

Blue Carbon Ecosystems and Their Role in Climate Change Mitigation—An Overview

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Abstract: Blue carbon ecosystems include mangroves and other tidal wetlands such as seagrasses and salt marshes. Coastal blue carbon is thought to provide climate change mitigation benefits in view of their ability to store carbon under adverse conditions and this in the recent times has garnered the attention of the scientific community at large. Mangroves are one of the most productive ecosystems and their carbon storage potential is much greater as compared to sea grasses and salt marshes. Mangroves sequester carbon in their living biomass as well as the sediments. The tropical Asian mangroves show the greatest mangrove diversity and the highest biomass accumulation. But, the carbon storage potential of their living biomass is outcompeted by their sedimentary carbon storage. Mangrove sediments play a special and quantitatively important role in carbon storage than previously thought. They store both autochthonous and allochthonous organic matter due to their strategic location at the interface between land and sea and prevailing reducing conditions.

Indian mangrove ecosystems which also comprises one of the largest mangrove forest of the world may offer a possible opportunity for the development of blue carbon market economy. But there exist a large number of gaps in the available blue carbon literature. The available studies largely focus on the living biomass storage and sedimentary storage is un-surveyed. Mangrove research in India have shown significant growth in the past few decades but the targeted approach towards delineating the ecosystems' carbon stocks and the factors controlling them are still lacking. The need of the hour is to correctly map and document the mangroves in India for their carbon storage in order to build a better and reliable picture of the role of these ecosystems in climate change mitigation.

Keywords: Blue carbon, Mangroves, Climate change, Sediments, Coastal ecosystems.

Introduction

Blue carbon is a recent conception and is a shorthand for the carbon used and sequestered by the coastal habitats in the form of their biomass and in the organic-rich sediments (Nellemann et al., 2009; Gordon et al., 2011; Pendleton et al., 2012). Blue carbon ecosystems include mangroves, seagrasses, salt marsh, and other tidal wetlands. Coastal blue carbon is thought to provide climate change mitigation benefits by their extraordinary carbon sequestration capacity under adverse conditions like prolonged waterlogging, anaerobic environment,

harsh intertidal current, strong winds, and high salinity. When compared to the terrestrial forests, the coastal wetlands are found to have a considerably larger contribution to the carbon sequestration and its long-standing storage (McLeod et al., 2011; Fourqurean et al., 2012). Thus, there has been growing concern for their improved management through conservation and restoration of biogeochemical processes owing to the newly recognised ecosystem service.

The Blue carbon ecosystems cover approximately 490,000 km² of earth's surface (Pendleton et al., 2012). Mangroves are only limited to the coastlines of the

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tropical and sub-tropical regions, whereas seagrasses and tidal marshes can be found in abundance in coastal environment around the globe. These coastal ecosystems represent less than 5% of the earth's total surface but play a significant role in regulating the global carbon cycle (Twilley et al., 1992). Collectively, these ecosystems store around 3418.5 metric tons of carbon dioxide equivalent per hectare ($t\ CO_2e/ha$) in their biomass and as sedimentary carbon. In most of these ecosystems, the sedimentary carbon storage has been found to be building up continuously since centuries at a rate much higher than the rate observed in terrestrial forests, and this carbon may remain sequestered for millennia (McLeod et al., 2011; Pendleton et al., 2012). Table 1 shows the mean carbon burial rates for the different blue carbon ecosystems and the terrestrial forests along with their global spread.

Table 1: The carbon burial rates and their global area for different blue carbon and terrestrial ecosystems

<i>Habitat type</i>	<i>Carbon burial rate (g C/m²/yr)</i>	<i>Global area (km²)</i>
Mangroves	226 ± 39	137,760 – 1,52,361
Seagrass	138 ± 38	177,000 – 6,00,000
Tidal marshes	218 ± 24	22,000 – 4,00,000
Temperate	5.1 ± 1.0	1,04,00,000
Tropical	4.0 ± 0.5	1,96,22,846
Boreal	4.6 ± 2.1	1,37,00,000

Data from McLeod et al., 2011 and references therein.

Besides the high carbon storage capacity, these coastal ecosystems provide variety of other functions. Acting as a protection against the natural hazards, recreational benefits, food, fuel, energy, and other cultural values are some of them (Lau, 2012; Beaudoin and Pendleton, 2012). These ecosystems have a large reserve of natural capital, with high productivity and provide a diverse set of habitats, species, and ecological services (Fisher et al., 2009). Despite the vast ecosystem benefits and socio-economic importance, these ecosystems are seriously threatened. The coastal ecosystems worldwide are among the most heavily used and highly vulnerable ecosystems (Lotze et al., 2006; Worm et al., 2006; Halpern et al., 2008). They are disappearing and degrading at an alarming rate due to intense natural and anthropogenic activities. Various studies have estimated that 35% of mangroves, 50% of salt marshes, and 29% of seagrasses have been either lost or degraded

worldwide over the past century (Valiela et al., 2001; MEA, 2005; Orth et al., 2006; UNEP, 2006; FAO, 2007; Waycott et al., 2009). The causes of this have been found to be geographically variable but largely are related to the increasing developmental pressures. Some of the activities threatening the coastal habitats are land use changes (conversion to aquaculture ponds and agricultural lands), overharvesting, industrial activities, dredging, eutrophication and nutrient enrichment, reduced freshwater flow due to damming of rivers, urban development, and accelerated sea-level rise and subsidence (Pendleton et al., 2012).

