CARBON RICH MANGROVE FORESTS: AN OVERVIEW FOR STRATEGIC MANAGEMENT AND CLIMATE CHANGE MITIGATION

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ABSTRACT

Carbon dioxide (CO_2) once emitted to the atmosphere, takes centuries for natural removal. Every 4 giga tones of carbon (GtC) emitted to the atmosphere results in a rise of one ppm of CO_2 in the atmosphere. Mangroves growing near the coast play an important role in carbon sequestration by acting as sink for carbon, thereby receiving considerable international attention. In India Mangroves occupy 4740 sqkm, about 3 % of the world's mangrove cover. Sundarbans in India is the largest mangrove site in the world, colonized with many threatened animal species. About 58 % of the mangroves occur on the east coast along the Bay of Bengal, 29 % on the west coast bordering the Arabian Sea, and 13 % on Andaman and Nicobar Islands (Dasgupta and Shaw 2013). The State forest report of 2015, states that out of total cover of mangrove, Sundarbans contributes about 44 %, followed by Gujarat 23 % and Andaman and Nicobar Islands 13%. On the basis of density of mangrove cover about 40 % area covered by the open mangrove, 29% by the moderately dense mangrove and 31% by the very dense mangrove. The paper attempts to highlight the Carbon storage in Mangrove living biomass and sediments and their help in climate sustainability. Reviews suggest that C storage in mangroves at different climatic regions, sites, stands and different depths of soils store more carbon per unit area. All the reviews suggest that mangroves are a globally significant contributor to the carbon cycle.

Key words: Carbon dioxide, carbon stock, GHGs, mangrove, soil carbon

INTRODUCTION

Mangroves are taxonomically diverse assemblages of wood plant communities belonging to several unrelated angiosperm families with special adaptations to saline conditions (Tomlinson, 1986). Mangrove ecosystems occur in tropical as well as subtropical regions and the floristically richest mangroves are occurring in the tropical Southeast Asia. Mangrove forests are considered to be a unique and complex major component of coastal zones in the tropical and sub-tropical regions. They represent transitional ecosystems where the sea, land and freshwater meet. The main vegetation consists of generally evergreen trees or shrubs that grow along coastlines, brackish estuaries or delta habitats. Mangrove habitats are easily recognized as they are located at tideland mud or sand flats inundated daily with sea water. They not only play critical roles in ensuring sustainability of coastal ecosystems, but also in fulfilling important socio-economic benefits to coastal communities.

Recently, the role of mangrove forest as an important atmospheric CO_2 sink has been highlighted. CO_2 is a major contributor to global warming. Thus increasing CO_2 emission is one of the major environmental concerns and it has been well addressed in 'Kyoto protocol'. The living vegetation, sea water and soils play a key role in absorbing atmospheric CO_2 (Rao, *et al*. 2017). In is context, the trees act as a major sink of CO_2 as they have high potential of tapping atmospheric carbon through photosynthesis. The sequestrated carbon is stored in the plant tissues which results in the growth (Gawali and Sheikh 2016).

Mangroves have long been known as extremely productive ecosystems that cycle carbon quickly, but until now there had been no estimation of how much carbon resides in these systems (Daniel Donato *et al* 2011). This essential information should be generated because when land-use change occurs, much of that standing carbon stock can be released to the atmosphere. The mangrove forest's ability to store such large amounts of carbon can be attributed to the deep organic rich soils in which it thrives (Daniel *et al* 2011). Mangrove sediment carbon stores were on average five times larger than those typically observed in temperate, boreal and tropical terrestrial forests, on a per unit area basis (Kibria G, 2013). The mangrove forest's complex root systems, which anchor the plants into underwater sediment, slow down incoming tidal waters, allowing organic and inorganic material to settle into the sediment surface. Low available oxygen conditions with slow decay rates, resulting in much of the carbon accumulating in the soil. In fact, mangroves have more carbon in their soil alone than most tropical forests have in all their biomass and soil combined (Mitra and Zaman 2014).

This high carbon storage suggests mangroves may play an important role in climate change management. Loss of mangrove through human interventions has been documented from many parts of the world as a result of land reclamation, grazing of live stock, cutting of timber (Walsh, 1974; Hussein, 1995; Semesi, 1998) salt pond construction (Terchunian *et al.*, 1986), oil spills (Ellison and Farnsworth, 1992) mining (Lewis, 1990; Wolanski, 1992) and dumping of rubbish (Saenger *et al.*, 1983). Reduction in the abundance of mangroves has usually been interpreted in terms of loss of biodiversity or fisheries resources. Since mangroves become increasingly threatened by various human impacts (ITTO, 1993, Pernetta, 1993; Farnsworth and Jackes, 1987), there is a need to investigate the mangrove vegetation with the purpose of predicting changes in the future. The present paper summarizes and discusses about the role of mangroves in the context of carbon sequestration as well as climate change mitigation, published over the years.

