



REVIEW ARTICLE

# Blue carbon: Mitigating climate change through coastal ecosystems

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Received: 18 March 2025; Accepted: 07 October 2025; Available online: Version 1.0: 15 December 2025

**Cite this article:** Suwethaasri D, Nandha Kumar R, Moulidharshan R, Baranidharan K, Kiruba M, Aiswaryalakshmi A, Tamizharasu T, Brindha BSA, Kalpana M, Karthick MBB. Blue carbon: Mitigating climate change through coastal ecosystems. *Plant Science Today*. 2025;12(sp4):01-09. <https://doi.org/10.14719/pst.8357>

## Abstract

The atmospheric concentration of CO<sub>2</sub> has risen to 420 ppm, 42.8 % higher than the pre-industrial levels, due to fossil fuel burning, deforestation and urbanization. This has resulted in global warming which leads to sea level rise, melting of ice and an increase in the temperature. The Paris Agreement aims to cap global warming at 1.5 °C, requiring a 45 % cut in emissions by 2030 and net zero by 2070. Carbon sequestration, especially through natural processes, is a key solution. Oceans and forests are a large carbon sink, but coastal ecosystems called “Blue Carbon” are also important. Mangroves, tidal marshes and seagrass ecosystems cover less than 0.5 % of the seabed, sequester carbon 10 times faster than tropical forests and store more than 50 % of ocean sediments carbon. Mangroves, for example, store 3-5 times more carbon per unit area than forests, with as much as 70 % stored in the soils. These ecosystems are, however, vulnerable to human activities like aquaculture and urbanization, leading to widespread degradation. Oceans absorb 25 % of anthropogenic CO<sub>2</sub> emissions, which has led to a 26 % increase in ocean acidity since industrialization. Blue carbon ecosystems also have ecological and economic advantages, such as coastal protection, support for biodiversity and livelihoods for millions. The conservation and restoration of ecosystems are key to achieving global climate goals and ensuring sustainable development. In conclusion, blue carbon ecosystems are crucial to climate change mitigation and their conservation is necessary for a sustainable future.

**Keywords:** blue carbon; climate change; mangroves; ocean; seagrass; tidal marshes

## Introduction

The current level of carbon dioxide in the atmosphere is about 420 ppm (1). The highest level has been reached over the past years. In comparison, the preindustrial value was about 280 ppm (2), a 42.8 % increase in the atmospheric CO<sub>2</sub> level. The release of CO<sub>2</sub> is mainly due to the burning of fossil fuels, changes in land use, clearance of vegetation, forest fires, agricultural activities, rapid urbanization and deterioration of ecosystems. Because of this, there is a rise in temperature, a rise in sea level and the melting of ice. According to the Paris Agreement 2015, the Global mean temperature limit is 1.5 °C, which must fall below 2 °C. Also, global emissions must fall by about 45 % by 2030 and we must achieve net-zero emissions by 2070 (3). To overcome those challenges, carbon sequestration is one of the best solutions. The Earth's climate system relies on physical, chemical and biological processes to remove CO<sub>2</sub> from the atmosphere and store it in land, oceans, or underground geological formations. Traditionally, the atmosphere, soil and terrestrial forests have been recognized as the largest natural carbon sinks. Research on

natural C sinks has focused predominantly on either ocean ecosystems (4) or terrestrial forest ecosystems (5). Oceans are the largest carbon sink and the best nature-based solution to mitigate climate change compared to other ecosystems. As the increasing scenarios of climate change in today's world are very high, blue carbon is one of the best nature-based solutions to mitigate climate change naturally through its process.

However, recent research has shed light on the remarkable role of coastal ecosystems, leading to the concept of “Blue Carbon”. Blue carbon refers to carbon captured and stored by coastal and marine ecosystems rather than by land-based systems like forests. Coastal ecosystems are the most productive ecosystems on earth. Blue carbon is the carbon captured by the world's ocean and coastal ecosystems. This new recognition of “Blue Carbon” (6) is based primarily on research demonstrating that seagrass meadows, mangrove forests and tidal salt marshes are highly efficient C sinks. Those marine ecosystems that contribute to climate change mitigation by sequestering excess carbon from the atmosphere are known as blue carbon ecosystems.

The Intergovernmental Panel on Climate Change (IPCC) defines blue carbon as “All biologically driven carbon fluxes and storage in marine systems that are amenable to management”. The focus has been on rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses. These ecosystems have high carbon burial rates on a per-unit area basis and accumulate carbon in their soils and sediments (7).

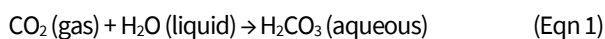
### The role of the ocean in the carbon cycle

The world's oceans are the second-largest carbon reservoir on Earth, storing an estimated 40,000 billion tonnes of carbon. Over the past few decades, the oceans have absorbed approximately 25 % of the carbon dioxide (CO<sub>2</sub>) emissions generated by human activities, significantly slowing the pace of climate change (4). The ocean plays a critical role in the global carbon cycle, with a carbon storage capacity more than 50 times greater than that of the atmosphere. The ocean continuously exchanges CO<sub>2</sub> with the atmosphere. In regions where surface waters are cooler (e.g., polar regions), the ocean absorbs more CO<sub>2</sub>, while warmer tropical waters may release CO<sub>2</sub> (8).

There is a constant exchange of carbon between the ocean and the atmosphere, with over 150 billion tonnes of carbon moving back and forth annually in the form of CO<sub>2</sub>. The oceans have absorbed about one-third of anthropogenic CO<sub>2</sub> emissions through physical, chemical and biological processes. The oceans' role as a sink for CO<sub>2</sub> is driven by two processes: the solubility pump and the biological pump (9).