Various studies have estimated the carbon sequestration by these coastal habitats (Twilley et al., 1992; Chmura et al., 2003; Murray et al., 2011; Donato et al., 2011; Alongi, 2012; Breithaupt et al., 2012; Siikamäki et al., 2013; Jardine and Siikamäki, 2014; Liu et al., 2014). All these studies contribute towards our understanding of the amount of carbon that is being stored in these ecosystems and points out that this same amount stands to be reintroduced in to the atmosphere in case of deforestation, sediment oxidation, land conversion, occurrence of storms, and other processes that negatively affects the stored carbon. In context of this, several international organizations and nongovernmental organizations (NGOs) have proposed developing an approach similar to REDD (Reduced emissions from deforestation and degradation) in order to protect blue carbon ecosystems. Furthermore, a 'Blue Carbon Initiative' was also started in 2010 by the United Nations and non-government partners with the aim of endorsing climate change mitigation through restoration and sustainable use of coastal and marine ecosystems. It is evident that the blue carbon research and management has gained a substantial momentum over the last few years, but, there still exists a large number of knowledge gaps which needs to be addressed before correctly ascertaining the importance of these coastal ecosystems against climate change.

The present paper reviews the role of blue carbon ecosystems in response towards climate change mitigation with special reference to the mangrove ecosystems. An attempt has been made to outline the various controls on the carbon storage and the relative importance of sedimentary carbon over the carbon stored in the biomass. Further, we review the existing market economy of the blue carbon in context of Indian mangroves and identify the existing knowledge gaps in the blue carbon research in India along with the proposed future outlook.

Why Mangroves?

Mangroves are very highly specialized ecosystems, which are characterized by salt resistant plants thriving in the intertidal areas along sheltered coasts and estuaries in the tropical and subtropical regions. They are commonly found in the latitudes between 24° N and 38° S (FSI Report, 2015), and almost cover up to 75% of coastlines worldwide (Pernetta, 1993). Mangroves are distributed worldwide in 112 countries and territories (Figure 1). The total mangrove cover globally is around 137,760 km² (Giri et al., 2011). Out of this total mangrove area, 41.4% of it exists in the Asian subcontinent (South and South-east Asia specifically). Asia has the largest extent of mangroves with five of the ten countries with the largest extent of mangroves worldwide being found in this sub-continent. These intertidal forests constitute more than 70 species of trees and shrubs, including some ferns and palm (Spadling et al., 2010). Mangrove roots also trap nutrients and fine sediments due to the calmer conditions produced by the slowing down of waves. Mangroves are found primarily in river deltas, estuaries, and coastal lagoons. Open coastlines with relatively low wave energy also provide suitable conditions for mangrove growth. In best environments, mangroves can even form a dense forest canopy as high as 30 m.

Mangrove ecosystems sequester the atmospheric carbon in the various forms, viz, above ground biomass, below ground biomass, litter, sediments etc. The mangrove sediments have a high trapping efficiency for carbon, and there are many carbon pools which support it significantly, like, allocthonous from riverine or marine transported material; autocthonous litter from trees, phytoplankton, benthic or epiphytic algae, etc. (Bouillon et al., 2004). In addition to this, mangroves have a broad range of environmental setting, organic carbon retention, vegetation, biotic influence, etc. which complicates the local conditions (McIvor and Smith, 1995; Twilley et al., 1997; Nordhaus et al., 2006). As an outcome, the mangrove environment witness intense carbon dynamics and are susceptible to show a likely substantial impact on the global carbon budgets (Borges et al., 2003; Dittmar et al., 2006; Alongi, 2007).

