

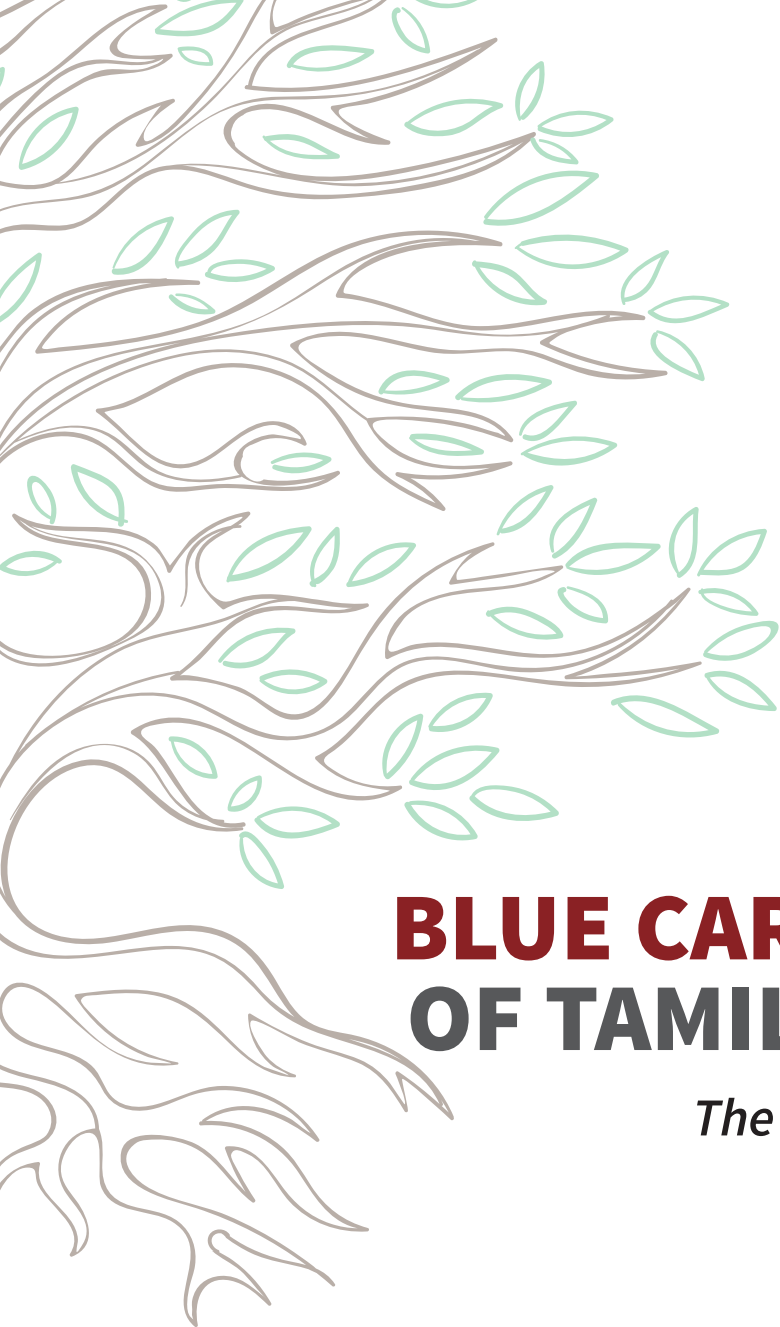


# **TECHNICAL REPORT**

# **BLUE CARBON WEALTH**

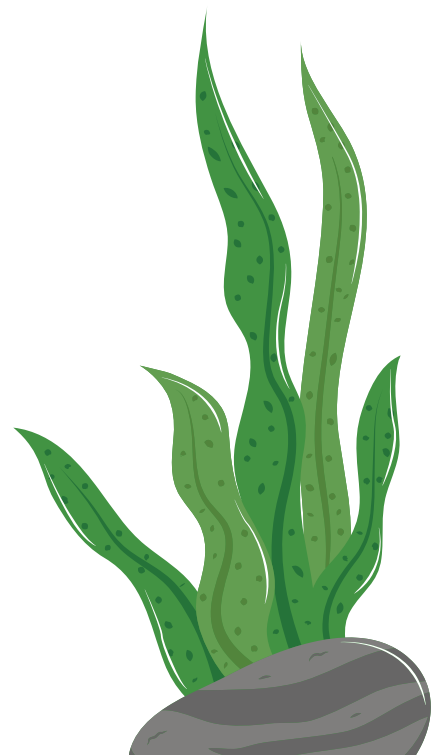
# **OF TAMIL NADU, INDIA**

*The role of coastal ecosystems  
as carbon sinks*



TECHNICAL REPORT  
**BLUE CARBON WEALTH**  
**OF TAMIL NADU, INDIA**

*The role of coastal ecosystems  
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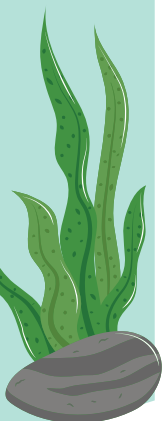
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# GLOSSARY



**Afforestation:** Afforestation is the action of planting trees on land, which has few or no trees.

**Bio-invasion:** Bio-invasion refers to the introduction and spread of non-native species into a new environment, which cause significant environmental, economic and social impacts.

**Blue bond:** Blue bonds are debt instruments issued by governments, development banks, or corporations to fund projects benefiting marine and coastal ecosystems, focusing on environmental, economic, and climate benefits.

**Blue carbon:** Carbon captured and stored by coastal and marine ecosystems such as mangroves, seagrasses and salt marshes; blue carbon is found within the soil, in the living biomass above ground (leaves, branches, stems), in the living biomass below ground (roots) and as the non-living biomass (litter and dead wood).

**Blue economy:** All the economic activities associated with the oceans and seas.

**Blue finance:** Blue finance involves financial mechanisms and investments supporting sustainable ocean and coastal resource use and conservation, attracting global interest from investors and financial institutions.

**Blue loan:** A blue loan is a unique financial instrument that exclusively raises funds for projects that promote a blue economy.

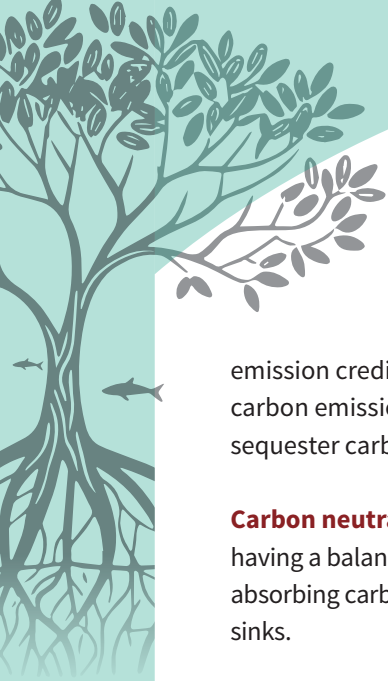
**Carbon credit:** Carbon credits are measurable carbon emission reductions from certified climate action projects.

**Carbon financing:** Carbon financing is a financial strategy that values carbon emissions and provides funding for activities aimed at reducing them.

**Carbon footprint:** A carbon footprint is the total amount of greenhouse gases, primarily CO<sub>2</sub>, emitted by an organization through its activities, including production, consumption, energy use, transportation, and waste management.

**Carbon markets:** Carbon markets are carbon pricing mechanisms that allow governments and non-state actors to trade greenhouse gas





emission credits, enabling them to offset their carbon emissions through projects that reduce or sequester carbon.

**Carbon neutrality:** Carbon neutrality means having a balance between emitting carbon and absorbing carbon from the atmosphere in carbon sinks.

**Carbon pool:** Carbon pools refer to carbon reservoirs such as soil, vegetation, water and the atmosphere that absorb and release carbon.

**Carbon sequestration:** Carbon sequestration is the process by which CO<sub>2</sub> is absorbed from the atmosphere and stored in the biomass and sediments of ecosystems.

**Carbon sink:** A carbon sink is anything that absorbs more carbon from atmosphere than it releases, such as forests, ocean, land or soil.

**Carbon stock:** The amount of total C stored in a carbon pool, such as the biomass and sediments of blue carbon ecosystems.

**Climate change:** Climate change refers to shift

in long-term temperature and weather patterns influenced by human activity, altering the global atmosphere composition.

**Decarbonisation:** Decarbonisation refers to the process of eliminating or decreasing the emission of carbon dioxide (CO<sub>2</sub>) into the atmosphere.

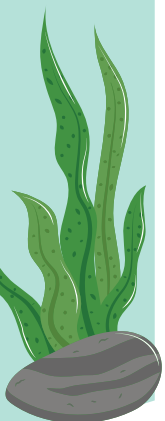
**Fossil fuels:** Fossil fuels are non-renewable energy sources such as coal, oil and natural gas.

**Net zero:** Net-zero corresponds to a situation where the amount of an organization's greenhouse gas emitted is equal to the amount of greenhouse gas captured or removed from the atmosphere.

**Ocean acidification:** A decrease in the pH of seawater due to the uptake of anthropogenic carbon dioxide.

**Ocean deoxygenation:** The overall reduction in the oxygen content in oceanic and coastal waters.

**Ocean eutrophication:** The process by which a part of the ocean is enriched with nutrient, leading to the increase in the growth of plant life.



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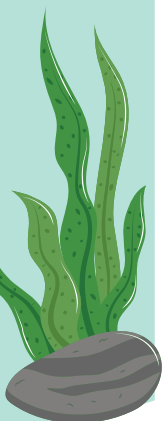
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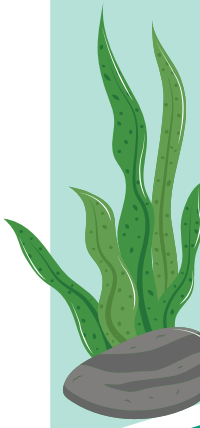
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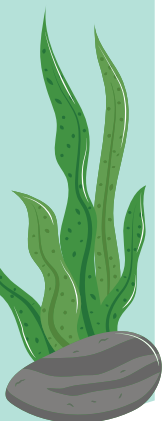
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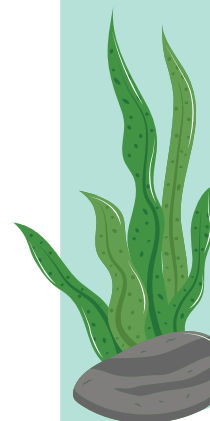
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*Suaeda monoica*



## KEY MESSAGES

■ Blue carbon ecosystems such as mangroves, salt marshes and seagrass meadows play important roles in sustaining biodiversity, performing ecosystem functions, and serving as carbon sinks. However, they are the most threatened coastal ecosystems and are at risk due to climatic and non-climatic factors; they need urgent conservation measures in order to tide over / withstand climate change implications.

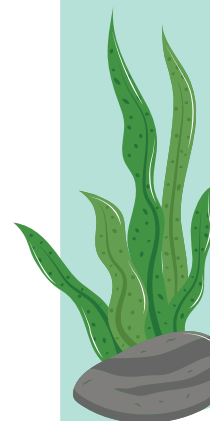
■ These three kinds of coastal ecosystems occur along the coast of Tamil Nadu. Given below are the values of the estimated average carbon stock in the top 1 m of soil per hectare, the total carbon stock in the top 1 m soil and their estimated economic value in different blue carbon ecosystems of Tamil Nadu. As

Blue carbon ecosystems	Estimated average carbon stock in top 1 m of soil megagrams of carbon (Mg C)/ hectare (ha)	Estimated total carbon stock in top 1 m soil in Tamil Nadu (Mg C)	Estimated economic value in million (US\$)
Mangroves	111 ± 10.46	5,00,355	12.8
Salt marshes	109 ± 12.32	6,63,436	17.0
Seagrasses	97 ± 13.19	37,97,983	97.5

India is in the process of developing Indian Crediting Mechanism, the nearby Thailand Voluntary Emission Reduction Program's mean carbon credit price of US \$7 for metric tonne of carbon dioxide equivalent (t CO<sub>2</sub>e) for the calculation of economic value of carbon stock has been used (<https://carbonpricingdashboard.worldbank.org/credits/instrument-detail>)

■ The state of Tamil Nadu is a national pioneer in the restoration of coastal habitats. The seagrass restoration started in the state in 2008 is considered the first of such conservation efforts in India. These restored habitats generate an additional 18.7 Mg C/ha of carbon in the top 1 m soil with 68.5 t CO<sub>2</sub>e, with an economic value of US\$ 479.6 /ha. The degraded seagrass ecosystem could emit 354.5 t CO<sub>2</sub>/ha with an economic loss of US\$ 2,481.7/ha.

■ Regular monitoring, wide-scale restoration, community participation, capacity building among the stakeholders, and more legal protection are imperative to conserve the integrity of the existing blue carbon ecosystems and to enhance their carbon storing potential.



*Syringodium isoetifolium* and  
*Thalassia hemprichii*





# EXECUTIVE SUMMARY

**R**ise in the level of atmospheric carbon dioxide (CO<sub>2</sub>) has been reported to be the primary cause of the climate change impacts we face today. The oceans with their complex internal dynamics are the major influencing factors determining the atmospheric CO<sub>2</sub> content over longer time periods. Blue carbon is the CO<sub>2</sub> absorbed from the atmosphere and captured by the world's oceans and coastal ecosystems. This carbon is stored in the form of biomass and also in the sediments in mangroves (Alongi 2014), salt marshes (Mcleod *et al.* 2011), seagrass meadows (Fourqurean *et al.* 2012), tidal freshwater forested wetlands (Neubauer 2014), kelp forest (Krause-Jensen and Duarte 2016), mudflats (Al Disi *et al.* 2023), coastal peat land (Page and Baird 2016), and polar and sub-polar ecosystems (Smith *et al.* 2015) and hence these ecosystems are called blue carbon ecosystems. Investment in blue carbon provides invaluable ecosystem services that contribute to people's ability to mitigate and get adapted to the impacts of climate change. Due to the remarkable carbon sequestration and storage potential of blue carbon ecosystems, many countries around the world have started to

implement blue carbon restoration projects using carbon financing mechanisms.

By absorbing 93% of heat and 25-30% of CO<sub>2</sub> emissions, the ocean performs a vital function in determining the global temperatures. However, ocean warming and acidification due to climate change threaten its essential functions and ecosystem services such as food production (Hoegh-Guldberg *et al.* 2019). Coastal ecosystems such as mangroves, salt marshes, and seagrass meadows are among the largest carbon storehouses. Mangroves growing in the intertidal zone provide habitats for endangered marine species and offer food security for coastal communities. They store and sequester large amounts of blue carbon through their extensive root systems and sediment trapping, enhancing their capacity for carbon sequestration. Salt marshes are recognized as blue carbon sinks due to their high primary production and carbon burial rates. Their co-benefits include providing coastal protection, erosion management, water purification, and support for fisheries. Seagrasses, which contribute 20% to global fisheries, are major blue carbon sinks,





trapping organic matter and promoting  $C_{org}$  preservation in the oxygen-poor sediment environments (Unsworth *et al.* 2019; Bosold 2012).

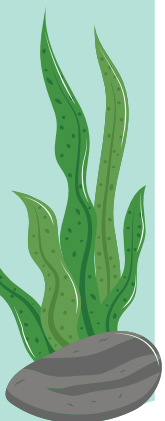
Oceans play a crucial role in the global carbon cycle, with 93% of Earth's  $CO_2$  stored and cycling within the sea. Mangrove, salt marsh, and seagrass ecosystems, covering less than 0.5% of the sea bed, contribute more than 50% of the carbon storage in ocean sediments (Duarte *et al.* 2005). Mangroves, covering 1,50,000  $km^2$ , can accumulate carbon with a global range of 0.17 to 4.3 Mg C/ha/year, which is significantly higher than land forests (Lamont *et al.* 2020). Salt marshes, covering 52,800  $km^2$ , have a high carbon storage capacity with an average carbon accumulation rate of 24,500 Mg C/ha/year (Ouyang and Lee 2014). Seagrass meadows, covering 3,00,000 to 6,00,000  $km^2$ , can store 140 Mg C/ha in the top one meter soil, storing 27.4 teragrams of carbon (Tg C)/year globally (Duarte *et al.* 2010). India has a mangrove cover of 4,975  $km^2$ , with a carbon stock of 386 tonnes/ha and a carbon sequestration potential of 702.42 million tonnes of  $CO_2$  e (Mathur *et al.* 2020). In India, the salt marsh cover is about 290  $km^2$  (Viswanathan *et al.* 2020) and the seagrass cover is about 517  $km^2$  (Geevarghese *et al.* 2018), with a carbon stock of 108 tonnes/ha and a total carbon sequestration potential of 10.2 million tonnes of  $CO_2$  e (Mathur *et al.* 2020).


Tamil Nadu is endowed with the three blue carbon ecosystems namely mangroves (covering about 45  $km^2$ ; Mathur *et al.* 2020), salt marshes (covering about 61  $km^2$ ; SAC 2011; Banerjee *et al.* 2017) and seagrass meadows (covering about 393  $km^2$ ) and they play a crucial role in carbon storage and sequestration, biodiversity support, and provision of livelihood for local communities. A study was conducted during February-May 2024 to estimate the blue carbon stocks in the top 1 m of the soil from the three ecosystems. A total of 72 soil cores were collected from 6 mangrove sites (Tuticorin region), 6 salt marsh sites (Tuticorin region) and 12 seagrass sites (Palk Bay and GoM regions). The mangrove sites represented four types of habitats namely degraded, restored,

sparse (mangrove cover with 3 to 6 nos/10m<sup>2</sup>) and dense (mangrove cover with more than 6 nos/10m<sup>2</sup>); the salt marsh sites represented three types of habitats namely degraded, sparse (with a salt marsh cover of less than 40%) and dense (with a salt marsh cover of more than 40%); and the seagrass sites represented four types of habitats namely degraded, restored, sparse (with a seagrass cover of less than 40%), and dense (with a seagrass cover of more than 40 %).

For the mangrove ecosystem in Tamil Nadu, the average blue carbon stock is 111.19  $\pm$  10.46 Mg C/ha, whereas the total estimated carbon stock is 5,00,355 Mg C with an economic value of US\$ 12.85 million. For the salt marsh ecosystem in the state, the average blue carbon stock is 108.76  $\pm$  12.32 Mg C/ha, whereas the total estimated carbon stock is 6,63,436 Mg C with an economic value of US\$ 17.03 million. For the seagrass ecosystem, the average blue carbon stock is 96.69  $\pm$  13.19 Mg C/ha, whereas the total estimated carbon stock is 37,97,983.2 Mg C with an economic value of US\$ 97.48 million. Seagrass restoration in Tamil Nadu generates an additional 18.69 Mg C/ha of carbon in the top 1 m soil with 68.51 t  $CO_2$  e, with an economic value of US\$ 479.58/ha. Similarly, it is estimated that the degraded seagrass ecosystem can emit 354.53 t  $CO_2$ /ha if all the  $C_{org}$  in the upper 1 m of the soil is oxidized to  $CO_2$  with an economic loss of US\$ 2,481.71 /ha.

On the global scale, the blue carbon ecosystems comprising mangroves, salt marshes, and seagrasses have an annual economic value of \$ 2.05 trillion. The Paris Agreement aims to limit global temperature increase to 1.5° C by 2050, while UN Sustainable Development Goal 14 aims to preserve and responsibly use Earth's oceans and marine resources by 2030. Blue finance, a new field in climate finance, aims to protect clean water, preserve underwater ecosystems, and support a sustainable water-based economy. This involves investing in ocean action, such as protection of mangroves and seagrass meadows, which can reduce  $CO_2$  emissions by 0.5-1.38 gigatons (Gt) per year. The Indian Ocean region's potential






for trade is 15% annually, reaching over US\$ 120 billion by 2025 (Wingnaraja *et al.* 2018). India aims to establish a carbon sink of 2.5-3.0 billion by 2030 through forest and tree cover expansion. Challenges include limited private sector participation, lack of data on carbon stocks, and geographic constraints. Currently, Tamil Nadu has started implementing various initiatives for tapping the blue carbon wealth.

Blue carbon ecosystems and the stock of carbon stored in the sediments and biomass are prone to a wide variety of threats leading to degradation. It has been estimated that about one-third of blue carbon ecosystems has been lost during the past several decades globally. Increasing temperature levels, rising sea levels, increasing CO<sub>2</sub> levels and intense and frequent storms caused by climate change have significantly impacted all the blue carbon ecosystems around the world. Human-induced threats differ from ecosystem to ecosystem in diversity and intensity. As mangroves occur at the interface of land and sea, they are prone to several coastal development activities and pollution. Due to their fragility, seagrass beds are significantly affected by coastal development activities, nutrient

enrichment, and destructive fishing methods. Salt marshes are affected primarily by land conversion along with other coastal development activities, enriched nutrient levels, pollution and bio-invasion.

In view of the continuous decline of blue carbon ecosystems and the diverse nature of the threats they face, it is imperative that they are regularly monitored and assessed in order to understand the trends and act accordingly. Wide-scale restoration of blue carbon ecosystems using viable protocols is warranted as the degradation and loss have been severe during the past few decades. Provision of proper education and capacity building among the stakeholders, in particular, coastal communities is of great importance for better and sustainable results. Climate change adaptation and mitigation measures should be developed and continuously implemented to conserve blue carbon ecosystems as the climatic scenario is deteriorating. Establishment of protected areas and co-management are also critical to conserve the blue carbon ecosystems not only to sustain their carbon storing capacity but also to sustain all the ecological and economic benefits they offer.



*Sesuvium portulacastrum*





## WAY FORWARD

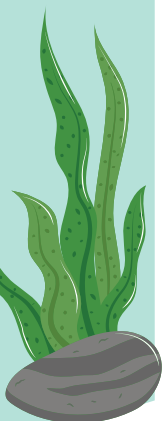
**Assessment and conservation:** The assessment of blue carbon stocks in representative sites of mangrove, salt marsh and seagrass ecosystems in Tamil Nadu gives firsthand information on the rich hidden wealth. A comprehensive study and mapping of stocks in all blue carbon ecosystems of Tamil Nadu not only helps in understanding the resource potential but also assists in taking appropriate conservation and management measures, which is of primary importance in retaining the stored carbon and also in enhancing ecosystem services in general.

**Restoration:** Blue carbon ecosystems along the Tamil Nadu coast have declined in status and health during the past couple of decades due to climatic and non-climatic factors. The wide-scale restoration of these ecosystems helps to compensate the loss and to improve the status. Use of standardized feasible protocols, involvement of community and regular monitoring and maintenance are important to improve the success rate.

**Research:** More research and studies are needed to manage, conserve and

utilize the blue carbon ecosystems in a sustainable manner. Short-term and long-term research programmes are needed focusing on blue carbon stocks in the biomass and sediments, mapping of the existing blue carbon ecosystems and increasing their carbon production potential to enable them to recover naturally. Regular and continuous monitoring of the status and health of all blue carbon ecosystems is necessary to identify any changes. In India, this is especially important for ecosystems with limited information, such as salt marshes, while we also need the information on other ecosystems like mangroves and seagrasses.

Prioritization of extensive studies is to be given to measure the carbon sequestration capacity of various blue carbon ecosystems, measurement of carbon stocks in all the potential compartments of an ecosystem (such as soil, aboveground living biomass, aboveground dead biomass, and belowground living biomass), and repeated measurements of carbon stocks over time to estimate the changes or flow of carbon in or out of a particular area.





*Enhalus acoroides*

**Carbon credits:** The carbon credit systems are being used around the world. By restoring or conserving blue carbon ecosystems, this compensates for the carbon emissions for individuals or companies. This system needs to be given importance to develop climate change adaptation and mitigation measures.

Carbon credit system can be promoted among the companies that emit carbon and they can pay for protecting and restoring blue carbon ecosystems for every tonne of CO<sub>2</sub> emitted from their concern. The carbon revenue flow should be through the Government and local communities for investing in restoration of blue carbon ecosystems to offset the emissions. Organizations, corporations, and people along the coast can be encouraged to purchase carbon offsets to reach net zero. Local blue carbon conservation projects can be prepared and sold in international carbon market for carbon credits. This system may greatly help in reducing the effect of climate change by spending on blue carbon ecosystems and it would also ultimately help the dependent communities as well as assist the entities for its success.



*Rhizophora mucronata*

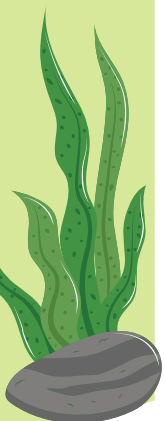


# 1

## INTRODUCTION TO BLUE CARBON

*Salicornia brachiata*





### 1.1. Introduction

The ocean plays a crucial role in controlling global temperatures. It not only absorbs 93% of the heat trapped in the atmosphere due to the increase in CO<sub>2</sub> caused by human action, but also absorbs about 25 to 30% of the human-caused CO<sub>2</sub> emissions that would otherwise stay in the atmosphere and contribute to increase the intensity of global warming (Hoegh-Guldberg *et al.* 2019a). The ocean is responsible for around 50 percent of the oxygen generated on Earth, thanks to the photosynthetic activities of marine plants and algae. The ocean's capacity to perform these essential functions are now under threat due to ocean warming and acidification (IPCC 2019), which damage the marine ecosystems and reduce their capacity to sustain food production, support livelihoods and protect coastal habitats on which billions of people rely (IPCC 2018).

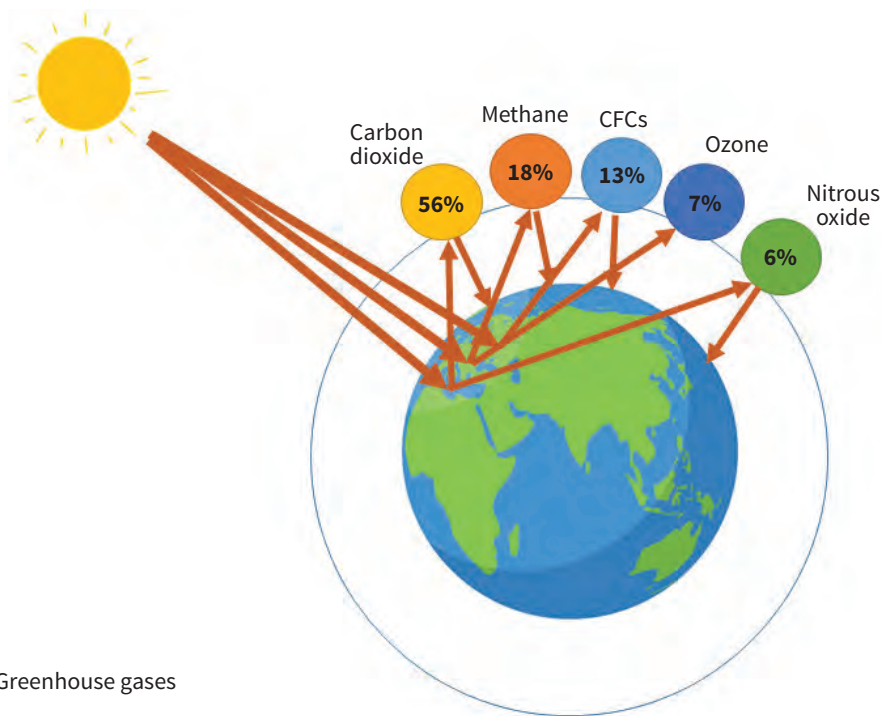
### 1.2. Carbon and global climate change

Most of our atmosphere is made up of nitrogen and oxygen but, unlike these gases, certain other gases absorb heat radiating from the earth's surface and release it back. Earth's

atmosphere naturally has certain gases that absorb thermal infrared radiation emitted by the earth's surface thus warming the atmosphere. The atmosphere then emits radiation that keeps the surface air temperature warm and this phenomenon is called the "greenhouse effect," and the gases that cause this effect are called "greenhouse gases" (Ledley *et al.* 2011). Without this greenhouse effect, the average temperature on earth's surface would be -19° C (Le Treut *et al.* 2007), making the earth non-liveable to most of the organisms. Greenhouse gases include CO<sub>2</sub>, water vapour (H<sub>2</sub>O), ozone (O<sub>3</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and chlorofluorocarbons (CFCs) (Fig. 1).

Among the greenhouse gases, CO<sub>2</sub> is the primary gas contributing about 20% of the thermal absorption (Schmidt *et al.* 2010; Fig. 2).

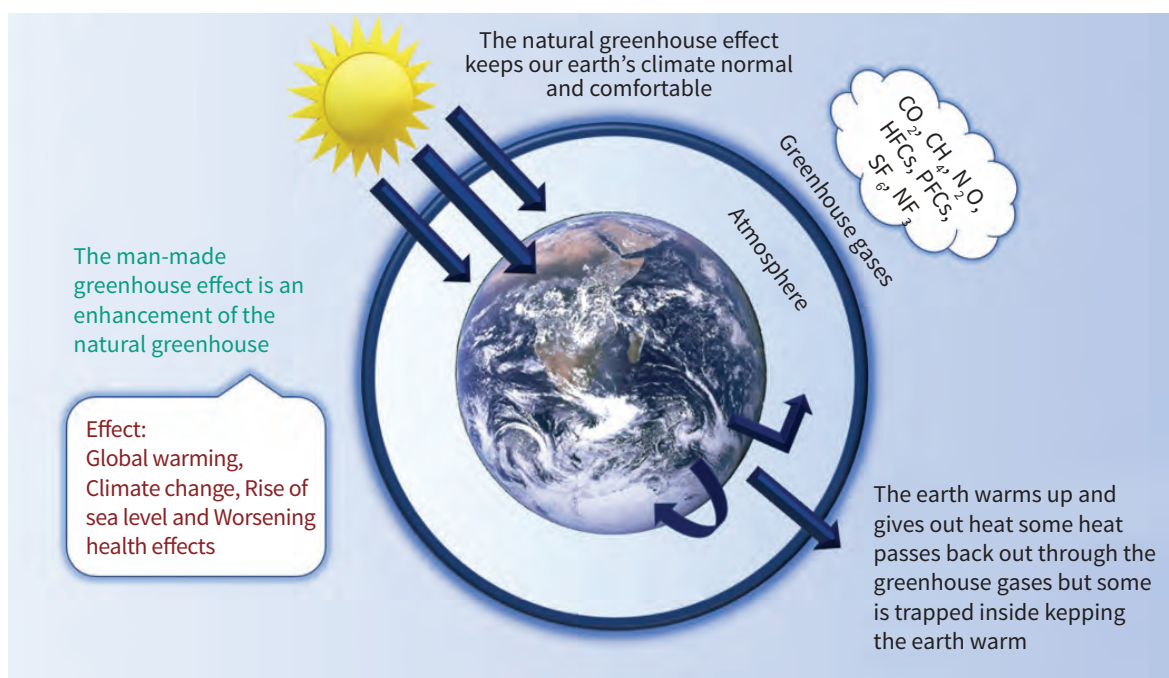
According to observations by the National Oceanic and Atmospheric Administration (NOAA), CO<sub>2</sub> alone was responsible for about two-thirds of the total heating influence of all human-produced greenhouse gases in 2021. There are certain natural sources of CO<sub>2</sub> such as the organic decomposition, volcanic eruptions, ocean-atmosphere exchange and



**Fig. 1:** Greenhouse gases

plant and animal respiration while human-induced sources include cement production, deforestation, burning fossil fuels such as oil and natural gas, etc. (Cassia *et al.* 2018). It is a well-known fact that human activities release

CO<sub>2</sub>, which increases the atmospheric carbon. It has also been understood that these gases are capable of altering earth's climate. Climate change refers to long-term shifts in temperatures and weather patterns.



**Fig. 2:** Effects of greenhouse gases

*Syringodium isoetifolium* and  
*Thalassia hemprichii*



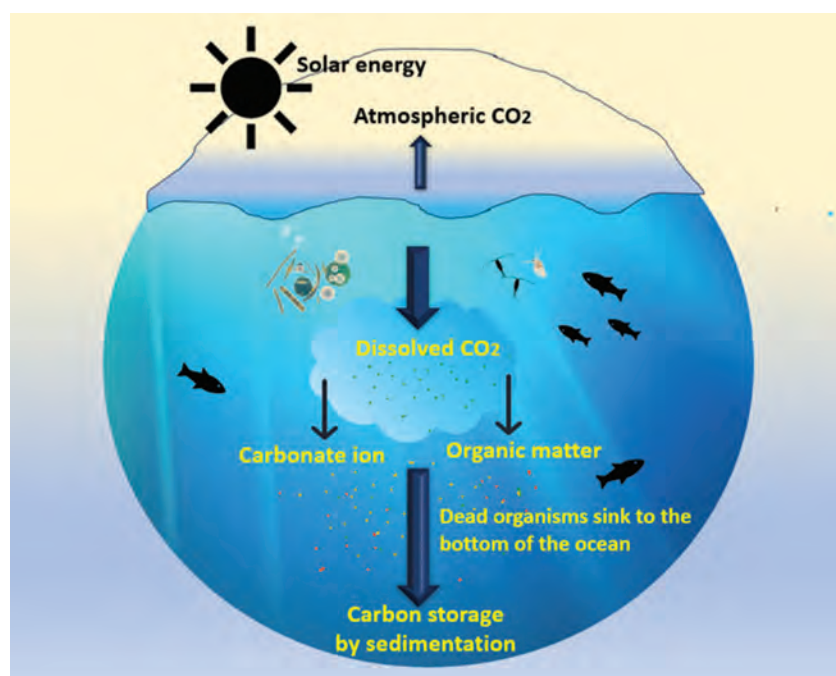
During the past 200 years, the average atmospheric concentration of CO<sub>2</sub> has increased from 280 parts per million volume to 422.38 parts per million volume, which is an increase of about 51% (<https://gml.noaa.gov/ccgg/trends/mlo.html>). It has been reported that about 50% of the anthropogenic CO<sub>2</sub> emissions from 1750 to 2010 has happened after the 1970s (IPCC 2014). Due to the increased human activities, carbon emissions have continued to grow fast, and current emissions are estimated to be more than 35 billion tonnes every year (Ritchie and Roser 2020).

### 1.3. Ocean and carbon absorption

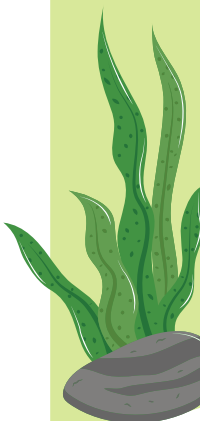
The oceans are often termed as the lungs of the planet as they generate about 50% of the oxygen we breathe and they act as a net carbon sink (Fig. 3). The solid earth is the largest carbon storage holding about 100,000 times more carbon than the atmosphere and the second largest carbon reservoir is the ocean having about 60 times more carbon than in the atmosphere (DeVries 2022). The global carbon cycle or the exchange of carbon happens between the solid earth, the ocean and the atmosphere.