#### Solubility pump

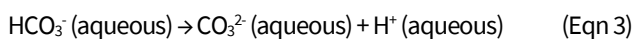
When atmospheric CO<sub>2</sub> comes into contact with surface waters (e.g., oceans and lakes), it dissolves into them, forming carbonic acid (H<sub>2</sub>CO<sub>3</sub>) (Eqn 1).



Carbonic acid (H<sub>2</sub>CO<sub>3</sub>) is a weak acid and quickly dissociates into bicarbonate ions (HCO<sub>3</sub><sup>-</sup>) and hydrogen ions (H<sup>+</sup>). This step releases hydrogen ions, which contribute to ocean acidification (Eqn 2).



Bicarbonate ions (HCO<sub>3</sub><sup>-</sup>) can further dissociate into carbonate ions (CO<sub>3</sub><sup>2-</sup>) and additional hydrogen ions (H<sup>+</sup>). Carbonate ions are important for marine organisms that use them to build calcium carbonate (CaCO<sub>3</sub>) shells and skeletons (Eqn 3)



In the presence of calcium ions (Ca<sup>2+</sup>), carbonate ions (CO<sub>3</sub><sup>2-</sup>) can form calcium carbonate (CaCO<sub>3</sub>), which is used by marine organisms like corals, mollusks and plankton. This process is critical for the formation of marine shells and coral reefs (Eqn 4) (10)

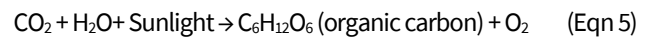


#### Biological carbon pump

The Biological Carbon Pump (BCP) is a critical process in the ocean's carbon cycle, where carbon is transported from the surface to the deep ocean through the activities of marine organisms, primarily phytoplankton (11).

Phytoplankton, microscopic photosynthetic organisms in the ocean's surface waters, absorb dissolved CO<sub>2</sub> and sunlight to produce organic carbon (e.g., glucose) through photosynthesis.

This process converts inorganic carbon (CO<sub>2</sub>) into organic carbon, which forms the base of the marine food web. This organic matter presents in two forms: (i) Particulate Organic Carbon (POC): In which carbon is bound in solid biological material, such as phytoplankton cells. (ii) Particulate Inorganic Carbon (PIC): Carbon present in calcium carbonate structures (e.g., shells and corals) (Eqn 5).



The process of aggregation and gravitational settling is a crucial mechanism in the biological carbon pump that facilitates the transfer of carbon from the surface ocean to the deep sea. This process is essential for long-term carbon sequestration and climate regulation. Phytoplankton through photosynthesis, converting it into organic carbon. However, not all this organic carbon remains as individual phytoplankton cells. Over time, various processes lead to the formation of aggregates, which are clusters of organic particles that sink faster than individual cells.

#### Types of organic carbon in aggregates

- (i) Particulate Organic Carbon (POC): Carbon bound in biological particles such as phytoplankton cells, fecal pellets and detritus.
- (ii) Particulate Inorganic Carbon (PIC): Carbon present in calcium carbonate (CaCO<sub>3</sub>) structures, such as the shells of coccolithophores.
- (iii) Dissolved Organic Carbon (DOC): Small organic molecules that can contribute to aggregation if they become trapped in particle clusters.

**Processes leading to aggregation:** Phytoplankton are consumed by zooplankton and other marine organisms, transferring organic carbon up the food chain. Some of this carbon is respired back into the water as CO<sub>2</sub>, while the rest is incorporated into the biomass of larger organisms. Phytoplankton and their organic matter form aggregates due to several mechanisms, like (i) When phytoplankton die, their cells rupture and clump together. (ii) Some phytoplankton (e.g., diatoms) produce sticky extracellular polymeric substances (EPS), which act as a glue, binding particles together. (iii) Zooplankton grazing on phytoplankton produces fecal pellets, which are denser and sink quickly. (iv) Water movement causes individual phytoplankton cells and organic debris to collide and stick together, increasing aggregate size. (v) Some bacteria excrete sticky substances that enhance particle aggregation. Once formed, aggregates sink due to gravitational settling. The speed at which they sink depends on their size, density and composition.

Zooplankton feed on phytoplankton, consuming and transforming organic carbon. Some zooplankton perform vertical migration, moving between the surface and deeper layers daily. This movement contributes to the downward transport of organic carbon, as carbon-rich waste (fecal pellets) and respiration (CO<sub>2</sub> release) occur at deeper depths. Bacteria break down organic matter, releasing dissolved organic carbon (DOC) back into the water. Some of this DOC is remineralized into (DIC) dissolved inorganic carbon, which can return to the surface and re-enter the atmosphere as CO<sub>2</sub>. Some of the dissolved and particulate carbon is subducted (transported downward) into the deep ocean. The deep ocean stores carbon for long time scales, ranging from centuries to millions of years. Estimated

carbon sequestration rates: 5–12 Gt C/year through physical transport, 0.12–0.72 Gt C/year via biological activity, ~0.02 Gt C/year stored in sediments for very long periods.

### Carbon removal timescales

The storage of carbon in the ocean depends on its depth (Fig. 1).

Surface ocean: Carbon can return to the atmosphere in months to years.

Twilight zone (~100–1000 m): Carbon takes decades to centuries to return.

Deep ocean (~1000 m+): Carbon is stored for millennia.