Mangroves are well established as one of the most carbon-rich forests in the tropics and their storage potential as predicted by Donato et al. (2011) ranges from 3,100–4,400 t of CO₂e/ha in their biomass and soils. This carbon storage is much greater as compared to the other coastal habitats like seagrasses and tidal marshes (Mateo et al., 1997; Chmura et al., 2003; Vichkovitten and Holmer, 2005; Gordon et al., 2011). Furthermore, mangroves play a significant role in the global carbon cycle as a greater part of mineralisation,

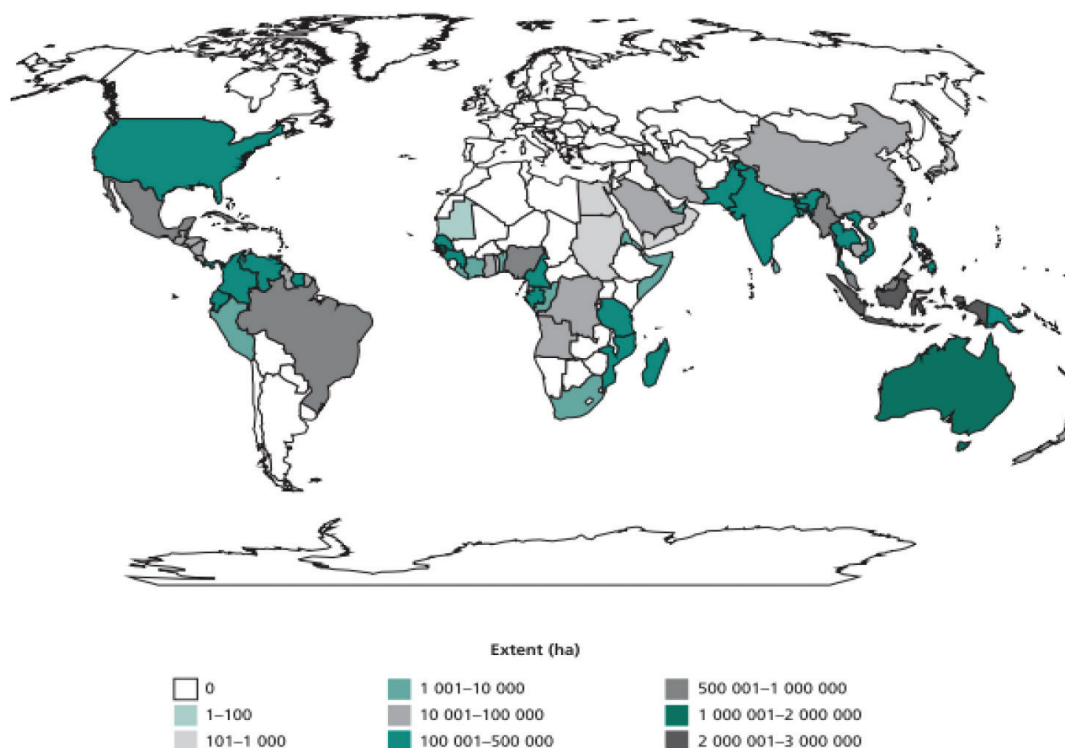


Figure 1: Worldwide extent of mangroves (FAO report, 2007).

carbonate production and accumulation and organic carbon burial take place in these coastal forests (Mackenzie et al., 2004; Duarte et al., 2005). Mangroves are also responsible for approximately 11% terrestrial particulate and dissolved organic carbon export to the oceans and approximately 15% of the sedimentary burial (Jennerjahn and Ittekkot, 2002). The carbon dynamics of these wetlands is well recognised as significant component of blue carbon budget (Twilley et al., 1992; Jennerjahn and Ittekkot, 2002; Dittmar et al., 2006; Donato et al., 2011).

Despite the well-recognised ecosystem and socio-economic benefits of these coastal ecosystems, they are highly threatened and vulnerable. The coastal regions worldwide, over the past decades, have witnessed an increasing migration, so much so, that in some coastal areas the population has almost doubled in the past 20 years. Roughly, around 60% of the total population of the world now lives near the coasts (Lindeboom, 2002). Mangroves, the forests at the interface between land and

ocean, are facing the rapid developmental and urban pressures and are being destroyed at an alarming rate of 1–2% per year (Alongi, 2002; Spalding et al., 2010). Consequently, there is a pressing need for mangrove conservation strategies

Above Ground and Below Ground Production

On the basis of average wood production estimates, above ground biomass production by mangrove is estimated to be 66.4 ± 37.3 Tg C (Terra gram; using %C as 41.5%) and average wood and litter ratio produce as 1.03 ± 0.54 (Malhi et al., 2004). Thus average litter fall to estimated wood production can be 66.7 ± 39.6 Tg C. Data for below ground production is scarce but estimated at 82.8 ± 57.7 Tg C by the ratio of root by litter fall ratio (in C equivalent) of 1.20 ± 0.76 (Raich and Nadelhoffer, 1989). Several studies have estimated the above ground and below ground stocks in mangrove ecosystems around the globe (Figure 2; Putz and Chan, 1986;