The ocean plays a very important role in the

global carbon cycle as it readily exchanges with the atmosphere. It has been estimated that the ocean acts as a carbon sink for about 31% of the carbon emissions between the beginning of the industrial revolution and the mid-1990s (Gruber *et al.* 2019). Thus, world oceans with their complex internal dynamics are the major influencing factor determining the atmospheric CO<sub>2</sub> content over longer time periods (Tanhua *et al.* 2013). Hence, changes in the marine carbon cycle under the increasing anthropogenic carbon emissions result in undesirable phenomena such as ocean warming, ocean eutrophication, ocean acidification, and ocean deoxygenation (Tanhua *et al.* 2013). The air-sea exchange of CO<sub>2</sub> between the ocean and atmosphere is instigated by the diffusion of gaseous CO<sub>2</sub> across the air-sea interface (DeVries 2022). The carbon sequestration capacity of oceans is stretched to uptake the additional anthropogenic CO<sub>2</sub>. Since the pre-industrial period, oceans have been reported to have absorbed half of the fossil-fuel CO<sub>2</sub>, consequently causing the oceans to become more acidic (Riebesell *et al.* 2007). The absorption of CO<sub>2</sub> by seawater and the subsequent chemical reactions are collectively called the seawater CO<sub>2</sub>-carbonate system, which controls the pH of ocean waters.



**Fig. 3:** Ocean and carbon absorption



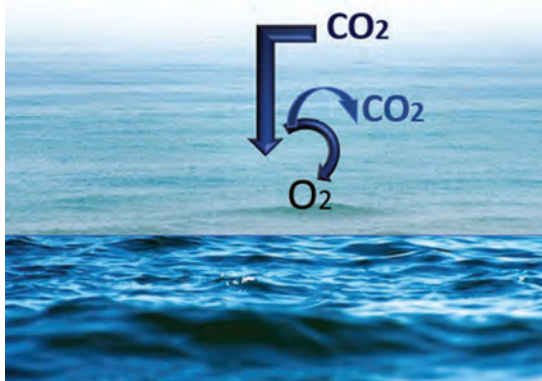


Fig. 4: Ocean acts as a carbon sink

#### 1.4. What is blue carbon?

Blue carbon is the  $\text{CO}_2$  absorbed from the atmosphere and captured by the world's oceans and coastal ecosystems (Fig. 4). The coastal blue carbon is stored in the form of biomass and sediments of the mangrove forests, tidal/salt marshes and seagrass meadows. Among the coastal blue carbon ecosystems, seagrass meadows are found distributed across the temperate and tropical regions, mangroves are predominantly restricted to tropical and subtropical regions and tidal/salt marshes occur in all regions (Pendleton *et al.* 2012). Increasing the blue carbon content is the most effective method for long-term sequestration and storage of carbon but this field has received importance only in recent years (Fig. 5). Blue carbon ecosystems have the potential to mitigate climate change impacts and they also provide other benefits such as coastal protection, biodiversity sustainability and fisheries enhancement (Nellemann *et al.* 2009; Macreadie *et al.* 2019).

Through photosynthesis, atmospheric carbon is stored as  $\text{C}_{\text{org}}$  in the biomass of these blue carbon ecosystems for decades and for thousands of years in sediments (Duarte *et al.* 2005; Barbier *et al.* 2011; Wedding *et al.* 2021). Blue carbon

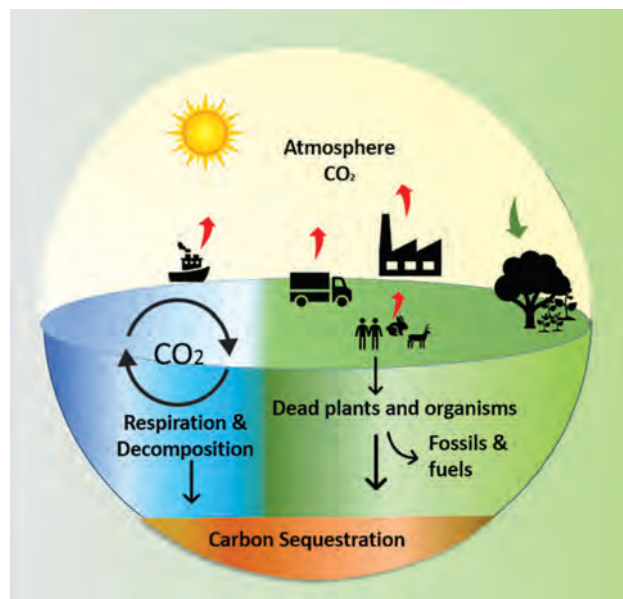


Fig. 5: Atmosphere and Ocean exchange  $\text{CO}_2$

ecosystems store huge amounts of  $\text{C}_{\text{org}}$  in the sediments as organic matter accumulates in these ecosystems. The comparatively higher rates of primary productivity and the ability to powerfully trap suspended particles in the water make these ecosystems better at trapping organic carbon than the terrestrial ecosystems. Further, the hypoxic conditions prevailing in the sediments of blue carbon ecosystems suppress the microbial decomposition of organic matter and control the remineralization processes (Duarte *et al.* 2013; Lovelock *et al.* 2017). The accumulation of organic matter in blue carbon ecosystems is also boosted by the trapping of organic material generated from other sources (Lovelock and Reef 2020).

The climate of the Earth is closely linked to the amount of blue carbon and hence it has been agreed that maintenance and enhancement of carbon storage in the blue carbon ecosystems will significantly contribute to climate change mitigation and adaptation (Lovelock and Reef 2020). Traditionally, terrestrial forests have been portrayed as carbon sequestration solutions, and numerous initiatives have been taken for reforestation, afforestation, and reductions in deforestation in order to mitigate climate change impacts, but blue carbon ecosystems have been

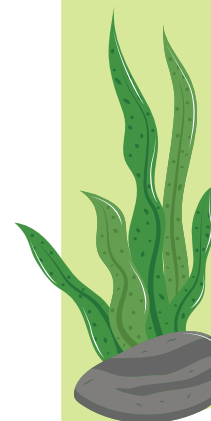
established in certain conditions to exceed the carbon capture capacity of the terrestrial forests (Wedding *et al.* 2021). During the past two decades, much of the attention has been given to the blue carbon ecosystems as the global climatic conditions continue to degrade. Blue carbon ecosystems have been proved to be a natural climate solution that can fight climate change implications. Blue carbon is of greater importance currently in the international and regional policy agendas along with private sector discussions around financing and carbon markets (Howard *et al.* 2023).

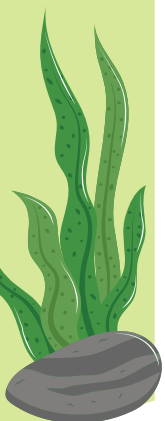
The global distribution of blue carbon ecosystems is estimated to be between 36 and 185 million ha that can potentially store from 8,970 to 32,650 Tg C and also provide various other ecological benefits (Macreadie *et al.* 2019). It has also been estimated that conservation of the existing blue carbon ecosystems can avoid emissions of 304 (141–466) Tg CO<sub>2</sub>e per year globally. Further, wide-scale restoration activities can eliminate another 841 (621–1,064) Tg CO<sub>2</sub>e per year by 2030, which is

equivalent to 3% of the annual global greenhouse gas emissions (Macreadie *et al.* 2019). It is an irony that earlier the ocean has been widely reported to be the victim of climate change, while it is now being represented as part of the solution to the climate crisis through blue carbon storage (De Pryck and Boettcher 2024).

### 1.5. Blue carbon sinks - role in human wellbeing

The industrial revolution brought about economic development, urbanization and industrialization and consequently the increase in the material wealth of human societies (Wang *et al.* 2022). Intense urbanization and industrialization puts significant pressure on climate systems and carbon emission increases every day. Both urbanization and industrialization involve lots of energy consumption and aggravate the carbon emission (Lin and Zhu, 2017). The use of fossil fuels, which primarily contributes to climate change and constant increase of carbon emission levels, is probably the most threatening factor among all (Nellemann *et al.* 2009).





Electricity has become a basic need for human wellbeing as it is necessary for lighting, cooking, travelling, cooling, heating and more, and the generation of electricity using coal is an important source of carbon emission. Thus, there is a strong relationship between human wellbeing and carbon emissions (Li and Chen 2021). It has been reported that there is a strong correlation between the use of electricity and living standards in developing countries and it is a decoupling condition in developed countries (Arto *et al.* 2016). It has also been reported that the annual carbon emissions from the combustion of fossil fuels have increased significantly every decade between the 1960s and the 2010s from an average of 3 billion tonnes of carbon per year to 9.5 billion tonnes (Friedlingstein *et al.* 2022). If sophistication of human lives through urbanization and industrialization is to continue, there should be mitigation measures that reduce carbon emissions and store carbon. It has become a reality that all the efforts in fighting climate change need

a transition to net zero emissions, but making it possible is challenging in the context of continual urbanization and industrialization.

Climate change is known to affect human wellbeing via extreme heat waves, sea level rise, flooding, droughts and hurricanes, changes in precipitation, and impacts on health conditions. Due to significant changes in the physico-chemical properties of the ocean, coastal organisms are seriously affected. For instance, marine heat waves have increased in frequency during the last century causing frequent extreme storms and mass coral bleaching events, consequently affecting sensitive marine organisms and the lives and livelihoods of billions of people (Lam *et al.* 2020; Gill *et al.* 2023). It is highly likely that many species that are unable to cope with changing climatic scenarios would become extinct in the near future affecting the dependent human population.

Nature-based solutions have been recommended



*Rhizophora mucronata*



*Halodule uninervis*  
with sea star

widely for decarbonization, through protection, restoration, and sustainable management of natural carbon sinks. However, these initiatives attach a disproportionately greater importance to green carbon through afforestation (Wang *et al.* 2023). Due to the capacity of coastal ecosystems to store carbon, blue carbon has gathered great interest during the past decade.

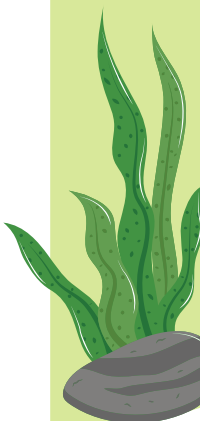
The contribution of blue carbon ecosystems to the global carbon budget and their value in mitigating the effects of climate change have made several international bodies including the Intergovernmental Panel on Climate Change (IPCC) to realize the importance of blue carbon stored in the ocean (Gouldsmith and Cooper 2022). More than 130 countries have committed net zero carbon targets and all the members of the Organisation for Economic Co-operation and Development (OECD) have committed to net zero carbon targets by 2050 (EY Net Zero Centre 2022). About 200 countries have committed to control the global average temperatures at 2° C above pre-industrial levels, but IPCC noted that global greenhouse gas emissions should fall to 'net zero'

levels by 2050 (IPCC 2018).

Investment in blue carbon provides invaluable ecosystem services that contribute to people's ability to mitigate and adapt to the impacts of climate change. Blue carbon ecosystems have a significant carbon storing capacity and have been estimated to contribute more than 60% of the total inorganic carbon though they occupy only 0.5% of the ocean floor (McLeod *et al.* 2011). Moreover, ten times higher annual carbon sequestration rates have been reported from blue carbon ecosystems than from the terrestrial forest ecosystems (Lovelock and Reef 2020). Hence, we need to pay much more attention to blue carbon ecosystems and take efforts to expand their cover for the wellbeing of humans in the deteriorating climatic conditions.

Human beings are very much dependent on biodiversity, and the loss of biodiversity will certainly affect humans by affecting the supply of food, clean water and other raw materials, and this effect will be worse for poor people and vulnerable communities (Sandifer *et al.* 2015). In line

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Salt marsh habitat





*Rhizophora sp.*

with this, the loss of blue carbon ecosystems has already affected coastal communities globally by affecting their livelihood locally. After the realization of the importance of these fragile ecosystems in fighting climate change impacts, it is now clear that the global loss of blue carbon ecosystems have actually affected the humankind in general irrespective of their existence in coastal regions or inland. It is also likely that the situation would get worse if blue carbon ecosystems are constantly affected. As human life is inseparable from the environment, reducing carbon emissions with the help of blue carbon ecosystems is very important (Ul-Durar *et al.* 2023).

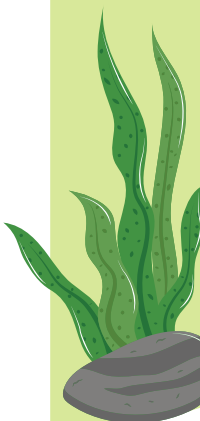
### **1.6. Blue carbon sinks in rapid decline**

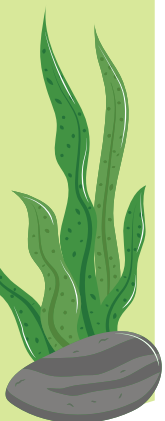
The worldwide degradation of coastal ecosystem has resulted in considerable emission of CO<sub>2</sub>, as carbon stored in biomass and sediments is disturbed and converted to CO<sub>2</sub> and released into atmosphere (Houghton 2003; Lovelock and Reef 2020). Blue carbon ecosystems and the carbon stored in the sediments and biomass are prone to a wide variety of threats leading to degradation

(Lovelock *et al.* 2017). Blue carbon ecosystems around the world are in severe decline primarily due to human activities. Similar to deforestation, the loss of blue carbon ecosystems has diminished the potential of carbon sequestration by the ocean. It has been estimated that about one-third of blue carbon ecosystems has been lost during the past several decades globally (Mcleod *et al.* 2011; Wedding *et al.* 2021). Though the exact amount of carbon stored in each of the blue carbon ecosystems is under significant research, the danger of carbon release due to their degradation is imminent.

Blue carbon ecosystems are significantly affected by human activities such as conversion of coastal wetlands for agricultural production, conversion of mangroves for aquaculture, coastal development and urbanization (Moritsch *et al.* 2021). These vegetated coastal ecosystems are often converted for many other uses like industries, recreation, dam construction, and road construction, apart from aquaculture and agriculture (Pendleton *et al.* 2012). These activities disturb

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the carbon-rich soil and release tonnes of stored carbon back into the atmosphere (Moritsch *et al.* 2021). Though degradation of blue carbon ecosystems has occurred for several centuries, the rate of degradation has accelerated during the past few decades.

About 25 to 50% of the global coastal ecosystems has already been lost due to various factors (Lovelock and Reef 2020). In the past 50 years, approximately one-third of world's mangroves forest has been lost (Alongi 2002), and since 1980 about 29% of seagrass cover has disappeared. This loss can primarily be attributed to human activities. The degradation of these ecosystems has caused significant alterations in marine biodiversity, coastal protection, nutrient cycling and a wide range of other ecological services along with the reduction in their capacity to act as carbon sinks. Thus, the degradation of blue carbon ecosystems has reduced their potential of climate change mitigation and other important ecological functions (Lovelock and Reef 2020). The release of stored blue carbon into the atmosphere has already caused significant economic impacts globally causing droughts, sea level rise, heat waves and extreme weather events (Tol 2009).

It has been estimated that degradation of blue carbon ecosystems may release 0.15 to 1.02 Pg (billion tonnes) of CO<sub>2</sub> per year globally into the atmosphere with an average of 0.45 Pg CO<sub>2</sub> and this loss could cost between \$ 6.1 and \$ 42 billion annually (Pendleton *et al.* 2012). Mangroves have the largest carbon stocks storing half the estimated total blue carbon emissions, followed by seagrass meadows and salt marshes, and the loss of these ecosystems may contribute to 3–19% additionally to the global emissions from deforestation (Van der Werf *et al.* 2009; Pendleton *et al.* 2012). Thus, the loss of blue carbon ecosystems around the world aggravates the climate change scenario.

### 1.7. Carbon markets

To tackle the climate change crisis, international agencies have taken several initiatives and carbon markets are one of them. In the midst of a technological revolution towards decarbonisation, the use of carbon credits has gained significant attention during the past few decades. Due to the increased carbon emission, carbon stored in natural carbon sinks are quantified using scientific methods and sold as credits and the buyers can use it to offset their emissions and this transaction is called emissions trading (Ullman *et*



*Suaeda maritima*

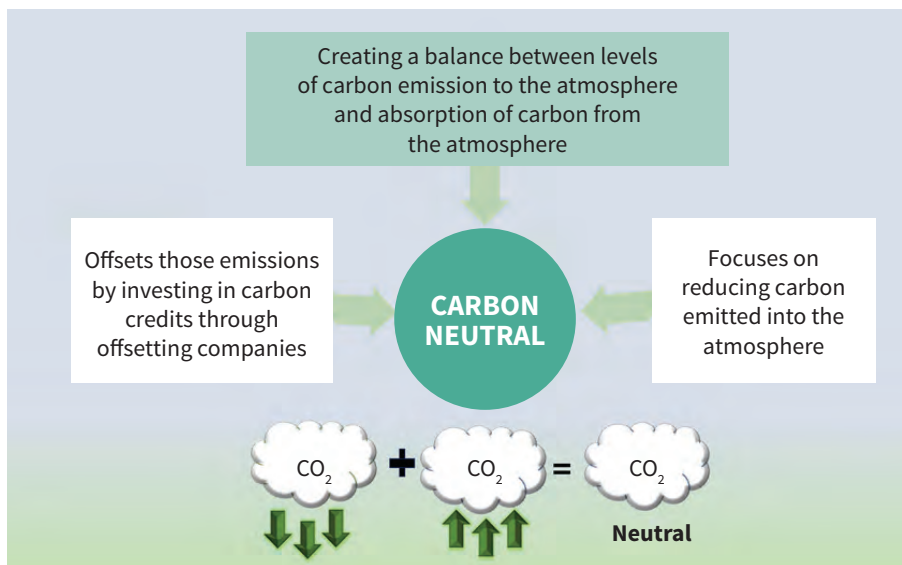


Fig. 6: Carbon neutrality

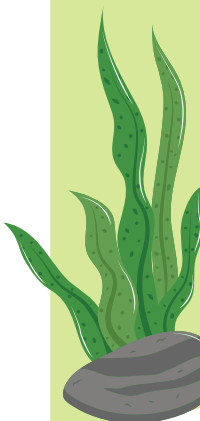
al. 2013). Due to the remarkable carbon sequestration and storage potential of blue carbon ecosystems, many countries around the world have started to implement blue carbon restoration projects using carbon financing mechanisms (Wylie *et al.* 2016). It refers to the provision of financial resources for economic activities that offer environmental improvements (Qi *et al.* 2024).

Carbon markets are mechanisms used to trade carbon credits to reduce greenhouse gas emissions. They can be categorized into voluntary carbon markets and regulatory (compliance) carbon markets. Voluntary carbon markets allow companies, organizations, and individuals to purchase credits without any regulatory obligation. These markets are driven by corporate social responsibility or sustainability goals, and typically come from emission-reducing or carbon-sequestration projects. Benefits include promoting innovation in emission reduction technologies and flexibility for buyers. Challenges include greenwashing risks and less oversight (TSCVM, 2021). Regulatory carbon markets, also known as compliance markets, operate under mandatory regulations set by national or regional governments to control greenhouse gas emissions. They are established as part of cap-and-trade systems, carbon tax systems, or emissions trading schemes (ETS). Benefits include incentives for emission reductions, transparency

and oversight, and increased accountability. Challenges include carbon price volatility and limited coverage, as only certain sectors are regulated, leaving significant global emissions unregulated. It is widely accepted that carbon markets have the potential to reduce the costs of achieving global emission targets. However, it is important to bring all the countries on board to make significant progress.

Creating a balance between the level of carbon emission into the atmosphere and the level of carbon absorption from the atmosphere is called carbon neutrality or net-zero radiations (Fig. 6). A total of 124 countries around the world have committed to strive for carbon neutrality by 2050 with the aim of keeping global warming at 1.5–2° C above pre-industrial levels by 2050 (UI-Durar *et al.* 2023).

However, global carbon levels remain high in spite of these attempts so far. Manufacturers and businesses that involve carbon emission should use techniques that decrease their carbon footprint and simultaneously enhance environmental performance for which all areas of the economy must work together. It has been suggested that to develop carbon neutrality, it is important to decrease emissions via switching from fossil fuels to carbon-free renewable energies (UI-Durar *et al.* 2023).



*Halodule uninervis*

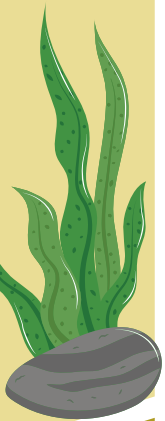


# 2

## **CONTRIBUTION OF COASTAL ECOSYSTEMS TO BLUE CARBON**

*Rhizophora mucronata*





### 2.1. Introduction

Coastal ecosystems are highly productive natural systems on Earth and they support a rich variety of life. They perform crucial ecological functions, such as safeguarding the coastlines from storms and serving as breeding places for fish. Coastal and marine ecosystems comprise several significant habitats, such as coral reefs, mangroves, seagrass meadows, salt marshes, sand dune systems, and salt marshes (Mathur *et al.* 2020). They are among the largest carbon storehouses on Earth with CO<sub>2</sub>

burial rates (the rate at which carbon is transformed into biomass via photosynthesis) 20 times higher than in any other land-based ecosystem, including boreal, temperate and tropical forests (Hamilton 2018). Policymakers worldwide are increasingly acknowledging the function of these ecosystems in sequestering and storing blue carbon from the atmosphere and seas. Now-a-days, carbon sequestration is also considered as the additional benefit offered by tropical coastal ecosystems (Osland *et al.* 2022).

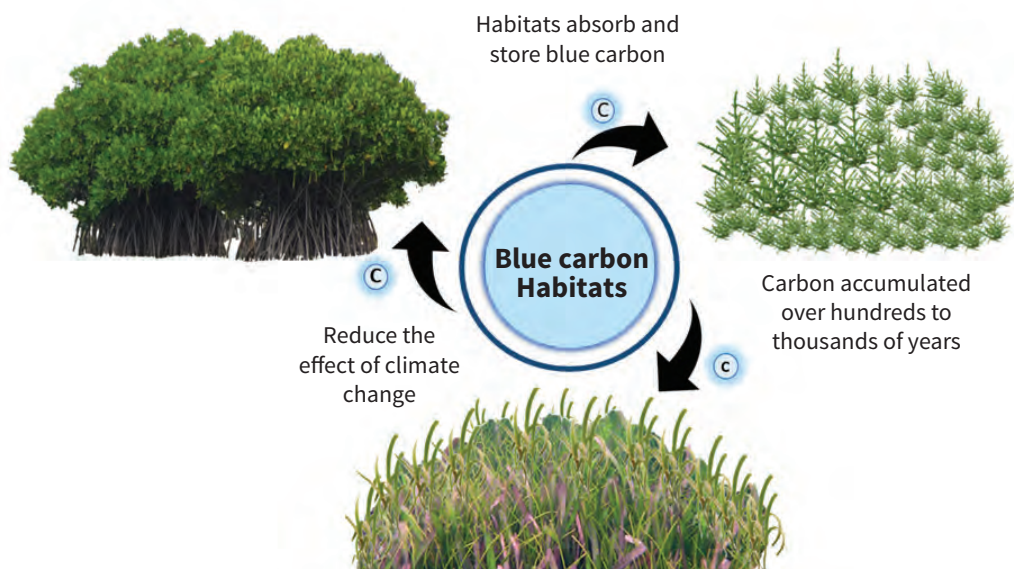
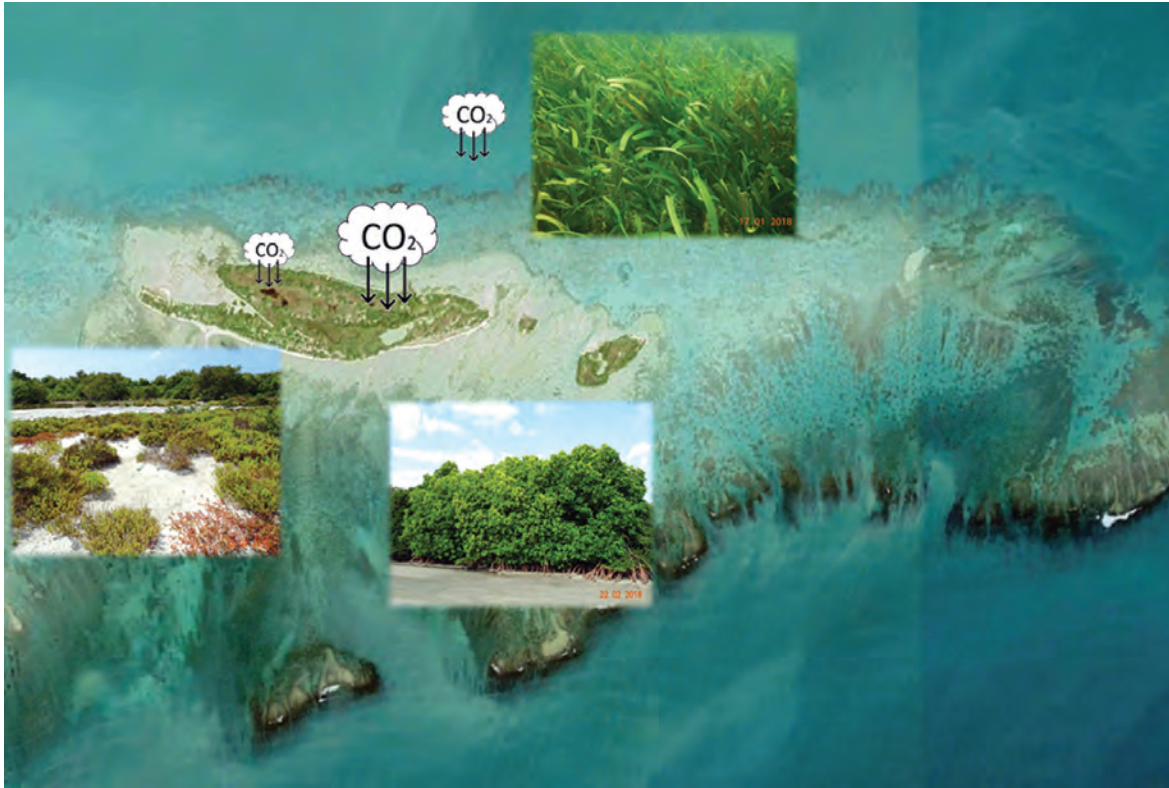


Fig. 7: Key blue carbon habitats



Manoli Island in Gulf of Mannar - CO<sub>2</sub> sequestration by mangroves, salt marshes and seagrasses  
(Source: Google Earth Image)

## 2.2. Blue carbon habitats

Mangroves, salt marshes and seagrass beds are three forms of coastal wetlands that are sometimes called blue carbon habitats (Fig. 7). These ecosystems offer a wide range of advantages in terms of mitigation, adaptation, and resilience. They provide a multitude of benefits and services that help individuals in their efforts to reduce and get adjusted to the effects of climate change. Several of these services are crucial for climate adaptation and resilience in coastal areas.

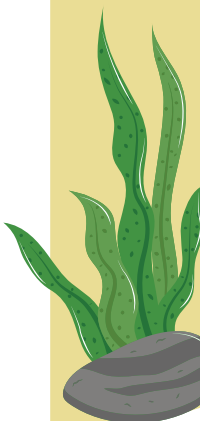
Some of these services are: safeguarding against storm surge and sea-level rise, mitigating shoreline erosion, regulating coastal water quality, recycling nutrients, trapping sediment, providing habitats for commercially important and endangered marine species, and ensuring food security for coastal communities worldwide (Robertson and Alongi 1992; King and Lester 1995; Kathiresan *et al.* 2001; Saenger and Saenger 2002; Gedan *et*

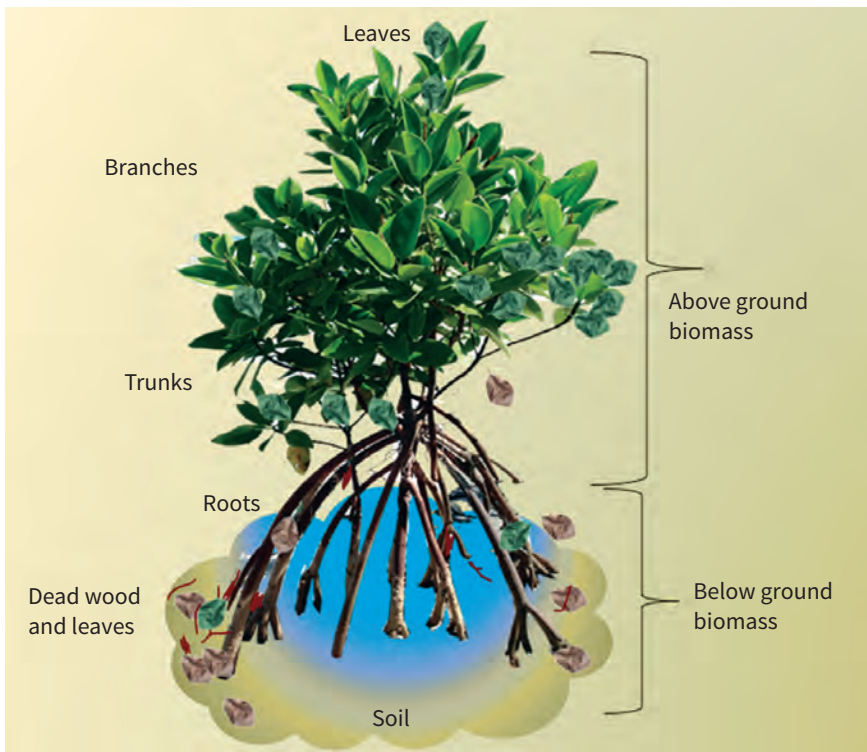
*al.* 2009; Mathur *et al.* 2020). Approximately 150 nations worldwide possess at least one of these coastal wetland habitats, whereas about 70 countries are endowed with all the three (Mathur *et al.* 2020).

### Autochthonous and allochthonous blue carbon

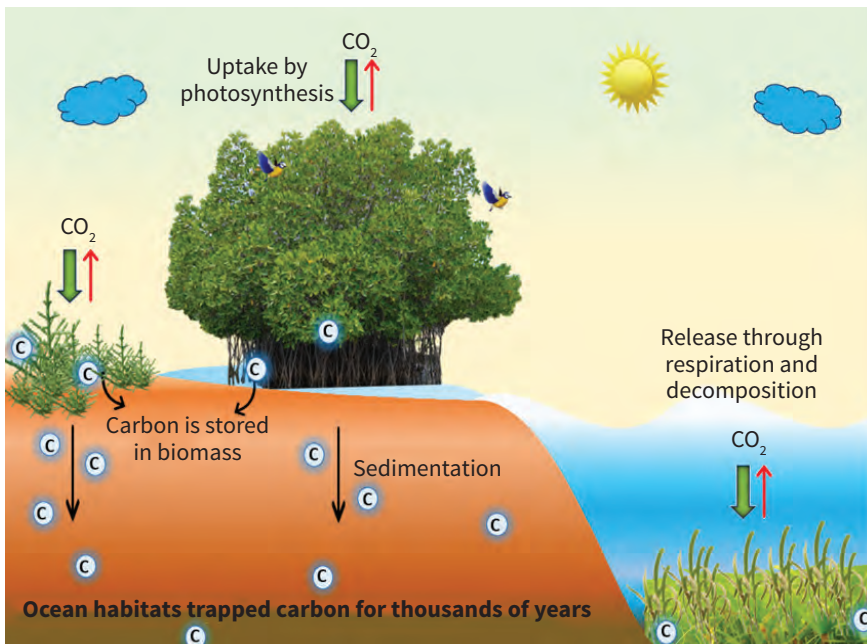
The stocks of blue carbon stored by mangroves, salt marshes, and seagrass meadows are mainly found in the four fundamental carbon pools namely the soil, the aboveground living biomass (leaves, branches, stems), the aboveground dead biomass (such as leaf litter and downed wood), and the belowground living biomass (roots and rhizomes) (Fig. 8).

The movement of plant and silt particles from the neighbouring habitats (mangrove, seagrass and salt marshes) is a common phenomenon. Seagrass beds often include a small number of





**Fig. 8:** Carbon pools in mangrove ecosystem

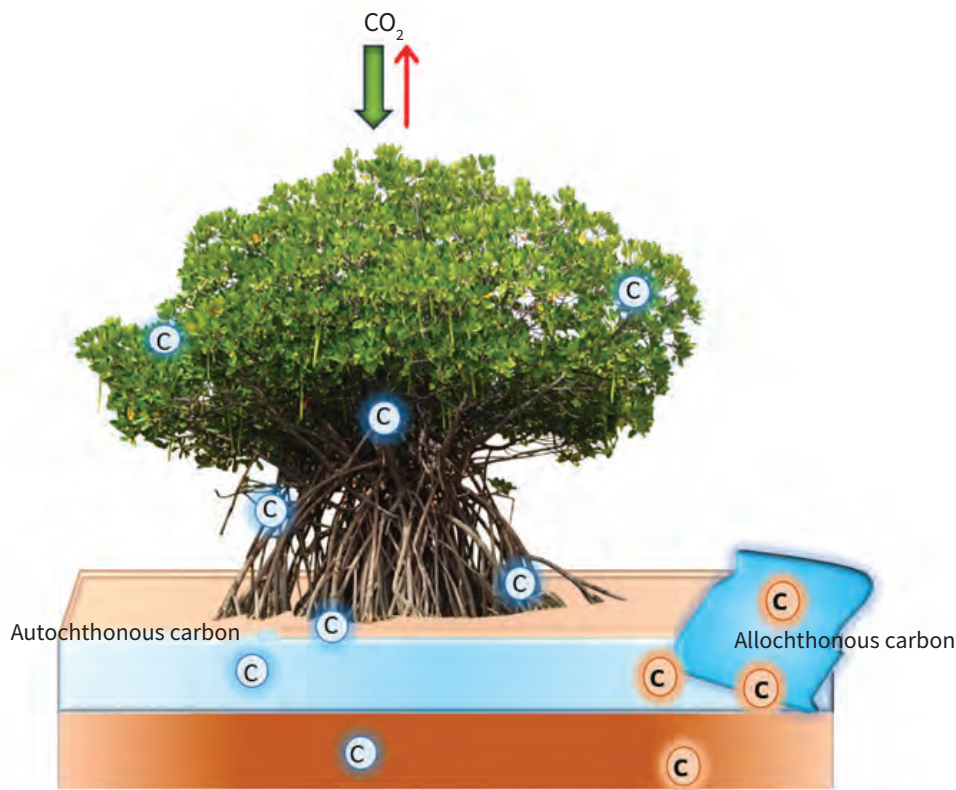


**Fig. 9:** Blue carbon ecosystems capturing and storing carbon

mangrove propagules and leaves, while seagrass leaves are often found in the sediments of mangroves and salt marshes (Fig. 9).

