones between high tide to low tide and up to a depth where 0.01 % photosynthetic light is available.

The primary productivity potential of seaweeds is quite high. Entrapment efficiencies of solar energy have been reported to be maximum in *E. intestinalis* (0.64%) and *U. lactuca* (0.43%) with an average of 0.35% by this group. A research conducted on this topic indicates that in the deltaic complex of Indian Sundarbans, *E. intestinalis* and *U. lactuca* are the most productive species, followed by *E. prolifera* and *Rhizoclonium* grande [4].

Unlike other blue carbon sectors (mangroves, seagrasses, and salt marshes), kelp forests and seaweed beds do not have such sedimentary substrata. Instead, their carbon-rich biomass detaches and is broken down in food chains by organisms that range in scale from grazing animals to pelagic and seabed bacteria. Knowledge on the scale of conversion of inorganic carbon into biomass, its subsequent sinking to the seabed and its sequestration over thousands of years form the basis of understanding the oceans as a potential sink for increasing levels of atmospheric carbon dioxide (CO_2). The other modes of fate of seaweed biomass depend on natural processes. The seaweed can be consumed by herbivores, whose faeces sink to the bottom and may remain there for a while. Moreover, distal portions of the fronds disintegrate during the summer season and those fragments enter the detritus food chain [6].Exudation as a dissolved organic material can be a critical loss. Therefore, some of the seaweed carbon will return to the water column and be either recaptured during photosynthesis or eventually returned to the atmosphere. However, a significant fraction of the algal carbon can be sequestered on the sea floor for a long period, perhaps centuries depending on location, currents etc.[18].

Compared to other vegetation, the carbon sequestration potential of seaweeds in estuarine and deltaic environments, are however poorly understood. In this paper, the seasonal and spatial variations in biomass production and carbon content of three major species of seaweeds as shown in Fig. 1A, 1B and 1C inhabiting two different sectors of Indian Sundarbans (western and central) with contrasting salinity have been estimated.

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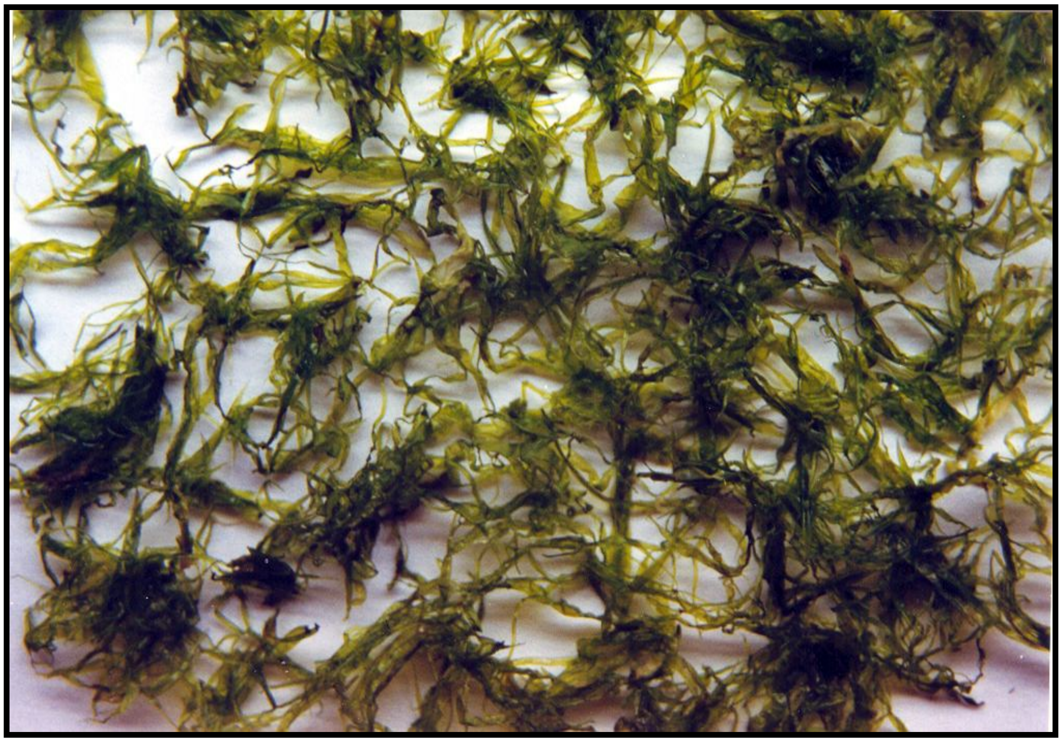