Seafloor sediments: Carbon is locked away for millions of years (12).

When phytoplankton and other marine organisms die, their organic matter (including carbon) sinks as marine snow (particulate organic carbon or POC). This sinking process transports carbon from the surface to the deep ocean. A portion of the sinking organic matter reaches the deep ocean, where it is either consumed by deep-sea organisms or buried in sediments. Carbon stored in the deep ocean can remain sequestered for centuries to millennia, effectively removing it from the atmosphere (13).

In recent decades, they have taken in about 25 % of human-made CO<sub>2</sub> emissions, significantly mitigating the effects of global warming. However, this comes at a cost: since the start of industrialization, ocean acidity has risen by 26 %, a rate of change unmatched in the past several million years (14). By regulating atmospheric CO<sub>2</sub> levels, the ocean provides an essential service to the planet, helping to curb climate change and its impacts.

In essence, blue carbon ecosystems primarily mangrove forests, tidal marshes and seagrass meadows are environments that excel at capturing and storing organic carbon. Though they occupy a tiny fraction of the Earth's surface, their impact on carbon sequestration is disproportionately large, making them vital players in the fight against climate change (15).

### Carbon sequestration potential of blue carbon ecosystems

Blue carbon ecosystems, including Mangroves, salt marshes, seagrasses and potentially macroalgae, are highly effective at sequestering and storing carbon and play a significant role in climate change mitigation. Blue carbon ecosystems collectively sequester carbon at a rate 10 times higher than terrestrial forests per unit area (6). Despite covering less than 0.5 % of the seabed, these vegetated coastal habitats account for more than 50 % and potentially up to 70 % of the carbon stored in ocean sediments (16). Mangroves, salt marshes and seagrasses dominate these habitats, yet they represent just 0.05 % of the plant biomass found on land. Despite their small size, they are incredibly efficient at storing carbon, sequestering amounts comparable to those of larger terrestrial ecosystems Fig. 2. These ecosystems capture CO<sub>2</sub> from the atmosphere, storing it in sediments, underground biomass and decaying plant matter. Besides these, it also provides some ecological services like prevention of storms and sea level rise, shoreline erosion, regulation of coastal water quality and provision of habitat.

### Types of blue carbon

**Autochthonous blue carbon:** Autochthonous blue carbon refers to the carbon that is produced and stored within the ecosystem itself. It originates from the primary production of the ecosystem, such as photosynthesis by plants (e.g., mangroves, seagrasses and salt marsh grasses).

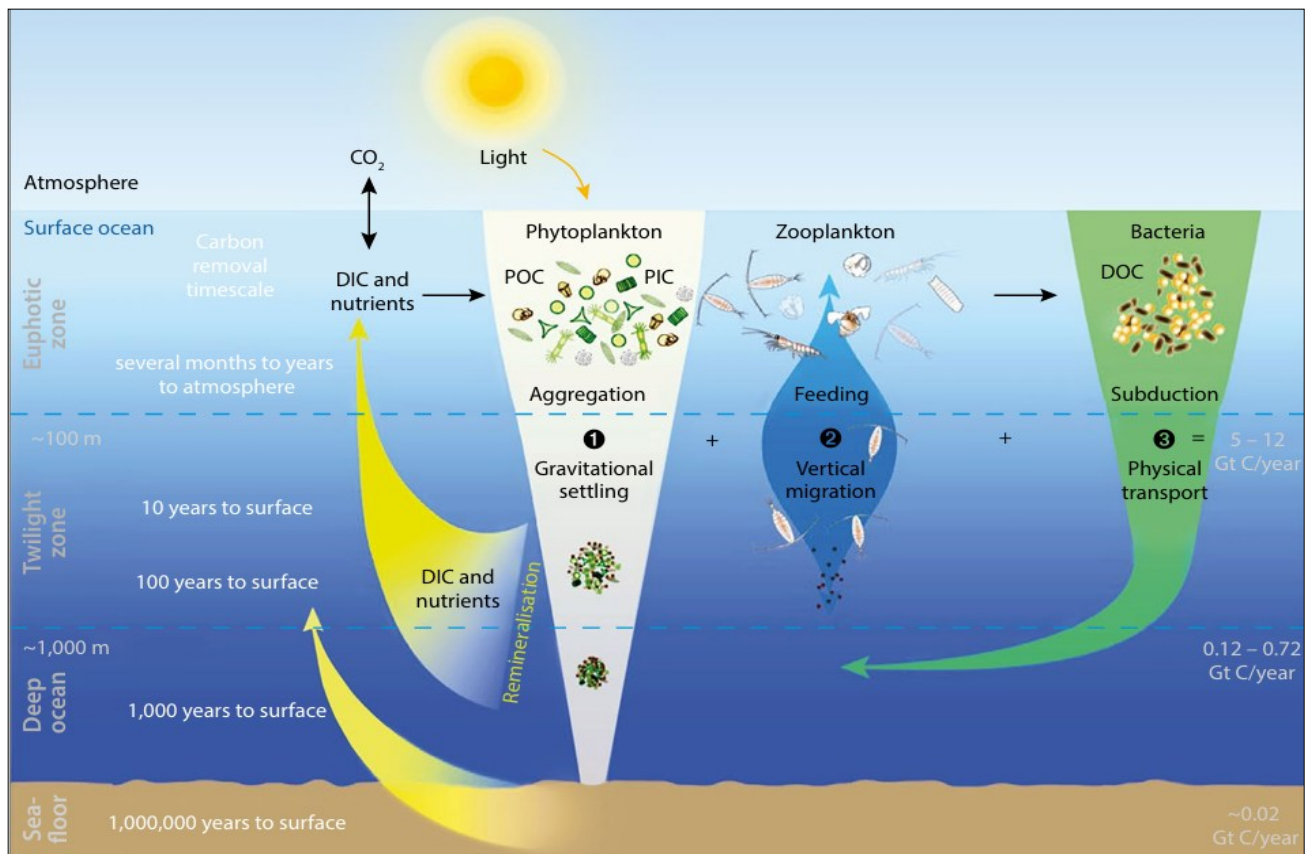


Fig. 1. Carbon removal timescale. Source: Ref. (12).