Additionally, it is possible for organic matter derived from land areas to be transported and

incorporated into blue carbon environments. The carbon in the blue carbon ecosystems is categorized into autochthonous and allochthonous carbon (Middelburg *et al.* 1997; Kennedy *et al.* 2010; Fig. 10). Plants extract CO<sub>2</sub> from the atmosphere and seawater by means of photosynthesis,



**Fig. 10:** Autochthonous and Allochthonous carbon in mangrove ecosystem

a process known as primary production. This  $\text{CO}_2$  is then transformed into a form that can be used by various parts of the plant, including leaves, stems, roots, and rhizomes, in order to enhance the overall mass of the plant.

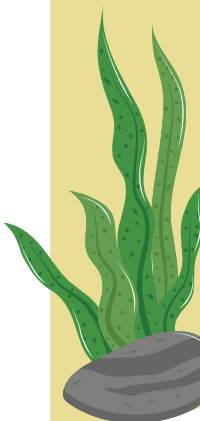
A significant proportion of plant biomass is directed towards the roots, where it undergoes gradual decomposition under anaerobic conditions, effectively sequestering carbon within the sediment. In contrast, allochthonous carbon is generated in a certain region and then transported and deposited in a different location.

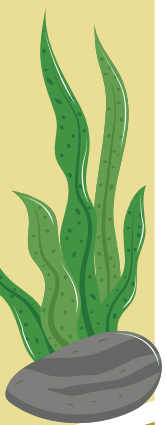
Blue carbon ecosystems thrive in highly dynamic environments, experiencing continual exposure to waves, tides, and coastal currents. These forces transfer sediments and  $\text{C}_{\text{org}}$  from neighbouring ecosystems (such as offshore or terrestrial ecosystems) to different locations. The plants present in these systems possess intricate

root structures and canopies that effectively capture sediment as it flows through the system, thereby contributing to the accumulation of (allochthonous) carbon in the surrounding area (Johnson *et al.* 2007).

### Soil carbon accumulation in blue carbon ecosystems

The main distinction between soil carbon accumulation in the terrestrial and coastal ecosystems lies in the fact that the potential carbon storage in upland soil is constrained by the abundant presence of oxygen, which facilitates aerobic microbial carbon oxidation and its subsequent release into the atmosphere (Schlesinger and Lichter 2001). In blue carbon ecosystems, the soil is saturated with water, which maintains an anaerobic condition with minimal to no oxygen. As a consequence, the soil continuously accumulates carbon vertically at high rates, leading to a continuous increase in carbon over time (Chmura *et al.* 2003).





Mangroves in Pichavaram

### 2.3. Mangrove ecosystem

Mangroves are woody plants that grow at the interface between land and sea in brackish to saline tidal waters of tropical and sub-tropical latitudes (Mitsch and Gosselink, 2000). Mangrove may be a tree, shrub, palm or ground fern that typically grows more than half a meter tall and is found in the intertidal zone of marine coastal areas and estuary edges, above the average sea level. Mangroves have a wide range of taxonomic richness, consisting of about 50-75 species of woody plants (Asante *et al.* 2023). They exhibit diverse morphological and physiological adaptations to endure the challenges posed by low oxygen levels, excessive salinity and regular tidal flushing. The adaptations include features like succulent leaves, sunken stomata, pneumatophores, vivipara, stilt roots, and buttresses. Mangroves are highly adapted to extreme conditions such as high salinity, extreme tides, and anaerobic soils (Kathiresan *et al.* 2001). The stilt roots provide support against the streams and unstable soil,

allowing growth up to 60 m. These roots extend sideways, providing stability to the substrate and ensuring the plants stability during daily tide shifts (Kathiresan *et al.* 2001). Mangrove plants, along with associated microbes, fungi, plants, and animals, form the mangrove forest community or mangal, which constitutes the mangrove ecosystem. The term ‘mangrove’ can refer to both the plants and the forest community.

#### Importance of mangroves

Mangrove forests are incredibly valuable coastal resources that are tremendously essential for socio-economic development; they defend the coast from a variety of natural calamities, such as tsunamis, cyclones and extreme weather conditions (Kumar *et al.* 2014; Raihan *et al.* 2019), and make a large contribution to the global carbon cycle. They also serve as breeding and nursing grounds for marine finfish and shellfish species of commercial importance (Carrasquilla-Henao *et al.* 2019). Mangrove soils are often

oxygen-deficient or anaerobic, causing flora and fauna to adapt.

The most prominent adaptation is the presence of breathing roots, or pneumatophores, which are above-ground roots filled with spongy tissue and with numerous small holes in the bark. Mangrove roots act as filters removing pollutants from inland waters and enhancing water quality, thus benefitting sensitive ecosystems like coral reefs in the nearby sea. In addition to being critical for limiting the risks associated with global warming, they play a significant part in the process of carbon sequestration (Kathiresan 2012).

### Blue carbon and the critical role that the mangroves play

Mangroves are crucial because of their ability to sequester and store carbon in both their biomass and the sediment. They store and sequester large area-specific quantities of blue carbon through their extensive root systems and sediment trapping, and are thus significant contributors to carbon storage and sequestration. They store  $C_{org}$  stocks in both the above-ground (leaves, branches) and below-ground (sediment, roots) parts of the soil, providing a means for long-term preser-

vation (Raihan *et al.* 2019). Radiometric studies have shown that the carbon build-up in mangroves ranges from 0.17 to 4.3 Megagrams (Mg) of carbon per hectare per year, which is consistent with soil carbon measurements. However, the rates of carbon accumulation obtained via root systems, ranging from 5.06 to 6.63 Mg of carbon per hectare per year, exceed estimations obtained from radiometric tests or soil mass carbon determination (Lamont *et al.* 2020).

Recent investigations have shown that the estimates of carbon sequestration via the falling of mangrove litter are higher than the values derived from radiometric and mass analysis. The total carbon stored in mangroves globally is between 5.23 and 8.63 Pg C (Alongi 2022), indicating an annual carbon burial in mangrove forests ranging from 9.6 to 15.8 Tg C  $Y^{-1}$ , which is 4 to 5 times higher than the carbon burial in boreal, temperate, and tropical highland forests (Alongi 2022).

### Why are mangroves effective in storing blue carbon?

Mangroves are highly effective in capturing blue carbon due to their high Net Primary Productivity, which represents the organic matter produced through photosynthesis. This organic matter is

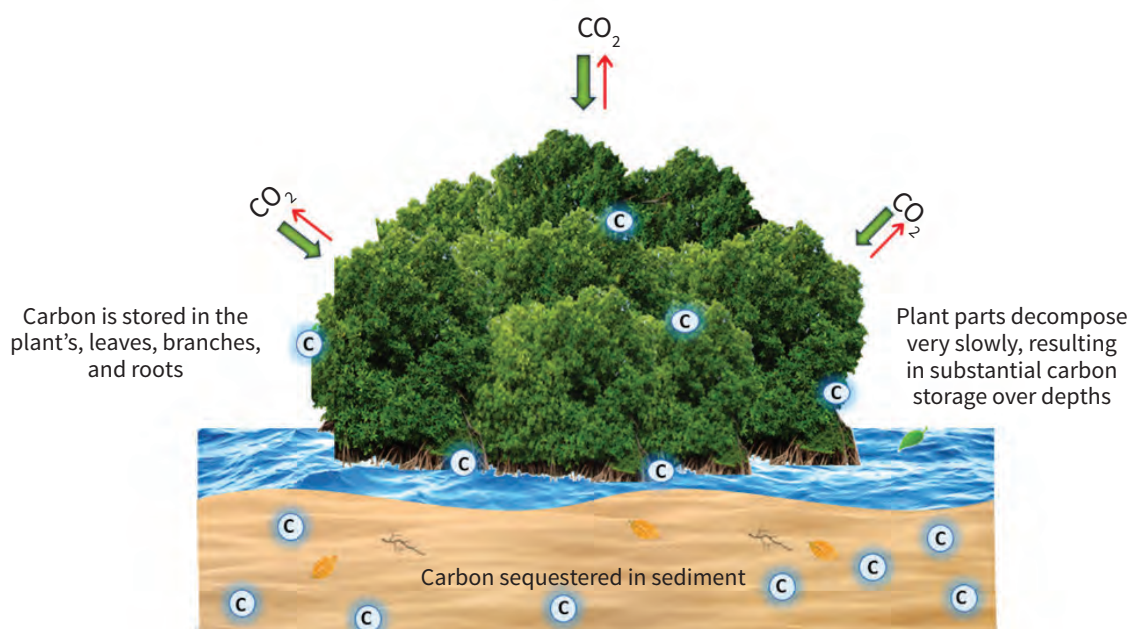
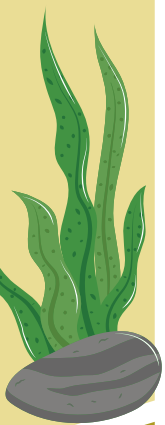


Fig. 11: Carbon stock in mangrove ecosystem



stored in the biomass and sediments of the mangrove ecosystem (Zhu and Yan 2022; Fig. 11). The unique root system of the mangroves traps and stores the sediment, stabilizing it and preventing erosion.

Mangroves are located in the tidal zone, which helps preserve the carbon stored in the sediments by limiting oxygen levels. When oxygen is present, it can react with the organic matter and release CO<sub>2</sub> back into the atmosphere. However, when sediment is flooded, oxygen is limited, and the organic matter is preserved (Emerson 2023). The mangroves' ability to store blue carbon is crucial for climate change mitigation. The carbon stored in mangrove ecosystems can remain sequestered for hundreds to thousands of years, making them a valuable tool for reducing CO<sub>2</sub> emissions (Emerson 2023). Similarly, the combination of mangrove species and their functions within an ecosystem play a crucial role in sequestering carbon more effectively (Gullström *et al.* 2021; Donato *et al.* 2011; Rahman *et al.* 2021). Maintaining a mixture of species can enhance sediment carbon storage in mangroves, while dominant species with high

wood density and stature promote blue carbon storage (Rahman *et al.* 2021). The ecosystem carbon balance in mangroves is influenced by plant diversity, which sustains carbon flows by influencing the community's functional composition and sediment carbon balance (Ariana and Amber 2016).

### **Mangroves ensure resilient and long term blue carbon storage**

Mangroves play a crucial role in sequestering and storing carbon, both above and below ground, making them one of the most effective natural ecosystems for long-term blue carbon storage. Their unique ecological characteristics contribute to their resilience and ability to store carbon over extended periods. Carbon is stored in both their biomass (roots, trunks, and leaves) and the organic-rich sediments they trap. Mangrove sediments act as anaerobic environments (low oxygen), which slow down the decomposition of organic matter, ensuring long-term carbon storage. Mangrove root systems stabilize sediments, preventing the release of stored carbon into the atmosphere due to erosion or flooding.

Mangroves exhibit resilience to rising sea levels by vertically accumulating sediments and maintaining their carbon storage capacity (Woodroffe *et al.* 2016). They act as buffers, protecting coastlines from storm surges and reducing the risk of carbon loss during extreme weather events.

### **Protecting mangroves for the biodiversity and environmental co-benefits**

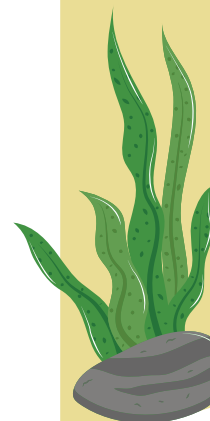
Mangroves render crucial ecosystem services for our well-being, providing habitats for various species, coastal protection, and offering breeding grounds for fish. They support a number of species from microscopic bacteria to the largest terrestrial mammal. Based on the IUCN Red list, 603 species of marine vertebrates are associated with mangrove ecosystems. Approximately 1,533 species are associated with mangroves in some way and nearly 15% of them face the danger of extinction. Mangrove associated fisheries practiced by small-scale fishers are seen in West and Central Africa, South Asia and South and Central

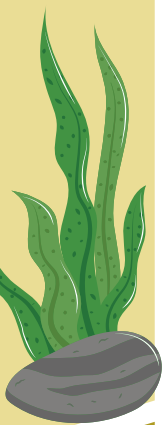
America (UNEP 2023). Mangroves are under threat from human activities such as aquaculture, agriculture, urban development, and climate change. Rising sea levels and increased storm frequency further put pressure on the mangrove ecosystem. The rate of mangrove deforestation is between 2 and 8 % per year (Miththapala 2008). The most significant net losses occurred in Asia Pacific, followed by the Americas and Africa; in particular, in Indonesia, Australia, Mexico and Myanmar (UNEP, 2023). Strategies necessary to protect and restore mangroves include establishing protected areas, promoting sustainable aquaculture practices, promoting sustainable tourism, supporting community-based conservation, reducing coastal pollution, addressing climate change, and restoring degraded mangroves (Primavera 2006; Spalding *et al.* 2014; Alongi 2015).

Preserving blue carbon in mangroves requires the maintenance of a variety of tree groups with a functional composition and diversity to ensure



*Rhizophora apiculata*





the continued storage of blue carbon. Species richness has positive indirect association with plants' above- and belowground biomass carbon through functional composition, while it has both direct and indirect association with sediment  $C_{org}$  and total ecosystem carbon (Rahman *et al.* 2021). The salinity of sediment influences the functional variety and uniqueness of organisms, which in turn impacts their relationships with blue carbon storage. Functional traits, namely the density of wood and the maximum height of the canopy, are essential factors in determining the amount of carbon stored in mangroves. The presence of a variety of plant species affects the movement of carbon by changing the types of organisms present and the amount and quality of carbon in sediment (Rahman *et al.* 2021). In order to conserve and restore mangrove ecosystems, it is crucial to maintain a variety of tree species and encourage sustainable practices.

#### 2.4. Salt marsh ecosystem

A salt marsh is a coastal ecosystem in the upper intertidal zone between land and open salt water or brackish water that is regularly flooded by the tides. It is dominated by dense stands of salt-tolerant plants such as herbs, grasses, or low shrubs (Howard *et al.* 2014). Salt marshes prevent the growth of mangroves, as well as tidal freshwater/brackish forests such as swamp oak, paperbark, cyprus swamps, and willows. Additionally, unvegetated salt flats are also absent in areas of salt marshes. The halophytic plants found in coastal salt marshes are not limited to intertidal or marine environments, which distinguishes them from mangrove and seagrass vegetation. These marshes are primarily occupied by herbaceous plants, particularly tidal grasses, sedges and rushes (Viswanathan *et al.* 2020). Additionally, tidal saltbushes and shrubs may be found in the area. The diversity of growth forms is a crucial



*Sesuvium portulacastrum*



factor in determining the quantity of carbon stocks due to the distinct biomass associated with each form. Salt marshes grow on soft substrates along the tidal areas of estuaries, embayments, and certain low-energy coastlines. They are important in coastlines that are not suited for mangrove forests or where development is restricted (Kangas and Lugo 1990). Therefore, these systems are predominantly found in temperate, subarctic, and arctic regions (Long and Mason 1983; Mitsch and Gosselink 2000). In tropical areas, salt marshes can be substituted in the intertidal environment by either mangroves in wet climates or saltpans in drier climates (Lopez-Portillo and Ezcurra 1989; Rodriguez *et al.* 2016).

### Importance of salt marsh

Throughout history, salt marshes have been an underestimated habitat and, in fact, neglected landform in general. The spatial distribution of salt marsh plants varies within the marsh and is influenced by marsh elevation as well as by variances in their tolerance to soil salinity, oxygen levels, sulphide levels, and hydro-period (Partridge and Wilson 1987). Salt marshes offer several ecological services such as the generation and export of organic matter, nitrogen cycling, protection against storm activity, and carbon sequestration (Mitsch and Gosselink 2000; Chmura *et al.* 2003). Salt marshes are commonly categorised into distinct zones according to differences in plant species. The text refers to the vertical position of the ground surface in relation to the tide, as described by Niering and Warren (1980). The low marsh area is situated at the minimum altitude and experiences frequent inundation by tides. The middle/high marsh experiences less frequent flooding, whereas the higher marsh is even less regularly inundated by the tide. Brackish marshes are commonly found in the inner boundaries of marsh areas, where the introduction of freshwater results in a brackish environment. Salt marshes have strong biological and physical connections with neighbouring coastal ecosystems, such as barren intertidal flats, oyster beds and reefs, and seagrass beds located at lower tidal

levels (Adam 2002). They frequently contribute to a habitat that is mosaic-like in nature, alongside mangroves or salt pans.

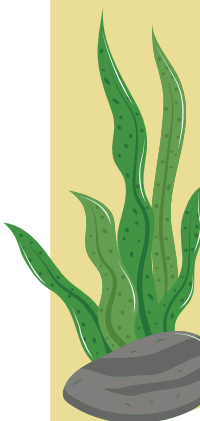
### Blue carbon and the critical role that the salt marshes play

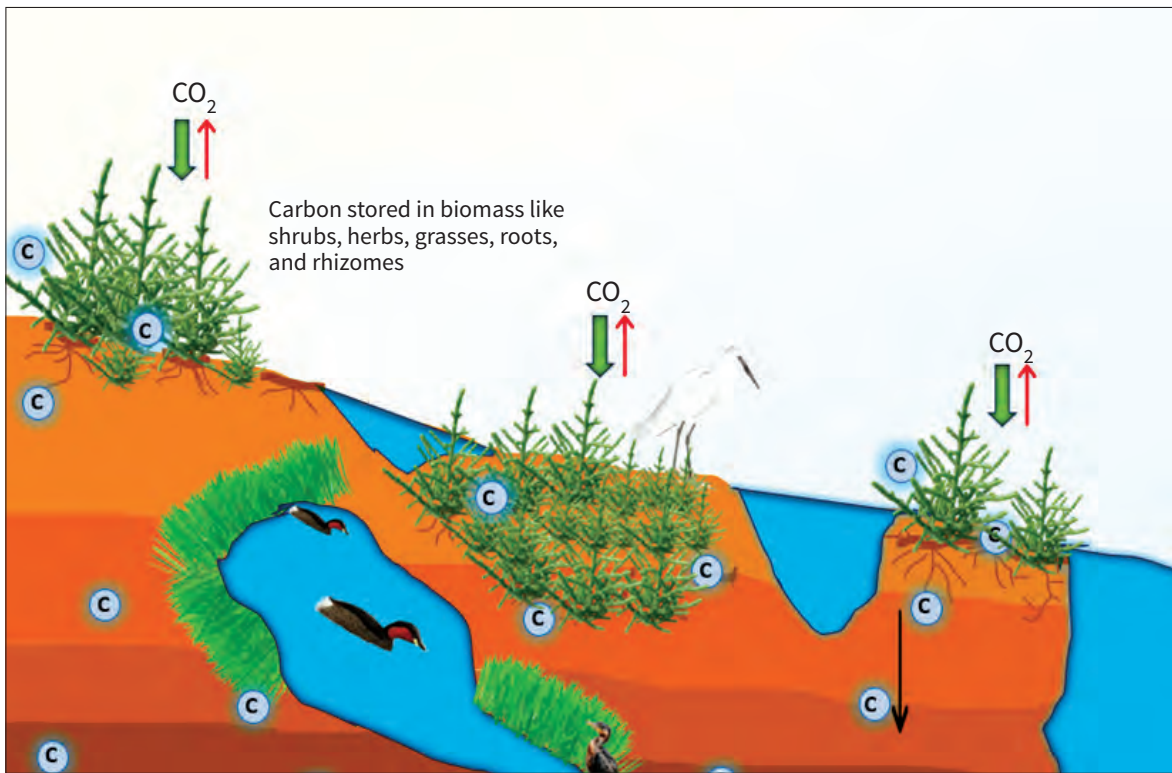
Coastal salt marshes are recognised as blue carbon sinks because they have significant levels of primary production and carbon burial rates (Mcleod *et al.* 2011). Vegetation is the key predictor of salt marsh carbon stocks because high primary productivity removes carbon from the atmosphere by photosynthesis (Duarte *et al.* 2005). Tidal oscillations regularly inundate salt marshes, transporting water and chemicals into and out of the ecosystem (Fagherazzi *et al.* 2013). The various regions of the marsh may exhibit variations in plant species composition and physical structure, which can impact the amount of living plant material both above and below the ground. Furthermore, the geochemical characteristics of the soil, such as the availability of nutrients and the presence of specific redox conditions, might have an impact on the retention of carbon in the soil (Fig. 12). Salt marshes often have belowground carbon pools that make up 65 to 95% of the total carbon stock in the ecosystem (Elsey-Quirk *et al.* 2011; Alongi 2015; Howard *et al.* 2014). Worldwide, salt marshes can store carbon ranging between 4.8 and 87.2 Tg C per year (Mcleod *et al.* 2011).

### Why salt marshes are effective in storing blue carbon

The major part of primary production in salt marshes takes place in the belowground biomass, specifically the roots and rhizomes. Research conducted by Valiela *et al.* (1976) has shown that root-to-shoot ratios, which represent the ratio of belowground to aboveground biomass, can range from 1.4 to 50 in salt marsh plants. This information is supported by studies conducted by Smith *et al.* (1979) and Darby and Turner (2008). Therefore, most of the carbon in salt marshes is stored in the living belowground biomass and the non-living soil carbon pool. In view of the difficulty in distinguishing between

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**Fig. 12:** Carbon stock in salt marsh ecosystem

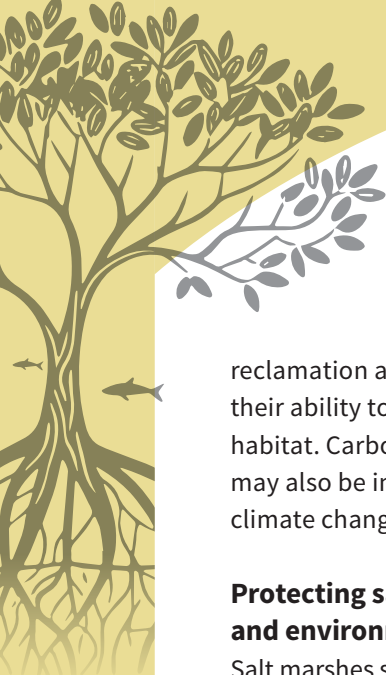
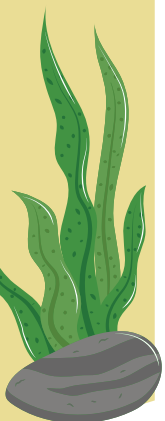
them, these two pools are commonly considered as a unified carbon pool (Chmura *et al.* 2003). Dead aboveground biomass is typically removed by the regular tides and may generally be disregarded in measurements without compromising accuracy. The salt marsh carbon pools play a dominant role in carbon sequestration, especially in the low and middle marsh zones. In the high marsh zone, the aboveground biomass assumes greater importance as a constituent of the overall carbon pool. Hence, it is crucial to distinguish between high, intermediate, and low marshes when devising a sample method. Salt marshes efficiently store blue carbon as a result of the tropical climate's promotion of high net primary production, lower carbon levels in marshes relative to mangroves, and increased carbon accumulation rates in sediments owing to tidal patterns and less aerobic decomposition. Sediments in salt marshes serve as a durable carbon reservoir in contrast to biomass, which only retains carbon for a shorter duration (Quintana-Alcantara *et al.* 2014).

### **Salt marshes ensure resilience and long-term blue carbon storage**

Salt marshes are highly effective in sequestering carbon, accumulating  $C_{org}$  in their soils at rates up to 55 times faster than tropical rainforests (McLeod *et al.* 2011). Salt marshes sequester carbon at rates ranging from 20 to 200 metric tonnes per hectare per year, depending on factors like marsh productivity, sedimentation rates, and hydrological conditions. The dense vegetation of salt marshes facilitates the capture and storage of atmospheric carbon, contributing to high rates of carbon sequestration (Chmura *et al.* 2003). A significant portion of blue carbon is stored in salt marsh sediments, where organic matter accumulates and undergoes anaerobic decomposition and burial. These sediments represent a long-term carbon reservoir, contributing to climate change mitigation efforts. Salt marshes also exhibit resilience to environmental stressors, such as sea-level rise, increased temperatures, and storm events (Kirwan *et al.* 2010). However, human activities, such as land

*Suaeda maritima*





reclamation and eutrophication, may reduce their ability to store blue carbon due to loss of habitat. Carbon sequestration by salt marshes may also be influenced by sea level rise and climate change.

### **Protecting salt marshes for the biodiversity and environmental co-benefits**

Salt marshes serve as habitats for several organisms and provide a multitude of significant advantages to humans. These benefits include the provision of raw materials and food, coastal protection, erosion management, water purification, support for fisheries, and opportunities for tourism, recreation, education, and research (Barbier *et al.* 2011). Salt marshes have a crucial role in the life of birds since they provide locations for foraging, breeding, and roosting (Hughes 2004). Salt marsh plants are also used for their nutritional and medicinal properties and their utility as livestock feed (Pattanaik *et al.* 2008). Salt marshes have high productivity, exceeding that of many terrestrial ecosystems. Their global carbon

storage capacity is substantial, with projected soil carbon stocks ranging from 862 to 1,350 Tg C (Macreadie *et al.* 2021). According to Duarte *et al.* (2008), the worldwide area of salt marshes has decreased by 25%–50% in recent decades compared to historical levels. Potential factors, such as alterations in natural water systems, animal grazing, waste disposal, land reclamation for salt production, prawn aquaculture, and coastal development, contribute to the deterioration of salt marsh ecosystems (Patro *et al.* 2017; MoMD&E 2019). These disruptions will reduce the ability of salt marshes to store carbon while also releasing the stored ancient carbon as emissions (Macreadie *et al.* 2013). Recently, salt marshes, as well as other coastal wetlands such as mangroves and seagrass meadows, have gained considerable recognition for their significance in conservation and potential for restoration.

### **2.5. Seagrass ecosystem**

Seagrasses are specialized marine flowering plants that have adapted to the nearshore



Seagrass beds in Gulf of Mannar



*Cymodocea serrulata*

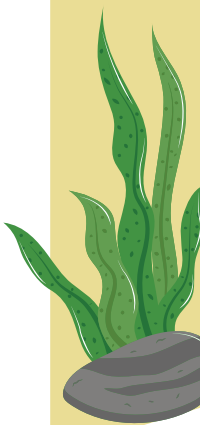
environment of most of the world's continents. Seagrass ecosystems are found all over the world, especially in the intertidal and subtidal zones of all the continents except for Antarctica (McKenzie *et al.* 2020). Some seagrasses can survive in a range of conditions encompassing freshwater, estuarine, marine, or hypersaline environment. Seagrasses form complex inter-linkages with other coastal ecosystems, such as mangroves, coral reefs and salt marshes, which are all important in maintaining a wide range of ecological functions in the marine environment (Mishra and Apte 2020; United Nations Environment Programme 2020). Seagrass ecosystems are the lungs of the sea and an area of one square meter of seagrasses can produce 10 litres of oxygen per day (McKenzie 2008). Seagrass distribution may highly vary with the environmental conditions, and they mostly thrive in nutrient-poor coastal waters, exposed to low-to-moderate hydrodynamic energy and sunlight (Roy *et al.* 2001; Pearson *et al.* 2021). Most of the seagrass species complete their life cycle

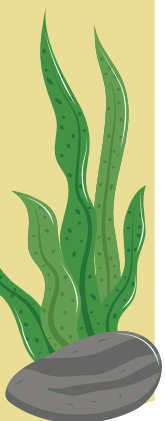
through submarine pollination (Tussenbroek *et al.* 2016).

### Importance of seagrasses

Seagrasses offer a wide range of services to humans and marine biodiversity. They directly contribute through primary production, providing surface for epiphytic growth, and providing habitat and nurseries for fishes, megafauna and other organisms (Nordlund *et al.* 2016; Sueversm *et al.* 2019). Many of the commercially exploited marine organisms are obligate inhabitants of seagrass beds for a part or the whole of their life cycle (Barry *et al.* 2021). Epiphytic organisms that depend on seagrass leaves include algae, fungi, protozoans, sponges, bryozoans, hydroids, and ascidians (Jiang *et al.* 2020). Different species of commercially important fish and crustaceans thrive exclusively in the seagrass beds as they get habitat for critical spawning, nursery, and refuge (Heise and Bortone 1999; Gullström *et al.* 2008). When compared to unvegetated areas, seagrass

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beds have been estimated to support 55,000 more fish per hectare (Jänes *et al.* 2020). Seagrasses contribute about 20% of the global fisheries by supporting biodiversity (Unsworth *et al.* 2019). Additionally, seagrass beds safeguard the shoreline from storm surges and help in preventing coastal erosion (Ondiviela *et al.* 2014; Potouroglou *et al.* 2017). Furthermore, seagrass meadows contribute towards climate change mitigation through carbon sequestration and storage (Kennedy *et al.* 2010; Mcleod *et al.* 2011; Fourqurean *et al.* 2012; Unsworth *et al.* 2022).

### Blue carbon and the critical role of seagrasses

Globally, seagrass ecosystems are considered as one of the major blue carbon sinks and thus indirect contributors to climate change mitigation (Gullström *et al.* 2018). On a global scale, seagrass meadows may store up to 19.9 petagrams (Pg) of  $C_{org}$  (Fourqurean *et al.* 2012). Unlike land-based ecosystems, the  $C_{org}$  deposited in seagrass sediments can remain trapped for hundreds or thousands of years (Duarte *et al.* 2005; Macreadie

*et al.* 2014). Seagrass meadows, while comprising less than 0.1% of the entire ocean bottom, play a significant role in the burial of carbon in the ocean. They provide 10-18% of the total oceanic carbon burial, as reported by Duarte *et al.* (2005) and Mcleod *et al.* (2011). Despite their high ecological value, global seagrass ecosystems are experiencing a significant decline at a rate of 0.4-2.6% each year (Pendleton *et al.* 2012; Short *et al.* 2011). By absorbing dissolved  $CO_2$  and increasing the oxygen levels in closed environments through photosynthesis, seagrass meadows act as a natural remedy for ocean acidification. They also store a significant amount of blue carbon in their above- (shoots) and belowground biomass (roots and rhizomes).

### Why seagrasses are effective in storing blue carbon

Seagrasses are a valuable resource for carbon sequestration and coastal ecosystem conservation due to their rapid carbon sequestration, extensive belowground biomass, and oxygen-poor sediment conditions. Their high primary production

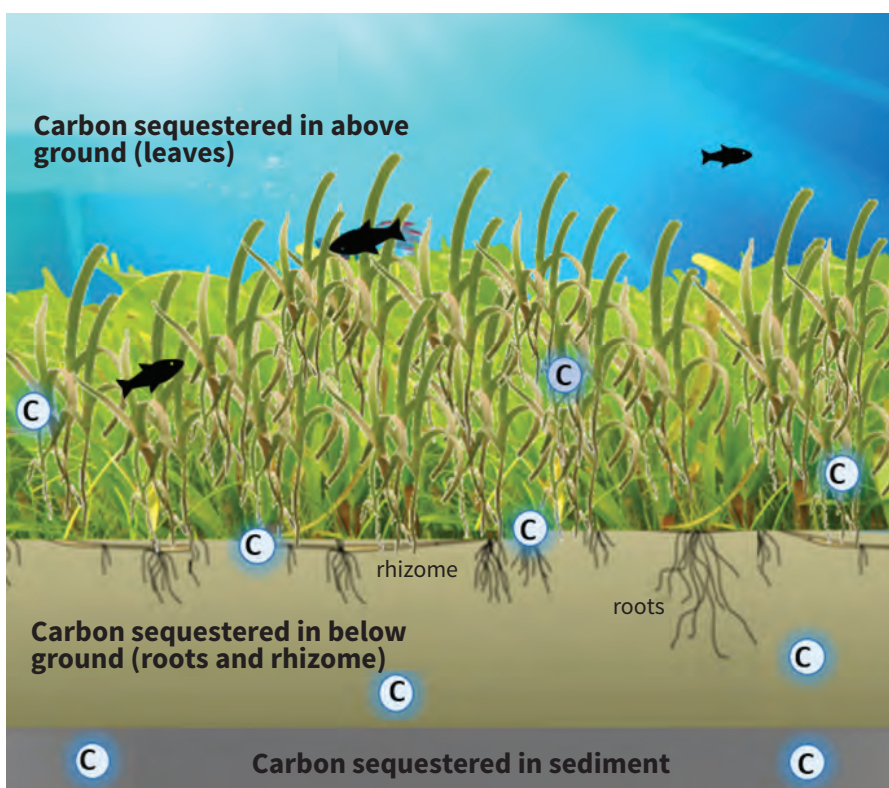
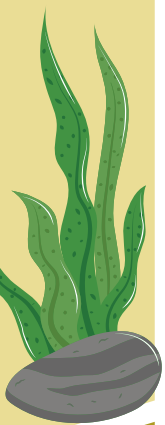


Fig. 13: Carbon stock in seagrass ecosystem



*Arthrocnemum glaucum*



and effective carbon uptake mechanisms allow them to trap carbon at rapid rates by photosynthesis and accumulate it in the plant biomass (Cebrian 1999). Seagrass meadows can store carbon at rates comparable to or higher than those of tropical forests (Macreadie *et al.* 2014). Seagrasses have a large amount of biomass below ground in the form of rhizomes and roots, which can make up as much as 90% of the total biomass of plants, providing them with a significant carbon sink (Kennedy *et al.* 2010; Fig. 13). They also aid in stabilising the sediment. Seagrass canopies also trap suspended organic particles, retaining them in the sediment as accumulated organic matter (Hendriks *et al.* 2008). Hence, the carbon sequestration and storage capacity are driven by allochthonous carbon in seagrass sediment and partly by sediment properties (Agawin and Duarte 2002).

The oxygen-poor sediment environment in which seagrasses grow creates conditions conducive to  $C_{org}$  preservation. This slows down the microbial decomposition, allowing for the accumulation of carbon-rich organic matter in the sediment (Fourqurean *et al.* 2012). According to an estimate, global seagrass beds store 140 Mg C/ha, which is 40 times higher than that stored by the terrestrial forests (Serrano *et al.* 2021).