Fig. 1A. Enteromorpha intestin**a**lis: common seaweed in Indian Sundarbans with a wide tolerance range of salinity

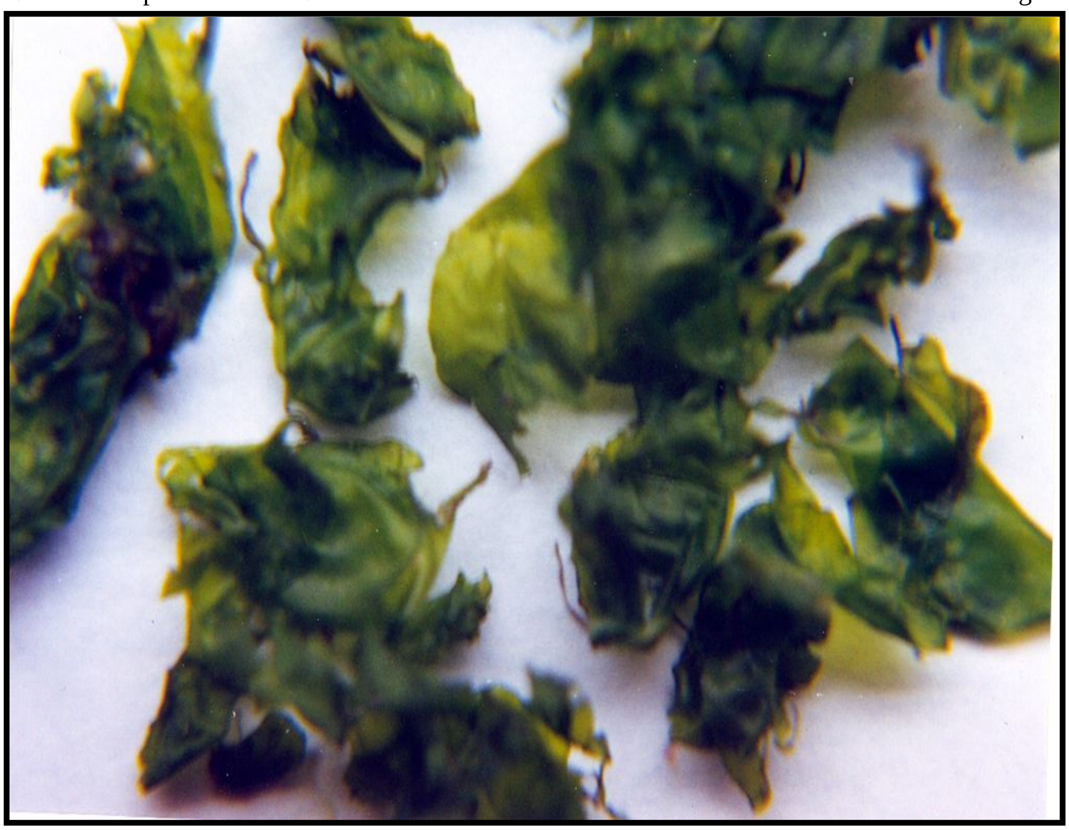

Fig. 1B. Ulva lactuca: common seaweed in Indian Sundarbans usually found in moderate and high saline zone