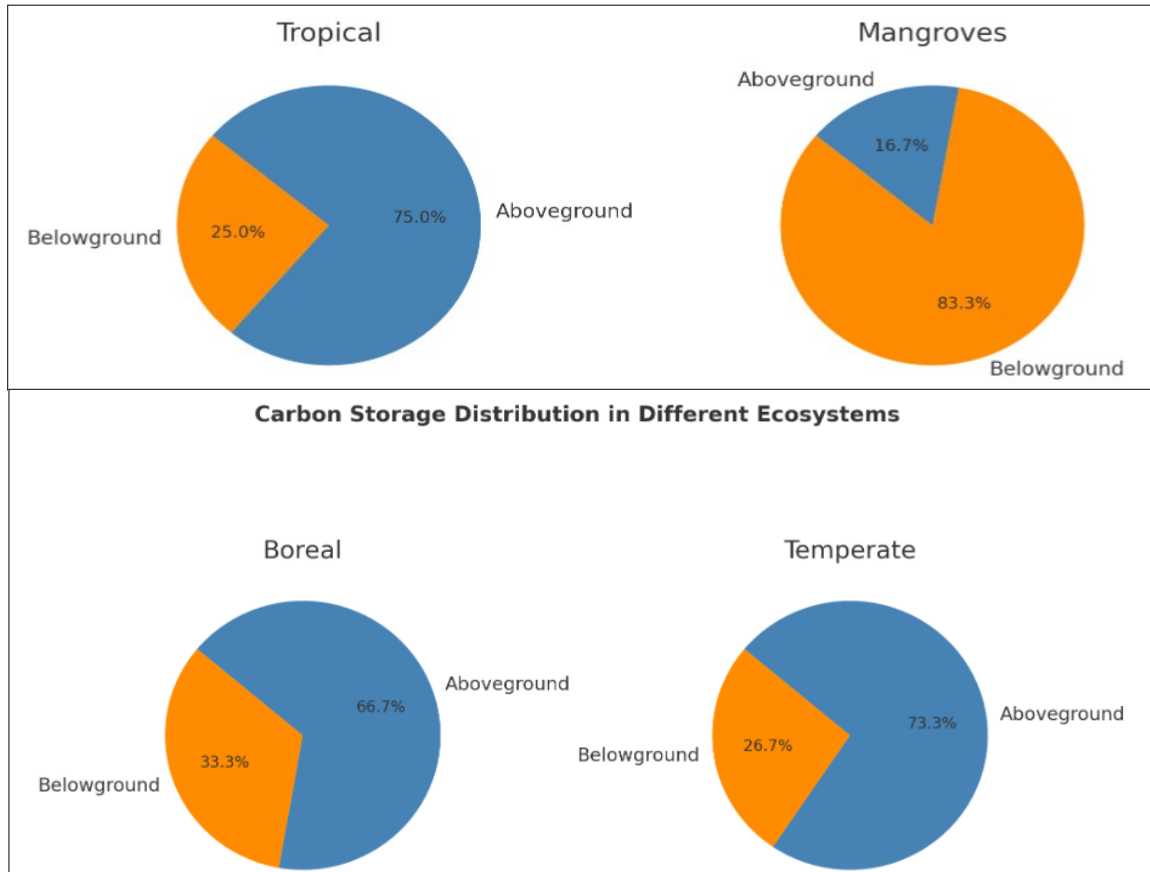


Fig. 2. Carbon storage distribution in different ecosystems.

**Allochthonous blue carbon:** Allochthonous blue carbon refers to the carbon that originates outside the ecosystem and is transported into it. This carbon comes from external sources, such as rivers, ocean currents or adjacent terrestrial ecosystems (17) (Fig. 3).

**Types of coastal ecosystems**

There are three major types of coastal ecosystems (i) Mangroves (ii) Tidal marshes (iii) Seagrass. Fig. 4 & 5 the image shows the global distribution of three coastal ecosystems: mangroves, salt marshes and seagrasses. Mangroves shown in black cover,