### **Seagrasses ensure resilience and long-term blue carbon storage**

Seagrass ecosystems play a crucial role in long-term blue carbon storage through sediment stabilization, organic matter accumulation, and carbon sequestration in anaerobic conditions for centuries to millennia (Mcleod *et al.* 2011; Smith 1981; Serrano *et al.* 2016). Seagrass roots and rhizomes stabilize sediments, reducing erosion and preventing carbon loss, ensuring the integrity of the sediment carbon sink over time (Fourqurean *et al.* 2012). Acting as long-term carbon sinks, seagrass beds retain the accumulating organic

matter for centuries. Anaerobic conditions slow down the decomposition of organic matter, allowing for long-term carbon storage (Duarte *et al.* 2013). Seagrass ecosystems are resilient to environmental changes, including variations in salinity, temperature, and nutrient inputs, enhancing their ability to maintain carbon storage capacity (Marba *et al.* 2015). Their evolutionary features, including clonal reproduction and adaptability to changing environmental circumstances, support their long-term viability and capacity to store carbon (Reusch *et al.* 2005).

### **Protecting blue carbon seagrasses for the biodiversity and environmental co-benefits**

Regardless of being amongst the most valuable ecosystems, seagrasses are drastically declining globally (Short *et al.* 2011) at the rate of 0.4-2.6% per year (Pendleton *et al.* 2012). As the seagrass ecosystem plays critical roles in supporting global biodiversity such as fish, invertebrates and seabirds, human wellbeing, and climate change adaptation and mitigation, these ecosystems should be protected.

The rapid degradation and loss of vegetated blue carbon habitats due to anthropogenic activity highlights the urgent need for widespread assessments of natural blue carbon sinks to spur conservation and restoration efforts (Davy *et al.* 2009; Duarte *et al.* 2013; Serrano *et al.* 2016). Degradation of seagrasses will lead to the release of the carbon that has been stored for centuries or millennia, so unintentionally contributing to increased greenhouse gas emission and exacerbating climate change implications (George 2019). Predictive modelling of habitat-carbon dynamics under global change is also crucial for accurate estimates of future economic impacts. This urgent need underscores the imperative necessity for sustainable development (Pendleton *et al.* 2012).

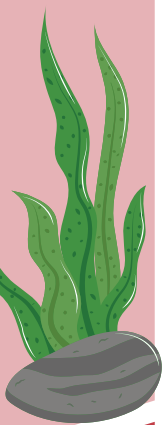
# 3

## BLUE CARBON ECOSYSTEMS

*Cymodocea serrulata* with sea cucumber



09/03



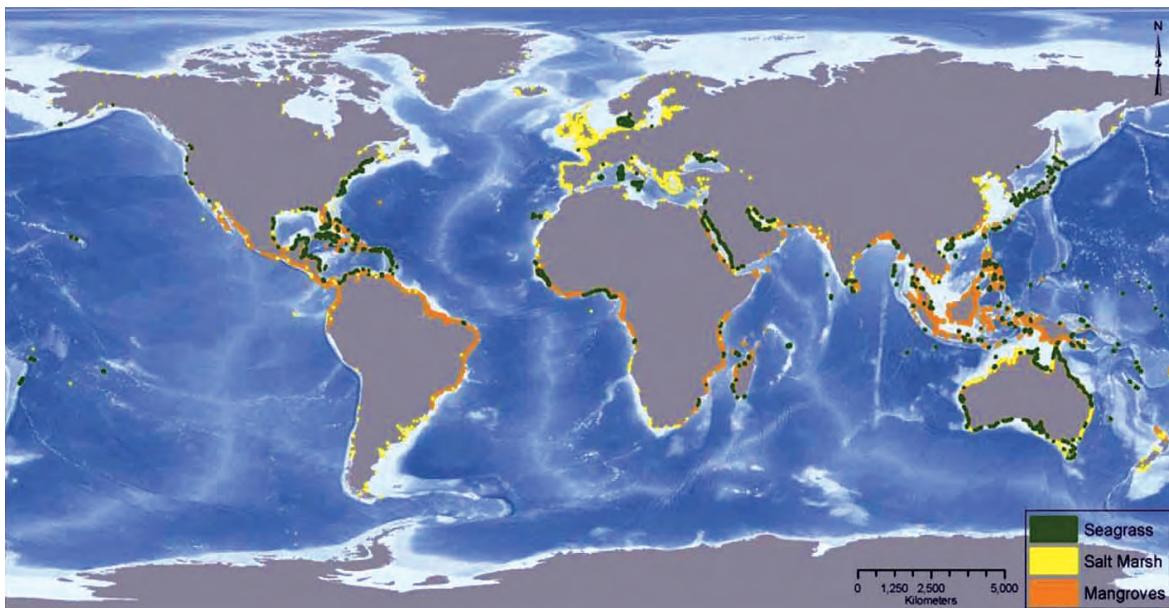
### 3.1. Introduction

Oceans have a substantial impact on the global carbon cycle. They not only serve as an important reservoir for carbon, but also play a crucial role in the storage and distribution of CO<sub>2</sub>. Approximately 93% of the CO<sub>2</sub> present on Earth, which amounts to over 40 tera tonnes (Tt), is stored and undergoes cycling within the seas. The oceanic coastal habitats, particularly mangrove, salt marsh and seagrass, cover <0.5% of the sea bed. But they contribute more than 50%, perhaps as much as 71%, of all carbon storage in the ocean sediment (Duarte *et al.* 2005), at significantly higher rates than the forests store per unit area (Mcleod *et al.* 2011; Duarte *et al.* 2010). Blue Carbon Ecosystems, including mangroves, salt marshes, and seagrass beds, are drawing more attention as a natural solution for climate change mitigation (Fourqurean *et al.* 2012; Duarte *et al.* 2013). The Blue Carbon Initiative (BCI) was established by the IOC-UNESCO, IUCN, and CI. The 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventory: Wetlands officially adopted blue carbon as a climate change solution. Blue carbon ecosystems also offer ecological services

like pollution purification, coastal disaster mitigation, nursery habitat provision and fisheries (Nellemann *et al.* 2009). Globally, coastal vegetation contains significant amounts of C<sub>org</sub> with different levels of concentration particularly in the sediments and biomass. Carbon present in the sediments does not remain just for decades or centuries like in rainforests, but rather for millennia (Nellemann *et al.* 2009). Mangroves are abundant in tropical and subtropical locations, whereas seagrass meadows and salt marshes are found from the equator to the poles.

### 3.2. Geographical overview and economic significance - Global Mangroves

Mangroves are tropical species often located on protected coastline and estuaries. They are often located above and below the equator, inside the confines of the 20° C isotherms (Spalding 2010). Mangrove distribution is locally extended by warm sea currents and decreased by cold currents. At higher latitudes, mangroves are often replaced by salt marshes (Kaiser *et al.* 2010). Mangroves, despite their extensive presence in 123 tropical and sub-tropical nations

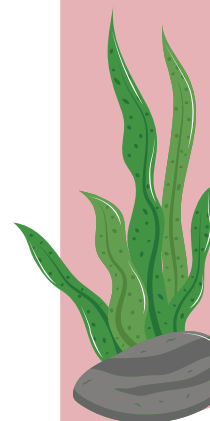


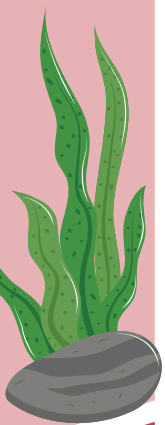
**Fig. 14:** Global distribution of mangrove, seagrass and salt marshes. Source: (Pendleton *et al.* 2012) - Mangrove coverage data are from UNEP-WCMC in collaboration with the International Society for Mangrove Ecosystems (ISME); Seagrass and salt marsh coverage data are from the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC).

and territories, are in fact rare at the global scale, covering less than 1% of all tropical forests globally (Spalding 2010). According to NASA report, the extent of mangrove cover is 1,37,760 km<sup>2</sup> on the Earth's surface, of which 42% is found in Asia, 21% in Africa, 15% in North and Central America, 12% in Australia and the islands of Oceania and 10% in South America (Giri *et al.* 2010). The global distribution of mangroves is shown in Fig. 14. According to an estimate, 35% of the area once covered by mangroves has been lost since the 1940s, with the current loss rates at 1 to 3% per year (Valiela *et al.* 2001). Mangroves provide considerable economic advantages. The overall economic values of mangrove environments vary from US\$ 2,772 /ha/yr up to as much as US\$ 80,334 /ha/yr, with an average of US\$ 28,662 /ha/yr (Salem and Mercer, 2012). The capacity of mangroves to capture and store substantial quantities of carbon is crucial to global carbon budgets and the mitigation of climate change impacts (Herr *et al.* 2012). They can trap 6 to 8 t CO<sub>2</sub> e per hectare annually. These rates are about two to four times higher than those seen in mature tropical forests (FAO 2003).

### Salt Marshes

Salt marsh habitats are vegetated coastal wetlands that are flooded by tides regularly or sometimes. These ecosystems are predominantly seen in temperate and subtropical areas. They are occupied by a diverse range of herbaceous and woody vascular plants (Adam 2002). These habitats emerge along the peripheries of estuaries, lagoons, behind sandbars and coastal rivers (Gullström *et al.* 2021). Even though precise global extent of salt marshes is hard to quantify due to varying definitions and data gaps, salt marshes globally have an extent of 52,880 km<sup>2</sup> (Worthington *et al.* 2023). Salt marshes are seen in the east and west coasts of North America, Europe, Asia, South America, Africa and Australia. Even though marshes are also an important coastal ecosystem in arid and tropical region, they are often overlooked (Viswanathan *et al.* 2020). Salt marshes capture and deposit nutrient and sediments (US EPA 2006). They also have the natural ability to transition landward inland in response to changes in sea level and increased frequency of inundation (Fagherazzi *et al.* 2020; Mazzocco *et al.* 2022). Salt marshes serve as natural barriers that assist





*Sesuvium portulacastrum*

in shielding areas from storm surges, flooding, and coastal erosion, potentially saving billions in disaster prevention and recovery expenses. They also support commercially important fish and shellfish species, contributing to \$2,537/acre as per study in the Narragansett Bay (Mazzocco *et al.* 2022).

Salt marsh is a unique ecosystem with high productivity in converting CO<sub>2</sub> into plant biomass and effective trapping of particulate C<sub>org</sub>, and having salient biogeochemical conditions within sediments (Alongi 2002). Salt marshes provide short-term storage of carbon through vegetation biomass and long-term storage through their capacity to store carbon in anaerobic sediments (Mcloed 2011). The carbon from belowground biomass with root-to-shoot ratio ranges from 1.4 to 50 and they are often difficult to separate, so are treated as single pool (Bayliss-Smith *et al.*

1979; Darby and Turner 2008). Salt marshes are prone to numerous anthropogenic pressures due to their proximity to densely populated areas (Neumann *et al.* 2015).

### **Seagrasses**

Seagrass meadows exist on all continents except Antarctica, mostly in shallow, clear coastal marine waters, such as bays, estuaries and lagoons (McKenzie *et al.* 2020; Gullström *et al.* 2021). These ecosystems survive in both tropical and temperate zones, creating vast underwater meadows. Worldwide, seagrasses encompass between 3,00,000 to 6,00,000 km<sup>2</sup>; however, this area is diminishing owing to environmental deterioration (Fourqurean *et al.* 2012). Australia has one of the most extensive seagrass meadows, encompassing over 92,000 km<sup>2</sup>. Indonesia and Philippines have abundant biodiversity with a multitude of seagrass species flourishing inside

the coral triangle. Southeast Asia is distinguished for its rich and thick seagrass beds, which sustain local fisheries and marine biodiversity. Similarly, the Mediterranean Sea also has extensive seagrass meadows. Seagrass distribution is greatly influenced by environmental variables such as light, temperature, salinity, and inorganic nutrients (Serrano *et al.* 2014). Seagrasses are vital for maintaining diverse marine ecosystems and they provide 24 distinct services such as habitats, nurseries for fish populations, marine megafauna, feeding and breeding grounds for many species including endangered dugongs (Nordlund *et al.* 2016; Gullström *et al.* 2008; Sueversm *et al.* 2019; Infantes *et al.* 2020). They also protect coastlines against storm surges and mitigate coastal erosion, facilitating climate change adaptation through sediment accumulation, carbon capture and seabed elevation (Ondiviela *et al.* 2014; Potouroglou *et al.* 2017). The livelihood income provided by the seagrass ecosystem is \$ 61,774 /ha/yr (Zulkifli *et al.* 2021).

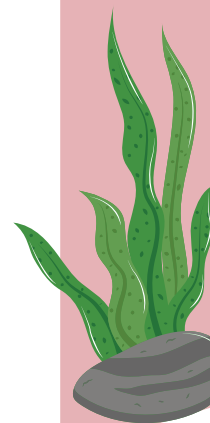
Even though seagrass covers less than 0.2% of the world's seas, they are believed to store 27.4 Tg C/yr, which is almost 10% of the annual projected carbon burial in the oceans (Mateo *et al.*, 2006). Seagrasses have the ability to form organic-rich soils consisting of both autochthonous and allochthonous  $C_{org}$  (Kennedy *et al.* 2010). In recent years, seagrasses face many challenges, and they are threatened by factors like declining water quality, overfishing, land reclamation, boating, coastal construction and aquaculture (Unsworth *et al.* 2019). According to Fourqurean *et al.* (2012), the current pace of seagrass loss may lead to the release of upto 299 Tg of carbon per year assuming that all the  $C_{org}$  in seagrass biomass and top meter of soil is remineralized.

### 3.3. Geographical overview and economic significance - India

India has all the three blue carbon ecosystems namely mangrove, salt marsh and seagrass (Fig. 15).

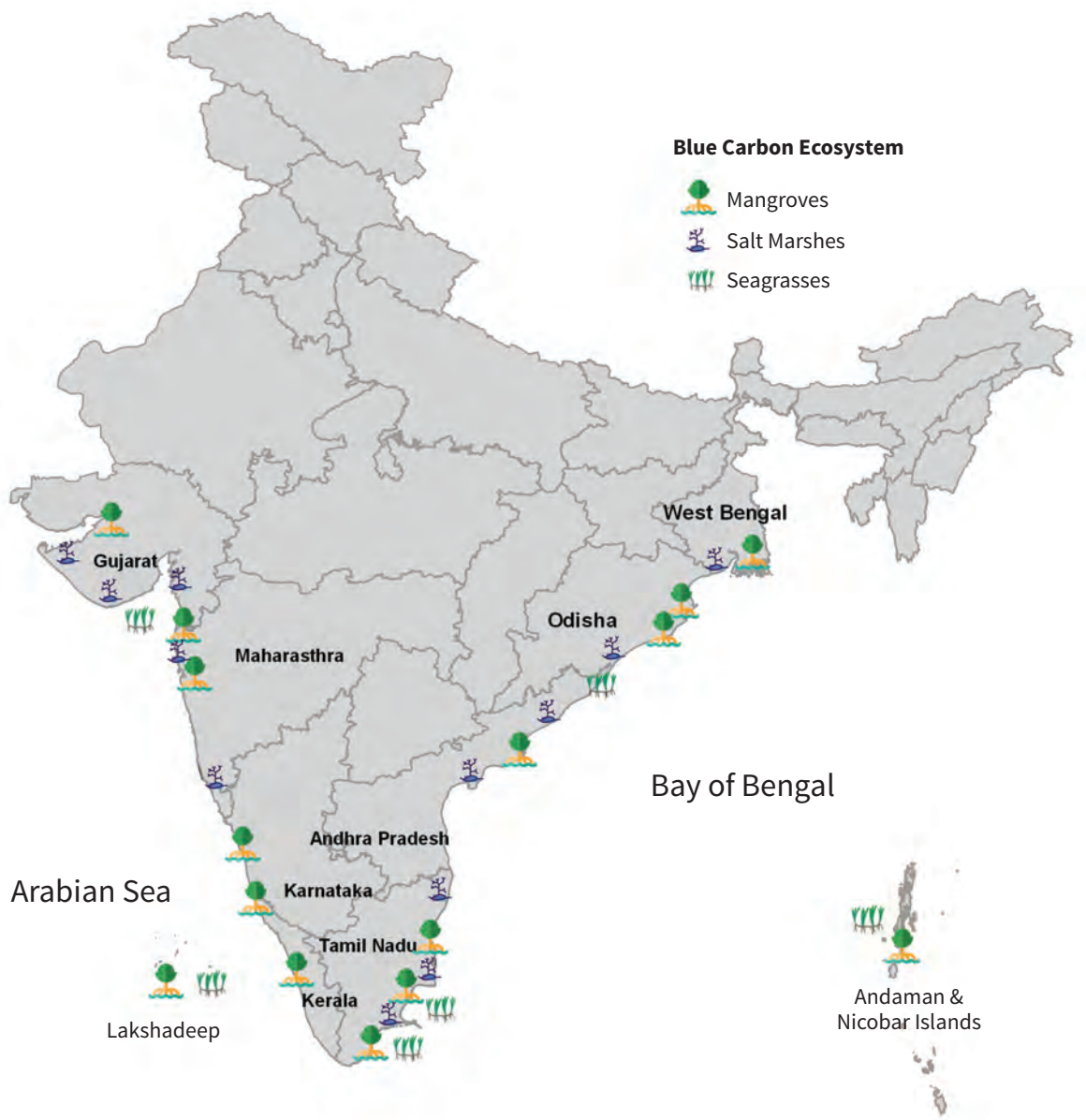


Mangrove habitat in Manakudy



*Arthrocnemum glaucum*



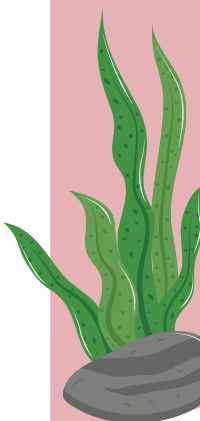


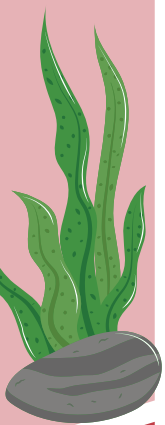
**Fig. 15:** Blue carbon ecosystem (mangroves, salt marshes and seagrasses) in India

### Mangroves

Forest Survey of India (FSI) has assessed that the mangrove cover spans 4,975 km<sup>2</sup>, accounting for 0.15% of the country's overall geographical area (Mathur *et al.* 2020; Fig. 15). The mean carbon stock in these mangroves is 386 tonnes/ha; the total carbon sequestration potential of the mangroves has been estimated at 702.42 million tonnes of CO<sub>2</sub>e; and the potential will increase to

748.17 million tonnes of CO<sub>2</sub>e by 2030. According to Mathur *et al.* (2020), conservation and protection of mangrove forests may help store an extra 207.91 million tonnes of CO<sub>2</sub>e. Ray *et al.* (2011) recorded a mean carbon storage of 39.93 ± 14.05 Mg C /ha in the aboveground biomass and 9.61 ± 3.37 Mg C /ha in the belowground biomass for Sundarbans mangroves. Additionally, they noted that the rate of carbon sequestration differed





between the living biomass (1.69 Mg C /ha/yr) and the soil pool (0.012 Mg C /ha/yr). By upscaling their results, they found that the whole Indian part of Sundarbans contains a significant amount of carbon, namely 26.5 Tg C (1 Tg C = 1012 g C). According to Harishma *et al.* (2020), the mangroves in Kerala have an average soil C<sub>org</sub> storage of 81.3 Mg C /ha. Patil *et al.* (2014) conducted a study to assess the levels of C<sub>org</sub> in the mangrove soils around Thane creek in Mumbai. They found that the C<sub>org</sub> content ranged from 0.07 Mg C /ha to 2.07 Mg C /ha. Similarly, Pattnayak *et al.* (2019) estimated the soil C<sub>org</sub> stock of 57.6 ± 3.2 Mg C /ha in the Bhitarkanika mangrove forest, Odisha.

### Salt marshes

Salt marshes in India are classified as Ecologically Sensitive Areas (ESA) under the Coastal Regulation Zone Notification 2019 under section 3 of the Environment (Protection) Act, 1986. Salt marshes

in India cover an area of approximately 1,611 km<sup>2</sup>, with 1,443 km<sup>2</sup> in Gujarat, 61 km<sup>2</sup> in Tamil Nadu, 60 km<sup>2</sup> in Andaman and Nicobar Islands, 40 km<sup>2</sup> in Andhra Pradesh, 6 km<sup>2</sup> in Maharashtra, 0.7 km<sup>2</sup> in Puducherry, and 0.6 km<sup>2</sup> in Daman and Diu (SAC, 2011; Banerjee *et al.* 2017; Fig. 15). In contrast, according to Viswanathan *et al.* (2020), the cover of salt marshes in India is only 290 km<sup>2</sup>, and this variation in area cover could be due to the inconsistency in identification of salt marsh species. The marsh plant species are crucial for maintaining the integrity of the coast and are often considered as halophytes, mangroves, mangrove associates, and coastal vegetation. However, there are disparities in the number of salt marsh species reported in India. A recent checklist enumerates 15 salt marsh species as observed along the Indian coast, which include *Arthrocnemum indicum*, *Cressa cretica*, *Fimbristylis ferruginea*, *Heliotropium curassavicum*, *Myriostachya wightiana*, *Porteresia coarctata*, *Phragmites karka*,



*Suaeda monoica*



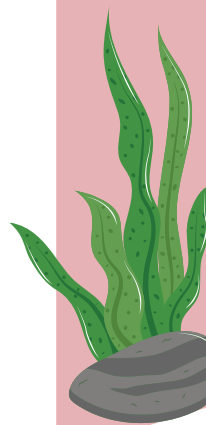
*Syringodium isoetifolium*

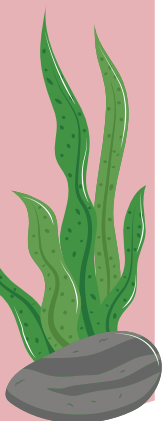
*Salicornia brachiata*, *Scirpus littoralis*, *Sesuvium portulacastrum*, *Suaeda maritima*, *Suaeda nudiflora*, *Suaeda monoica*, *Suaeda fruticosa* and *Urochondra setulosa* (Nayak and Bahugune, 2001; Kathiresan and Ramanathan, 2004; Patro *et al.* 2017) and the most diverse family is represented by Amaranthaceae (Viswanathan *et al.* 2020). The overall mean density of salt marsh vegetation is  $19 \pm 1$  plants per  $m^2$  with the highest density recorded in Lakshadweep ( $28 m^{-2}$ ) followed by Tamil Nadu ( $23 m^{-2}$ ), West Bengal ( $19 m^{-2}$ ), Maharashtra ( $18 m^{-2}$ ), Andhra Pradesh ( $17 m^{-2}$ ), Gujarat ( $15 m^{-2}$ ) and Puducherry ( $10 m^{-2}$ ) (Viswanathan *et al.* 2020). Studies focusing on the salt marsh ecosystems in India are scarce, with a few being species-specific and mainly focused on plants with pharmaceutical, biotechnological, and bioremediation significance, plant-microbe interactions, habitat characterization, and nutritional assessments. A few studies have explored salt marsh carbon sequestration in

India (Jana *et al.* 2013) suggesting the potential of the salt marsh plant *Porteresia coarctata* in sequestering carbon due to its unique growth patterns and biomass. Das *et al.* (2015) indicated the aboveground biomass to be around 90% of the total plant biomass in *Suaeda maritima* in Sundarban wetland. Rathore *et al.* (2016) studied the carbon content in the biomass of *Salicornia brachiata*, a salt marsh species with a biomass range of 2.51–6.07 Mg/ha, equivalent to 0.77–1.93 Mg C/ha. They measured the  $C_{org}$  content in the soils beneath this species, which varied between  $0.51 \pm 0.03\%$  and  $0.91 \pm 0.01\%$  across different sites. However, they did not conduct any carbon stock assessment in the salt marsh soils per unit area.

### Seagrasses

Seagrass meadows are seen in the shallow coastal zones and offshore regions in India (Fig. 15). A combination of extensive fieldwork and





remote sensing studies has shown that the Indian coastlines contain a total of 517 km<sup>2</sup> of seagrass (Geevarghese *et al.* 2018). Seagrasses are most common in the southeast coast of India, particularly in the Palk Bay and Gulf of Mannar in Tamil Nadu and Chilika Lake in Odisha. They also occur in Andaman and Nicobar and Lakshadweep islands. Minor seagrass beds are present along the Gujarat coast, Lakshadweep, Kakinada Bay in Coringa Wildlife Sanctuary, and Pulicat Lake. Seagrass flora of India is represented by 6 genera and 15 species (Balaji *et al.* 2012). Seagrasses can absorb CO<sub>2</sub> at higher rates than tropical forests, allowing a seagrass meadow to store twice as much carbon as temperate and tropical forests. An acre can sequester 3,350 kg of carbon per year (NASCM 2015). No extensive blue carbon stock assessment and sequestration studies have been undertaken in India, except for a very few local studies. Mathur *et al.* (2020) have estimated the carbon stocks in the seagrass meadows as 108 tonnes/ha and the total carbon sequestration potential as 10.2 million tonnes of CO<sub>2</sub>e. The rate

of sequestration of CO<sub>2</sub> has been put at 434.9 tonnes/km<sup>2</sup>/year with an annual net CO<sub>2</sub> sink of 0.75 million tonnes for an area of 517 km<sup>2</sup> (MoEF-CC). Ganguly *et al.* (2017) found that the seagrass of Palk Bay can sequester and store carbon of 0.03 Tg C in the aboveground biomass and nearly three times more in the belowground biomass. However, the carbon locked in sediments is 38 times higher than in live biomass.

### 3.4. Geographical overview and economic significance - Tamil Nadu

Like India, Tamil Nadu also has mangrove, salt marsh and seagrass blue carbon ecosystems (Fig. 16).

#### Mangroves

In Tamil Nadu, mangroves are seen along the coastal zone and in the estuaries and backwaters with an area cover of 45 km<sup>2</sup> (Mathur *et al.* 2020; Fig. 16). Altogether 18 species of mangroves have been recorded in the Tamil Nadu coast (Kathiresan *et al.* 2013). Mangroves are seen in the



*Avicennia marina*

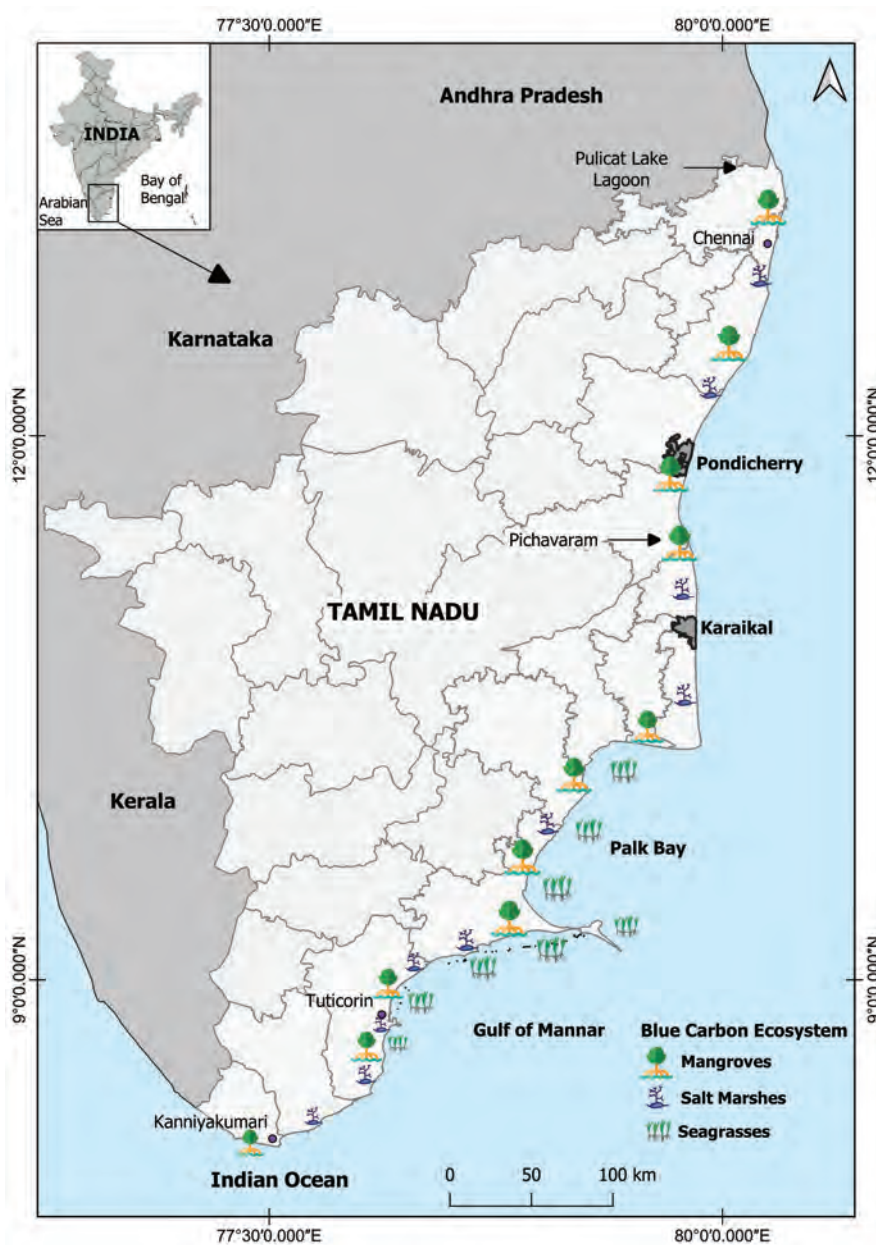
Cauvery deltaic regions. The Pichavaram region is characterised by a thriving mangrove forest, mostly consisting of *Rhizophora* spp., *Avicennia marina*, *Excoecaria agallocha*, *Bruguiera cylindrica*, *Lumnitzera racemosa*, *Ceriops decandra*, and *Aegiceras corniculatum* as the dominant plant species. Mangroves are also found in locations like Vedaranyam, Kodiakarai (Point Calimere), Muthupet, Chatram, and Tuticorin.

The mass of withered mangrove leaves in Pichavaram was estimated to be 8 tonnes per hectare

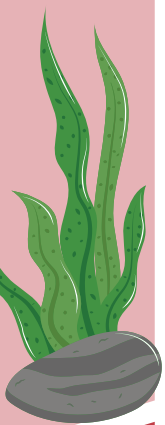
per year. Gnanamoorthy *et al.* (2019) assessed the quantity of soil  $C_{org}$  stored in the Pichavaram mangroves in Tamil Nadu. The researchers recorded a diverse range of soil  $C_{org}$  content, ranging from 57.41 Mg C /ha to 146.1 Mg C /ha in mangrove stands of different ages, ranging from 12 to 21 years. The carbon in the living biomass of mangroves was estimated at 62.81 Mg C /ha (Kathiresan *et al.* 2013).

### Salt marshes

The coastal zones of Tamil Nadu have salt



**Fig. 16:** Blue carbon ecosystems (mangroves, salt marshes and seagrasses) in Tamil Nadu



*Suaeda monoica*

marshes with a total area cover of 61 km<sup>2</sup> as estimated by a recent remote sensing study (SAC 2011; Banerjee *et al.* 2017; Fig. 16). The density is 23 plants per m<sup>2</sup> (Viswanathan *et al.* 2020). Gopi *et al.* (2019) mapped 37 salt marsh locations in Tamil Nadu using LISS and LandsAT imageries. In total, seven species of salt marsh flora under 4 genera and 3 families namely *Arthrocnemum indicum*, *Salicornia brachiata*, *Sesuvium portulacastrum*, *Suaeda fruticosa*, *S. maritima*, *S. monoica* and *S. nudiflora* have been reported by Gopi *et al.* (2019). Studies related to salt marsh ecosystems in Tamil Nadu are scarce, with limited information on species diversity and zonation patterns. Sivakumar *et al.* (2014) found a high soil C<sub>org</sub> stock of 4.2 – 4.8% in the mangrove-associated salt marshes of Muthupet. Kaviarasan *et al.* (2019) observed that there was variation in aboveground biomass, belowground biomass and sediment organic stocks for dry and wet seasons in Tuticorin coastline. Sediment organic stocks

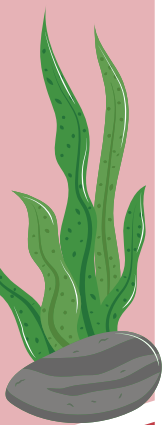
ranged from 8.42 ± .640 to 54.46 ± 1.46 Mg /ha for dry and wet seasons.

### Seagrasses

In Tamil Nadu, seagrasses are most common in the Palk Bay and Gulf of Mannar with minor distribution in the Pulicat Lake. The largest seagrass patch in the Gulf of Mannar has been reported to occur across the shallow coastal stretches between Mandapam and Keelakarai with an area of 39.22 km<sup>2</sup> (Geevarghese *et al.* 2018; Fig. 16). Encompassing the 21 islands and the surrounding shallow waters, the total seagrass area cover within the Gulf of Mannar Marine National Park has been reported as 76 km<sup>2</sup> (Mathews *et al.* 2010).

The seagrass flora of India is represented by 6 genera and 15 species, of which the maximum number of species is harboured by the Gulf of Mannar (Balaji *et al.* 2012) and Palk Bay (Mathews





*Halophila ovalis*

*et al.* 2010). The seagrass meadows of the Gulf of Mannar and Palk Bay provide a significant grazing ground for the sea cow, *Dugong dugon*. According to Mathews *et al.* (2010), *Thalassia hemprichii*, *Syringodium isoetifolium* and *Cymodocea serrulata* are the dominant seagrass species observed in Gulf of Mannar. Ganguly *et al.* (2017) found that the Palk Bay seagrass can sequester carbon and store 0.03 Tg C in the aboveground biomass and nearly three times more in the belowground biomass. However, the carbon locked in sediments is 38 times higher than in live biomass. Considering the carbonate concentrations to a depth of 1 m, it is inferred that

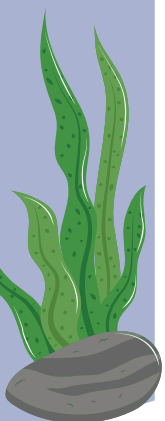
the seagrass beds of Palk Bay have a carbon stock of 4.6 Tg C (Ganguly *et al.* 2017). A recent study by Kaladharan *et al.* (2021) analyzed the blue carbon stock of seagrass meadows in the Gulf of Mannar and Palk Bay off the Coromandel Coast, south India, which is dominated by *C. serrulata* and *S. isoetifolium*. The blue carbon stock in GoM was estimated at 0.001782 Tg, while in PB it was 0.043996 Tg. The estimated value of blue carbon stored in GoM was US\$ 17,820 and in PB US\$ 43,99,682. The blue carbon stock of Pulicat Lake was estimated to be  $0.998 \pm 0.418$  Mg C /ha, which could be worth about US\$ 74,487 (Kaladharan *et al.* 2021).