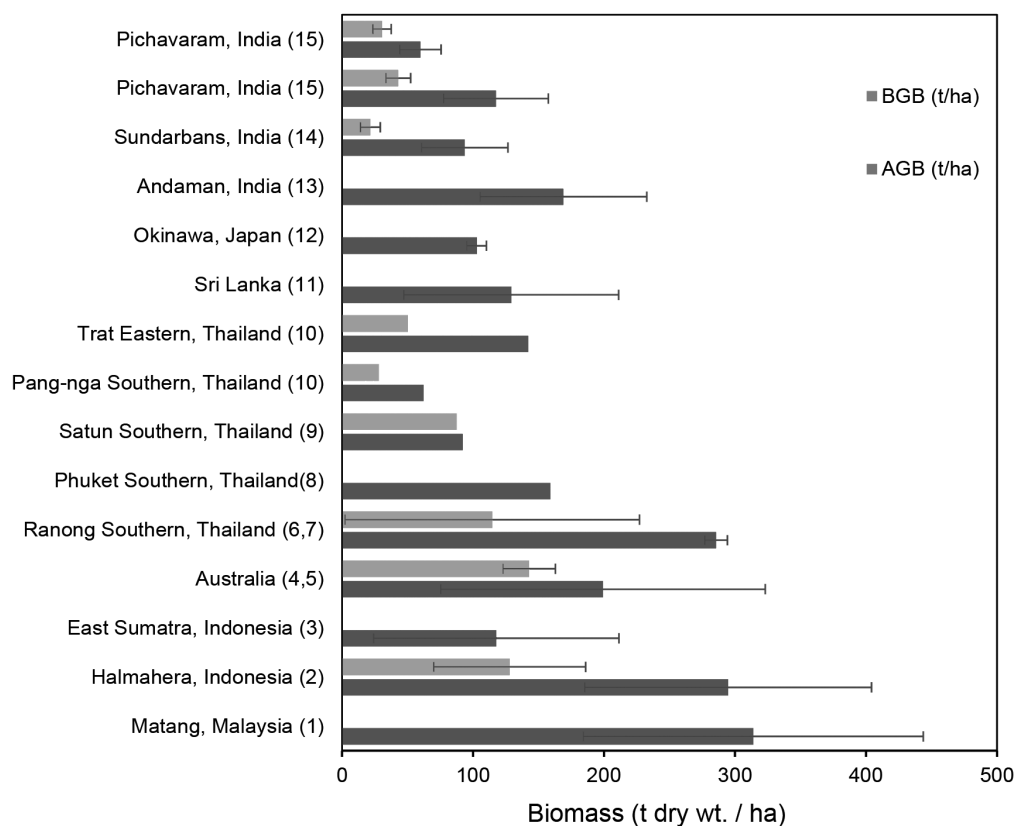


Figure 2: Above ground biomass (AGB) and below ground biomass (BGB) estimates from different mangrove ecosystems in the Indo-Pacific region.

1. Putz and Chan, 1986; 2. Komiyama et al., 1988; 3. Kusmana et al., 1992; 4. Mackey, 1993; 5. Briggs, 1977; 6. Komiyama et al., 1987; 7. Tamai et al., 1986; 8. Christensen, 1978; 9. Komiyama et al., 2000; 10. Pongparn, 2003; 11. Amarasinghe and Balasubramaniam, 1992; 12. Suzuki and Tagawa, 1983; 13. Mall et al., 1991; 14. Ray et al., 2011; 15. Kathiresan et al., 2013.

Komiyama et al., 1988; Kusmana et al., 1992; Mackey, 1993; Briggs, 1977; Komiyama et al., 1987; Tamai et al., 1986; Christensen, 1978; Komiyama et al., 2000; Pongpan, 2003; Amarasinghe and Balasubramaniam, 1992; Suzuki and Tagawa, 1983; Mall et al., 1991; Ray et al., 2011; Kathiresan et al., 2013). On an average, the biomass is greatest in tropical Asian mangroves and lowest in subtropical stands (Murray et al., 2011). Fine root are most active component of below ground biomass and contribute more to net primary productivity than coarse root (Clark et al., 2001). Comparing the litter fall to total mangrove net primary productivity, shows that it contributes as much as 32% (Bouillon et al., 2008). Litter fall provides dominant organic carbon input to the sediment, 52% of litter fall gets exported and 25% gets mineralised (Duarte et al., 2005).

Special Role of the Sediments

The mangroves remove the atmospheric carbon as well as the oceanic carbon through the process of production. This carbon is then stored in the plants and some part of it gets deposited in the sediment below by means of various processes like litter fall, sediment accretion etc. Mangroves are thought as one of the most effective carbon sinks with most of blue carbon stored in the organic-rich sediments than in above-ground plant materials (biomass), as is the case with tropical forests (Donato et al., 2011; Murray et al., 2011). Though mangroves occupy only 0.5% of the global coastline, their contribution to the global sediment carbon storage is 10–15% (Jennerjahn and Ittekkot, 2002).