Extent of Mangroves

Giri *et al.* (2011) estimated that largest extent of mangroves found in Asia (42%) followed by Africa (20%), North and Central America (15%), Oceania (12%) and South America (11%). Approximately 75% of mangroves are concentrated in just 15 countries. The mangroves grow in river deltas, lagoons and estuarine complexes; also occur on colonized shorelines and islands in sheltered coastal areas with locally variable topography and hydrology.

Table 1. Previous estimates of global extent of mangroves.

Reference	**Reference year**	**No. of countries included**	**Estimated total area (ha)**
FAO, UNEP, 1981	1980	51	15 642 673
FAO, 1994	1980-1985	56	16 500 000
Spalding *et al*., 1997	1997	112	18 100 077
Aizpuru *et al*., 2000	2000	112	17 075 600

Table 2: Current and Past Mangrove Extent by Region (1980-2005)

Region	**Most recent reliable estimates**		**1980**	**1990**	**2000**	**2005**
	X 1000 ha	**Ref year**	**1000 ha**	**1000 ha**	**1000 ha**	**1000 ha**
Africa	3.243	1997	3,670	3.428	3,218	3,160
Asia	6,048	2002	7,769	6,741	6,163	5,858
North and Central America	2,358	2000	2,951	2,592	2,352	2,263
Oceania	2,019	2003	3,181	2,090	2,012	1,972
South America	2,038	1992	2,222	2,073	1,996	1,978
World	**15,705**	**2000**	**19,794**	**16,925**	**15,740**	**15,231**

Source: (Lang'at, 2013).

As can be seen from Table 2, the most extensive area of mangroves is found in Asia, followed by Africa and South America. Four countries (Indonesia, Brazil, Nigeria and Australia) account for about 41 percent of all mangroves and 60 percent of the total mangrove area is found in just ten countries.

These forests provide important ecosystem goods and services to the region's dense coastal population and support important functions of the biosphere. Mangroves are under threat from both natural and anthropogenic stressors. They mapped the current extent of mangrove forests in South Asia and identified mangrove forest cover change (gain and loss) from 2000 to 2012 using Landsat satellite data. Giri *et al* (2015) stated that mangrove forests in South Asia occur along the tidal sea edge of Bangladesh, India, Pakistan and Sri Lanka.

They also conducted three case studies in Indus Delta (Pakistan), Goa (India) and Sundarbans (Bangladesh and India) to identify rates, patterns, and causes of change in greater spatial and thematic details compared to regional assessment of mangrove forests.

Table 3. Areal extent of mangrove forests and forest gain and loss in each country

Country	**Mangrove area in ha**	**Loss**	**Gain**
Bangladesh	411,487.0	16179.4	6575.4
India	3,065.2	8020.7	29654.7
Pakistan	411,487.0	7691.6	44230.7
Sri Lanka	21,437.1	243.5	0.0

Table 4. Mangrove rich countries and their percentage (Giri *et al* 2011).

Country	**Area**	**Percentage of global total**	**Cumulative percentage**
Indonesia	3,112,989	22.6	22.6
Australia	977,975	7.1	29.7
Brazil	962,683	7.0	36.7
Mexico	741,917	5.4	42.1
Nigeria	653,669	4.7	46.8
Malaysia	505,386	3.7	50.5
Burma (Myanmar)	494,584	3.6	54.1
Papua new Guinea	48,121	3.5	57.6
Bangladesh	436,570	3.2	60.8
Cuba	421,538	3.1	63.9
India	368,276	2.7	66.6
Guinea Bissau	338,652	2.5	69.1
Mozambique	318,652	2.3	71.4
Madagascar	278,078	2.0	73.4
Philippines	263,137	1.9	75.3