# 4

## ESTIMATED STOCK OF BLUE CARBON IN TAMIL NADU

Blue carbon soil core sampling





#### 4.1. Introduction

Tamil Nadu, a southern Indian state, has a coast of 1,076 km (DADF 2014) with diverse eco-sensitive areas including coral reefs, seagrasses, mangroves, and salt marshes. Among them the blue carbon ecosystems play a crucial role in carbon sequestration and storage, biodiversity support, and livelihood for local communities. Mangroves cover a total area of 45 km<sup>2</sup>, with Pichavaram as a prominent center (Mathur *et al.* 2020). Salt marshes cover 61 km<sup>2</sup> (Viswanathan *et al.* 2020) and seagrass meadows grow in 392.8 km<sup>2</sup> in

the Palk Bay and Gulf of Mannar area, indicating the state's potential for blue carbon, which offers ecological, economic, and climate mitigation benefits.

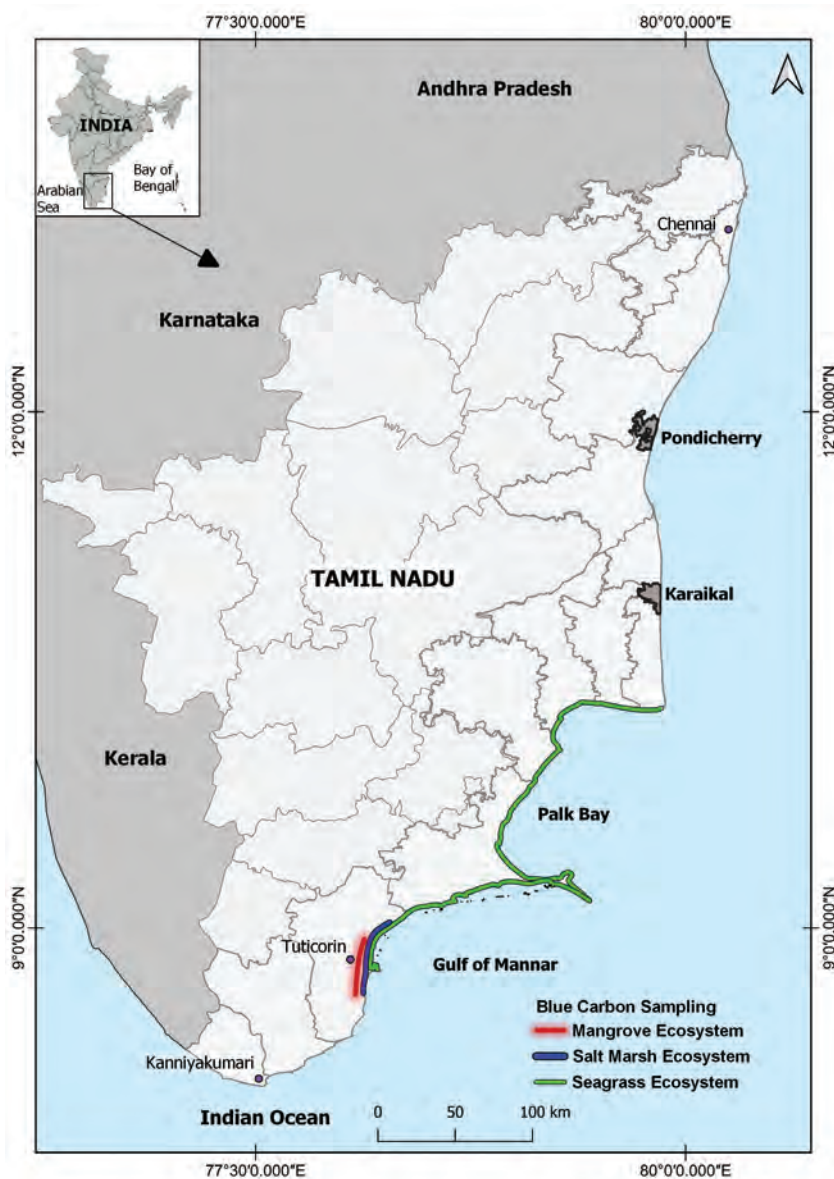
#### 4.2. Estimation of blue carbon stocks in the sediments

##### Study area

In order to estimate the blue carbon stocks in the sediments of mangroves, salt marshes and seagrass meadows in Tamil Nadu (Fig. 17), soil cores were collected



Blue carbon soil core sampling



**Fig. 17:** Map showing blue carbon sampling regions in Tamil Nadu

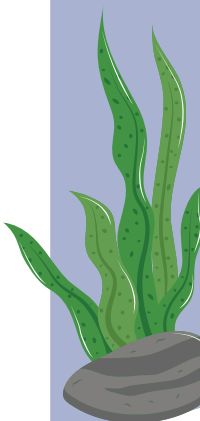
from randomly selected sites representing dense, sparse, restored and degraded. For mangrove, Tuticorin and adjoining regions were selected representing dense mangrove cover with more than 6 nos/10m<sup>2</sup>, sparse with 3 to 6 nos/10m<sup>2</sup>, restored and degraded habitats; for salt marsh ecosystems, Tuticorin and its adjoining regions were selected, representing dense (with salt marsh cover of more than 40%), sparse (with a salt marsh cover of less than 40%) and degraded habitats; for the seagrass meadows, the Palk Bay and Gulf of Mannar regions were selected, representing dense (with a seagrass cover of more than 40%), sparse (with a seagrass cover of less

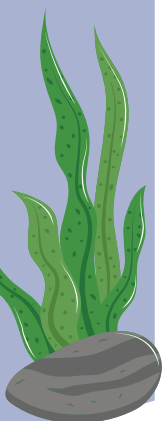
than 40%), restored and degraded habitats.

Totally, 72 soil cores were collected from 6 sites of mangrove ecosystem, 6 sites of salt marsh ecosystem and 12 sites of seagrass ecosystem. Density of mangroves and salt marshes were assessed using the Transect Line Plot method (Selvam *et al.* 2005) and for seagrass cover, the underwater Line Intercept Transect survey was employed (English *et al.* 1997).

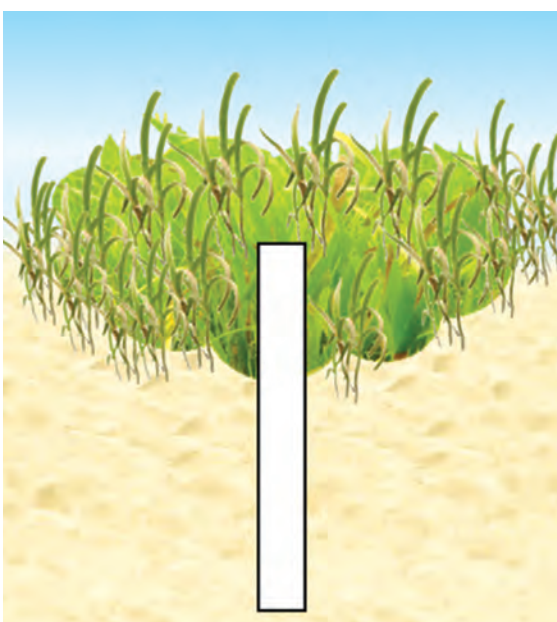
#### Sampling of soil cores

Triplicate soil cores were collected at each site for a depth of 1 m using thick-walled plastic pipes





Blue carbon soil core sampling



**Fig. 18:** Pictorial depiction of soil core sampling in seagrass ecosystem

with an inner diameter of 5 cm (Fig. 18). Under-water collection was done by SCUBA divers in the seagrass sites. The core was driven into the soil using a sledgehammer and correction was done

for compaction (Rahmawati *et al.* 2019; Fig. 19). The collected samples were subsampled at every 5 cm.

#### **Analysis of dry bulk density and organic carbon**

To accurately determine the soil carbon density, two parameters were analysed: soil dry bulk density and  $C_{org}$  content. Determination of dry bulk density was done by drying each sample fully in an oven at 60°C until it reached a constant weight. The volume of the sample was estimated taking into account the radius of the core sampler and the thickness of each subsample (Howard *et al.* 2014). The  $C_{org}$  content of sediment samples is measured by two methods, 1) the CHN analyser method using an automated elemental analyser and 2) the Loss on Ignition (LOI) method using combustion and empirical relationships between  $C_{org}$  and organic matter (Heiri *et al.* 2001). For the present study, the LOI method and empirical relationships were used (Craft *et al.* 1991; Fourqurean *et al.* 2012; Howard *et al.* 2014; Breithaupt *et al.* 2023).



**Fig. 19:** Soil core sampling in mangrove, salt marsh and seagrass ecosystems

### Calculation of soil carbon stocks and their economic value

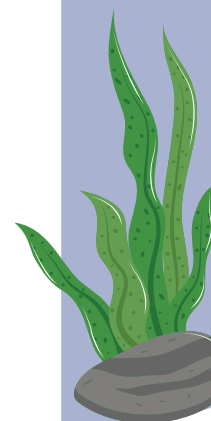
The soil carbon stock in each site was calculated using parameters such as sediment depth, sub-sample intervals, dry bulk density, and  $C_{org}$  percentage (Howard *et al.* 2014). The average carbon stock was then calculated for the different ecosystems, including the restored and degraded sites.

The economic value of blue carbon stock in sediments was calculated using the IPCC (2003) conversion formula for  $CO_2$  and the value of carbon credit on Voluntary carbon market was calculated as \$7 for one tonne of  $CO_2$  e (As India

is in the process of developing Indian Crediting Mechanism, we use the nearby Thailand Voluntary Emission Reduction Program's mean carbon credit price for the present calculation; <https://carbonpricingdashboard.worldbank.org/credits/instrument-detail>).

### 4.3. Mangrove ecosystem – soil blue carbon stock

In the present study, 6 sites were selected from the mangrove ecosystem of the Tuticorin region. In total, 18 soil cores were taken from these sites representing dense, sparse, restored and degraded blue carbon soil stocks. The average blue carbon stock in the sediment of mangrove





*Rhizophora* sp.

ecosystems of the study region is  $111.19 \pm 10.46$  Mg C/ha, while the average blue carbon stock in the sediment of the restored mangroves in the region of the study area is  $123.6 \pm 1.43$  Mg C/ha and the average blue carbon stock in the sediment of degraded mangrove is  $93.19 \pm 7.94$  Mg C/ha. The greater concentration of blue carbon stock in the restoration site could be due to the restoration of *Rhizophora mucronata* in the restoration site, and this indicates that blue carbon sequestration is higher in mixed-species habitats. According to Tamil Nadu Government record, the area cover of mangrove in Tamil Nadu is approximately 45 km<sup>2</sup> (Mathur *et al.* 2020). To estimate the present blue carbon stocks in the sediment of the mangrove

ecosystem in Tamil Nadu, we considered the present average blue carbon value with the total area of mangrove, which indicates a total carbon stock of 5,00,355 Mg C for the top 1 meter soil. Similarly, the total amount of potential CO<sub>2</sub> sequestered in the top 1 m soil of mangrove ecosystem is 18,34,635 t CO<sub>2</sub> e. The economic value of CO<sub>2</sub> sequestered in the top 1 m of the mangrove ecosystem of Tamil Nadu is US\$ 1,28,42,445 (Table 1).

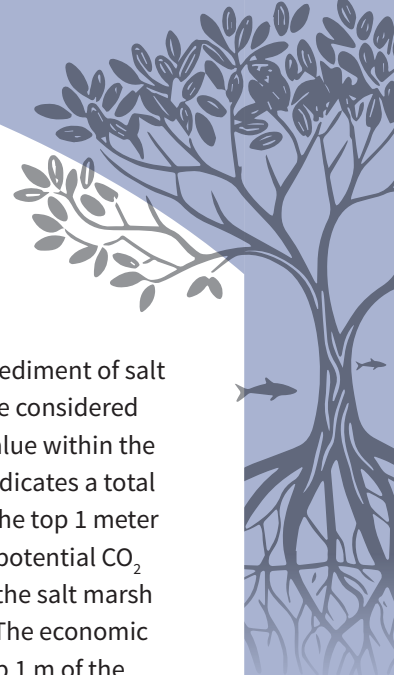
#### 4.4. Salt marsh ecosystem – soil blue carbon stock

In the salt marsh ecosystem, 6 sites were selected for the present study, and 18 soil cores were taken from these sites representing dense, sparse and

**Table 1:** Estimated blue carbon stock in the mangrove sediments of Tamil Nadu and its economic value

Total mangrove cover (Hectare)	Estimated average carbon stock/ hectare (Mg C/ha)	Estimated total carbon stock in sediments (Mg C)	Total t CO <sub>2</sub> e*	Estimated economic value of CO <sub>2</sub> (\$7/ tonne of CO <sub>2</sub> <sup>#</sup> ) - in million
<b>4,500</b>	<b>111.19</b>	<b>5,00,355</b>	<b>18,34,635</b>	<b>12.84</b>

(\*IPCC, 2003; <https://carbonpricingdashboard.worldbank.org> ##)



degraded blue carbon soil stocks. The average blue carbon stock in the sediments of the salt marsh ecosystem of the study area is  $108.76 \pm 12.32$  Mg C/ha, while the average blue carbon stock in the sediments of degraded salt marsh of the study region is  $80.89 \pm 3.39$  Mg C/ha. No restoration of salt marshes has been carried out in this region so far. An earlier study on the distribution of salt marshes in the coastal track of the Tamil Nadu estimated an area cover of  $61 \text{ km}^2$  (Viswanathan *et al.* 2020). In order to estimate the

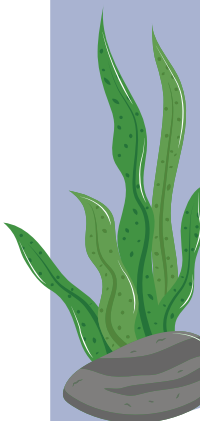
present blue carbon stocks in the sediment of salt marsh ecosystem in Tamil Nadu, we considered the present average blue carbon value within the total area of salt marshes, which indicates a total carbon stock of 6,63,436 Mg C for the top 1 meter soil. Similarly, the total amount of potential  $\text{CO}_2$  sequestered in the top 1 m soil of the salt marsh ecosystem is 24,32,598.67 t  $\text{CO}_2$ e. The economic value of  $\text{CO}_2$  sequestered in the top 1 m of the salt marsh ecosystem of Tamil Nadu was estimated to be US\$ 1,70,28,190.67 (Table 2).

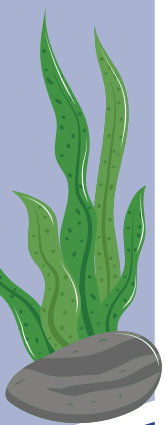
**Table 2:** Estimated blue carbon stock in the salt marsh sediments of Tamil Nadu and its economic value

Total salt marsh cover (Hectare)	Estimated average carbon stock/ hectare (Mg C/ha)	Estimated total carbon stock in sediments (Mg C)	Total t $\text{CO}_2$ e*	Estimated economic value of $\text{CO}_2$ (\$7/ tonne of $\text{CO}_2$ *) - in million
<b>6,100</b>	<b>108.76</b>	<b>6,63,436</b>	<b>24,32,598.67</b>	<b>17.03</b>

(\*IPCC, 2003; [#](https://carbonpricingdashboard.worldbank.org))

Salt marsh habitat





*Cymodocea serrulata* and *Syringodium isoetifolium*

#### **4.5. Seagrass ecosystem – soil blue carbon stock**

In the present study, 12 sites were selected from the seagrass ecosystems of Palk Bay and Gulf of Mannar regions of Tamil Nadu, 6 sites from Palk Bay and 6 sites from Gulf of Mannar including dense, sparse, restored and degraded sites. In total, 18 soil cores were taken from the Palk Bay region. The average blue carbon stock in the seagrass sediments of the Palk Bay region is  $97.94 \pm 15.2$  Mg C/ha, while the average blue carbon stock in the restored seagrass sediments of the Palk Bay is  $89.27 \pm 1.68$  Mg C/ha and the average blue carbon stock in the degraded seagrass sediments of the Palk Bay region is  $71.19 \pm 1.46$  Mg C/ha. The average blue carbon stock in the seagrass sediments of the Gulf of Mannar region is  $95.45 \pm 13.07$  Mg C/ha, while the average blue carbon stock in the restored seagrass sediments of the Gulf of Mannar is  $79.61 \pm 4.34$  Mg C/ha and the average

blue carbon stock in the degraded seagrass sediments of the Gulf of Mannar is  $60.12 \pm 5.53$  Mg C/ha. The total seagrass cover in Tamil Nadu is 392.8 km<sup>2</sup>, in which the respective values of Palk Bay and Gulf of Mannar are 231.6 km<sup>2</sup> and 161.2 km<sup>2</sup>. Considering this, the estimated total carbon stock is 37,97,983.2 Mg C (22,68,290.4 Mg C for Palk Bay and 15,38,654.0 Mg C for Gulf of Mannar) in the top 1 meter soil. Similarly, the total amount of potential CO<sub>2</sub> sequestered in the top 1 m soil of the seagrass ecosystem is 1,39,25,938.4 t CO<sub>2</sub> e (83,17,064.8 t CO<sub>2</sub> e for Palk Bay and 56,41,731.33 t CO<sub>2</sub> e for Gulf of Mannar). The economic value of CO<sub>2</sub> sequestered in the top 1 m of the seagrass ecosystem of Tamil Nadu is US\$ 9,74,81,568.8 (US\$ 5,82,19,453.6 for Palk Bay and US\$ 3,94,92,119.33 for Gulf of Mannar) (Table 3). The total carbon stocks and the economic values of CO<sub>2</sub> in the restored and degraded areas of Palk Bay and Gulf of Mannar are given in Table 4 (Fig. 20).

**Table 3:** Estimated blue carbon stock in the seagrass sediment of Tamil Nadu and its economic value

Total seagrass cover (Hectare)	Estimated average carbon stock/ hectare (Mg C/ha)	Estimated total carbon stock in sediments (Mg C)	Total t CO <sub>2</sub> e*	Estimated economic value of CO <sub>2</sub> (\$7/ tonne of CO <sub>2</sub> #) - in million
<b>39,280</b>	<b>96.69</b>	<b>37,97,983.2</b>	<b>1,39,25,938.4</b>	<b>97.48</b>

(\*IPCC, 2003; <https://carbonpricingdashboard.worldbank.org> #; Howard *et al.* 2014)

**Table 4:** Estimated economic value of blue carbon due to seagrass restoration

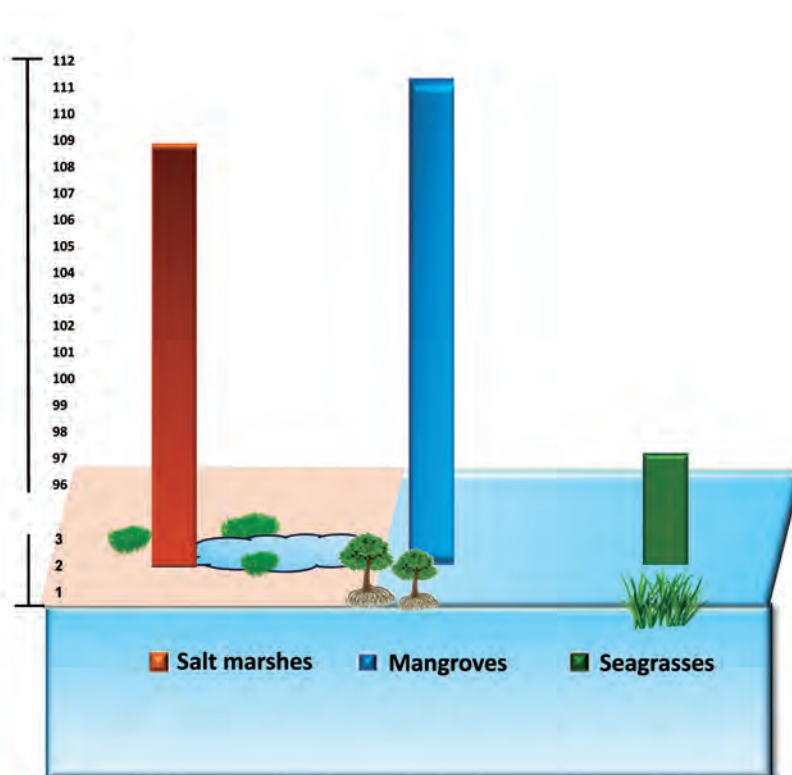
Average carbon stock in the restored area (Mg C/ha)	Average carbon stock in degraded area (Mg C/ha)	Difference in carbon storage due to restoration (Mg C/ha)^	Total t CO <sub>2</sub> e*	Economic value of CO <sub>2</sub> (\$7/ tonne of CO <sub>2</sub> #)
<b>84.34</b>	<b>65.66</b>	<b>18.68</b>	<b>68.51</b>	<b>479.58</b>

(^ for a period of 10 years; \*IPCC, 2003; <https://carbonpricingdashboard.worldbank.org> #)

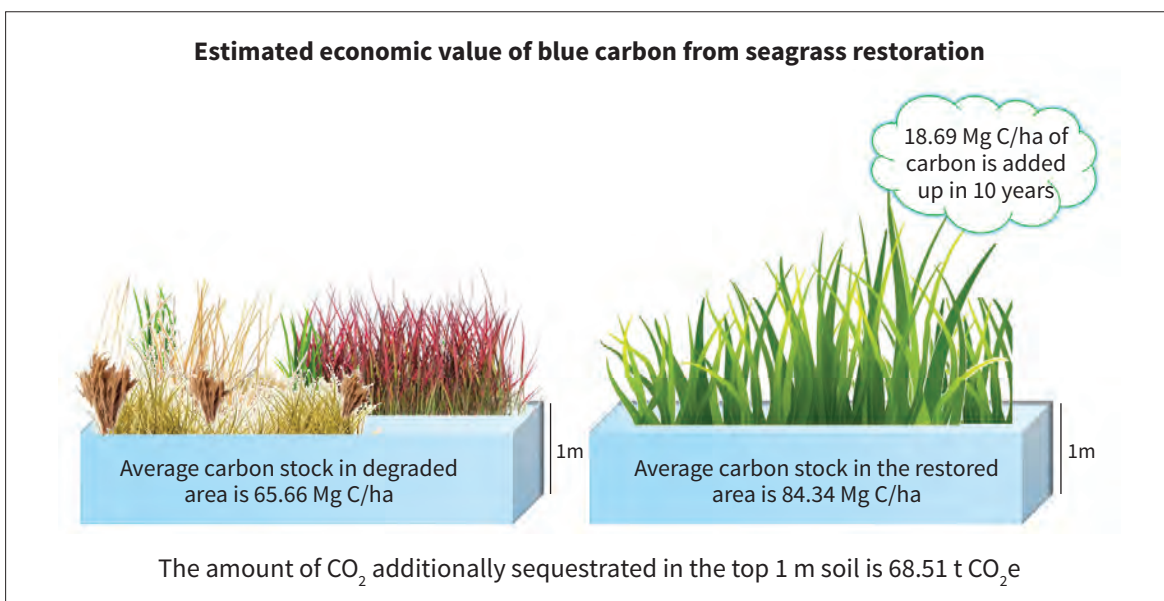
#### 4.6. Economic benefits of seagrass ecosystem conservation

Conservation and restoration of blue carbon habitats, like mangroves, salt marshes and seagrasses, provides economic benefits beyond carbon sequestration and climate management. They store carbon in biomass and sediments, reduce atmospheric CO<sub>2</sub> levels and mitigate

climate change. Carbon credits can be generated through conservation initiatives and exchanged in carbon markets. Healthy ecosystems improve fisheries productivity, protect coastal infrastructure, attract visitors, and promote ecotourism and cultural tourism. They also improve water quality by filtering contaminants and cycling nutrients, promoting sustainable aquaculture methods,



**Fig. 20:** Estimated average carbon stock in top 1 m of soil (Mg C/ha)



**Fig. 21:** Estimation of blue carbon observed due to restoration of seagrass ecosystem of Tamil Nadu

and reducing the risk of waterborne illnesses. An estimate of the economic values of carbon credits generated due to seagrass restoration activities in Tamil Nadu is provided in Table 4 (Fig. 21). As indicated by the present study, an additional amount of 18.69 Mg C/ha of carbon could be added up in the top 1 m soil of the degraded seagrass region in a period of 10 years. The amount CO<sub>2</sub> additionally sequestered in the top 1 m soil would then be 68.51 t CO<sub>2</sub>e, which has an economic value of US\$ 479.58 for every hectare of seagrass restoration.

Apart from the enhanced carbon storage, an additional livelihood income of \$ 61,774 per ha/yr could be provided by the seagrass ecosystem (Zulkifli *et al.* 2021) and \$ 3 114.8 (0.2 – 12,305) per ha/yr by the mangrove ecosystem (Hutchison *et al.* 2014).

Globally, blue carbon habitats are declining, and at the present rate of decline, about 30-40% of salt marshes and seagrasses (IPCC, 2007) and nearly 100% of mangroves (Duke *et al.* 2007) will be lost in the next 100 years. When these habitats are degraded or converted to other land uses, the carbon in the sediment is destabilised or exposed to oxygen, leading to the eventual release of a significant quantity of CO<sub>2</sub> into the atmosphere or water column (Sweetman *et al.* 2010).

The potential CO<sub>2</sub> emissions from one hectare of the seagrass ecosystem of Tamil Nadu would then be 354.53 t CO<sub>2</sub>/ha (with an economic value of US\$ 2,481.7) if all the C<sub>org</sub> in the upper 1 m of the sediment is oxidized to CO<sub>2</sub> due to degradation.

# 5

## **BLUE CARBON ECONOMY AND FINANCE FOR SUSTAINABLE DEVELOPMENT - GLOBAL, NATIONAL AND STATE PERSPECTIVES**

*Cymodocea serrulata*





### 5.1. Introduction

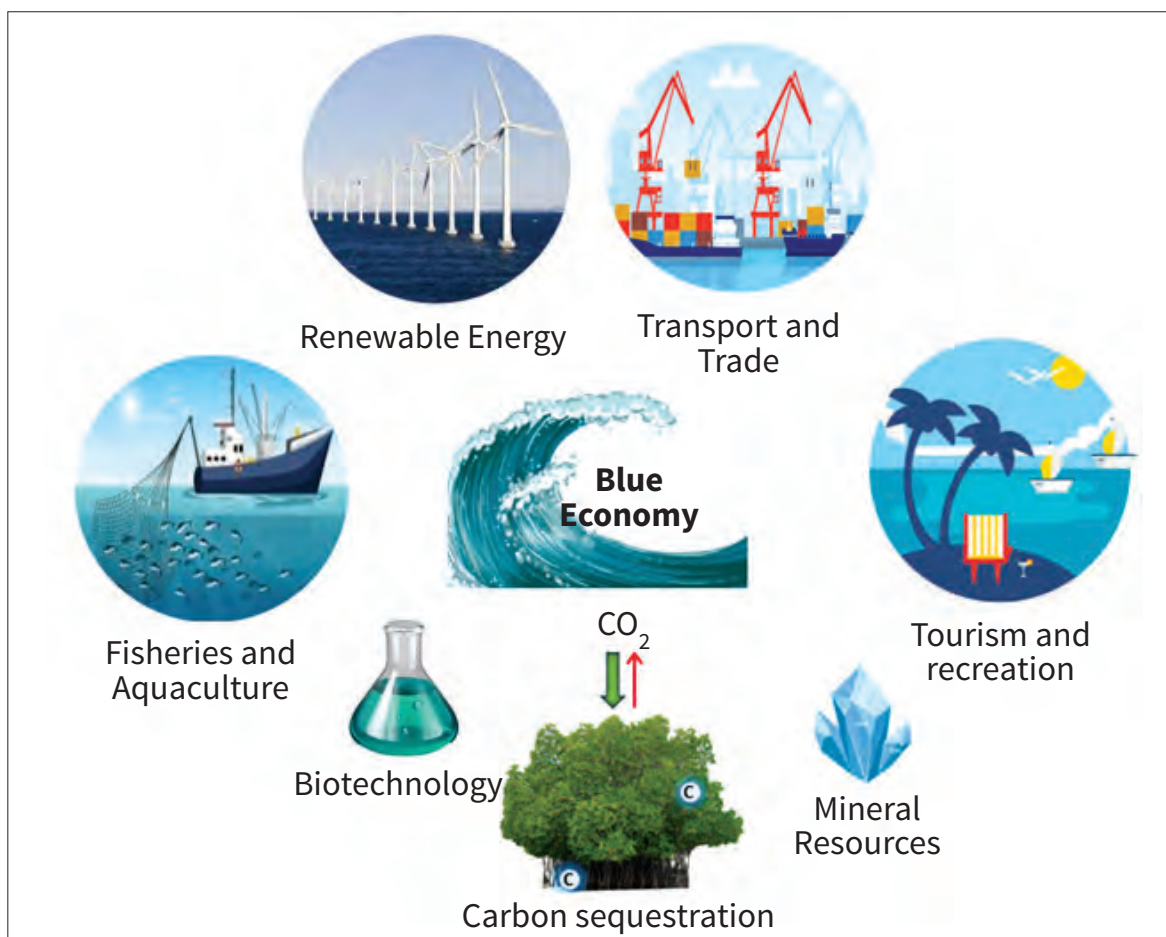
Blue Carbon Economy (BEC) is a growing field that acknowledges the crucial role of coastal and marine ecosystems in carbon sequestration. Coastal habitats such as mangroves, salt marshes and seagrasses not only mitigate the climate change impacts but also offer many economic and environmental advantages (UNEP 2012). Sustainable development in the blue carbon economy sectors requires financial systems and policies that support conservation, restora-

tion and economic growth. However, challenges such as high initial expenses, unpredictability in carbon forecasts, limited profitability, and shortfall of funds for several initiatives hinder the progress. Similarly, challenges such as the intricate governance structures and absence of recognised accounting methods also hinder the process of blue carbon initiatives. Despite these obstacles, the blue carbon market holds potential for significant financial gains (Benzaken *et al.* 2024).

*Rhizophora apiculata*



14-09-2022



**Fig. 22:** Activities related to Blue economy

## 5.2. Global perspectives

### Future prospect

The ocean, which encompasses 70% of the Earth’s surface, is the biggest ecosystem on the planet and a crucial centre of biodiversity, supporting 80% of the different species found on Earth. The major function of this entity is to provide oxygen and act as a natural reservoir for carbon, thereby reducing the effects of climate change by absorbing human-generated CO<sub>2</sub> ([www.unepfi.org/blue-finance](http://www.unepfi.org/blue-finance)). The ocean serves as a vital food source, supplying protein (nutrition) to 3 billion individuals and maintaining over half of the world’s population. The ocean’s health is crucial for the functioning of major industries including shipping, fishing, aquaculture, and coastal tourism, which together contribute to the ‘blue economy’ (Fig. 22).

The interconnected sectors play a vital role in the well-being of the planet. The blue carbon economy, a part of Blue Economy, refers to economic initiatives connected with CO<sub>2</sub> absorbed from the atmosphere and stored in the water. Mangrove, salt marsh and seagrass ecosystems play an important role in the carbon sequestration process. Blue economy has an annual economic profit worth USD 2.5 trillion, positioning it as the 7th biggest economy in the world, whereas the blue carbon economy has an annual economic profit worth USD 190 billion (Bertram *et al.* 2021).

At present, financial institutions provide financing, investment, and insurance for marine sectors, attracting investors, insurers, bankers, and policymakers. However, this sector’s rapid growth can lead to environmental risks, eroding the ocean’s resource base, and creating regulatory, market,

Seagrass habitat with sea anemone



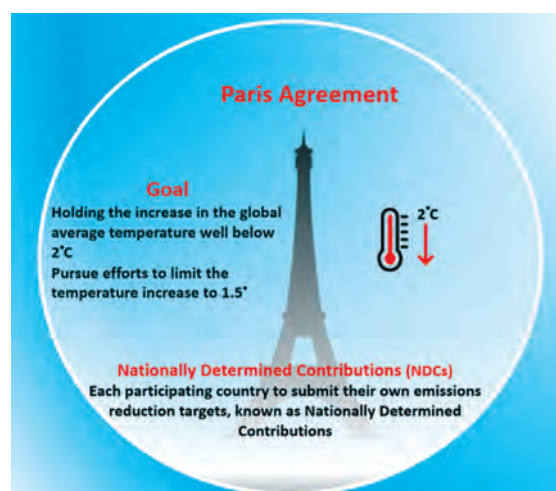


*Sesuvium portulacastrum*, *Suaeda monoica* and *Suaeda maritima*

reputational, and physical risks for financial institutions and clients, and result in the increase of greenhouse gas emission and temperature. However, the impact of the ocean economy on climate change is not yet fully understood (European Commission), but recent studies indicate that around 0.20 to 0.24 Gt of CO<sub>2</sub>e are emitted each year due to the conversion and degradation of these ecosystems. This accounts for a range of 3% to 19% of the deforestation worldwide, leading to economic losses amounting to USD 6 billion to USD 42 billion annually.

The Paris Agreement was a notable achievement in international collaboration over climate change, as the participating nations pledged to restrict the rise in global average temperature to less than 2° C above the preindustrial levels, with an even more ambitious target of 1.5° C (Fig. 23). Countries establish their own Nationally Determined Contributions (NDCs) to showcase their utmost commitment to reducing global greenhouse gas emissions. The agreement emphasised the significance of coastal blue carbon ecosystems in

mitigating global emissions and called on nations to proactively safeguard them. The United Nations Framework Convention on Climate Change (UNFCCC) designated coastal and marine habitats as significant repositories and reservoirs of greenhouse gases. Additionally, Article 5 of the Paris Agreement explicitly urged the parties to protect and improve these ecosystems.