Mangroves are sites of high sediment accumulation due to their unique root structures (Bouillon, 2011). This special ability of mangroves, when combined with the high net ecosystem productivity and low sediment respiration, gives the mangrove sediments the potential for long-term sequestration of C_{org} . Thus, mangrove sediments play an important role in the global carbon cycle (Fourqurean et al., 2012; Donato et al., 2011; Bouillon et al., 2008; Jennerjahn and Ittekkot, 2002). Many carbon related studies in the mangrove ecosystems have focused singly on mangrove vegetation. Largely, the mangrove litter fall and root biomass have been implicated as the ultimate source of organic matter that is regenerated and the source of C exported out or stored in these ecosystems (Bouillon et al., 2000). However, evidences from deep organic-rich sediments suggest that these components are quantitatively more important

to carbon dynamics in mangrove systems. Although our understanding of these crucial subject matter is improving, there are still large gaps in our knowledge.

Mangrove ecosystems can be classified on the basis of their geomorphological settings. The two main classes of mangroves are oceanic which are abundant along the sea, and estuarine which are found in the deltaic regions. Table 2 demonstrates the relative importance of the sediment organic carbon over the living biomass in different mangrove environments. The mangrove carbon estimates here are based on the values from the Indo-Pacific region as this region comprises nearly 40% of the global mangrove area and exhibits the greatest mangrove diversity (Donato et al., 2011). The results indicate that the sedimentary carbon constitutes the most dominant fraction of the total ecosystem carbon storage in mangrove ecosystems. The sedimentary carbon storage is found to be roughly seven times greater than the carbon stored in living biomass in case of estuarine mangroves, whereas, in the case of oceanic mangroves it is twice as much as the carbon stored in living biomass.

Table 2: Averages for above ground carbon, root carbon and sedimentary organic carbon for the mangrove ecosystems from the Indo-Pacific region

<i>Geomorphic settings</i>	<i>Above ground Carbon (Mg C/ha)</i>	<i>Root Carbon (Mg C/ha)</i>	<i>Sedimentary Organic Carbon (Mg C/ha)</i>
Estuarine	101.7	34.2	938.0
Oceanic	197.6	111.6	680.4

Adapted from Donato et al., 2011

Similar results were observed by Murray et al. (2011). They compared the carbon storage in different pools for different blue carbon ecosystems (Figure 3). The sedimentary carbon was found to be the largest pool of carbon for these coastal habitats and mangroves showed a much greater carbon storage as compared to tidal marshes and seagrasses. The study considered only the top 1 m of the sediments as this is the region that is most prone to the risks of activities like bioturbation, land conversion etc. which negatively impact the stored carbon. In the sediments, organic carbon was found to be spatially variable, but, on an average, 50% to 90% of the total carbon stock of the mangrove ecosystems was found to be present in the sedimentary pool (Murray et al., 2011).

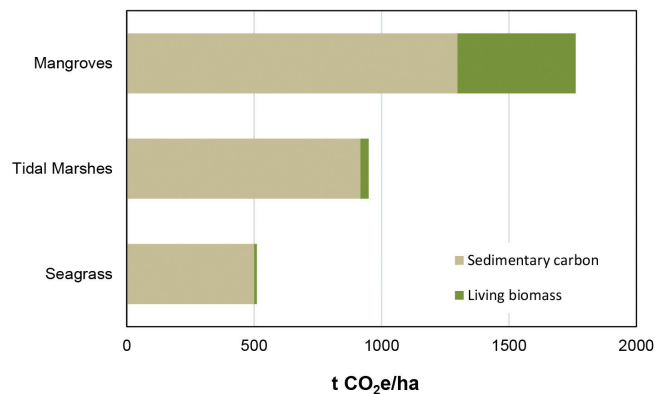


Figure 3: Global averages for carbon pools of different blue carbon ecosystems (redrawn from Murray et al., 2011).

Allochthonous Carbon v/s Autochthonous Carbon

Mangroves are situated where the land meets the sea; thus, they tend to receive the material from both the matter produced locally in these ecosystems as well as transported and relocated matter from the hinterland and the marine end (Jennerjahn and Ittekkot, 2002). A conceptual representation of the different sources of organic matter, pathways, and sinks in a mangrove ecosystem is shown in Figure 4. In the context of organic matter sources, the different types of mangroves,

based on their geomorphic settings, will behave differently. It has been well established that the river and tide-dominated settings are the most important in context of carbon studies as they receive high inputs of biogenic and abiogenic materials from land and from sea and are in permanent exchange with coastal waters. These mangrove ecosystems can produce/receive considerable amounts of organic carbon depending on the net ecosystem production and influence of rivers and their water discharge. Ultimately, this organic carbon is deposited with sediments or exported to the estuary and the coastal shelf due to tidal flushing (Dittmar and Lara, 2001). For global carbon budgets it is important to know whether the carbon buried is freshly fixed from atmospheric CO₂ or relocated, and possibly very old, carbon from another reservoir. Therefore, the identification of carbon sources is a critical issue for constructing the carbon budget in mangrove ecosystems so as to differentiate between the recent autochthonous or relocated allochthonous carbon that gets accumulated in the sediments.