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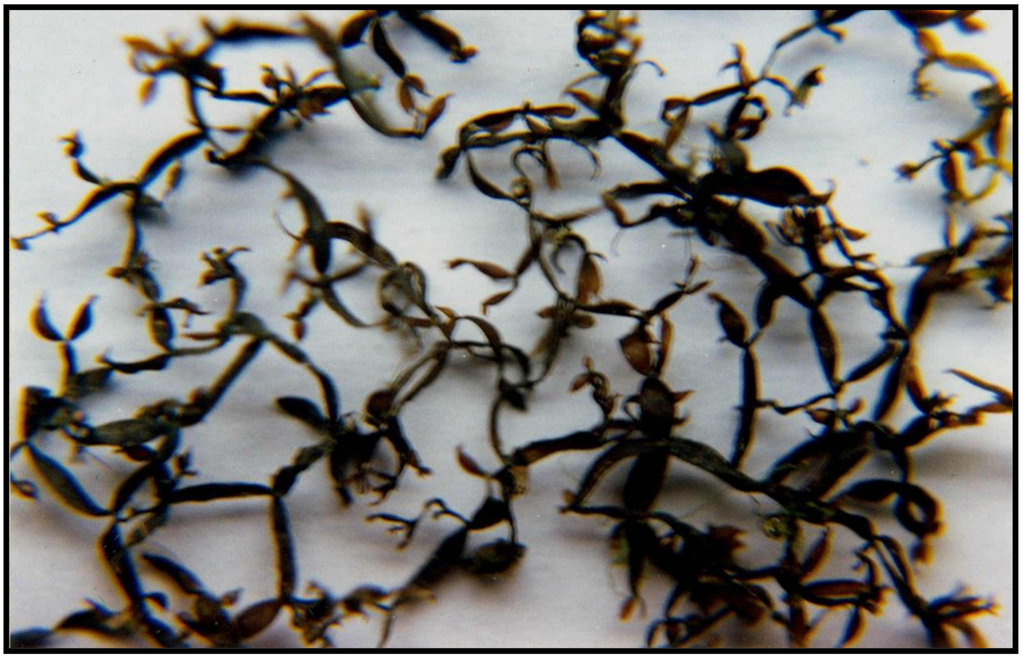

Fig. 1C. Catenella repens: common seaweed in Indian Sundarbans usually found in high saline zone

II. MATERIALS AND METHODS

A. Sampling Site

The Indian Sundarbans and its adjacent region is a mangrove dominated deltaic complex situated at the confluence of the River Ganga and the Bay of Bengal. Two sampling sectors were selected each in and around the western and central sectors in the study region (Fig. 2). The western sector of the deltaic lobe receives the snowmelt water of mighty Himalayan glaciers after being regulated through several barrages on the way. The central sector on the other hand, is fully deprived from such supply due to heavy siltation and clogging of the Bidyadhari channel in the late 15th century. Contrasting salinity thus exists in the deltaic complex that has made the region a unique test bed to observe the impact of salinity on biotic community. With this background, four sampling stations (two each in western and central sectors) were selected (Table 1 and Fig. 2) to analyze the data of stored carbon in the common seaweed species.

Table 1: Sampling stations with coordinates and salient features

Station	Coordinates	Salient Features
Nayachar Island (Stn. 1)	21° 45′ 24" N; 88° 15′ 24" E	It is located in the Hooghly estuary and faces the Haldia Port-cum-industrial complex that houses a variety of industrial units. The region also receives the industrial wastes from the upstream region. (Fig. 3)
Sagar South (Stn. 2)	21° 39′ 04" N; 88° 01′ 47" E	Situated at the confluence of the River Hooghly and the Bay of Bengal on the western sector of Indian Sundarbans.
Gosaba (Stn. 3)	22° 15′ 45" N; 88° 39′ 46" E	Located in the Matla Riverine stretch in the central sector of Indian Sundarbans.
Annpur in Satjelia Island (Stn. 4)	22° 11′ 52" N; 88° 50′ 43" E	Located in the central sector of Indian Sundarbans. Noted for its wilderness and mangrove diversity