**Fig. 23:** Paris Agreement



*Rhizophora sp.*

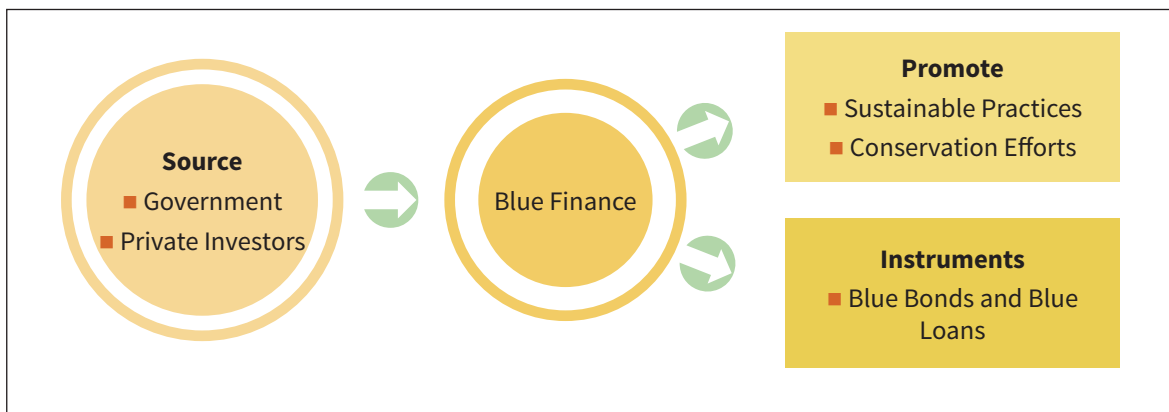
A total of 28 nations have specifically included coastal blue carbon habitats in their NDCs, and 59 countries have included them into their adaptation efforts ([www.ndcpartnership.org](http://www.ndcpartnership.org)). This is a small proportion of the total number of countries holding coastal blue carbon ecosystems, with 151 countries having at least one and 71 countries containing all three ecosystems. Facilitating more countries to pursue blue carbon in the NDCs through policy support and technical exchanges could lead to greater action on the ground.

The United Nations Sustainable Development Goal (SDG) 14, known as 'Life Below Water', seeks to preserve and responsibly use the Earth's oceans, seas, and marine resources by the year 2030 ([www.un.org](http://www.un.org); Fig. 24). It has seven targets for a sustainable ocean economy. However, so far the progress has been limited, with focus on sustain-



**Fig. 24:** Sustainable Development Goal-14

ability in fisheries and an expansion of Marine Protected Areas (MPAs), but these initiatives cover only around 7.5% of oceans (Mc Bain 2023). According to the High Level Panel for a Sustain-

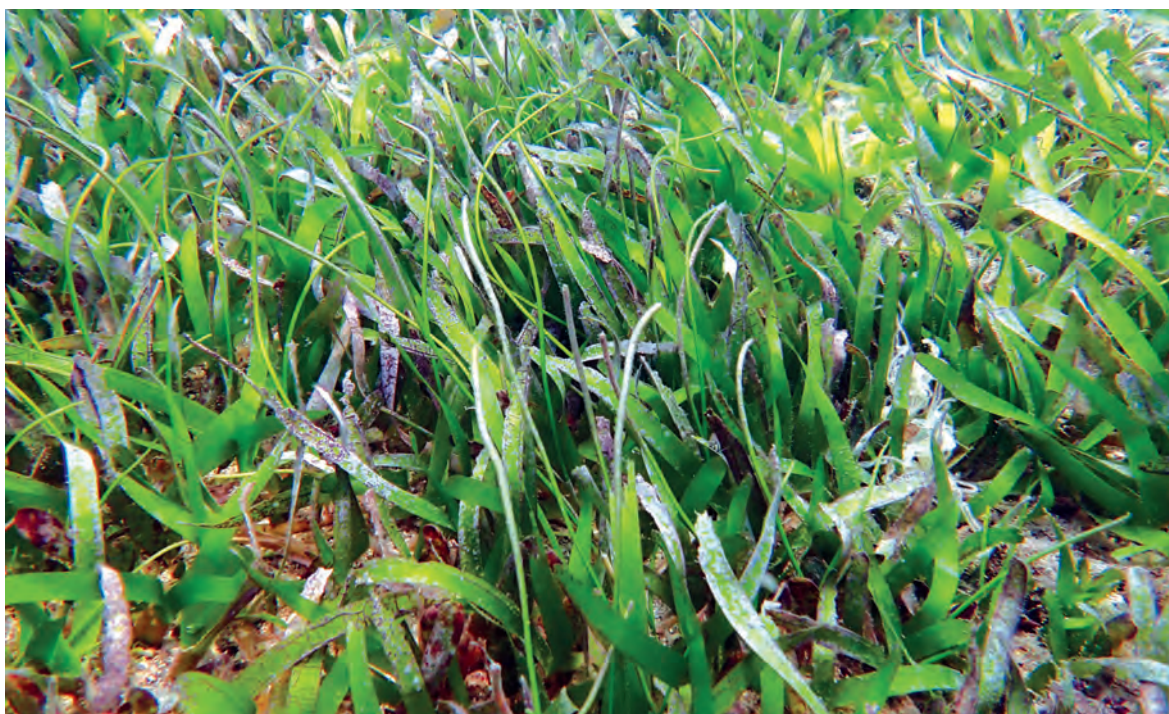


**Fig. 25:** Blue finance components

able Ocean Economy, the ocean economy has the potential to decrease greenhouse gas emissions by 21% to achieve the goal set by the Paris Agreement of limiting global temperature increase to 1.5° C by 2050 (Hoegh-Guldberg *et al.* 2019a). According to the World Economic Forum, a total of USD 175 billion in financial resources would be needed to accomplish SGD 14 by the year 2030.

Blue finance, an emerging field within climate finance, is attracting international attention for

its capacity to safeguard clean water accessibility, preserve underwater ecosystems, and support the development of a sustainable water-based economy (Mc Bain 2023b; Fig. 25). Investing in ocean action, sometimes known as ocean finance or ‘blue finance’, has the potential to bring positive climate benefits. Blue bonds and blue loans are innovative financial tools created to specifically allocate financing towards projects that promote ocean health and protect clean water resources (Grieg-Gran *et al.* 2017).



*Thalassia hemprichii* and *Syringodium isoetifolium*



*Salicornia brachiata*

The International Finance Corporation (IFC) introduced guidelines for Blue Finance in 2022, which provide detailed instructions on requirements for blue carbon projects, issuances, and financing. These standards conform to the Green Bond Principles and Green Loan Principles of the International Capital Market Associations (ICMA), as well as SDGs 6 (Clean Water and Sanitation) and 14 (Life Below Water) (Holbein 2024). Governments and companies are investing in nature-based solutions to climate change, such as carbon sequestration, coastal protection, biodiversity conservation, and waste management. Neutralizing residual carbon emissions and compensating for ongoing emissions are often included in the subsequent net-zero strategies. Net-zero commitments by companies, cities and organisations tripled between 2020 and 2021. The value of voluntary carbon market's issuances exceeded with USD 1 billion in 2021 and 80% of the loan issuances for projects are for nature-based solutions and renewable energy sectors (IFC 2023).

The restoration and conservation of mangroves, salt marshes, and seagrass meadows have the

capacity to reduce CO<sub>2</sub> emissions by 0.5 to 1.38 Gt per year (Hoegh-Guldberg *et al.* 2019a). Specifically, mangroves can offset 0.06 to 0.73 tonnes of CO<sub>2</sub> per year, salt marshes can offset 0.07 to 0.1 tonnes of CO<sub>2</sub> per year, and seagrasses can offset 0.28 to 0.37 tonnes of CO<sub>2</sub> per year (Hoegh-Guldber *et al.* 2019a). According to estimates, these options would be economically feasible if the cost is around USD 18 per t CO<sub>2</sub>. This is within the range of the current pricing in the voluntary carbon markets, but is far lower than the prices in the EU Emissions Trading Scheme, which are now trading at roughly EUR 80 to EUR 90. This oceanic blue carbon could potentially offset another 1.8 Gt CO<sub>2</sub> per year (Claes *et al.* 2022). As for 2022, a total of 23 registered pipeline projects are to achieve an estimated annual reduction of about 11 million t CO<sub>2</sub> once they are completely implemented, which may take many years or even decades for the project to be fully implemented (IFC 2023). According to the market research conducted by Climate Focus (2022), it is anticipated that the current increase in carbon pricing would persist, rising from USD 15 to USD 24 in 2022 to a range of USD 40 to USD 65 in 2040, whereas



**Fig. 26:** Challenges in blue carbon economy

the blue carbon projects have the potential to fetch prices at the higher end of these ranges (IFC 2023). The price of blue carbon offsets will increase relatively steeply during 2021 to 2030 and then the price will stabilize after 2030 (IFC 2023). Emerging financial methods such as insurance underwriting for mangrove protection, seagrass restoration and sustainability-linked financing are also gaining popularity. Recent studies indicate that ocean-based initiatives offer high return on investments (ROI) with benefits five times higher than the expenses (Hoegh-Guldberg *et al.* 2019b). Every dollar spent on mangrove conservation and restoration generates a benefit of 3 dollars in return (Konar and Ding 2022).

### Challenges

The management and restoration of coastal blue carbon ecosystems is complex and faces significant challenges in financing capital investments

for conservation (Fig. 26). These include the high risk profile of blue carbon projects, which require banks and investors to commit to a relatively marginal asset class. Small-scale projects are often based on long time-frames and therefore it is difficult to reach a cost-effective approach. Climate change impacts, such as sea level rise and warming, make tidal wetlands particularly vulnerable. There is unpredictability in carbon forecasts. High start up costs needed for stakeholder engagement and scientific research, which can be a barrier for project development. Institutional complexities and lack of capacity are also significant barriers. Many countries and national agencies lack the experience, technical expertise, and financial literacy, and such lack of an established accounting mechanism poses obstacles to develop carbon projects in tidal wetlands (Friess *et al.* 2022; Benzaken *et al.* 2024). The slow translation of international policies to national

Seagrass habitat



and subnational levels may hinder domestic plans and regulations, and tidal wetlands are often not mainstreamed in the design of public infrastructure projects. Fragmented approaches to the allocation of marine resources across nations hinder comprehension of the environmental consequences of the blue carbon economy. Land tenure is a significant bottleneck for investment in sustainable land management forms, and the conservation of tidal wetlands requires multifaceted community-led development projects to address underlying drivers of destruction and unsustainable use. Similarly, there is issue in benefit sharing - local communities should be major beneficiaries from carbon market project, especially if they lose access to resources and benefits should be captured by elites or government. In recent years, new financing sources and structures have emerged to bridge the financing gap and tackle specific challenges around blue carbon project development. The transition to a sustainable blue economy creates opportunities for multiple investment and financing streams

that can complement blue carbon finance in the mid- to long-term (IFC 2023).

### 5.3. National perspectives

#### Future prospect

India has a vast coastline of 7,500 km, including both mainland and islands. India's EEZ has over 5,000 species of flora and fauna. Sustainably harnessing ocean resources can create livelihoods. Research indicates that the economy of the Indian Ocean region has the potential to expand by 15% each year, reaching a value of over USD 120 billion by the year 2025 (Wingnaraja *et al.* 2018). Approximately 14 million people are involved in fishing and related activities as a means of subsistence, while also having to adjust to the negative effects of climate change. India has significant blue carbon potential, with studies showing high carbon stocks in mangrove forests and seagrass ecosystems along the coast. Previous research indicates that the blue carbon ecosystems in India have a collective carbon stock of 67.35 Tg C (mangroves,

*Rhizophora* sp.





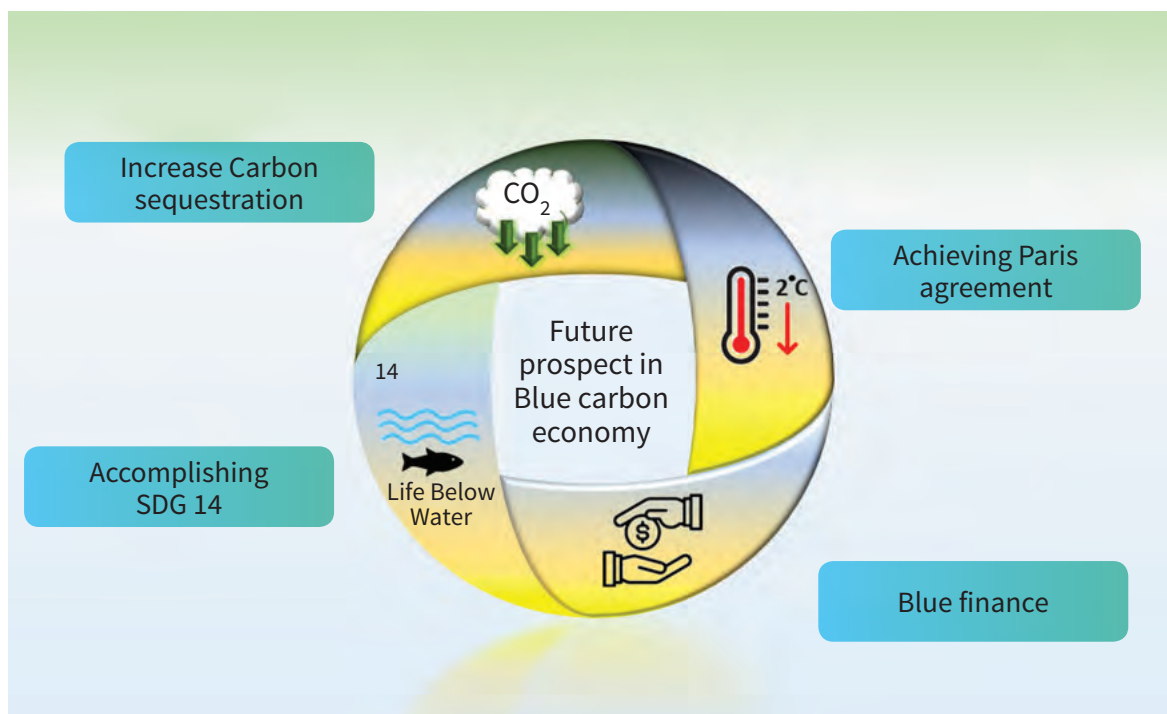
seagrass and salt marsh with 67 Tg C, 0.063 Tg C and 0.0049 Tg C respectively) (Akhand *et al.* 2023). Multiple studies have consistently calculated the geographical area covered by mangroves (about 4,975 km<sup>2</sup>), seagrass (approximately 517 km<sup>2</sup>) and salt marsh (with ranging from 290 to 1,611 km<sup>2</sup>) (Akhand *et al.* 2023). The green payment against the blue carbon ecosystems of India can be as high as USD 9.6 billion, whereas the social value of carbon stored by these ecosystems can range from USD 0.47 to 5.43 billion (Akhand *et al.* 2023). Research also indicates that there is a significant uncertainty in this value due to the limited number of studies. The coastal states such as Tamil Nadu, Maharashtra, Goa, Gujarat and West Bengal have higher blue carbon potential.

India's Nationally Determined Contributions (NDCs) under the Paris Agreement involve the commitment to establish an additional carbon sink of 2.5 to 3 billion by 2030 (i.e. to reduce 45% in GHG emission to 2005 level) through the expansion of forest and tree cover, including mangroves

(Fig. 27). India also aims to enhance its ability to cope with climate change by increasing investment in sectors that are susceptible to its effects, particularly coastal regions. Additionally, India plans to invest in advanced climate technology. State-level Integrated Coastal Zone Management Plans (ICMPs) also provide supports to meet the national coastal plan ([www.worldbank.org](http://www.worldbank.org)). India's pioneer project in blue carbon is entitled "India Sundarbans Mangrove Restoration Program", which covers an area of 4,675 ha and is estimated to reduce an annual emission of 51,249 TCO<sub>2</sub>e (IFC 2023). Similarly, other small-scale conservation and restoration of mangrove and seagrass are undertaken in different parts of India. Hence, there is a lot of potential in India for conservation and restoration of blue carbon ecosystems to meet the net zero target to mitigate climate change while also supporting biodiversity and livelihood of local communities. Even a small expanse of these coastal systems can sequester carbon considerably faster and for millions of years. The government has to commercialize the



*Halophila ovalis*



**Fig. 27:** Future prospect in blue carbon economy

blue economy to increase the sequestration of CO<sub>2</sub> in India. National Steering Committee for Indian Carbon Market (NSCICM) oversees the functioning of the Indian Carbon Market (ICM) under the Carbon Credit Trading Scheme (CCTS) and they are developing the carbon crediting framework.

### Challenges

India has the potential for blue carbon economy, but several aspects need close attention. At present the government is playing a crucial role in protecting and funding mangrove and seagrass ecosystems, while the participation of the private sector is only limited. However, there is significant potential to monetize the blue economy both at the national and international level. Similarly, there is only limited data available on carbon stock and sequestration rates for mangrove, seagrass and salt marsh ecosystems in India. Some of the other gaps are limited stakeholder engagement, lack of standards for estimating blue carbon footprints, carbon credit and financial mechanisms, geographic constraints and engaging of local communities.

## 5.4. State perspectives

### Future prospect

Tamil Nadu has a coastal length of approximately 1,076 km, which is more than 13% of India's total coastline (DADF 2014). The state is also endowed with the three blue carbon ecosystems namely mangrove forests, seagrass beds and salt marshes. Tamil Nadu has 45 km<sup>2</sup> of mangrove cover, with Pichavaram as one of the main hubs (Mathur *et al.* 2020). Extensive seagrass beds are seen in the Palk Bay and Gulf of Mannar region. Salt marshes cover an area of 61 km<sup>2</sup> in Tamil Nadu (Viswanathan *et al.* 2020). Taking into consideration the significance of the Paris Agreement and committed Nationally Determined Contributions, the Tamil Nadu Government has already set in motion the blue carbon initiatives. The state has a vision of adding another 60 km<sup>2</sup> of mangrove cover within the next five years ([www.timesofindia.com](http://www.timesofindia.com)). The state is also engaged in the restoration of seagrass ecosystem and so far a total of 6.8 ha of area has been restored for seagrass in the Palk Bay and Gulf of Mannar region. There is a lot of area available for future



Salt marsh habitat

conservation and restoration of mangroves, seagrasses and salt marshes in the Tamil Nadu coastal region, which ecosystems function as potential carbon sequestration engines, thereby fight climate change.

### **Challenges**

As far as the challenges are considered, the Tamil Nadu state encounters the same challenges as India as a whole. Regular monitoring of smaller patches of blue carbon ecosystem is needed,

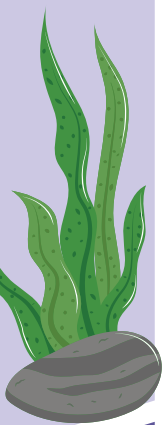
and measurement of carbon stocks in all compartments is yet to start. Coupling of a financial mechanism with blue carbon conservation activities has to be done in order to address the areas of climate change, biodiversity and human well-being. Participation of local communities is essential for effective management. Still numerous gaps exist in the measurement of carbon stocks and sequestration rates in all the potential compartments of the mangrove, seagrass and salt marsh ecosystems.

# 6

## THREATS TO BLUE CARBON ECOSYSTEMS

*Rhizophora* sp.





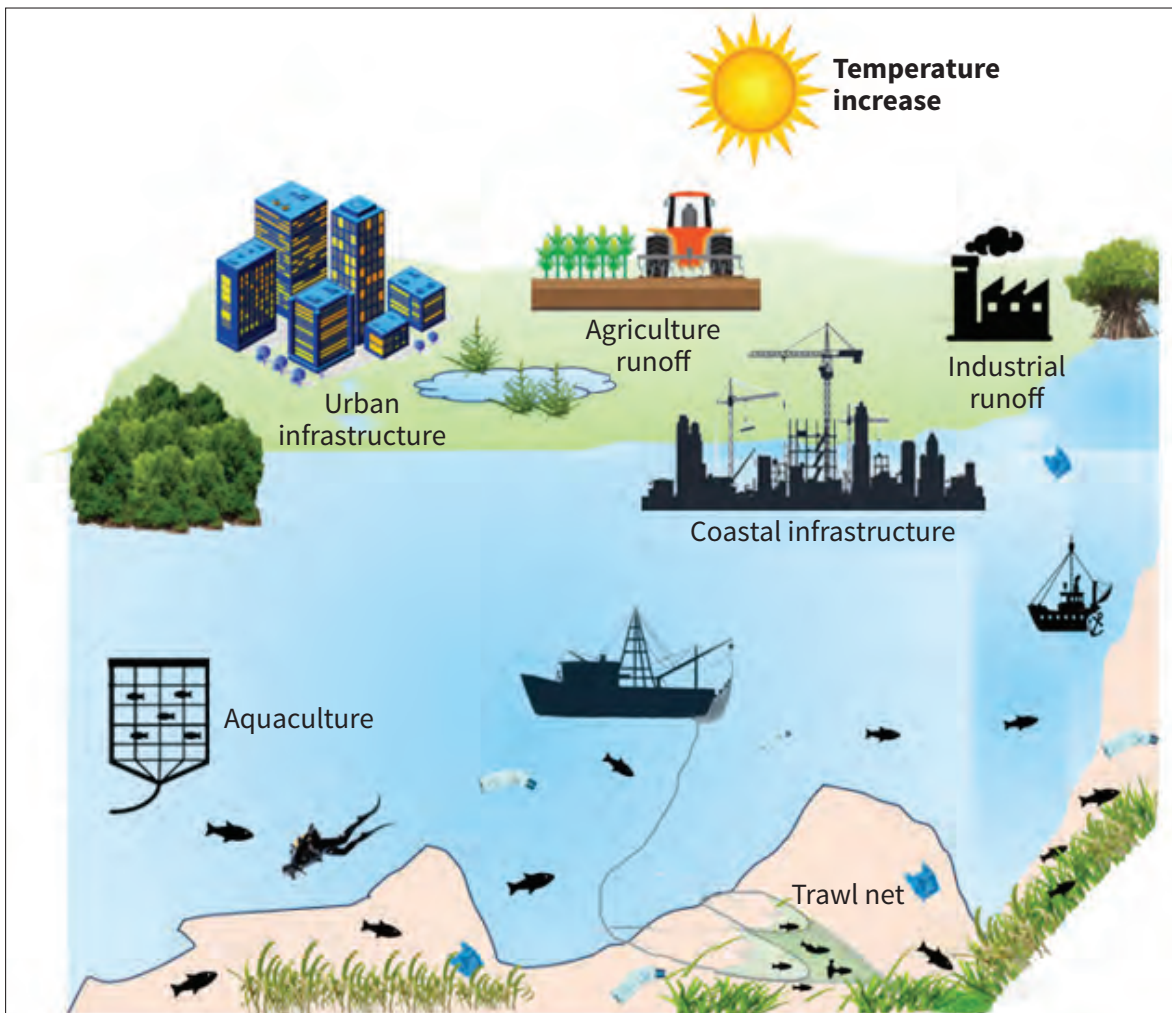
### 6.1. Introduction

Blue carbon ecosystems around the world have been affected by various natural and human-induced threats and the intensity of threats varies according to the ecosystem. Mangroves are hardy plants possessing both terrestrial and ecological adaptations and hence are resilient to slighter disturbances (Fig. 28). However, climate change induced alterations in the environment are too great for mangroves to tolerate.

Moreover, human-induced threats have been severe on mangroves over the past several decades leading to huge declines in global mangrove forest cover. Globally, seagrass beds have declined during the past several decades due to their sensitivity to poor water quality, coastal development activities, and nutrient enrichment (Green *et al.* 2021). Factors like natural fragmentation by the action of waves and currents, destructive fishing methods, pollution, and



Degraded salt marshes



**Fig. 28:** Threats to blue carbon ecosystems

recreational activities have all been linked with seagrass destruction (Alsaffar *et al.* 2020; Dunic *et al.* 2021). Similar to mangroves and seagrasses, salt marshes are also affected by various natural and anthropogenic threats. Climate-change effects, conversion of marsh land, invasive species and pollution are some of the major threats to salt marshes (Hansen and Reiss 2015). The following factors contribute much to the degradation of blue carbon ecosystems.

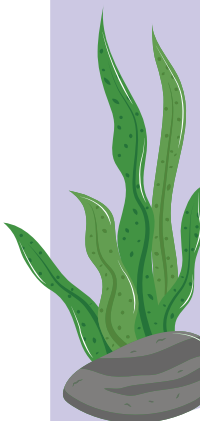
## 6.2. Climate change impacts

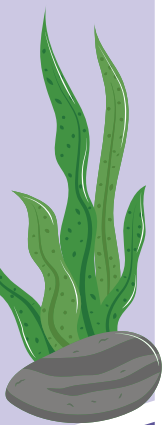
Increasing temperature levels, rising sea levels, increasing CO<sub>2</sub> levels and intense and frequent storms caused by climate change have significantly impacted global blue carbon ecosystems around the world (Portner *et al.* 2019; Dangendorf *et al.* 2017; Sippo *et al.* 2018; Lovelock and Reef

2020). It is likely that these phenomena will become more intense causing more trouble to these fragile ecosystems.

### Sea level rise

Climate change has resulted in rising seawater levels in many regions causing erosion (Qazim 1999). Due to the combined effect of thermal expansion and polar ice melting, sea level rise is obvious in all the oceans (Alongi 2002). The mean global rate of rise in sea level (RSL) has been estimated at 1.8 mm/yr in the last century. Mangroves are significantly affected by sea level rise with varying impacts on both short-term and long-term processes. Among the many threats, sea level rise is the most disturbing as mangroves are sensitive to changes in the duration and frequency of inundation and salinity (Friess *et al.*





2012). The increased duration of inundation affects the mangrove plants at the seaward margin and may cause changes in species composition (Ward *et al.* 2016). However, to a certain extent, mangroves can adjust to sea level fluctuations by modifying their surface elevation and by migrating landward (Ward *et al.* 2016).

The primary impact of sea level rise on seagrasses is the increase of depth, which consequently affects the light penetration. Sea level rise increases water depths that in turn limits the light availability to seagrass plants and intensifies wave action, consequently making the area unfavourable for seagrass growth (De Boer 2007). Changes in tidal range due to sea level rise cause changes in light intensity, current velocities, depth, and salinity distribution, which in turn affect the distribution and abundance of seagrasses (Short and Neckles 1999). Current velocity, circulation flow patterns, and flow duration affect leaf biomass, width, canopy height, photosynthesis and pollination of seagrass plants (Short and Neckles 1999). Sea

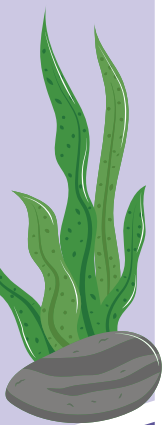
level rise thus makes seagrasses either adapt to new conditions or migrate to newly available areas (Duarte *et al.* 2018).

Generally, salt marshes are adapted to a certain extent of sea level rise, but the rise coupled with human disturbances tends to affect them (Hansen and Reiss 2015). Sea level rise pushes the coastal wetlands landward, but engineered coastal protection measures, dams, and other human modifications compromise the adaptation capacity of salt marshes. Decreased sediment supply due to the coastal development activities reduces the capacity of salt marshes to cope with sea level rise (Mattheus *et al.* 2010).

### **Increasing temperature levels**

Instigated by climate change, global temperature values are increasing at alarming levels that affect the mangrove species composition, productivity, phenology and distribution (Ward *et al.* 2016). It has been reported that photosynthesis rates of many mangrove species peak at or below





30° C, and leaf CO<sub>2</sub> assimilation rates decline at temperature levels from 33 to 35° C (Ball and Sobrado 1990). Increased temperature levels can to some extent enhance the growth, reproduction, photosynthesis and respiration, but further increase disrupts these processes (Tittensor *et al.* 2010; Alongi 2015). Increasing temperature levels coupled with reduction in the frequency of extreme cold events have pushed mangroves into salt marsh areas at higher latitudes through complex ecological interactions (Alongi 2015).

Increasing temperature levels have been widely reported to limit seagrass distribution (Duarte *et al.* 2018). Seagrass metabolism and carbon balance maintenance are directly affected by temperature anomalies causing changes in distribution and abundance of seagrass beds (Short and Neckles 1999). Increasing water temperatures reduce oxygen solubility and CO<sub>2</sub> availability and thus affect the efficiency of seagrasses for photosynthesis (York *et al.* 2013). Flowering and germination in certain species

of seagrasses are also significantly affected by extreme temperature levels (Short and Neckles 1999). Moreover, the wasting disease that affects seagrasses has been reported to be more potent under extreme temperature levels (Olsen *et al.* 2014).

### **Rising atmospheric CO<sub>2</sub>**

Similar to temperature, elevated levels of CO<sub>2</sub> enhance the growth of certain mangrove species though growth also depends on other parameters such as salinity, nutrient availability, and water-use efficiency (Alongi 2015). However, it has been accepted that temperature anomalies instigate more fluctuations in the physiological processes of mangroves (Luo *et al.* 2010). Changes in precipitation affect salinity levels as decreases in precipitation and increases in evaporation increase the soil salinity, thus paving the way for conversion to hypersaline mudflats. Further, higher precipitation may extend the mangrove area by pushing further into salt marsh regions (Ward *et al.* 2016).





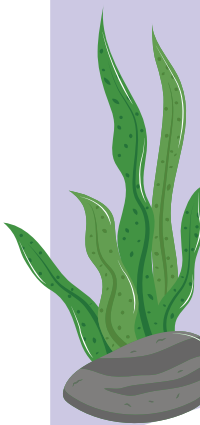
Coastal developmental activities affecting salt marshes

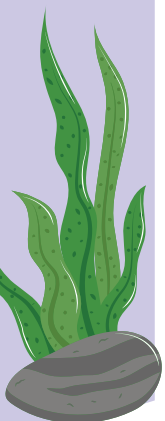
Increasing levels of CO<sub>2</sub> have widely been reported to significantly affect the productivity and carbon storage capacity of seagrass beds (Gullström *et al.* 2018; Russell *et al.* 2013). Though increased CO<sub>2</sub> levels help to scale up the photosynthetic activity of seagrasses to a certain level, productivity is affected when the threshold is breached (Rehpolho *et al.* 2017). Likewise, ocean acidification leads to wider seagrass cover and larger biomass initially but affects growth and species composition after reaching the threshold (Brodie and De Ramon N'Yeurt 2018).

Increased CO<sub>2</sub> levels, fluctuations in precipitation, hydrological and biogeochemical processes and species composition have also been linked with the degradation of salt marshes (Hansen and Reiss 2015; Giuliani and Bellucci 2019). As the global temperature levels are increasing, soil evaporation accelerates, which in turn pushes up soil salinities in salt marshes reducing productivity (Crosby *et al.* 2017).

### Cyclones and storms

It is obvious that there have been significant changes in rainfall around the world and this condition is aggravated by temperature fluctuations that affect evaporation and transpiration. Changes in rainfall patterns affect the distribution, extent, and growth of mangrove forests (Ward *et al.* 2016). Extreme storm episodes have been reported to cause both positive and negative impacts on mangroves. Severe cyclones can affect mangroves by wave activity from the seaward side, which may uproot mangrove plants, breaking branches and destroying the canopy (Doyle *et al.* 1995). More severe cyclones can completely eradicate the mangrove forest causing peat collapse and decrease in soil elevation (Paling *et al.* 2008). Damage activated by storms develop some resilient physiological traits in certain species, which include increased nutrient turnover, increased nutrient reserves, and increased tolerance to salinity and inundation (Ward *et al.* 2016).





Due to the elevated temperature levels, intense storm and cyclone events have increased during the past few decades causing changes in precipitation patterns and physical damage to coastal areas (Perry *et al.* 2019). The direct effects of these episodic events include erosion by wave action, shading from suspended sediments, and smothering by sediment deposition affecting seagrass beds (Short and Neckles, 1999). Moreover, increased rainfall triggered by these events causes significant changes in water circulation, vertical stratification, sedimentation and nutrient cycling affecting seagrass beds (Collier *et al.* 2012). Intense storm events affect the freshwater inflow, sediment dynamics and nutrient levels in salt marshes (Giuliani and Bellucci 2019).

Salt marshes are a natural shield to protect coastal communities from intense storms and cyclones as they stabilize shorelines by reducing velocity, height and duration of waves. However, intense storms can cause detrimental effects on salt marshes through scouring and erosion (Hansen and Reiss 2015).

### Human impacts

It has been estimated that about 75% of the global population lives within the 50 km distance from the coastline and more than 1 billion people,

particularly in Asia, live in low-lying coastal areas (Broom 2022; Sunkur *et al.* 2023). Hence, the impacts of anthropogenic activities on blue carbon ecosystems are severe and often irreversible. While human impacts affect all these ecosystems, there are differences in the intensity and response of the specific ecosystems.

### Mangroves

In spite of their intrinsic value, mangroves have been significantly affected by human activities particularly by the conversion of mangrove areas for economic land uses such as aquaculture, agriculture and urban development (Friess *et al.* 2021; Fig. 29). It has been estimated that about 62% of the loss of global mangrove in the 21st century is due to human activities (Goldberg *et al.* 2020). Further, about 80% of the human-induced loss happened in Southeast Asian countries (Goldberg *et al.* 2020). A combination of commercial activities, such as agriculture, aquaculture and oil palm cultivation, contributes 47% of the global mangrove loss while non-productive conversions add another 12% loss.