Status of Above Ground Carbon Stock by Mangroves

Mangroves function like other forests in exchanging gases with the atmosphere and like other tidal ecosystems, exchange gases, solutes and particles with the coastal ocean and or sea as they inhabit the margin between land and sea (Alongi, 2009). Mangroves are tightly linked to land, ocean and atmosphere, yet still manage to store carbon and other elements in their biomass and soils (Feller *et al*., 2010). Mangroves are, on average, highly productive tidal forests utilizing an advantageous strategy of maximizing carbon gain and minimizing water loss with high water use and nutrient use efficiencies and low transpiration rates. These physiological mechanisms result in rapid rates of CO_2 uptake and respiratory release despite living in waterlogged saline soils (Ball, 1988). Despite mangrove accounting for only 0.7% of tropical forest, it generates emissions up to 10% from total global deforestation (Pan *et al*., 2011). Hence, mangroves are considered as an important component in climate change mitigation and reducing emissions from deforestation and degradation. Mangroves have experienced rapid deforestation worldwide with 30-50 per cent decline in the past 50 years. Mangrove deforestation generates green house gas emissions of 0.02-0.12 pentagrams of carbon per year, which is equivalent up to 10 per cent of carbon emissions from global deforestation, according to the report of Daniel (2011). The global storage of carbon in mangrove biomass is estimated to be 4.03 pg (petagram) C, 70% of which occurs in coastal margins from 0^0 to 10^0 latitude (Twilley *et al.*, 1992).

Alongi and Mukhopadhyay (2015) studied the characteristics of mangrove carbon cycling, such as the allocation of fixed carbon into biomass and patterns of respiratory CO_2 release, are strikingly similar to tropical humid forests. They store more about 6 times more carbon (26 Tg C yr^{-1}) than is buried in sediments (≈4Tg C yr^{-1}) of subtropical and tropical coastal margins. The export of mangrove derived Particulate organic carbon, dissolved organic carbon and dissolved inorganic carbon (POC, DOC and DIC) accounts for 18%, 10% and nearly one-third (29%) of tropical river discharge of these compounds globally. The mangrove contribution to the tropical coastal carbon cycle is modest due to their small global area. However, their contribution to coastal sequestration is much larger (30% of total C burial). Kauffman *et al.* (2011) quantified ecosystem C storage at the Palau site ranged from 479 Mg/ha in the seaward zone to 1,068 Mg/ha in the landward zone; in the Yap site C storage ranged from 853 to 1,385 Mg/ha along this gradient. The living biomass of estuarine mangroves sequester 237 -563 tonnes CO_2 ha^{-1} compared to only 12- 60 tonnes CO_2 $ha^{-1}$for marshes (Murray *et al.* 2011). This is also consistent with earlier work of (Day *et al.*, 1989) that showed the typical standing crop of biomass for marshes and mangroves are 500 to 200 g dry wt m^2 and 10,000 to 40,000 g dry wt m^2 according to Twilley *et al.*, 1992. In the paper of Lee (2016) data from the regional sources of South China Sea (SCS) countries suggests average C contents of mangrove litter at 41%. Total estimated influxes of C from mangrove litter production from the SCS countries in 2010 are 2.04×10^6 tC y^{-1}. The value was 2.86×10^6 tC y^{-1} in 1997. The influx from mangroves therefore has decreased by 28.6% between 1997 and 2010. Sitoe *et al.* (2014) found that C more concentrated in live trees, with 28.0 Mg ha^{-1} (47.8% of plant carbon). The average carbon stock in the mangrove forest was 218.5 Mg ha^{-1}, around 73% of which was stored in the soil, supporting the findings of other studies that the soil of mangrove forests contains about 72–99% of the total carbon of these types of forests. Similar result was found by Fatoyinbo *et al.* (2008). Stringer *et al.* (2015) quantified the ecosystem C stock of the Zambezi River Delta mangroves utilizing a rigorous, yet operationally feasible approach. The average biomass C density for the height classes ranged from 99.2 Mg C ha^{-1} to 341.3 Mg C ha^{-1}. Ecosystem C stocks of sampled mangrove forests ranged from 437 Mg C ha^{-1} to 2186 Mg C ha^{-1} (Murdiyarso *et al.*, 2009). This C storage is exceptionally high compared with upland tropical forests, which typically store between 150 and 500 Mg C ha^{-1} (Murdiyarso *et al.*, 2002) and is perhaps second only to the renowned C stocks of peat swamp forests (Page *et al.*, 2002).

Table-5 Biomass and carbon stock of plantation and natural stands in Mahanadi Mangrove Wetland MMW (Sahu *et al.* 2016).