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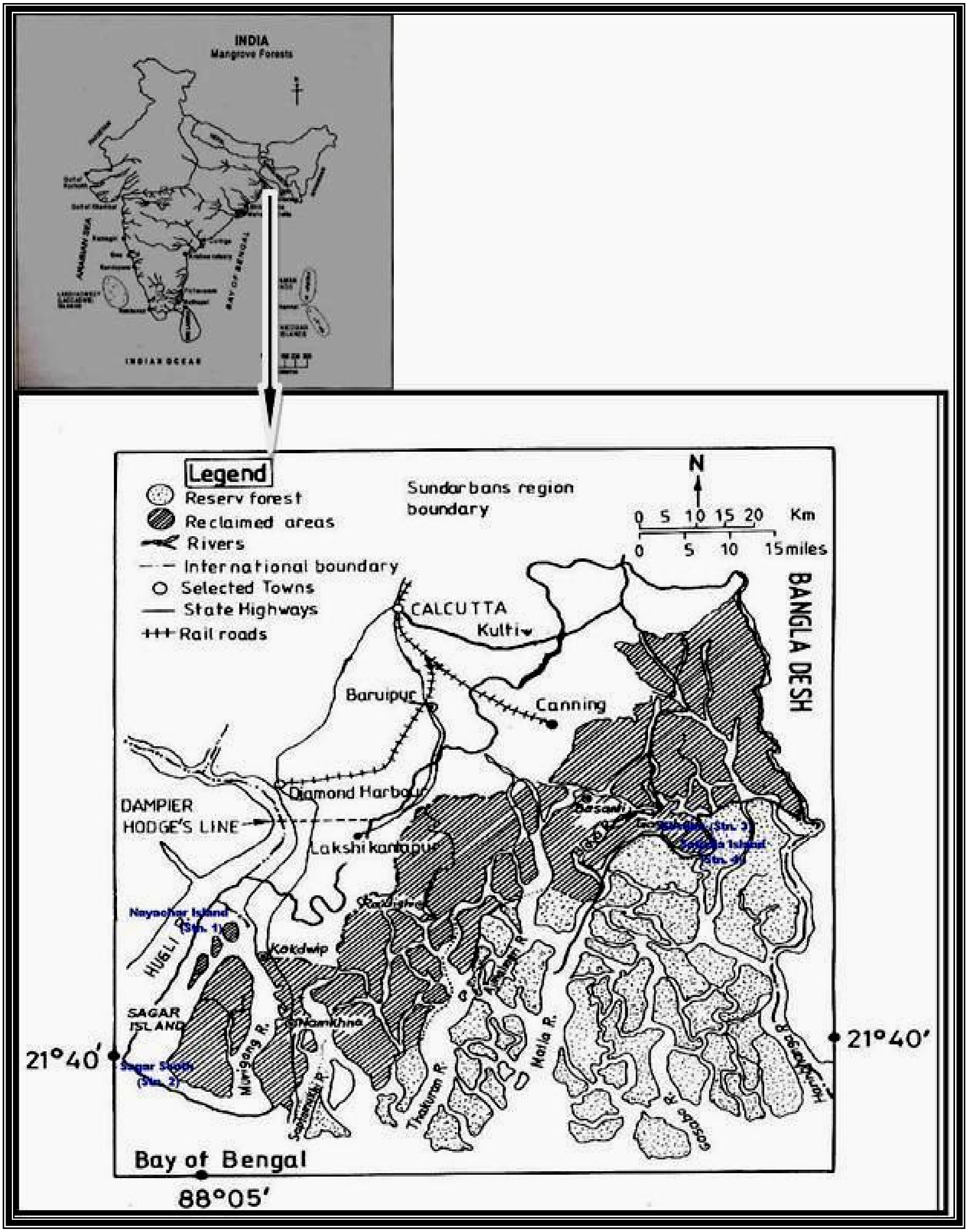

Fig. 2. Location of sampling stations (marked in blue) in and around Indian Sundarbans. Stns. 1 and 2 are in the western sector and Stns. 3 and 4 are in the central sector of the study area.