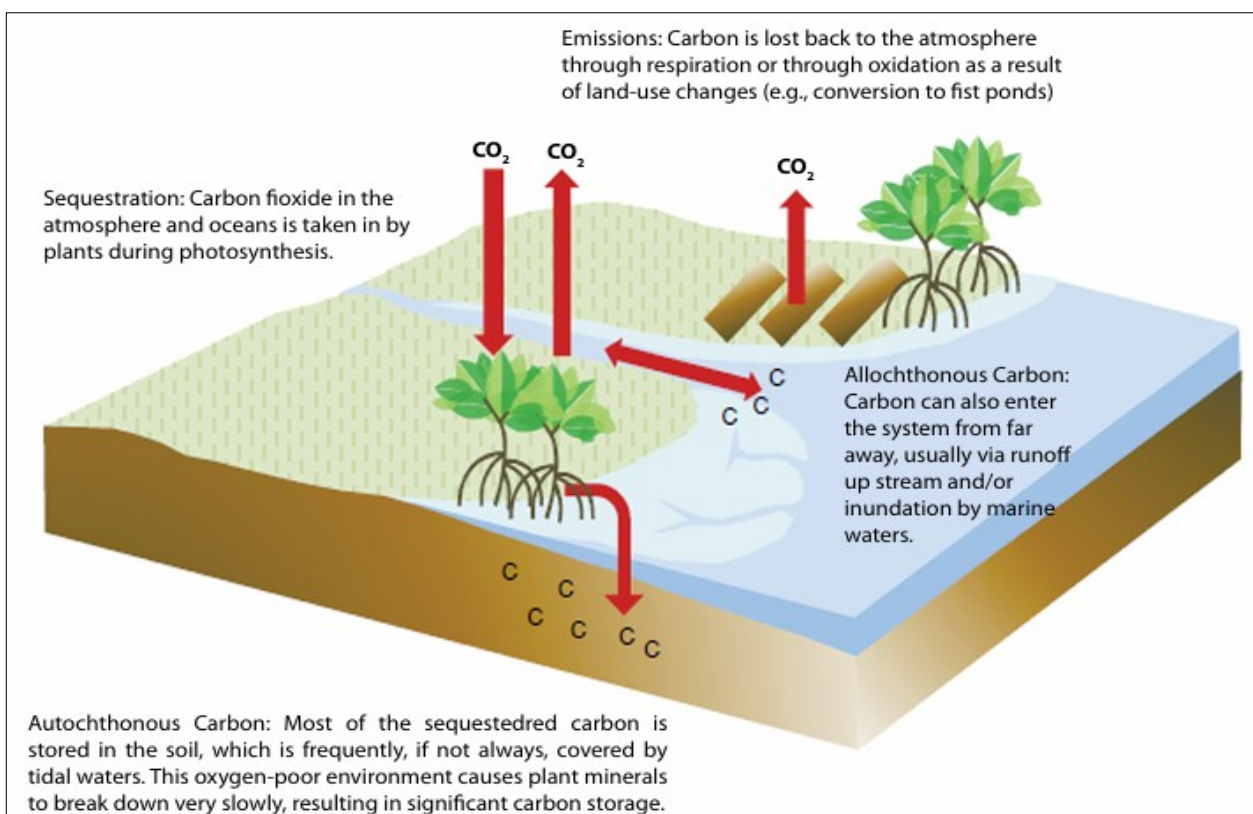
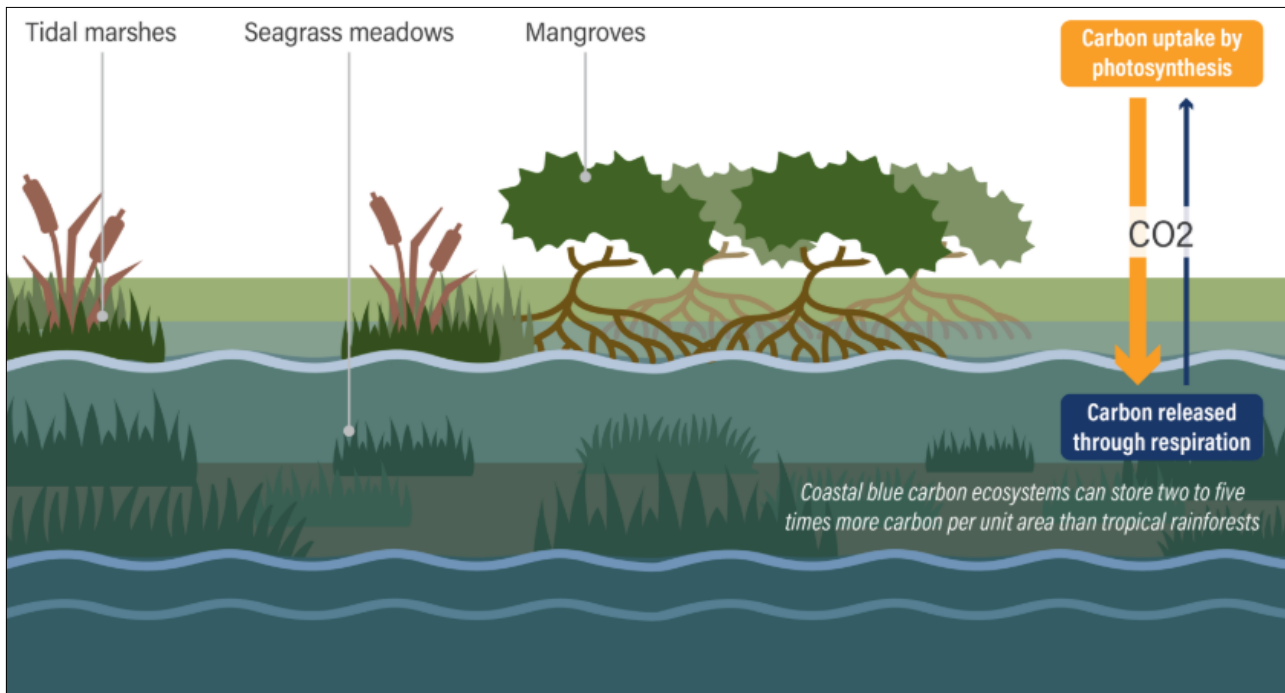
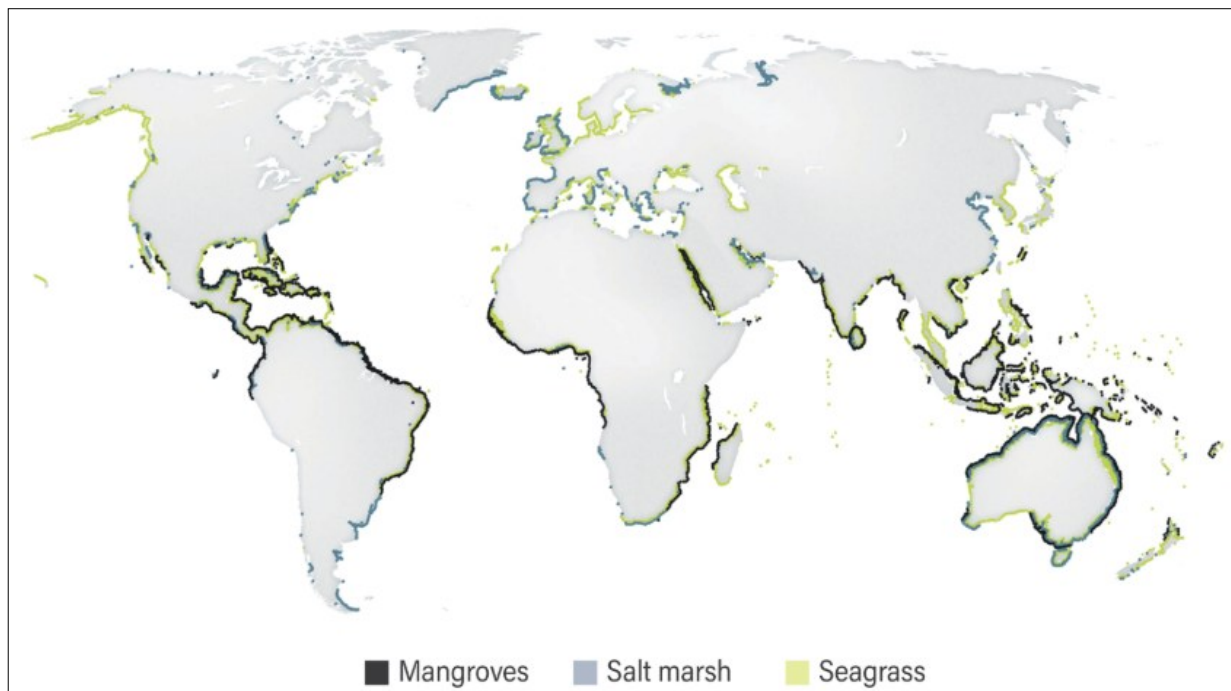