As mangroves occur at the interface of land and sea, they are prone to several coastal development activities such as the development of resorts, power plants, desalination plants,

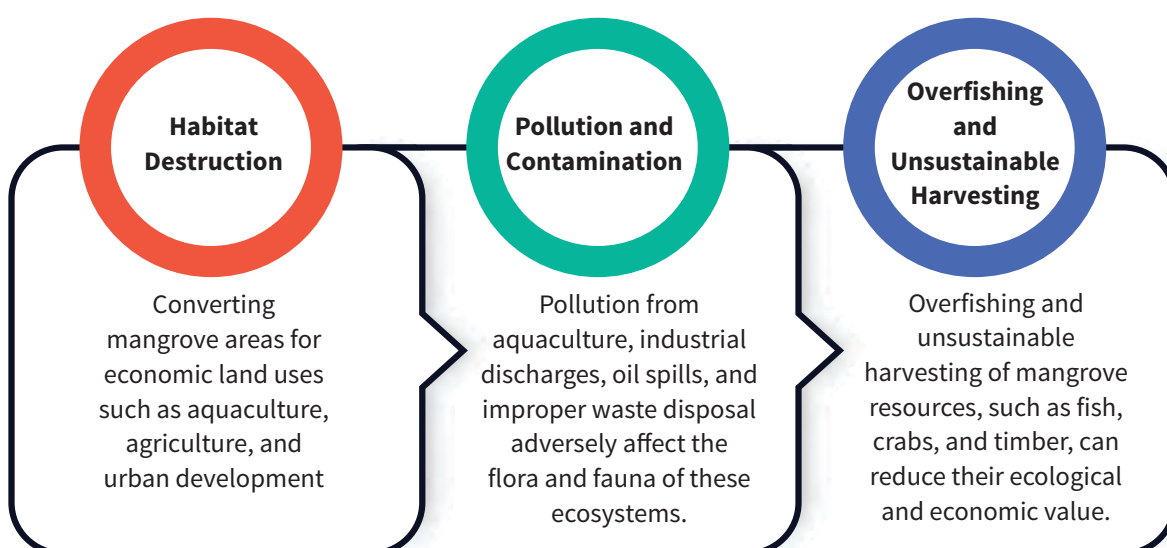


Fig. 29: Threats to mangrove ecosystems



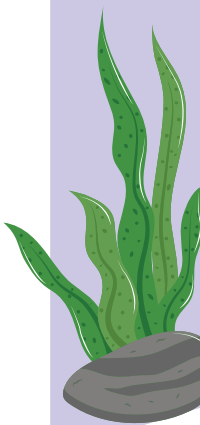
Stunted mangroves due to coastal developmental activities

ports, nuclear plants, dams and aquaculture ponds. These activities cause pollution and soil erosion, and alter ecological settings leading to the degradation of mangroves. Coastal development restricts and alters the water flow into the sea causing changes in temperature, salinity, alluviation and infiltration (Akram *et al.* 2023). Development of roads, erosion control structures and drainage canals affects the natural hydrological flow, which in turn affects important processes such as transportation and deposition of sediment, restricting the mangrove restoration through secondary succession (Sahavacharin *et al.* 2022). Importantly, these impacts on mangrove areas not only affect the mangrove plants but also destroy the associated organisms (Akram *et al.* 2023). Mangrove deforestation for timber has been happening traditionally, accounting for about 26% of mangrove loss (Ferreira *et al.* 2022). The discharge of nutrient-rich pollutants into mangrove areas from commercial activities leads to the bloom of harmful microalgae result-

ing in episodic hypoxic conditions that kill marine organisms (Akram *et al.* 2023). Tourism provides economic benefit to several countries and at the same time it also affects the integrity of mangrove ecosystems directly and indirectly through the activities related to tourism (Akram *et al.* 2023).

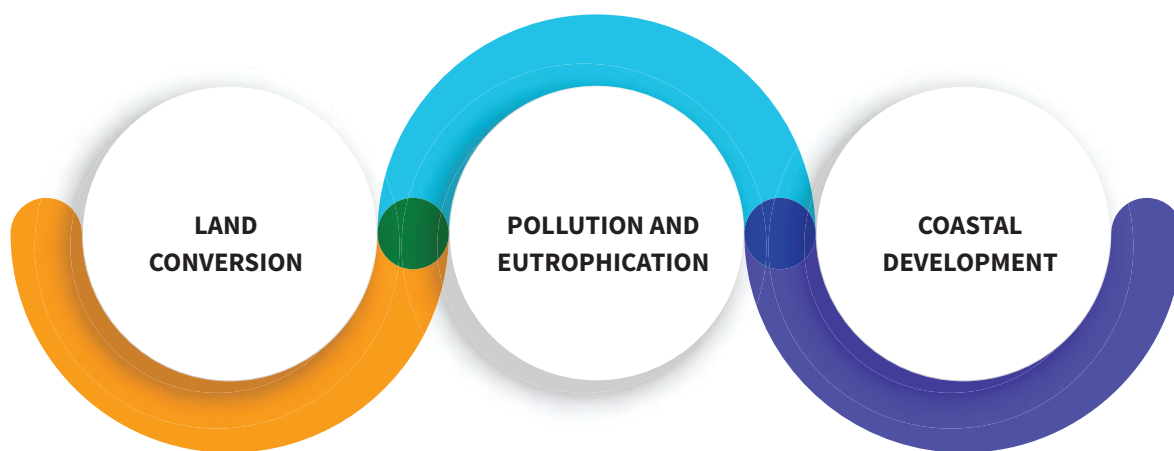
Aquaculture practices, in particular shrimp farming, have had significant impact on mangrove areas. Aquaculture activities have been estimated to be the primary reason for mangrove area conversion contributing 52% globally in the past three decades (Richards and Friess 2016). Southeast Asian countries such as Thailand, Vietnam, Indonesia, Myanmar, Malaysia, Bangladesh, Philippines and India contribute much to this conversion degrading hundreds of hectares of mangroves (Richards and Friess 2016; Akram *et al.* 2023). Aquaculture activities have caused, for example, mangrove deforestation, increased salinity, eutrophication, introduction of invasive species, pollution and disease (Aslan *et al.* 2021).

**Technical Report: Blue Carbon Wealth of Tamil Nadu, India**  
The role of coastal ecosystems as carbon sinks



Washed ashore seagrasses





**Fig. 30:** Threats to salt marsh ecosystems

The enhanced commercial activities in the mangrove areas due to the increased population have significantly increased the amount of non-degradable litter globally. Domestic sewage, industrial discharges, inorganic chemicals, oil spills along with solid wastes contribute significantly to the decline of mangroves (Dan *et al.* 2022).

### Salt marshes

Among the several human-induced threats to salt marshes, the primary factor that affects salt marshes is the filling for agricultural fields or urban development (Fig. 30). Salt marsh lands are converted for agriculture, habitation, roads, railways and industries as well as for other human activities. Moreover, dredging and reclamation activities associated with land use cause sedimentation, enriched nutrient levels, pollution and bioinvasion (Hansen and Reiss 2015; Giuliani and Bellucci 2019). It is likely that the above-mentioned development activities will increase in the future considering the ever increasing global coastal population affecting salt marsh communities.

Increasing coastal population and consequent developments cause eutrophication and pollution (Deegan *et al.* 2012). When the salt marsh area is affected by nutrient pollution, it becomes more prone to biological invasions and the invading species may have destructive effects on physical and biological properties (Gedan *et al.* 2009).

Excess nutrient levels increase the above-ground biomass, decrease the below-ground biomass, and decrease organic matter accumulation causing eventual degradation of salt marshes (Turner *et al.* 2009; Hansen and Reiss 2015). Oil spills have also been reported to cause extensive damage to salt marsh ecosystems.

Freshwater runoff, groundwater inputs, and tidal flooding are important hydrologic settings for the sustenance of salt marshes and changes in these settings affect salinity, oxygen levels, and microbial regimes. Alterations in hydrologic settings due to human activities would severely impair the salt marsh ecosystems (Giuliani and Bellucci 2019).

### Seagrasses

The decline of seagrass beds around the world has been reported to have increased during the 20th century. Deteriorating water quality has been the primary contributor to this human-mediated decline via eutrophication, smothering drift, light attenuation and toxic substances (Vieira *et al.* 2022; Fig. 31). Light availability and water clarity are important for the survival of seagrasses and they are vulnerable to degradation when the light penetration is affected (Duarte *et al.* 2004). Increasing inputs of nutrients, atmospheric deposition, and watershed run-off, extensive sediment discharge and clearing of the mangrove fringe are some of the activities that affect the water quality in seagrass areas (Duarte *et al.* 2004). Mechani-

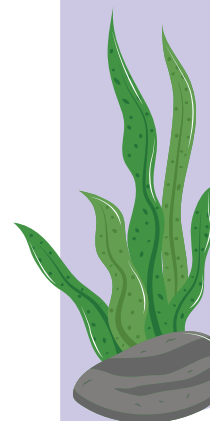




Fig. 31: Threats to seagrass ecosystems

cal damages caused by fishing and aquaculture, introduction of invasive species, boating and anchoring, and dredging and reclamation affect seagrass beds severely (Duarte *et al.* 2004)

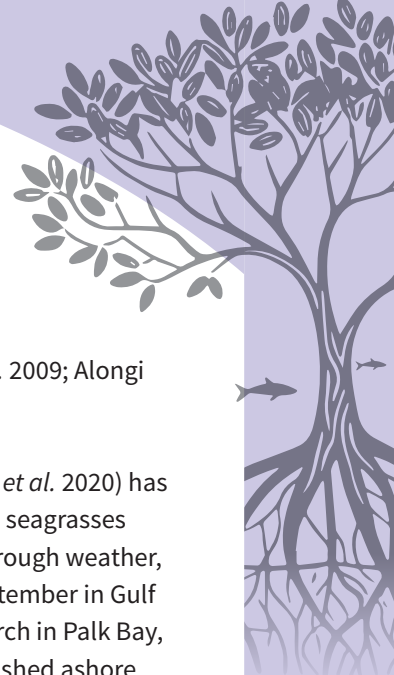
Studies have proved that removal of top predators disturb the food web and pave the way for eutrophication. Human activities can cause phase shifts (i.e. shifting from seagrass dominated areas to macroalgae dominated areas) and make the seagrass recovery difficult (Eklöf 2008). Aquaculture activities in the seagrass areas cause shading, eutrophication and sediment deterioration (Duarte *et al.* 2004). Coastal development activities such as the building of ports, resorts, roads, industries and other developments also affect seagrass beds significantly. Human activities do not impact all seagrass species alike as there are species-specific responses causing regional variations in vulnerability (Grech *et al.* 2012).

### 6.3. Threats to the blue carbon ecosystems of Tamil Nadu

All the climatic threats mentioned above have impacts on the blue carbon ecosystems of Tamil Nadu. Elevated temperature levels, sea level rise, cyclones and increased CO<sub>2</sub> levels are obvious along the Tamil Nadu coast affecting the blue carbon ecosystems of the state. Human-induced threats, however, cause immediate consequences that affect the status, health and diversity of mangroves, seagrasses and salt marshes along the state's coast. Some of the major threats that affect the blue carbon ecosystem of Tamil Nadu coast are presented below.

#### Climate change impacts

The limited research works done on the mangroves of Tamil Nadu have demonstrated that climate change impacts affect them severely. Sediment erosion, inundation stress and increased



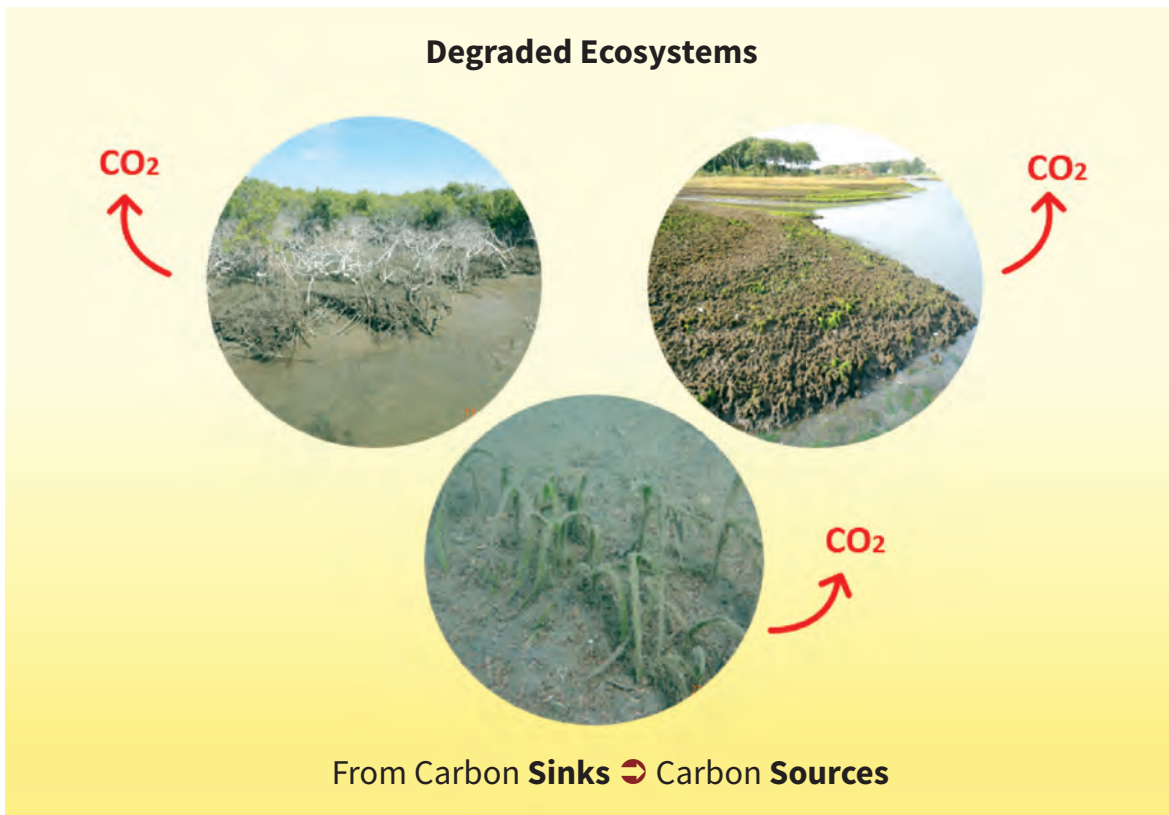
salinity have been reported in the mangrove areas of Tamil Nadu (Khan *et al.* 2012). The carbon storage capacity of mangroves in Tamil Nadu is affected by rising temperatures, decreasing rainfall, variation in salinity, and changes in tidal inundation patterns (Gnanamoorthy *et al.* 2020).

Seagrasses in Tamil Nadu are also affected by the deleterious effects of climate change as elevated temperature levels, sea level rise and climate change mediated microalgal blooms affect the harmony of seagrass beds in the Gulf of Mannar and Palk Bay (Fig. 32). Due to sea level rise, some of the islands of the Gulf of Mannar have become submerged and some are under pressure from severe erosion (Raj *et al.* 2015; Asir *et al.* 2020). Similarly, temperature levels along the Tamil Nadu coast are also increasing (Raj *et al.* 2021) affecting coastal vegetation, such as mangroves, seagrasses and salt marshes. Increasing thermal stress on mangroves will affect the photosynthesis and respiration, and cause bleaching and de-

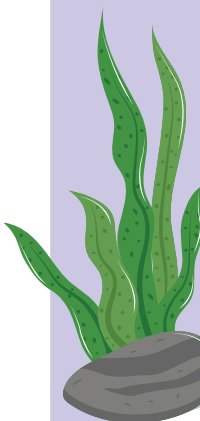
creased productivity (Waycott *et al.* 2009; Alongi *et al.* 2016).

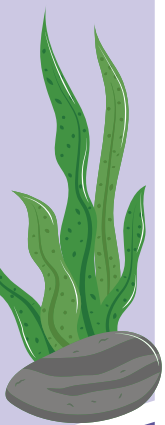
Blooms of *Noctiluca scintillans* (Raj *et al.* 2020) has also caused significant damages to seagrasses and associated organisms. During rough weather, particularly between April and September in Gulf of Mannar and from October to March in Palk Bay, a huge quantity of seagrasses is washed ashore due to strong waves and water currents. Freshwater runoff during the monsoon season is also a threat, which reduces the seawater salinity and causes heavy turbidity. This is obvious in Palk Bay, where several rivers enter the sea and the intensity of runoff is particularly severe during monsoon seasons. Sedimentation has always been on the higher rate in the Gulf of Mannar and Palk Bay, which reduces the light intensity and affects seagrass photosynthesis.

Climate change causes the natural growth of mangroves into nearby salt marsh ecosystems



Degraded ecosystems - carbon sinks to sources





**Fig. 32:** Degraded seagrasses

over time (Gopi *et al.* 2019). However, it is obvious that all the above-mentioned climatic threats affect the integrity of salt marshes.

### **Human induced threats**

Though much of the mangrove areas in Tamil Nadu is well protected, human-induced activities such as land conversion for aquaculture activities, tree-cutting for firewood, dumping of garbage and wastewater discharge affect the mangroves (Fig. 33). In Pichavaram, regular inflow of pollutants from domestic, industrial and agricultural sources affect mangroves (Ghosh *et al.* 2015). Further, the loss of connectivity between mangroves and the Vellar estuary has resulted in the formation of large mud flats instead of beach formation. Tidal water inflow to the wetland has also decreased due to the formation of a sand pit (Selvam *et al.* 2002; Ghosh *et al.* 2015). Similar effects are observed in all the mangrove areas

of Tamil Nadu. Heavy-metal pollution has been reported in the areas of halophytic and mangrove vegetation in Tamil Nadu coast (Agoramoorthy *et al.* 2008).

The human population along the coasts of the Gulf of Mannar and Palk Bay is very large and consists mostly of fishermen who depend on fish (and shellfish) from seagrass beds for their livelihood. Wealthy seagrass beds occur near the shore, where much of the fishing practice is undertaken by small-scale fishermen. This puts severe stress on seagrass beds and the associated fauna (and flora), especially commercially important organisms. There are several hundreds of mechanized trawlers operating along the Tamil Nadu coast affecting all the bottom-dwelling organisms including seagrass beds (Samuel *et al.* 2002, 2012; Edward *et al.* 2007). Many trawlers can be seen fishing near the mainland or islands



of the Gulf of Mannar, where extensive seagrass beds are available. Apart from the mechanical damage inflicted by trawlers on seagrass beds, sedimentation caused by trawling also affects the light penetration needed for the photosynthesis of seagrass plants. Similar to mechanized trawling, push net operation (Edward *et al.* 2012) causes mechanical damage to seagrasses, induces sedimentation and also affects the seagrass inhabitants. As trawling is not prohibited by law, it is prevalent in the Gulf of Mannar and Palk Bay causing damages to seagrass beds.

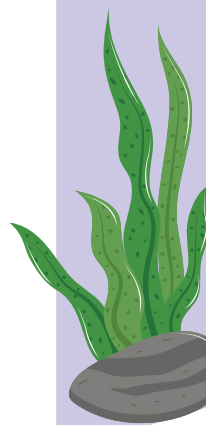
Shore seine is another version of bottom trawling that happens on the shore with or without involving a boat (Raj *et al.* 2017). Apart from bottom trawling, there are some other fishing methods

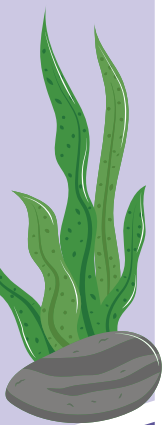
causing considerable damage to the seagrass beds of the Gulf of Mannar and Palk Bay. These destructive methods include surface-supplied diving, anchoring in the seagrass areas, setting cage culture rafts over seagrass beds, laying bottom set gill nets, setting traps in seagrass areas, walking on seagrass beds, throwing stones and sandbags that are used as weights in the fishing nets and moving the boat with a wooden pole sticking into seagrasses (Mathews *et al.* 2010; Raj *et al.* 2017; Edward *et al.* 2019).

Seaweed farming along the Palk Bay has significant impact on seagrass beds such as reducing light, productivity and carbon storage capacity, and causing toxicity. In view of the above-mentioned chemical and physical perils, seaweed



**Fig. 33:** Degraded mangroves





cultivation sites in Palk Bay are becoming empty bottoms devoid of seagrasses. Seaweed farming in Palk Bay depends only on the invasive red alga *Kappaphycus alvarezii*, which has been termed as a destructive and dangerous invasive species by the Global Invasive Species Database (GISD) of the International Union for Conservation Network (IUCN) (<http://www.iucngisd.org/gisd/species.php?sc=738>). The shading effect is significantly higher in the case of *K. alvarezii* than the other native species because this alga forms thick mats that completely blocks the sunlight for the underlying organisms. The Government of Tamil Nadu issued an order (G.O. Ms. No. 229 dated 20.12.2005) to disallow the cultivation of *K. alvarezii* near the eco-sensitive zones of the Gulf of Mannar and Palk Bay in order to protect coral reefs and seagrass beds. In spite of this order, people continue to cultivate the alga in south Palk Bay affecting seagrass beds. It is also likely that the cultivation sites may turn into algae-dominant areas from seagrass-dominant ones.

The coast of the Gulf of Mannar and Palk Bay has several urbanized areas, industries, salt pans, and aquaculture farms (Edward and Samuel 2004, 2007; Kumaraguru *et al.* 2006; Samuel *et al.* 2012; Edward *et al.* 2021). As there are several stringent rules for effluent treatment for industries, industrial pollution has so far not been reported to cause significant damage to seagrass beds. However, the hyper-saline water from salt pans, after evaporation, is flushed out daily into the canals that discharge at different places within the Gulf of Mannar and Palk Bay (Samuel *et al.* 2012) and the increased salinity affects seagrass beds. Shrimp farms are found throughout the coast of Palk Bay, especially in the northern parts

of the bay system. Due to the release of nutrients-rich waters from the shrimp farms, eutrophication and consequent minor blooms are always likely, which reduces the light and dissolved oxygen necessary for seagrasses. There are numerous sewage outlets along the coast of the Gulf of Mannar and Palk Bay that bring untreated domestic waste to the sea (Kumaraguru *et al.* 2006; Rajesh 2013). As most of the seagrasses occur near the shore, they are affected by the pollution along with all the associated organisms.

Due to the increasing population, there has been a significant increase in the number of crafts, the use of fishing gears and the use of plastic materials along the coast of the Gulf of Mannar and Palk Bay affecting seagrass beds. Pollution from recreational activities and pilgrimage also affect seagrass beds of Tamil Nadu coast. There are several development activities taking place along the coast of the Gulf of Mannar and Palk Bay, especially the establishment of fishing jetties and deployment of groynes for coastal protection. These development activities have irreversibly damaged seagrass beds and the associated biodiversity at the constructed areas.

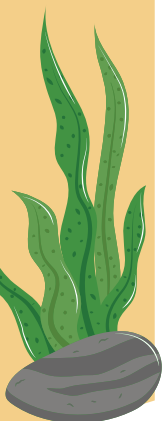
Salt marshes in the Tamil Nadu coast occur in between other coastal wetland areas or in between the commercial development areas and hence are affected by any threat to the adjacent ecosystems. As salt marshes occur more in the landward side, coastal development activities without realizing the importance of salt marshes affect them significantly. Fluctuations in tidal range, salinity, water inflow, temperature and nutrient levels also affect the salt marshes of the Tamil Nadu coast (Gopi *et al.* 2019; Viswanathan *et al.* 2020).

# 7

## **CONSERVATION AND MANAGEMENT OF BLUE CARBON ECOSYSTEMS**

Seagrass habitat





### 7.1. Introduction

Systematic collection of data on the status, health, diversity and area cover of blue carbon ecosystems helps to understand why changes happen and to respond to and manage them properly. On the backdrop of the diverse nature of the threats that blue carbon ecosystems face and the continuous decline they undergo, it is imperative that they are regularly monitored and assessed in order to conserve them for long to tackle climate change impacts.

Moreover, restoration of lost coastal vegetation is of utmost importance to compensate for the loss. There are several restoration techniques used around the world to restore each of the blue carbon ecosystems with varying success rates (Fig. 34). Climate change adaptation capacity should be developed so that future climatic scenarios can be handled without much hassle. Community involvement and co-management are of great importance as coastal people are the primary stakeholders



*Rhizophora apiculata*



**Fig. 34:** Blue carbon ecosystem conservation

in managing blue carbon ecosystems. Development of sanctuaries, marine national parks, and conservation reserves has helped in conserving coastal ecosystems in various regions around the world. Hence, such initiatives are needed to conserve the blue carbon ecosystems and also to sustain the livelihood options of the dependent population.

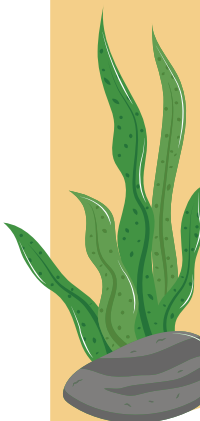
## 7.2. Monitoring and assessment

### Mangroves

Mapping and quantifying the extent of mangroves helps in estimating the services they provide, which include carbon storage, coastal protec-

tion, biodiversity support and more (Sunkur *et al.* 2024). The lack of baseline information on the status of mangroves leads to improper management and inefficient conservation efforts. Hence, the first step would be to assess the extent, distribution and diversity of mangroves. In Tamil Nadu, mangroves in Pichavaram and Muthupetta are comparatively well studied while mangrove patches in other areas have not been given much attention. Satellite imagery and remote sensing are widely used to assess mangroves around the world and field confirmation is also very important while estimating the cover and distribution.

Identifying changes in mangrove landscape is



*Sesuvium portulacastrum*



very important and it can be done by chronological comparison of satellite imageries. However, the accuracy of such information is dependent primarily on the affected area and the resolution of the imagery (Cárdenas *et al.* 2017). Apart from identifying changes in mangrove cover, the influence of water under the canopy and the consequent changes should also be studied. Tidal height and canopy density have been reported to affect the spectral signature of mangroves (Saito *et al.* 2003). Long-term studies should be undertaken to understand and respond to specific changes in mangrove ecosystems. Sunkur *et al.* (2024) state that remote sensing helps in various mitigation and adaptation strategies, which include early detection of changes, vulnerability assessment, mapping coastal dynamics, carbon sequestration and community engagement. These parameters should be regularly and continuously assessed to formulate proper response during the times of crisis.

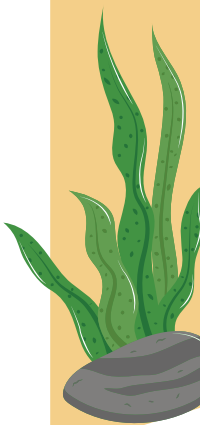
According to Schmitt and Duke (2015), mangrove

monitoring protocols should detail methodology, frequency of sampling, intensity of sampling, sampling unit size, sampling pattern, the location of the plots, when to do the surveys, and when to stop the monitoring, as well as organization of finance and administration. Ellison (2012) demonstrates field-based monitoring and assessment of mangrove areas. There are three levels of mangrove monitoring; the first level is transect-based surveys recording mangrove locations, species zones, mangrove condition and identifying pressures; the second level involves vegetation plots in each zone recording community structure, height and diameter of trees, density of seedlings; and the third level consists in sedimentation monitoring and a litter productivity study (Ellison 2012).

The monitoring and assessment of carbon sequestration in mangrove areas can be carried out following standard manuals such as 'Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in man-



Seagrass habitat





*Salicornia brachiata*

grove forests’ by Kauffman and Donato (2012) and ‘Mangrove carbon estimator and monitoring guide’ by Broadhead *et al.* (2016).

### **Salt marshes**

Unlike mangroves and seagrasses, salt marshes do not get much attention though they contribute significantly to blue carbon. Comprehensive science-based information is required on the ecological status in order to develop proper management actions. Anthropogenic and climatic threats to salt marshes, response variability inherent in marsh types or settings, and impact on the ecosystem functions and services and response actions need to be understood properly (Kutcher *et al.* 2022). Things to be monitored in salt marshes should include the broad-scale extent and habitat composition of salt marsh plants, detailed assessment on the status of salt marshes based on plant communities, human disturbances, and response to disturbance, and research-based assessments such as the impact of accelerated sea-level rise. In Tamil Nadu, baseline surveys should be carried out to assess and map salt marsh ecosystems and

to understand the status, health and diversity.

### **Seagrasses**

Unlike mangrove monitoring, seagrass monitoring requires the skill of SCUBA diving and versatility in underwater assessment protocols. Ascertainment of the presence or absence and area distribution of seagrasses is the primary step in seagrass monitoring. Changes in seagrass landscapes can then be measured after the development of baseline information (Krause-Jensen *et al.* 2004). Colonisation depth, area cover, biomass, shoot density, epibenthic organisms, associated macrofauna, and inhabitant fish populations are other parameters that need to be monitored regularly to understand temporal changes.

Seagrass cover explains the fraction of benthic area covered by seagrasses and thus is a measure of seagrass abundance (Krause-Jensen *et al.* 2004). The measurement of cover gives information on whether the seagrasses are dense or patchy. Another important parameter to be

assessed is seagrass biomass that is the weight of seagrasses per m<sup>2</sup> that can be expressed as either total biomass of all seagrasses in an area or for each available seagrass species separately. Shoot density of seagrasses, which is the count of number of seagrass shoots, in a particular area is also important and it can also be measured for individual species.

Seagrass assessment is carried out using satellite imagery and remote sensing in many parts of the world (Koedsin *et al.* 2016; Geevarghese *et al.* 2018; Bremner *et al.* 2023). This method is especially useful for a vast area where field-level assessment is expensive or not possible. However, seagrass assessment using satellite measurements has several limitations such as fluctuations in resolution, reflection, and other atmospheric factors during imagery, which limit the accuracy. Also, the lack of adequate field confirmation makes the satellite approach less reliable. Hence, field-level seagrass assessment is more reliable and accurate but it requires underwater skills and knowledge of seagrass ecology apart from special equipment and financial resources. In particular, seagrass beds in Tamil Nadu are similar at shallower depths in the Gulf of Mannar and Palk Bay. Hence, field-level observations are possible and considering the high level of sedimentation, it is inevitable. Seagrass beds along the Tamil Nadu coast have been comparatively well studied to propose appropriate conservation actions.

Seagrasses and their carbon sequestration capac-

ity can be assessed and monitored using standard manuals such as 'Guidelines for the rapid assessment and mapping of tropical seagrass habitats' by McKenzie (2003), 'Seagrass Net manual for scientific monitoring of seagrass habitat' by Short *et al.* (2015) and 'Blue carbon in seagrass ecosystem: guideline for the assessment of carbon stock and sequestration in Southeast Asia' by Rahmawati *et al.* (2019).

### 7.3. Restoration

#### Mangroves

Conservation of the remaining global mangrove forests has become imperative, with the focus on rehabilitation and restoration of mangroves to compensate for the loss (Lovelock *et al.* 2022; Fig. 35). If practiced properly, mangrove restoration is a cost-effective approach to improve the biogeochemical and ecological functions of mangroves (Su *et al.* 2021). The track record on mangrove restoration programs reveals that not all restoration initiatives are successful as there are many failures primarily due to inappropriate or unsuitable environmental locations (Lee *et al.* 2019) and limited engagement of local stakeholders (Friess *et al.* 2022). Enhancing the integration of scientific and local knowledge into mangrove restoration projects and improving stakeholder engagement and public awareness are paramount for achieving desirable outcomes in mangrove restoration (Rodríguez-Rodríguez *et al.* 2024). It is suggested that along with restoration efforts, it is important to focus on reducing the threats that lead to man-

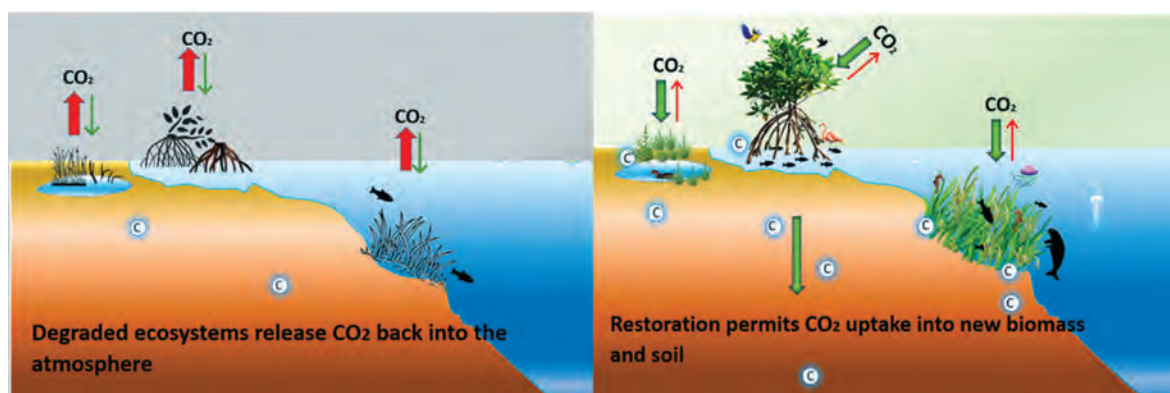


Fig. 35: Release and uptake of CO<sub>2</sub> from degraded and restored regions



Restored mangroves in Pichavaram

grove degradation (Lovelock *et al.* 2022). In India, there have been several restoration and reforestation initiatives to restore mangroves, which have helped to achieve an increase of 252 km<sup>2</sup> of mangroves between 2015 and 2021.

Mangrove restoration has been in practice in Tamil Nadu for several years as Tamil Nadu Forest Department has carried out several mangrove plantation initiatives. Recently, the department has planned to restore degraded mangrove areas in Pichavaram and increase mangrove cover in the region by 100 hectares in the year 2023-24 to create bio-shields. Likewise, several restoration initiatives have already been carried out and some are currently under progress in many mangrove regions of the state.

In Muthupettai, healthy mangroves are found in regions where canal fishing occurs, as this practice help prevent the stagnation of tidal water within the mangroves, which in turn supports the maintenance of suitable soil salinity for their growth ([www.indo-germanbiodiversity.com/arti-](http://www.indo-germanbiodiversity.com/arti-)

[cles-details-42.html](#)). Hence, these fishing canals have been restored in order to protect the saline/freshwater interface necessary for mangrove rejuvenation. More of such restoration projects have to be implemented along the Tamil Nadu coast to increase the cover of mangroves and associated organisms, not only for blue carbon but also for all the ecological and economic benefits they offer (Fig. 36).