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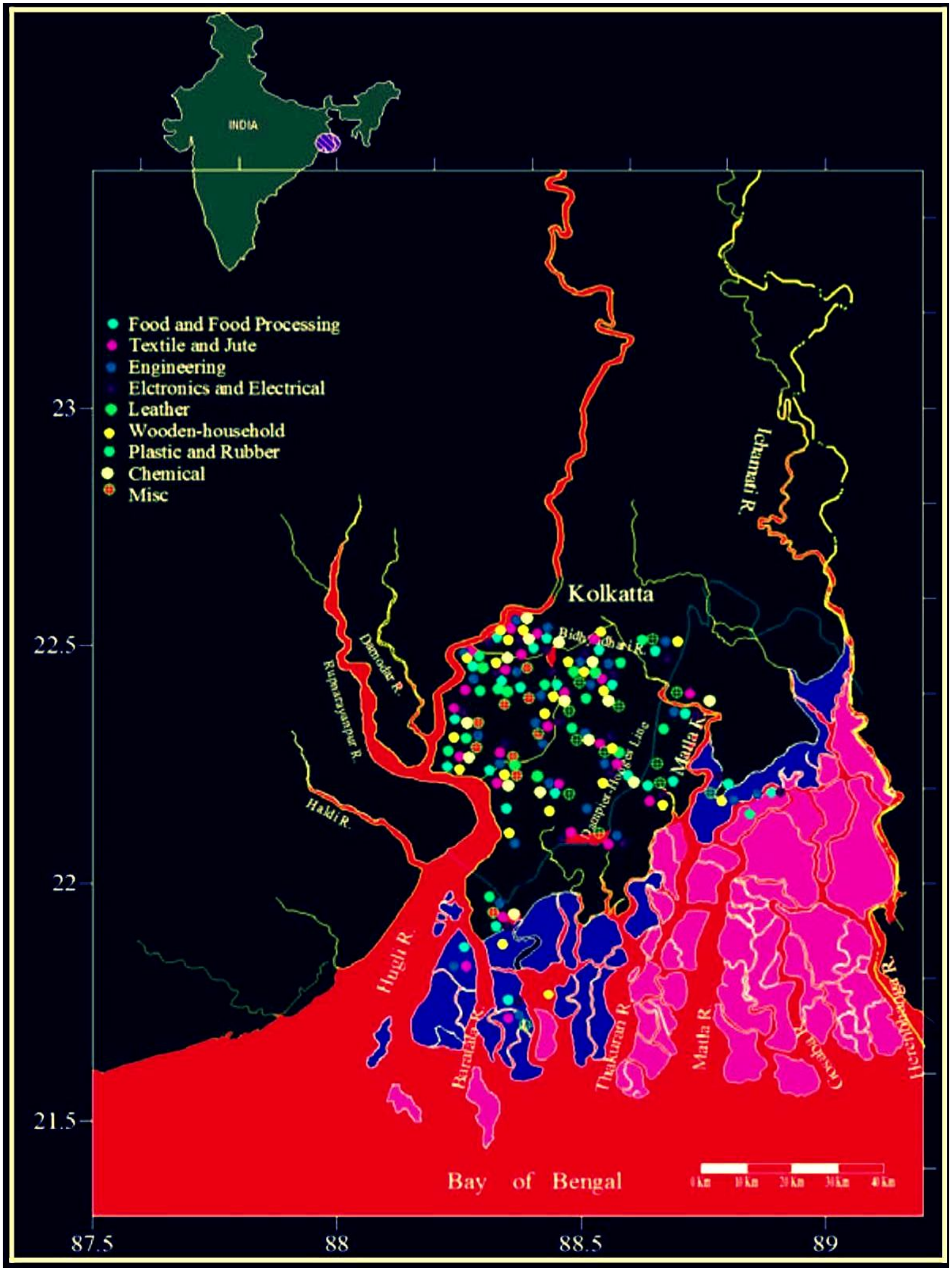