Fig. 3. Types of blue carbon. Source: Ref. (14).



**Fig. 4.** Types of coastal blue carbon ecosystems. Source: Ref. (19).



**Fig. 5.** Global distribution of blue carbon ecosystems. Source: Ref. (43).

mainly in tropical and subtropical regions and present along the coasts of Southeast Asia, Africa, the Caribbean, South America (Amazon Basin) and Australia which is particularly dense in Indonesia, Brazil, Nigeria, India and serve as vital buffers against coastal erosion and storm surges. Salt Marshes shown in blue colour predominantly found in temperate and high-latitude regions. Major concentrations along the coasts of the United States (East Coast), Canada, Europe and parts of China are, Crucial for coastal flood protection and habitat for migratory birds. Seagrass is shown in Light Green colour which is found in shallow coastal waters worldwide, including North America, Europe, Australia and parts of Asia. Plays a significant role in carbon storage, water filtration and supporting marine life and often found near coral reefs and mangrove forests (18).

#### **Mangroves**

Mangroves are highly efficient at capturing and storing carbon, making them one of the most carbon-rich ecosystems on Earth. They sequester carbon through two main processes: Aboveground biomass and Belowground biomass. Mangroves store carbon in their trees and vegetation. Their dense root systems and canopy cover contribute to significant biomass accumulation also larger amounts of carbon stored in their soil, which can retain carbon for centuries or even millennia due to waterlogged and anaerobic soil conditions that slow down decomposition. Mangroves can store 3-5 times more carbon per unit area than terrestrial forests. It can sequester approximately 6-8 Mg CO<sub>2</sub>e ha<sup>-1</sup> yr<sup>-1</sup> (megagrams of CO<sub>2</sub> equivalent per hectare per year). They can store an estimated 1023 Mg CO<sub>2</sub>e ha<sup>-1</sup> in their biomass and soil with up to 70 % of this carbon stored in the soil

(20). Mangroves are often cleared for aquaculture (e.g., shrimp farming), agriculture and urban development. Industrial and agricultural runoff, including heavy metals and pesticides, can degrade mangrove ecosystems. Mangroves are often harvested for timber, fuelwood and charcoal production, leading to habitat degradation. Over the past few decades, 35 % of the global mangrove area has been lost (21). The effectiveness of carbon storage depends on ecosystem health and management practices.