Autochthonous sources of carbon depicts carbon that is produced and deposited at the same locations. Thus, in a mangrove ecosystem autochthonous carbon may include organic matter sourced from the inherent mangrove vegetation, benthic and epiphytic algae etc. All these autochthonous sources freshly fix the atmospheric or oceanic CO₂ by the process

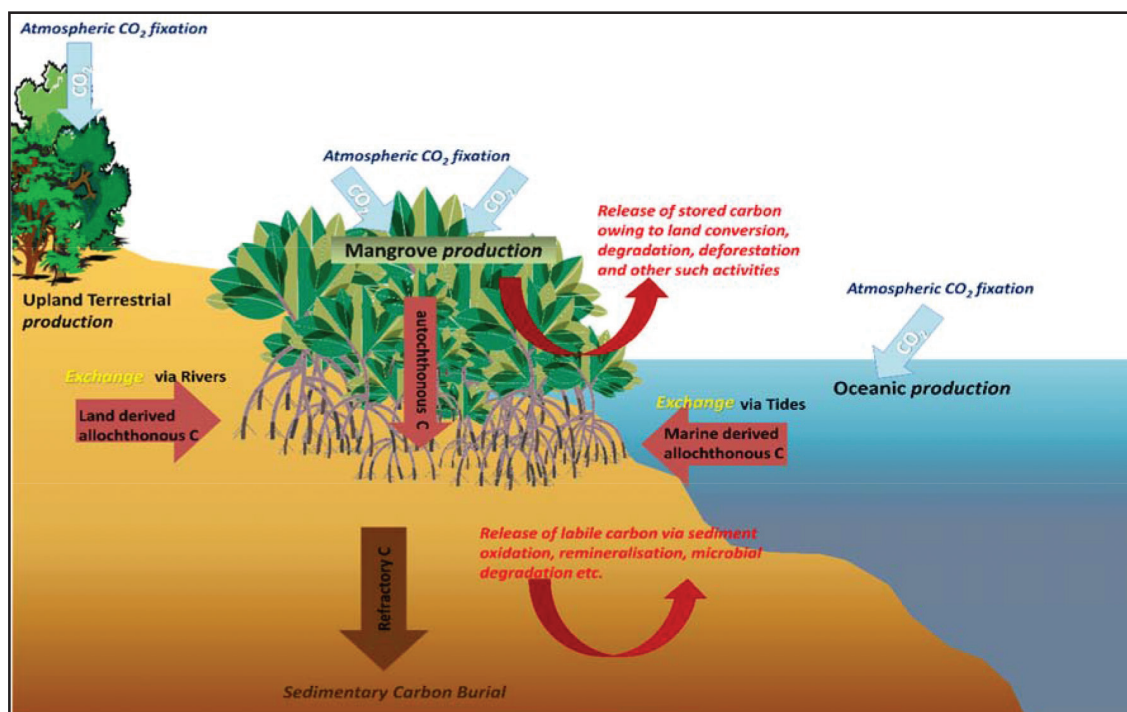


Figure 4: Conceptual diagram showing pathways, sources and sink of carbon in a mangrove ecosystem.

of photosynthesis and transform it as biomass (above ground or below ground). When this biomass decomposes under the effect of the prevailing anaerobic conditions characteristic of a mangrove environment, it forms a part of sedimentary carbon storage (Middelburg et al., 1997; Kennedy et al., 2010). On the other hand, allochthonous sources of carbon are the one that are produced in one location and gets deposited at some other location. Allochthonous carbon can be sourced from the floating phytoplanktons or zooplanktons that may get carried away by the active hydrodynamic setting in a mangrove environment and thus getting deposited at locations different from the ones they were produced in. Apart from this, old carbon from the hinterland may also get transported and deposited in the mangroves settings which have active riverine influence. It is to be noted that the complex mangrove roots structures have a special role to play in trapping the allochthonous carbon sources and incorporating them in the mangrove sedimentary storage.

It is seldom seen that the carbon in mangrove sediments necessarily originate from the dominant local vegetation completely (Bouillon et al., 2003; Breithaupt et al., 2012). There exists a wealth of studies that delineate the sources of carbon and their importance in a mangrove ecosystem (Bouillon et al., 2003; Gonneea et al., 2004; Kristensen et al., 2008; Ranjan et al., 2011; Yong et al., 2011; Gontharet et al., 2014). They highlight that it is not imperative that the carbon in these ecosystems is sourced from the autochthonous mangrove production, instead, additional sources of carbon which have been otherwise neglected can become equally significant. Thus it can be misleading to assign very high significance and priority concern to mangrove production in mangrove conservation strategies as compared to other sources of production in a mangrove environment. It is important to determine the relative contribution of autochthonous and allochthonous carbon sources towards the sedimentary storage in mangrove ecosystems in order to accurately determine the role of mangroves alone, towards carbon sequestration.