Fig.3. Industrial zone in the upstream region of the study area

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B. Sampling

Seasonal samplings for biomass and carbon estimation of seaweed species (*E. intestinalis, U. lactuca and C. repens*) were carried out at ebb tides during May, 2015 (premonsoon), September, 2015 (monsoon) and November, 2015 (postmonsoon) from the intertidal mudflats. Samples of seaweed species were scrapped and handpicked from sluice gates, mangrove trunk and concrete jetties. Immediately after collection, the thallus of each species was thoroughly washed separately in the ambient seawater, as well as with double distilled water, to remove adhering debris and sediments. Altogether 10 quadrants (area, 1 m^2) were sampled for each species randomly mixed and weighed accurately in an electronic balance (IRD Balance; Model No. 290). The mean biomass is expressed in g m^{-2}.

C. Carbon Estimation

Seaweed samples were dried in a hot air oven (60ºC) for 72 hrs until a constant weight was obtained. Dried sampled were ground to a fine powder. Direct estimation of percent carbon in the thallus body of each seaweed species for each season and for each sampled locations was separately carried out by Vario MACRO elementar make CHN analyzer, after grinding and random mixing the oven dried seaweed samples. This method is followed for estimating carbon percentage in coastal vegetation [12] [17]. At about 990°C, the seaweed sample was mineralized. Formation of carbon monoxide is possible at this temperature even in the presence of excess oxygen. The complete oxidation is reached through a tungsten trioxide catalyst which is passed by the gaseous reaction products. The samples were finally analyzed through CHN mode, which is the most universal of the analysis modes because of the combination of the reagent design and the optimize combustion control parameters and expressed in percentage [8].

D. Statistical Analysis

Sector-wise and station-wise data on biomass and carbon content during different seasons in three seaweed species of Indian Sundarbans were subject to statistical analyses. Analysis of variance (ANOVA) as expressed by Wellman (1998) [20], was used to evaluate whether biomass and carbon content varied significantly between (i) the two sectors (ii) selected stations and (iii) seasons. Possibilities less than 1% level ($p < 0.01$) were considered statistically significant. All statistical calculations were performed with Statistical Package for Social Sciences (SPSS) 14.0 for Windows.

III. RESULT

A. Enteromorpha intestinalis

The biomass of *E. intestinalis* ranged from 2860.11 gm m^{-2} (at Stn. 3, during May 2015) to 3172.14 gm m^{-2} (at Stn. 1, during December 2015). The carbon content exhibited lowest value at Stn. 3 (921.05 gm m^{-2} during September 2015) and highest at Stn. 2 (1163.02 gm m^{-2} during May 2015). ANOVA reveals uniformity in the standing stock/biomass and carbon content (Table 2 and 3) of the species with no statistically significant spatio-temporal variations. The highest carbon content in premonsoon may be attributed to congenial temperature and solar radiation in the study area that have profound influence on the photosynthetic rate.

B. Ulva lactuca

The biomass ranged from 96.12 gm m^{-2} (at Stn. 1, during September 2015) to 789.91 gm m^{-2} (at Stn. 2, during May 2015). The carbon content showed the lowest value at Stn. 1 during September 2015 (26.10 gm m^{-2}) and highest at Stn. 2 during May 2015 (250.50 gm m^{-2}). ANOVA results exhibit pronounced seasonal and spatial variations of biomass and carbon content ($p < 0.01$) (Table 2 and 3) of the species. The highest values of biomass and stored carbon in *U. lactuca* during premonsoon are again the result of synergistic effects of temperature, solar radiation and salinity.