#### **Tidal marshes**

Tidal marshes are coastal wetlands characterized by deep soils formed through the accumulation of mineral sediment and organic material. They are regularly flooded by salty water brought in by tides (22). There are two types viz., freshwater and saltwater tidal marshes. Salt marshes are flooded by saltwater from the ocean, with salinity levels ranging from 18 to 35 ppt (parts per thousand). Dominated by salt-tolerant plants such as cordgrass (*Spartina* spp.), saltwort (*Salicornia* spp.) and black needlerush (*Juncus roemerianus*) (23). Soils are rich in organic matter and minerals, with high rates of sedimentation. Anaerobic conditions slow decomposition, leading to significant carbon accumulation. Salt marshes sequester carbon at a rate of approximately 210 g C m<sup>-2</sup> yr<sup>-1</sup> (24). Salt marshes can store 100 to 400 Mg C ha<sup>-1</sup> in their soils, with carbon remaining sequestered for centuries or millennia (9). The primary productivity will be high in salt in comparison in fresh tidal marshes. Tidal freshwater marshes have salinity levels of less than 0.5 ppt, as they are located further inland where saltwater influence is minimal. Dominated by freshwater plants such as cattails (*Typha* spp.), bulrushes (*Schoenoplectus* spp.) and arrowheads (*Sagittaria* spp.) (9). Soils are rich in organic matter but may have lower mineral content compared to salt marshes. Decomposition rates are slightly higher due to less anaerobic conditions. Tidal freshwater marshes sequester carbon at a rate of approximately 100 to 150 g C m<sup>-2</sup> yr<sup>-1</sup>. Soil carbon stocks in tidal freshwater marshes range from 50 to 200 Mg C ha<sup>-1</sup>. For instance, pristine salt marshes accumulate more organic matter in their soil than impacted ones (9). Furthermore, well-managed mangrove areas show carbon stocks up to 1061 Mg C ha<sup>-1</sup>, whereas degraded areas contain only 717 Mg C ha<sup>-1</sup> (20).

#### **Seagrass**

Seagrasses are submerged flowering plants with deep roots, forming meadows along the shores of every continent except Antarctica (22). Carbon accumulates in seagrass soils, which are anoxic (oxygen-poor), preserving organic carbon for decades to millennia. Seagrass soils can be up to four meters deep (25). Carbon sequestration rates in seagrass meadows vary by species, sediment characteristics and habitat depth, but the average burial rate is approximately 138 g C m<sup>-2</sup> yr<sup>-1</sup>. Although seagrasses cover less than 0.2 % of the world's oceans, they sequester approximately 10 % of the carbon buried in ocean sediments annually (27.4 Tg of carbon per year). Seagrasses can store up to twice as much carbon per hectare as terrestrial forests, with the global seagrass ecosystem organic carbon pool estimated at 19.9 billion metric tons (26). Seagrass meadows filter sediment and nutrients from the water, improving water quality. They also stabilize sediments, reducing coastal erosion and buffering against storms and flooding. Seagrass meadows provide critical habitat for fisheries and flagship marine species,

such as sea turtles, manatees and juvenile fish. Seagrasses are among the world's most threatened ecosystems, with an annual global loss rate of 1.5 %, which has been accelerating in recent decades. Approximately 29 % of Earth's seagrass ecosystems have been lost (27). Degradation of water quality due to poor land use (e.g., deforestation, agricultural runoff), coastal development, dredging and climate change (e.g., rising sea temperatures and ocean acidification). Seagrasses contribute significantly to climate change mitigation by sequestering "Blue Carbon" and reducing greenhouse gas emissions. Protecting and restoring seagrass meadows can enhance their carbon storage potential (28). Seagrass restoration projects have shown promise in recovering lost meadows and enhancing carbon sequestration. For example, the Seagrass Restoration Initiative in Virginia has successfully restored over 3000 hectares of seagrass meadows (29).

#### **Algae**

Algae, including macroalgae (seaweeds) and microalgae, are increasingly being explored for their potential in carbon sequestration and climate change mitigation. Algae lack the complex lignin found in terrestrial plants, which means the carbon they capture is released back into the atmosphere more quickly. This makes them less effective for long-term carbon storage compared to terrestrial plants or blue carbon ecosystems like mangroves and seagrasses (30). Algae are considered a short-term carbon storage pool. They can be harvested and used as feedstock for biofuels, bioplastics and other biogenic products, effectively recycling the captured carbon. Bicarbonate-Based Integrated Carbon Capture and Algae Production Systems (BICCAPS): BICCAPS is a novel system developed by Washington State University and Dalian Ocean University. It uses alkaliphilic microalgae to capture carbon from flue gases in the form of bicarbonate, which is then utilized for photosynthesis (31). Many species of cyanobacteria, microalgae and macroalgae can use carbonate as a carbon source for photosynthesis, making them effective at capturing carbon from industrial emissions. South Korea's Coastal CO<sub>2</sub> Removal Belt (CCRB): South Korea has established the CCRB, which combines artificial and natural ecosystems, including large areas of kelp forests, to capture and store carbon. This initiative aims to enhance coastal carbon sequestration and mitigate climate change (32). Kelp farming is being explored as a scalable method for carbon sequestration. Kelp grows rapidly and can be harvested for bioenergy or sunk into the deep ocean for long-term carbon storage (33). Microalgae are highly efficient at converting CO<sub>2</sub> into biomass, which can be processed into biofuels such as biodiesel, bioethanol and biogas. This provides a renewable energy source while capturing carbon. Algae can be used in wastewater treatment to remove nutrients like nitrogen and phosphorus while capturing CO<sub>2</sub>. This dual function makes them valuable for both environmental management and carbon sequestration. Challenges include the high cost of algae cultivation, energy-intensive harvesting processes and the need for large-scale infrastructure. Additionally, the long-term stability of carbon stored in algal products needs further research.