	Above ground		Below ground	
Stand	Biomass (tonne ha^{-1})	Carbon (tonne ha^{-1})	Biomass (tonne ha^{-1})	Carbon (tonne ha^{-1})
Plantation	125.55	62.77	55.72	27.86
Natural Forest	124.91	62.45	53.3	26.69

The study reveals that MMW stores substantial amount of atmospheric carbon and therefore needs to be conserved and sustainably managed to maintain as well as increase carbon storage. Kishwan (2009) has estimated carbon sequestration per unit area by littoral and swam forests of India as 106.9 t ha^{-1}. Mitra *et al.* (2011) evaluated carbon stocks in the above ground biomass (AGB) of three dominant mangrove species (*Sonneratia apetala, Avicennia alba* and *Excoecaria agallocha*) in the Indian Sundarbans. Examined whether these carbon stocks vary with spatial locations (western region *vs*. central region) and with seasons (pre-monsoon, monsoon and post-monsoon). Among the three studied species, *S. apetala* showed the maximum above ground carbon storage (t ha^{-1}) followed by *A. alba* (t ha^{-1}) and *E. agallocha* (t ha^{-1}). The AGB varied significantly with spatial locations but not with seasons

Gujarat has the second largest mangrove cover (1058 sq km) of India. Mangrove being the major woody habitats forms the important carbon sinks in the coastal regions. Pandey and Pandey (2013) have examined the carbon sequestration by mangroves of Gujarat. A total of 8.116 million ton carbon has been sequestered by mangroves of Gujarat.

Soil Carbon Stock

Mangrove forests play an important role in the terrestrial and oceanic carbon cycling (Liu *et al.*, 2014), where they contribute to 10% of the total net primary production and 25% of the carbon burial in the global coastal zone although they colonize only 0.7% of the global coastal zone (Alongi, 2007).

In 1998, German Advisory Council on Global Change (WBGU), estimated areas and carbon storage (Gt) for various biomes. Deserts/semi deserts are biomes with the largest area ($45.5x10^6$ km^2), but store only a relatively small amount of organic carbon. Boreal forests store the highest total amount of carbon (559 Gt), which is mainly attributed to the carbon pool in the soil (471 Gt). Tropical forests have the largest vegetation carbon pool (212 Gt), which makes this biome the second largest carbon pool in total. In comparison to other biomes, wetlands cover a smaller area but with relatively high carbon storage in it.

Table 6- soil carbon stock (for top 1-100 cm soil) of estimated areas of mangrove sites

Reference	**Global carbon (Gt C)**
Sjors *et al.*(1980)	300
Adams *et al.*(1990)	202-377
Eswaran *et al.*(1993)	357
Batjes, (1996)	330
WBGU (1998)	225

According to Chmura *et al*. 2003 carbon sequestration rates by ecosystem type (mangrove swamp or salt marsh) overall average rate of carbon sequestration per unit area is about 210 g CO_2 m^2 yr^1

Plants remove CO_2 from the atmosphere to prepare carbohydrates, some of which are incorporated into plant tissues. As plants and plant parts die, some of these tissues are added to the soil as soil organic matter (Lal, 1998). Given the proper conditions, some soils can become net C sinks (Mosier, 1998), because CO_2 can be removed from the atmosphere by the soil plant system. interest in soil C sequestration is increasing. Coastal wetlands are areas with high NPP their soils and sediments sequester C at high rates. Grossman *et al.* (1998) shown that, where sedimentation rates are high, organic C may be sequestered at depths greater than those typically sampled during soil studies. Soil C density was the largest measured C pool, containing 274.6 Mg C ha^{-1} to 314.1 Mg C ha^{-1} and accounting for 45-73% of the height class ecosystem C densities (Stringer *et al.* 2015) at Zambezi River Delta.

Mangrove sediments are characterized by intense carbon processes with a potentially high impact on the global carbon budget (Alongi, 2007). Ceron-Breton *et al* (2011) determined carbon sequestration rate in mangrove forest soil located within the natural protected area. The organic matter content and organic carbon decreased at greater depths of soil. The sampling areas with sandy soils where the buttonwood mangrove is the dominant species showed a reduced ability to capture carbon (1.2 kg C m^{-2}) and black mangrove-red mangrove-white mangrove, showed the highest rates of carbon sequestration (22.2 kg C m^{-2}). The accumulation of organic matter and organic carbon content were higher during the dry season. It was expected, since in this climatic period the evapotranspiration process increases, which concentrates salts and dissolve organic carbon. Carbon storage was lower in the days of "rain" when the dilution effect was greater, resulting in lower concentrations of dissolved organic carbon, salinity and density. Bianchi *et al.* (2013) conducted a study and determined Carbon sequestration rates were in the Mud Island Mangrove and the Marsh sites ranged from 253 to 270 and 101-125 g C m^{-2} yr^{-1}, respectively in wetland soils of the north western Gulf of Mexico. Significantly higher carbon sequestration in mangrove compared to marsh sites on Mud Island, are consistent with the recent reports on blue carbon sinks, which show that mangroves store more carbon than marshes on a global scale (Cai, 2011; Donato *et al.*, 2011).