Factors Affecting Carbon Storage

The rate of organic carbon sequestration and the magnitude and quality of sedimentary carbon stock depends on various factors viz. climate, sediment types, amount of biomass, moisture content, temperature and chemical composition of the litter, natural or managed state, tillage-induced perturbations, decrease in sediment

aggregation and reduction in physical protection of the sedimentary organic matter, and increase in erosion etc. Important climatic factors like precipitation, potential evapotranspiration (PET) has significant effect on soil organic carbon as soil organic carbon increase with decrease potential evapotranspiration ratio (ratio of PET and precipitation) (Post et al., 1982).

Landscape influence on soil water regime (Gulledge and Schimel, 2000) also affects sedimentary organic carbon. Mangrove forest, due to their conspicuous root system, accumulates fine grained organic rich sediments and thus a large portion of the sedimentary carbon can be allocated to root system (Hutchings and Saenger, 1987; Komiyama et al., 1987). Similarly, factors affecting landscape and forest such as wind, fire, drought etc. affecting soil moisture, texture, temperature, forest cover, salinity, nutrient status, and suspended sediment supply impact soil organic carbon stock (Overby et al., 2003). Fire changes soil profile and decomposition rate of sedimentary organic carbon (Page-Dumroese et al., 2003). Temperature variation changes sediment respiration rate as it is higher in cooler compared to hotter climate (Raich and Schelsinger, 1992) thus affecting sequestration of carbon in sediments. Change in temperature changes productivity and thus affect carbon stock as slight increase in temperature increase productivity but higher temperature result in stress thus reduce in productivity and carbon stock (Ellison, 2000). Flooding of mangrove permanently bury the accumulated organic rich layer thus maintains carbon stocks.

Human induced actions like deforestation, aquaculture, tourism, and agriculture affect sedimentary organic carbon stocks. Forest management and plantation increase the carbon stocks whereas harvesting and irrigation decreases the carbon stock by leaching dissolved organic carbon (Kalbitz et al., 2000). Land use changes and anthropogenic influences in coastal ecosystems have a major impact on carbon stock. Due to deforestation, sediments are exposed and when wetland is drained there is an increased rate of nutrient recycling and microbial activity on the exposed surface; thus, carbon stock which were earlier resistant to decay under anaerobic environment are lost through aerobic respiration (Couwenberg et al., 2010). Deforestation or exposure of sediment also lead to high erosion, thus enhancing leaching of organic carbon ultimately reducing carbon stock in the sediments. Besides this, agriculture and fertilizer use are known to affect the carbon stocks as it cause eutrophication which lead to

plants die-off and reduction in extensive root system of plant which results in erosion and release of carbon.

Market Economy of Blue Carbon

Blue carbon management is well thought as a cost effective programme for climate change mitigation. So, blue carbon in the present times holds a considerable interest for the scientific and policy making communities as it can be related with the carbon market and the climate finance market. In comparison to the terrestrial ecosystems, the carbon restored in coastal ecosystems is extensive and it remains stored there for a very long time resulting in large stocks of carbon (Duarte et al., 2005; Lo Iacono et al., 2008). The future of carbon sequestration and blue carbon marketing depends on the rate, extent, and features of future economic growth and climate change impacts. One such economic analysis of the blue carbon market efficiency has been done by Murray et al. (2011) and it suggests that blue carbon market can attract government and private stakeholders/landlords and help in conservation and restoration programme only if potential revenue exceeds direct and transactional costs. But it still lacks more scientific data on the sequestration and emission fluxes and policy design to give a full fledged market economy.

A promising climate policy mechanisms for Blue Carbon management are regulated cap-and-trade schemes (Ullman et al., 2013). A cap and trade scheme is one of most simple and best strategy to control climate change, using economic incentive for achieving reduction in emission of potent greenhouse gases. Under this plan an upper limit or cap is fixed for amount of greenhouse emission by a central authority. The upper limit is sold by central authority in the form of credit to other country or institution to emit specific allocated volume of greenhouse gases. The total amount of emission credit should not exceed the upper limit or cap. Thus, the country or institution which wants to emit greenhouse gas can buy credits and while the country or institution which sells their credit will be awarded for reducing emission. Similar economic incentive developed to help in conservation and sustainable management of ecosystems through a marketing approach is payments for ecosystem services (PES). A number of PES projects are currently running in the tropics (Anglesen, 2009; Muradian and Kumar, 2009). This idea is more practical than other approaches as it involves the local participation and assumes that one adequately manages and conserves what they value most.