C. Catenella repens

The biomass of *C. repens* collected from the selected stations ranged from 44.55 gm m^{-2} (at Stn. 1, during December 2015) to 315.90 gm m^{-2} (at Stn. 2, during May 2015). In the thallus body of the species, the values of stored carbon ranged from 9.11 gm m^{-2} (at Stn.1, during December 2015) to 76.89gm m^{-2} (at Stn. 2, during May 2015). ANOVA results also confirm significant spatial and seasonal variations in the carbon content of the species ($p < 0.01$) (Table 3).

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Table 2**:** Results of ANOVA for seaweed standing stock in and around Indian Sundarbans during (premonsoon, monsoon and postmonsoon seasons of 2015)

Variable	Fcal	Fcrit
Enteromorpha intestinalis		
Between sectors	1.59	18.51
Between stations	1.77	4.76
Between seasons	2.03	4.14
Ulva lactuca		
Between sectors	19.12	18.51
Between stations	31.73	4.76
Between seasons	10.32	4.14
Catenella repens		
Between sectors	27.38	18.51
Between stations	6.89	4.76
Between seasons	14.70	4.14

Table 3**:** ANOVA for carbon content in seaweeds in unit area in and around Indian Sundarbans during 2015 (premonsoon, monsoon and postmonsoon seasons)

Variable	F_{cal}	F_{crit}
Enteromorpha intestinalis		
Between sectors	5.15	18.51
Between stations	3.31	4.76
Between seasons	4.04	4.14
Ulva lactuca		
Between sectors	20.84	18.51
Between stations	5.54	4.76
Between seasons	10.34	4.14
Catenella repens		
Between sectors	25.38	18.51
Between stations	5.86	4.76
Between seasons	13.23	4.14

IV. DISCUSSION

The recent thrust on global warming phenomenon has generated tremendous interest in the carbon-storing ability of coastal vegetation. Carbon fixation by seaweeds forms an important bio-mechanism to diminish the increment of CO_2 in the atmosphere and thereby alleviate the trend toward global warming. Primary producers of coastal and marine biotopes such as microalgae, seaweed and seagrass are excellent carbon sequestering agents than their terrestrial counterparts [21]. The carbon stored in the marine and estuarine floral species is referred to as blue carbon and a number of literatures have addressed the importance of the community to climate change [7] [16] [5]. Several researches have been initiated on the carbon fixation capacity of seaweeds for the purpose of developing blue carbon register. One of the important problems in the sphere of blue carbon is the turnover time of the marine plants. According to Smith (1981), [19] most of the terrestrial plants have a relatively high biomass and have a turnover time of several years to decades. On contrary, the turnover time of marine seaweeds is about one year [15], although they have highest biomass among the marine ecosystems. This means that the seaweeds are more effective carbon sinks than phytoplankton, but less effective than the terrestrial ecosystem. The carbon sequestration in this unique producer community is a function of biomass production capacity, which in turn depends upon interaction between edaphic, climate, and topographic factors of an area [12] [9]. Hence, results obtained at one region may not be applicable to another. Therefore region-based potential of storing and sequestering carbon by coastal vegetation on different land types or substratum characteristics needs to be estimated [12].The seaweed carbon is acquired through photosynthetic and non-photosynthetic processes. Carbon assimilation in marine algae is largely accomplished by light dependent photosynthesis. However, there are active and significant light-independent carboxylation pathways operating as well [3] [2], indicated that photosynthetic and non-photosynthtic carboxylation pathways are regulated, atleast partially, by the activity of Ribulose 1, 5 bis-phosphate carboxylase oxygenase (RuBisCO) and phosphoenolpyruvate carboxylase (PEPCK). Furthermore, differences between the *in vivo* and *in vitro* carboxylation in the thallus of *Laminaria setchellii* suggest structural, biochemical and functional differences that impact the dynamics of production of kelp species. Photosynthetic and light-independent carbon fixation (LICF) processes in marine algae have been shown to vary as a function of seasonal changes in irradiance and temperature, and carbohydrate levels in the tissue [1]. The seasonal variation of carbon content in seaweeds is attributed to variation in their biomass. The quantity of algal biomass that accumulates is normally stated as the amount of carbon fixed by photosynthesis per unit area of space or volume, per unit of time. Most estimates are expressed as net primary production, taking into account the costs of respiration [6].