Yang *et al.* (2014) stated that mangroves are an important affecter of atmospheric CO_2 level via sequestrating carbon and trapping sediments. In order to detect the determinants of organic carbon sequestration, study investigated four mangrove fringing locations along the Surface and core sediment samples were collected from these sites and analyzed sedimentary organic carbon content (SOCC). It was found that a significantly higher concentration and density of organic carbon were preserved in the interior surface sediments regardless of location or surface grain size distribution of coast of the Leizhou Peninsula. The belowground C pools of the mangrove forest transects were greater at 315, 428, and 818 Mg/ha for the seaward, interior, and landward zones, respectively (Kauffman *et al.* 2011).

SOC content in the study of Eid and Shaltout (2016) is greatest in the surface soil where most carbon inputs occur and decreases with depth, this lies in agreement with some previous studies such as Eid and Shaltout (2013), Khan *et al.* (2007), Lunstrum and Chen (2014). Variation in SOC content distribution with depth are the result of interaction of complex processes such as decomposition, biological cycling, leaching, illuviation, soil erosion, weathering of minerals and atmospheric deposition (Girmay and Singh, 2012) total mean of SOC content in the 0-10 cm soil depth accounts for 35.5% indicating the importance of top soil layers as good sources of carbon sink, but also as a potential for large amount of CO_2 emission upon conversion and mismanagement. Similar results were reported by Eid and

Shaltout (2013) in Lake Burullus (a Mediterranean wetland in north Egypt) who indicated that 40.7% of the SOC content was located in the top 10 cm of the soil profile.

Sahu *et al.* (2016) revealed that the soil carbon stock in natural stands was 54.3 ± 3.0 Mg C ha^{-1} and in plantation it was 60.9 ± 5.6 Mg C ha^{-1}. The mean overall C-stock of natural stands and plantations was 57.6 ± 3.2 Mg C ha–1. A positive correlation was found between vegetation biomass and soil organic carbon in the surface soil (0–30 cm), indicating the role of vegetation in building surface soil organic carbon.

The carbon content in the soil of mangroves generally changes much more slowly with depth than in the upland forest Sitoe *et al.* (2014). In the miombo woodlands of Malawi for instance, Walker and Desanker (2004) found an exponential decrease of carbon concentration up to a depth of 150 cm, indicating a sharp decrease in carbon concentration with the increase of soil. According to Wendling (2005), the reduction of carbon concentration with depth is more common in terrestrial forests due to high concentrations of biological activity, particularly litter deposition and decomposition near the soil surface, while deposition of sediments from the river stream constitute an important source of organic matter in mangrove soils depth. Panday and Panday (2013) was also examined carbon sequestered in the soil (up to 30 cm depth) by mangroves of Gujarat and revealed that mangrove soils contribute more than mangrove plants in the overall carbon sequestration.

The amount and dynamics of SOC in soil differ greatly in different mangroves, which are mainly influenced by the tidal gradient, mangrove forest age, biomass and productivity, as well as species composition and sedimentation of suspended matter. Proportions of soil carbon to the total ecosystem carbon suggest that mangrove soils are the most carbon rich when compared to upland ecosystem in the same region.

Conclusion

Recent studies have shown that coastal wetlands such as mangroves, salt marshes and sea grass beds are among the most efficient carbon (C) sinks on the planet. The data presented show that mangroves hold C-pools that are among the largest in the tropics. Plantation can store as much carbon as natural mangrove forests. This highlights the need for expanding mangrove plantations. Some study demonstrates that the biomass and carbon storage capacity of mangrove species vary with spatial locations due to varying salinity, perhaps moderated by soil and water management. Mangroves store more carbon than marshes on a global scale. As mangroves become recognized as important carbon storages, the need for quantifying and reducing the uncertainty of carbon inventories, such as those arising from specific carbon contents, becomes increasingly emphasized. Many aspects of mangroves make them unique ecosystems. Improving their management, including wise use of resources, would enhance collateral benefits for both global and local communities.

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