In the context of Indian mangrove ecosystems, there is a vast potential and advantage for setting up a blue carbon economy. Indian coastline and the island territories host nearly 3% of the world's mangrove area (FAO, 2007). Sundarbans, the largest mangrove ecosystems lies on the delta of the Ganges, Brahmaputra and Meghna rivers on the Bay of Bengal and are shared between India and Bangladesh. Several studies have calculated the carbon stocks in the Indian mangrove ecosystems (Table 3) but their approach restricts to calculating the carbon stored in the living biomass. There is a dearth of studies that address the carbon storage in the sedimentary environment in the Indian mangroves. Furthermore, there are a large number of mangroves regions in the Indian subcontinent which are still understudied.

Table 3: Available carbon stock data for the different mangrove ecosystem of India

<i>Mangrove</i>	<i>Carbon stock (mg C/ha)</i>	<i>References</i>
West Bengal	506.7	Ray et al., 2011
Gujarat	24.57	Pandey and Pandey, 2013
Andaman	118.3	Mall et al., 1991
Tamil Nadu	62.81	Kathiresan et al., 2013
Karnataka	50.41	Suresh et al., 2013

In order to have efficient marketing scheme we need to first make a carbon inventory which requires the understanding of (a) distribution of mangrove ecosystems, (b) current carbon stocks in the different carbon pools and (c) the potential carbon emission from these ecosystems. In addition to that, in order to have a strong economic market we need a strong market policy design and until that time blue carbon market schemes will not bear any fruits. The market economics will not work till the time the revenue generated by implementing the blue carbon schemes outcompetes the cost of ecosystem restoration.

Knowledge Gaps in Blue Carbon Research in India and Future Outlook

Mangroves are well established as one among the most productive forests on earth, storing large amount of carbon and most of it as the underground storage. They have been a subject of tremendous research in the recent years. However, there are still very limited data sets available in terms of the global reach. There

are a large number of coastal habitats that are still unrepresented in these estimates and thus, it provides a great deal of opportunity for future research. In view of the mangrove research in India, a keyword search (“Mangroves AND India”: topic search mode; 1990-2015) in *Web of Science* (Thomson Reuters) resulted into listing of 810 peer reviewed articles which is approximately only 7% of the published research across the world (Figure 5). Mangrove research have gathered the attention of scientific community in India over the past two decades and it is important to note that there has been substantial growth in the research during the past couple of years (Figure 6). Majority of studies carried out in India during the recent years focused on mangrove pollution and their management. But, there is still a much wider scope for studies with a targeted approach towards delineating blue carbon storage and stocks in these ecosystems.

The need of the hour is to correctly map and document the un-surveyed blue carbon ecosystems for their carbon storage and include them in the existing estimates to build a better and reliable picture of the role of blue carbon ecosystems acting towards climate change mitigation. The studies, apart from estimating the existing blue carbon stocks should also focus on the emission of carbon from these ecosystems. The knowledge of inputs and outputs of carbon along with their rates of introduction and removal will present a much more robust carbon budget. These studies need to be conducted keeping in mind the role of human activities in ecosystem degradation and their increased

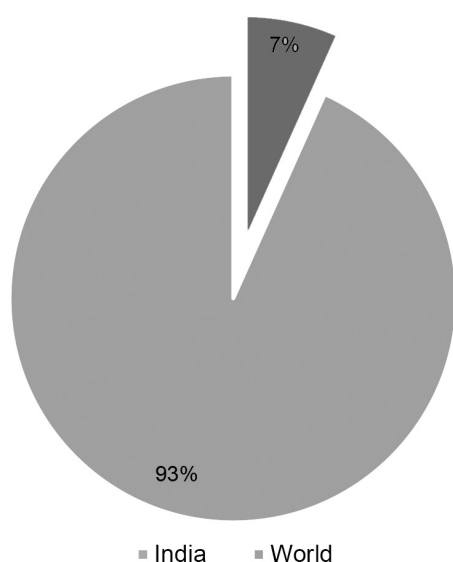


Figure 5: Indian mangrove research in context of the mangrove research around the globe.

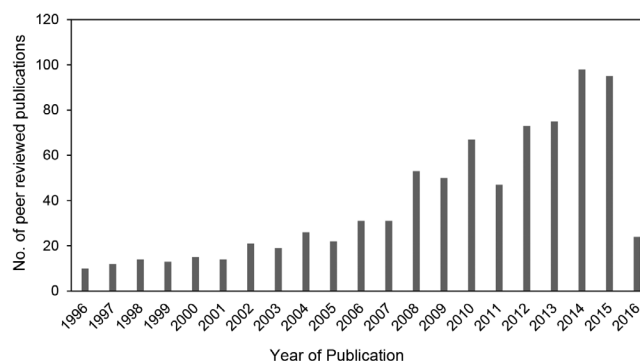


Figure 6: Growth in mangrove research in India during 1996-2016.

contribution with time. Another important consideration while designing the blue carbon studies, should be given to microbial decomposition and microbial processes in soil which effect the carbon storage through organic matter remineralisation and have been largely neglected in the available literature.

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