### **Salt marshes**

The restoration of salt marshes is not as developed as the restoration of the other blue carbon ecosystems. However, due to the continuous loss of salt marshes and their importance in storing carbon, restoration of salt marshes has been initiated at many locations around the world to combat the habitat loss (Adam 2019). Increasing awareness of their ecological importance and understanding of the degradation have urged the scientists to go for salt marsh restoration initiatives (Fig. 37). The majority of the salt marsh restoration projects have been carried out in the United States and Europe, and most other areas

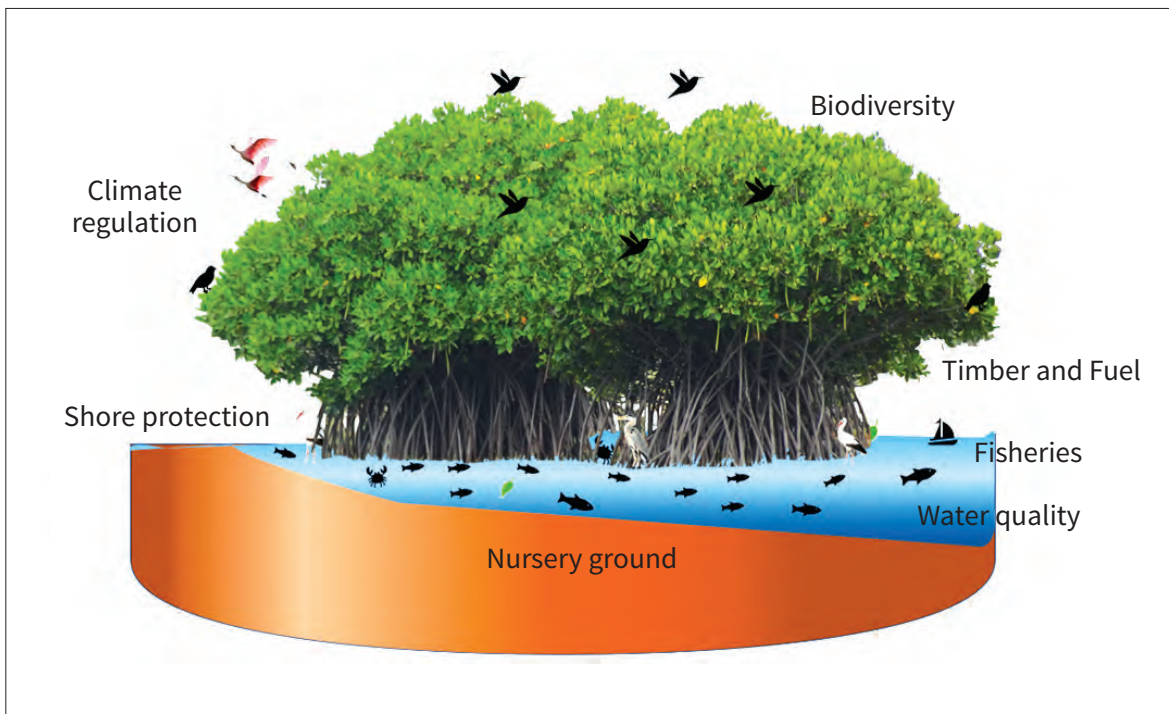
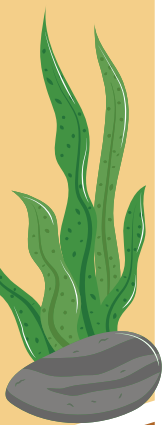


Fig. 36: Benefits of mangrove restoration



Fig. 37: Benefits of salt marsh restoration



need restoration of salt marshes considering the degradation (Adam 2019). Attempts have not been made in India to restore salt marshes and such initiatives should be started soon considering the enhanced awareness of their blue carbon potential. Viable low-cost techniques should be developed to restore salt marshes to enhance the carbon storage capacity.

### Seagrasses

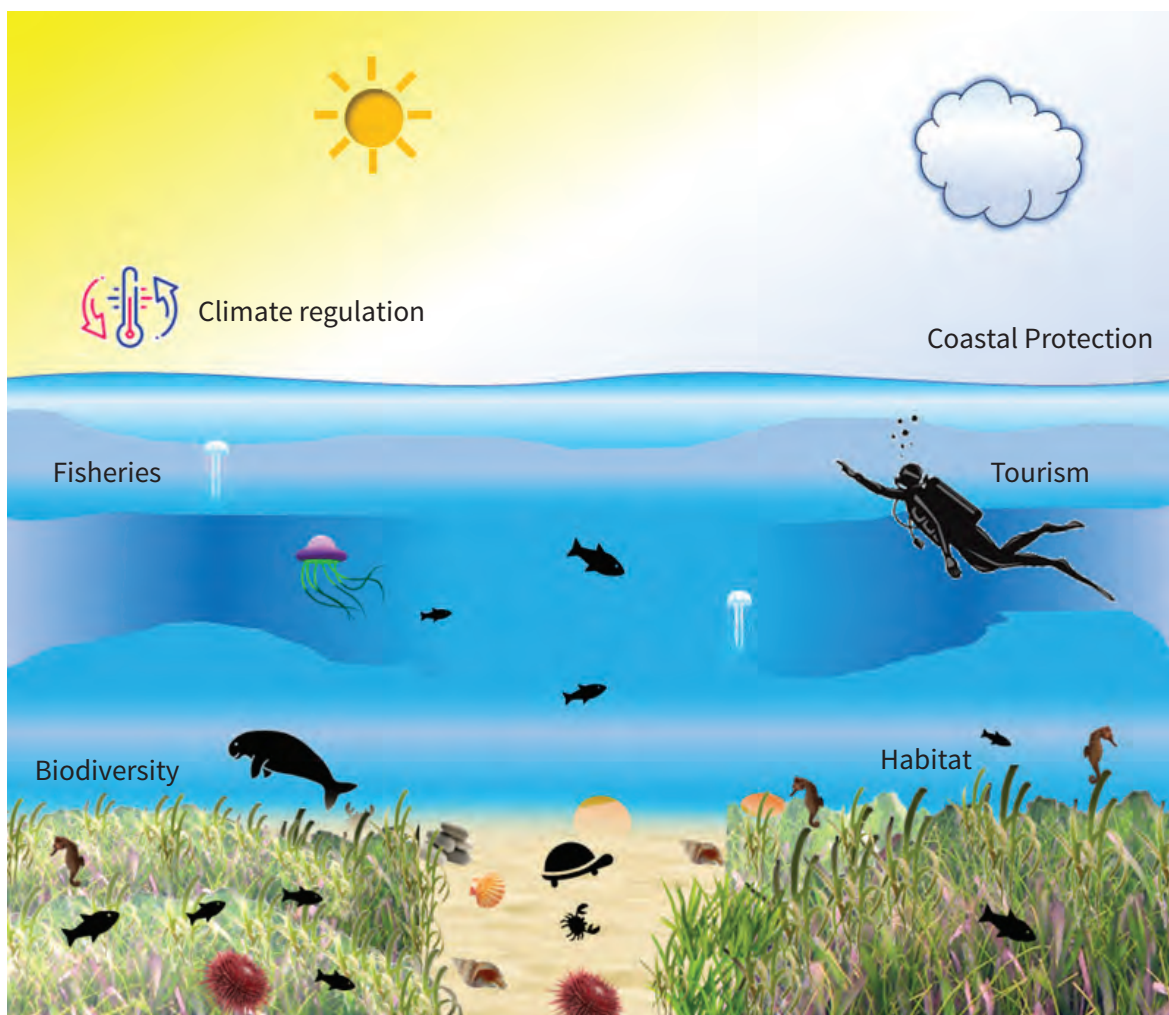
Increasing instances of seagrass degradation around the world have prompted researchers to seriously think about the restoration of seagrass beds. Measures for the restoration of seagrasses were first taken in as early as 1939 in Europe (Reigersman *et al.* 1939). Various techniques have been attempted for the restoration and recovery of seagrasses, with varying success rates (Treat and Lewis 2006). Seagrass restoration is an evolving science with both successful and failed projects (Paling *et al.* 2009). Planning, formulating a policy, defining management guidelines,

prescribing apt planting methods, selecting suitable sites, developing methodology appropriate to site conditions, improving seagrass spreading and coverage rates, accounting for self-facilitative properties, minimizing donor bed damage, means of reducing costs, saving labour and time, and preventing bioturbation are important before initiating a seagrass restoration project (Edward *et al.* 2019).

Seagrass restoration in India is still in a primitive stage as it has been carried out only in Tamil Nadu. Manual transplantation of sprigs has been reported to be the best choice for seagrass restoration in seagrass beds along the Gulf of Mannar and Palk Bay (Edward *et al.* 2019). In the sprigs method (Perrow *et al.* 2002), mature seagrass sprigs collected from healthy donor sites are tied with biodegradable jute twines across 1 m<sup>2</sup> PVC quadrats. Then these quadrats with sprigs are immediately taken underwater and fixed at the restoration site. The quadrats and the jute strings



Seagrass restoration in Gulf of Mannar



**Fig. 38:** Benefits of seagrass restoration

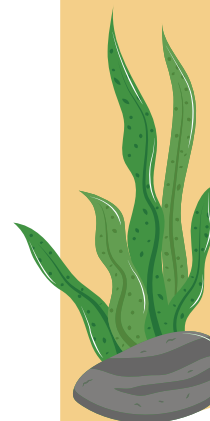
keep the seagrass intact and in contact with and firmly established in the bottom minimizing disturbance from waves, tides and currents. The sprigs method is a low-tech and low-cost method that has yielded significant positive outcomes in the restoration of seagrass beds along the Tamil Nadu coast (Edward *et al.* 2019). Instead of PVC frames, wooden sticks of 1 m have also been used to prepare the quadrats in Tamil Nadu to reduce the plastic usage. Though this method seems to be eco-friendly, it involves serious compromises on the survival of transplanted seagrasses and hence is not suggested for wide-scale restoration projects. Eco-friendly coir ropes to replace PVC frames have also been used to restore seagrass beds in Tamil Nadu with promising results. More seagrass restoration projects have been planned

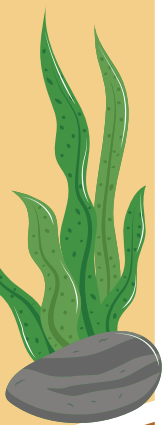
to be executed in the Gulf of Mannar and Palk Bay by the Government of Tamil Nadu to enhance their ecological and economic benefits (Fig. 38).

#### **7.4. Education and capacity building**

Knowledge and awareness of blue carbon ecosystems is relatively new and is improving around the world. Social considerations and public sector perspectives are lacking among the literature related to blue carbon (Thomas 2014; Pricillia *et al.* 2021).

Environmental justice, land ownership, and gender equality are some of the important aspects to be kept in mind while involving the local communities in blue carbon initiatives. Partnerships between public, private, and civil sector groups





are important to achieve climate change mitigation and adaptation success (Spalding 2016). Community-based management of blue carbon ecosystems has been proved very effective. Livelihood of the dependent communities should always be given priority in order to get the support of communities. Through carbon financing, blue carbon projects should be developed to generate income for communities, which in turn would get their support (Damastuti and de Groot 2019; Quevedo *et al.* 2020). These approaches would educate the community leading to enhanced awareness regarding blue carbon ecosystems and their importance.

The actions taken by individuals or groups with various levels of capacity, to protect and responsibly use the environment in order to maintain the ecological, social and economic benefits are termed as stewardship, which is essential for conserving blue carbon ecosystems (Bennett *et al.* 2018; Contreras and Thomas 2019). For this to happen, capacity of all the stakeholders should be developed and enhanced to manage and conserve blue carbon ecosystems. Local community assets and governance factors should always be taken into account when doing capacity building among the communities. Local assets should include social capital, financial capital, physical capital, cultural capital, human capital and institutional capital (Lockwood *et al.* 2010; Pricillia *et al.* 2021). Governance factors such as laws, policies, organizations, powers, and politics should also be considered (Pricillia *et al.* 2021). Thus, eliciting local community's participation in conservation of blue carbon ecosystems through building awareness, capacity and skills, organizing local communities at the grass-root level, empowering them and facilitating provision and adoption of alternate livelihood options would help sustaining integrity of blue carbon ecosystems of Tamil Nadu coast or elsewhere. Apart from the local community, all types of stakeholders including researchers, academicians, policy makers, managers and industrialists should also be incorporated in the education and capacity building initiatives for improved results. Several

education and capacity building programs are already in place in Tamil Nadu that need to be scaled up to improve the conservation efforts. It is to be noted here that mangroves often get the attention in these programs due to the easy access but equal importance should also be given to seagrasses and salt marshes.

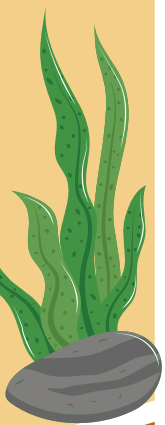
### **Climate change adaptation**

Increasing awareness of the importance of blue carbon ecosystems in climate change adaptation has prompted the blue carbon conversation. However, there is a need for enhanced capacity to implement and understand the scientific, technical, policy and institutional aspects of carbon emissions and removals from blue carbon ecosystems (Murray *et al.* 2023). Blue carbon ecosystems bury and accumulate a high amount of carbon on a per-unit-area basis and they also provide many non-climatic benefits and offer ecosystem-based adaptation to climate change (Hilmi *et al.* 2021). When degraded, blue carbon ecosystems would release their carbon back to the atmosphere and hence conserving them from degradation is very important. Apart from the carbon sequestration and storage capacity of blue carbon ecosystems, our ability to manage them for achieving net additional climate change adaptation and mitigation benefits is important in the context of policy and market frameworks for managing climate change implications (Howard *et al.* 2023). Hence, it is important to build awareness with governments and other stakeholders on the feasibility of blue carbon as a national climate adaptation and mitigation measure (Howard *et al.* 2023).

Effective policy frameworks incorporating blue carbon ecosystems can mitigate climate change implications by sustainably using carbon ecosystems to support vulnerable communities and this is called ecosystem-based adaptation (Hilmi *et al.* 2021). Adaptation plans should incorporate the potential of blue carbon ecosystems for carbon sequestration and other services such as protection from storm damage and flooding and the provision of resources, and also the co-benefits that arise from them (Hilmi *et al.* 2021). Blue

*Ehhalus acoroides* and  
*Syringodium isoetifolium*





carbon ecosystems offer critical services, which help the community to mitigate and get adapted to climate change impacts. These services are important for coastal climate adaptation including protection from storm surge and sea-level rise, prevention of erosion along shorelines, coastal water quality maintenance, nutrient recycling, sediment trapping, habitat provision for numerous commercially important species and more (Mathur *et al.* 2020).

Nature-based solutions have been reported to be effective in protecting, managing, and restoring blue carbon ecosystems and in addressing societal challenges such as food security and coastal protection and thus in providing human well-being and biodiversity benefits (Cohen-Shacham *et al.* 2016). For instance, increasing the biodiversity among the blue carbon ecosystems could play a critical role in climate adaptation as more species would increase the ecosystem functions (Duffy

2016). Blue economy should be considered in climate change mitigation and adaptation strategies to promote sustainable development and the strategies should focus on the ways to combine nature-based solutions for coastal development as it can bring positive social, economic, and financial impacts (Seddon *et al.* 2019). Tamil Nadu is one of the forerunners to develop adaptation and mitigation efforts to conserve blue carbon ecosystems for sustainable utilization. Restoration of mangroves and seagrasses is already in full swing as methodologies have been standardized and there are plans to expand these important initiatives. Protocols should be developed to restore salt marshes in order to sustain their blue carbon potential and other ecological benefits.

### **7.5. Co-management**

Coastal communities are the primary stakeholders in the management and conservation of blue carbon ecosystems and they must be encour-



Salt marsh habitat



*Rhizophora* sp.

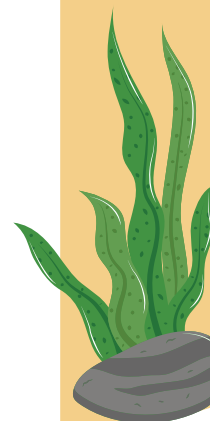
aged to participate in the implementation of the conservation practices. As fisheries are a traditional means of livelihood, the aspirations of the dependent coastal fisherfolk have to be considered, and their active inclusion in conservation planning and action has to be ensured. Conservation programs need to be socially acceptable and they have to secure cooperation, coordination and support from multi-sectoral agencies and organizations (Melkani 2012). Coastal communities are the first to recognise the value of healthy blue carbon ecosystems for their livelihood and sustainability, apart from carbon storage, and hence local knowledge is crucial to developing and implementing sustainable blue carbon actions at all levels (Murray *et al.* 2023). Moreover, the dependence of coastal communities on blue carbon ecosystems is critical for gender equity, and women must be engaged in conservation and management efforts (Murray *et al.* 2023). In many cases, women often rely on fisheries associated with blue carbon ecosystems to generate revenue for their families (Bosold 2012).

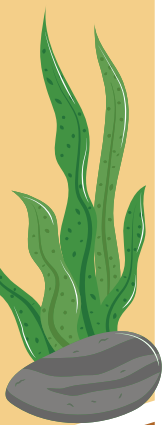
Tamil Nadu Government has already carried out co-management initiatives with great success. For instance, grass root level community organizations such as the Village Marine Conservation and Eco-development Committees, with a mandate for linking conservation and livelihood improvements, were established by the Gulf of Mannar Biosphere Reserve Trust (GOMBRT) to conserve the important marine habitats and associated biodiversity along with maintaining the livelihood options of fishermen (Melkani 2012). It has proved to be highly successful both in biodiversity conservation and in enhancing the coastal fisherfolk's standard of living. Such initiatives should be expanded along the coast of Tamil Nadu in order to conserve and manage the blue carbon ecosystems.

#### **Protected areas**

When compared with unprotected sites, the protected areas are more effective in increasing biodiversity, reproductive output, and coastal protection (Jacquemont *et al.* 2022). As they enjoy

**Technical Report: Blue Carbon Wealth of Tamil Nadu, India**  
The role of coastal ecosystems as carbon sinks





Planted *Rhizophora* sp. in Karankadu

legal protection, the protected areas can be effectively used for the promotion of ecosystem and community resilience and the restoration of degraded ecosystems through proper management (Murray *et al.* 2023). Further, increases in income support through the formation of conservation reserves would enhance the livelihood of fishermen and consequently build social adaptive capacity to meet climate change implications through increased food security (Jacquemont *et al.* 2022).

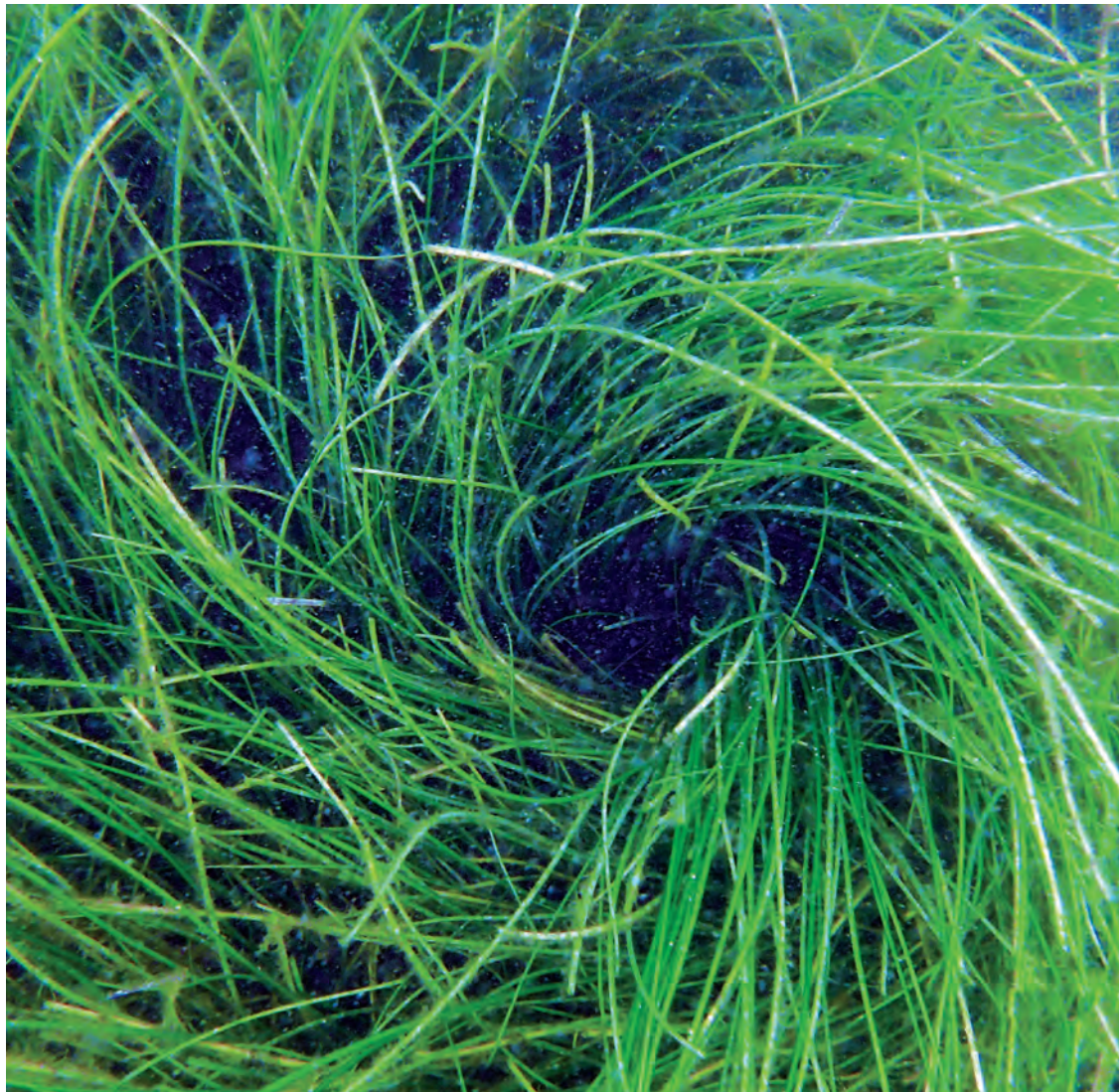
The coast of Tamil Nadu has several protected areas of different conservation levels including biosphere reserve, conservation reserves, sanctuaries and a marine national park. These protected areas play a vital role in conserving the blue carbon ecosystems along the coast. However, there are plenty of areas with blue carbon ecosystems in Tamil Nadu that are not

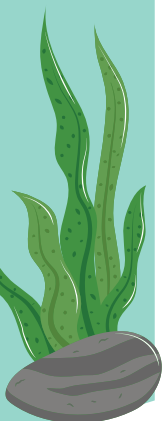
protected under these legalized boundaries. Declaration of protected areas has helped greatly in reducing the human-induced threats to coastal ecosystems and sustaining the biodiversity in Tamil Nadu. For instance, the declaration of Gulf of Mannar Marine National Park has helped to conserve and restore coral reefs along the Gulf of Mannar coast. The recent announcement of dugong conservation reserve in Palk Bay is a great step in conserving dugongs and seagrass ecosystems. More attention, more funding and more research are always available for dedicated protected areas while the areas outside these boundaries are often neglected. Hence, it is imperative that areas with significant amount of mangroves, seagrasses and salt marshes should be provided some sort of legal protection in order to conserve them for their sustainable ecological roles.

# 8

## CONCLUSION

*Syringodium isoetifolium*





**T**he ocean plays a crucial role in regulating global temperatures and absorbing heat, but human activities are causing ocean warming and acidification. Blue carbon ecosystems, which sequester atmospheric carbon through photosynthesis, are essential for climate change mitigation. Investing in these ecosystems can help reduce emissions and improve human well-being. Over 130 nations have pledged to achieve net zero carbon emissions by 2050, and strategies like carbon markets and credits are needed to address climate change.

Coastal blue carbon ecosystems, including mangroves, salt marshes, and seagrass beds, are vital for life support and storm protection. They are among the largest carbon storehouses on Earth, with CO<sub>2</sub> burial rates 20 times higher than other land-based ecosystems. These ecosystems store blue carbon in soil, aboveground, dead, and below-ground living biomass. Mangroves store and sequester large amounts of blue carbon through their extensive root systems and sediment trapping. Salt marshes store 65-95% of the total carbon stock and are consid-

ered blue carbon sinks. Seagrass ecosystems contribute to marine biodiversity and indirectly contribute to climate change mitigation.

*Syringodium isoetifolium and Cymodocea serrulata*



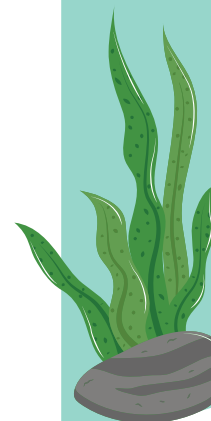
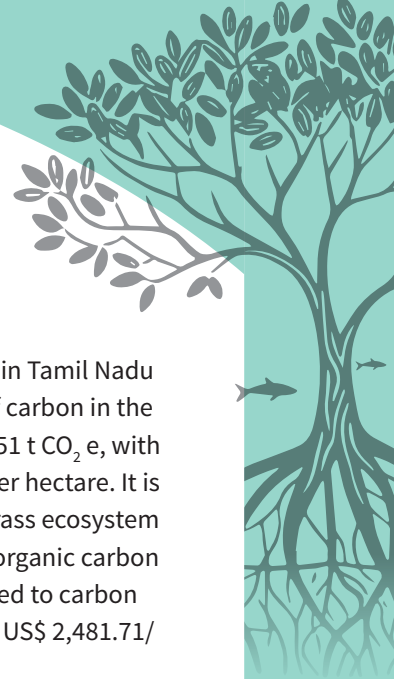
Tamil Nadu possesses three blue carbon ecosystems: mangroves spanning approximately 45 km<sup>2</sup>, salt marshes covering around 61 km<sup>2</sup>, and seagrass meadows extending about 393 km<sup>2</sup>. The present study reveals that the mean blue carbon stock in the mangrove environment is  $111.19 \pm 10.46$  Mg C/ha, whereas the overall estimated carbon stock in Tamil Nadu is 5,00,355 Mg C, with an economic value of US\$ 12.84 million. The mean blue carbon stock in the salt marsh ecosystem is  $108.76 \pm 12.30$  Mg C/ha, whereas the overall estimated carbon stock in Tamil Nadu is 6,63,436 Mg C, with an economic value of US\$ 17.03 million. The mean blue carbon stock in the seagrass ecosystem is  $96.69 \pm 13.19$  Mg C/ha, whereas the total estimated carbon stock in Tamil Nadu is 37,97,983.2 Mg C, with an economic value of US\$

97.48 million. Seagrass restoration in Tamil Nadu produces an extra 18.68 Mg C/ha of carbon in the upper 1 m of soil, equivalent to 68.51 t CO<sub>2</sub> e, with an economic value of US\$ 479.58 per hectare. It is projected that a deteriorated seagrass ecosystem may produce 354.53 t CO<sub>2</sub>/ha if all organic carbon in the top 1 m of sediment is oxidised to carbon dioxide, with an economic value of US\$ 2,481.71/ha.

The blue carbon economy, focusing on coastal and marine habitats, is gaining global attention for its potential to mitigate climate change effects. India, with its vast coastline and biodiversity, is a potential blue carbon economy. Blue bonds and loans aim to provide clean water access, protect marine habitats, and foster a sustainable aquatic economy. However, challenges include initial costs, uncertainty, and limited funding. As a part of its first Nationally Determined Contributions (NDCs), India pledged to reduce the greenhouse gas (GHG) emission intensity of its economy by 45% by 2030 from 2005 levels. India is developing Carbon Credit Trading Scheme framework.

Now-a-days, blue carbon habitats, particularly mangroves and seagrasses, are significantly impacted by climate change, elevated sea levels, CO<sub>2</sub> concentrations, and recurrent storms. Rising sea levels affect mangroves by increasing water depth and limiting light infiltration. Salt marshes can tolerate some sea level rise but are hindered by coastal defenses and reduced sediment supply. Human activities, including aquaculture, deforestation, and tourism, contribute to the destruction of mangroves and salt marshes.

The Tamil Nadu coastal blue carbon ecosystems are particularly affected by these environmental issues and continuous monitoring and evaluation studies are required to mitigate climate change effects. It is the right time to conserve these blue carbon ecosystems by collaboration across various sectors, community-based management and stakeholder engagement for mitigating climate change impacts.



*Rhizophora mucronata*

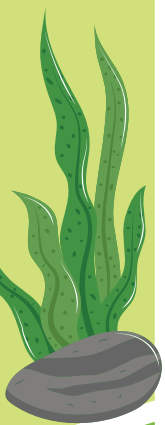


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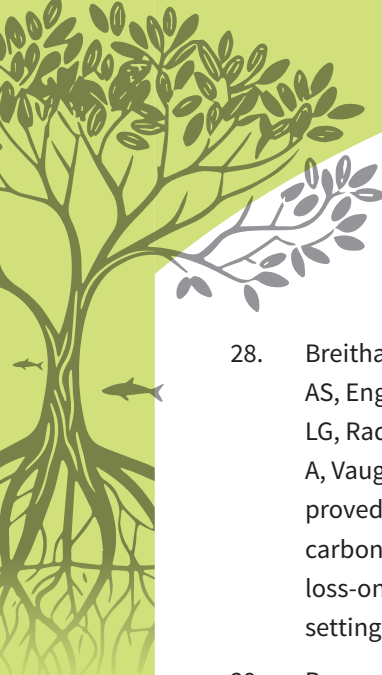


*Avicennia marina*


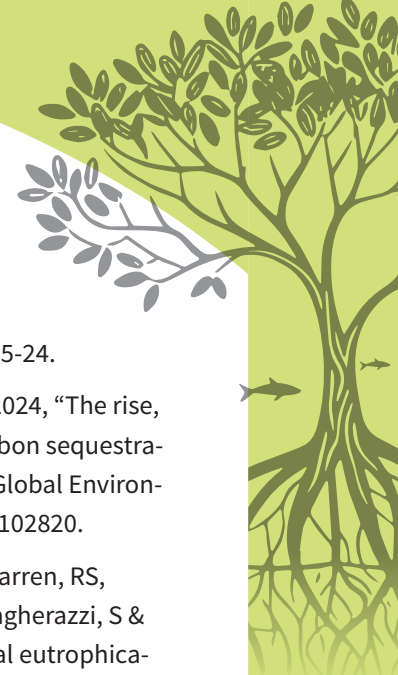


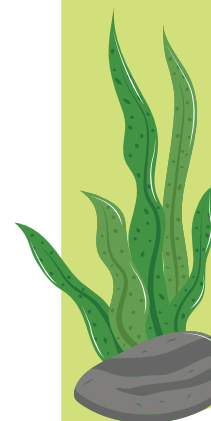


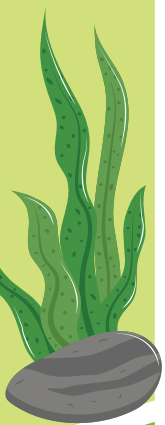
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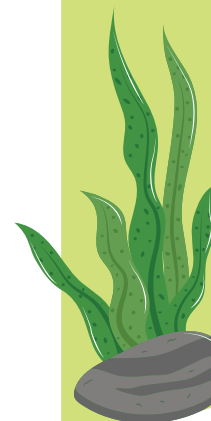
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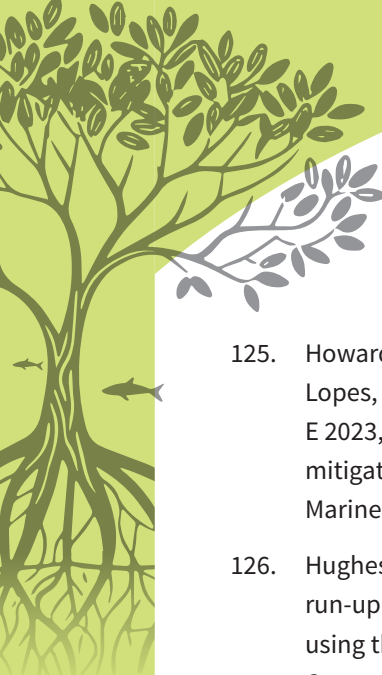


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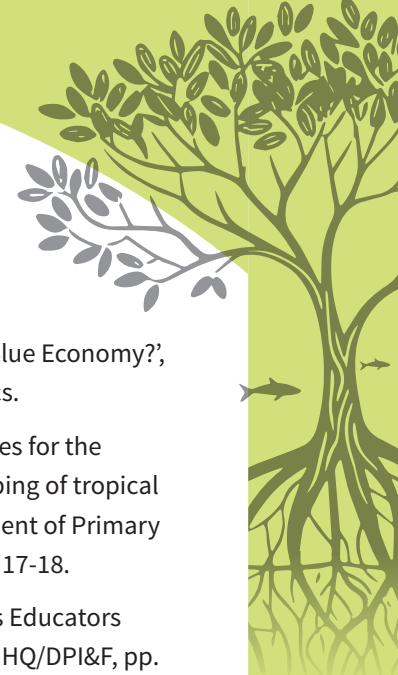
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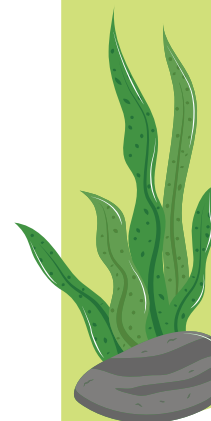
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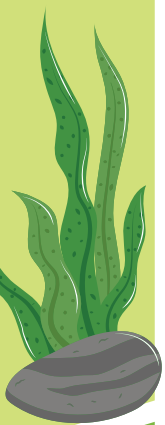






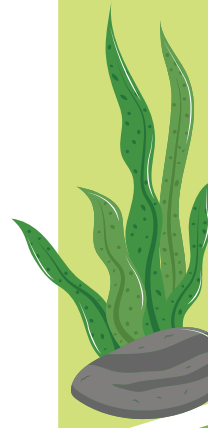
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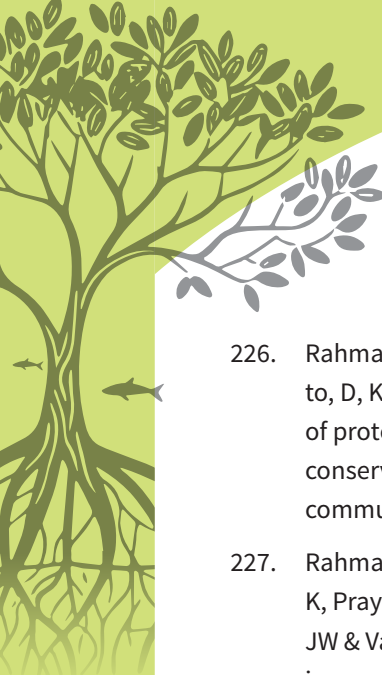

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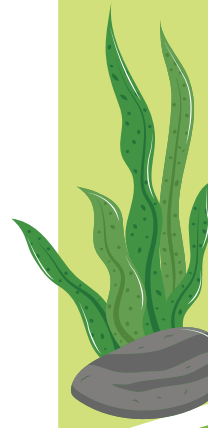


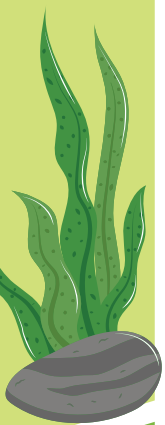


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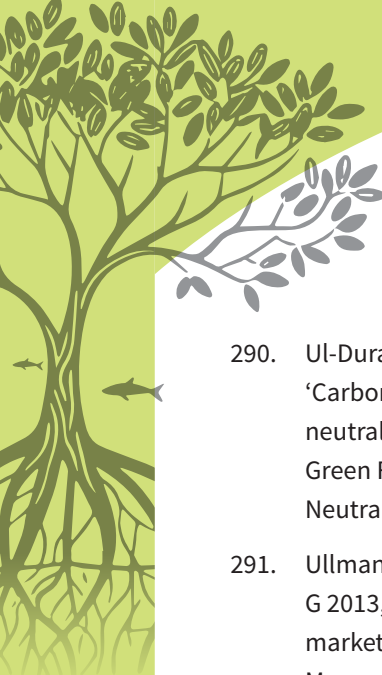




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*Rhizophora mucronata*