The present study indicates that carbon storage in seaweed species is species-specific in nature. The highest value is observed in *E. intestinalis* followed by *U. lactuca* and *C. repens*. Similar observation was also documented through a study done by Muraoka (2004) [15] where the carbon absorption capacity by seaweeds varied as per the order *Laminaria* > *Ecklonia* > *Sargassum* > *Gelidium*. The species-wise variation of stored carbon may be attributed to the morphological structure of the seaweed. Unlike *U. lactuca* and *C. repens*, the extremely coiled and spiral structure of *E. intestinalis* exposes more area of the species to ambient water, which enables relatively more capture of carbon through diffusion. Due to presence of high surface area per unit volume of the *E. intestinalis* thallus, the absorption of carbon dioxide from the ambient water is more compared to *U. lactuca* and *C. repens*.

In the present study area, *C. repens* is common seaweed under rhodophyceae, which is characterized by reddish phycobilin pigments - phycoerythrin and phycocyanin- that mask the color of the chlorophylls (the major photosynthetic machinery that synthesize organic carbon through photosynthesis). This masking effect may be one of the reasons for lowest carbon content in *C. repens*.

Some interesting observations were documented with respect to biomass and stored carbon in the selected seaweeds species. These observations also point towards the tolerance of the species to ambient environment which is an important criterion for being a potential store house of carbon. In case of *E. intestinalis*, the ANOVA reflects no significant differences in biomass between sectors, stations and seasons which show a wide range of tolerance of this species to salinity (Table 2). It has also been documented that *E. intestinalis* can thrive luxuriantly even in freshwater [11] *U. lactuca* exhibits a different picture with statistically significant difference between sectors, stations and seasons. In case of *C. repens,* similar trend (as seen in *U. lactuca*) was documented.

A comparative study of biomass between three seaweeds species points out that *E. intestinalis* is one of the most potential species for carbon sequestration because of its uniform growth and biomass in different salinity regimes and seasons. Indian Sundarban is characterized with dynamic seasonal salinity profile with high value during premonsoon followed by monsoon and postmonsoon seasons. The spatial variation of salinity is also a unique feature of Indian Sundarbans [17] [13] [14]. In some areas of deltaic complex (particularly at station 1), the pre-monsoon salinity of ~ 10 psu drops down to 0 psu during monsoon [13] *E. intestinalis* can withstand such a drastic oscillation of salinity, and hence can be a potential store house of carbon throughout the year. Except few experimental studies that observed the rate of absorption of CO_2, studies on seaweed carbon are scanty; particularly no baseline data is available on the carbon content in seaweed species collected from different salinity profile for comparative purposes. An experimental study conducted by Kaladharan et al (2009) [10], revealed that the green seaweed *U. lactuca* can register 100 % utilization of CO_2 towards carbon fixation from ambient water and beyond 15 mg/l there is a decline of 16%. The researchers also estimated that the seaweed biomass along the Indian coast is capable of utilizing 9052 t $CO_2 d^{-1}$ against emission of 365 t CO_2 d^{-1} indicating a net carbon credit of 8687 t d^{-1}. The present study is thus a baseline representation of carbon content in the dominant seaweed species of lower Gangetic delta region.

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