#### **Anaerobic soil**

Coastal wetlands are vital carbon sinks due to their unique anaerobic soil conditions. Which are highly effective at storing carbon, largely due to their anaerobic (oxygen-deprived) soil

conditions. In these ecosystems, only a thin surface layer of soil is typically oxygenated and above water, while the majority of the soil remains submerged. Since oxygen diffuses very slowly through water, the saturated soils in these wetlands are largely devoid of oxygen. This anaerobic environment significantly slows down the decomposition of organic plant material. As a result, the carbon contained in this plant matter remains preserved rather than being broken down by microbes and released back into the atmosphere as carbon dioxide. This process makes coastal wetlands exceptional carbon sinks, capable of storing substantial amounts of carbon over long periods. Coastal wetlands contribute to carbon sequestration through the continuous growth of vegetation, which captures carbon dioxide from the atmosphere during photosynthesis. Over time, this carbon is transferred to the soil, where it can remain stored for centuries or even millennia under the right conditions. Recent studies have highlighted the critical role of coastal wetlands in mitigating climate change, emphasizing their ability to store carbon at rates significantly higher than many terrestrial ecosystems (34).

### Importance of blue carbon ecosystem

Blue carbon ecosystems, including mangroves, tidal marshes and seagrasses, play a critical role in climate change mitigation, coastal protection and supporting biodiversity and livelihood. When degraded or destroyed, blue carbon ecosystems release the carbon they have stored for centuries. Experts estimate that 1.02 billion tons of CO<sub>2</sub> are emitted annually from degraded coastal ecosystems, equivalent to 19 % of emissions from tropical deforestation (35). Mangroves, tidal marshes and seagrasses act as natural barriers, reducing the impact of storms, floods and coastal erosion. For example, mangroves can reduce wave energy by 50-90 %, protecting coastal communities (36). The root systems of mangroves and seagrasses stabilize sediments, preventing coastal erosion and maintaining shoreline integrity (37). It acts as a biodiversity hotspot, these ecosystems support high levels of biodiversity, including endangered species such as sea turtles, manatees and migratory birds (38). Blue carbon ecosystems filter pollutants, sediments and nutrients from runoff, improving water quality and reducing the risk of harmful algal blooms. Mangroves alone are estimated to provide US\$1.6 billion annually in ecosystem services, including fisheries support, timber and coastal protection. Over 120 million people worldwide depend on mangroves for their livelihoods, including fishing, tourism and timber harvesting (39). Protecting and restoring blue carbon ecosystems can contribute to global carbon offsetting goals, helping countries meet their climate targets under the Paris Agreement (28). Blue carbon ecosystems are estimated to store over 30 billion metric tons of carbon globally. Blue carbon ecosystems contribution to climate mitigation is prominent (Table 1), whereas the comparison of carbon storage potential in different ecosystems was analysed in Fig. 1.

**Table 1.** Global contribution of mangroves and other coastal habitats to carbon sequestration in the global coastal ocean

Habitat	Area (10 <sup>12</sup> m <sup>2</sup> )	Sequestration rate (gC m <sup>-2</sup> yr <sup>-1</sup> )	Global carbon sequestration (Tg yr <sup>-1</sup> )
Mangroves	0.14 (0.5 %)	174	24 (14 %)
Salt marshes	0.22 (0.8 %)	150	33 (20 %)
Seagrasses	0.3 (1.1 %)	54	16 (10 %)
Estuaries	1.1 (4.0 %)	45	50 (30 %)
Shelves	26 (93.6 %)	17	44 (26 %)

Source: Ref. (20).

### Threats

Blue carbon ecosystems are estimated to store over 30 billion metric tons of carbon globally. Their degradation could release up to 1.02 billion metric tons of CO<sub>2</sub> annually, equivalent to 19 % of emissions from global deforestation (37). The release of hydrogen ions (H<sup>+</sup>) during these reactions lowers the pH of seawater, making it more acidic, leading to ocean acidification. Increased acidity can dissolve calcium carbonate structures, harming marine organisms that rely on them. This process reduces the availability of carbonate ions, threatening marine organisms that rely on calcium carbonate for their shells and skeletons (10). The major threats are mainly due to Coastal development, Pollution, Agriculture, Overexploitation of resources and climate change Table 2. The study conducted by (40) states that the Sundarbans mangrove forest is experiencing rapid submergence due to sea level rise, particularly in areas with limited sediment supply. It also concluded that because of this, mangroves could drown by 2025, leading to significant carbon emissions. Due to aquaculture, shrimp farming, agriculture and urban expansion, the mangrove forest has been cleared, releasing the stored carbon and causing the loss of biodiversity (41). In Chesapeake Bay, USA, the seagrass area has declined mainly due to Nutrient runoff from the agriculture and eutrophication (42). Tourism-related activities, such as boating and diving, physically damage seagrass beds in the ocean.

**Table 2.** Global loss of blue carbon sinks (total percent loss and annual rate of loss

Ecosystem	Percent of global loss	Annual rate of global loss
Mangroves	20 % (since 1980s) 30-50 % (since 1940s)	~0.7-3 %
Seagrasses	50 % (since 1990s)	~7 %
Salt marshes	25 % (since 1800s)	1-2 %

Source: Ref. (20).

### Conclusion

The carbon storage capacity of blue carbon ecosystems varies significantly depending on the type of ecosystem, its health and management practices. Mangroves, seagrasses and salt marshes are highly efficient carbon sinks, but their effectiveness is reduced by degradation and poor management. Conservation, restoration and sustainable management are critical to maximizing their carbon sequestration potential and mitigating climate change. Blue carbon ecosystems collectively sequester carbon at a rate 10 times higher than terrestrial forests per unit area. Blue carbon ecosystems are critical for climate change mitigation due to their high carbon sequestration and storage capacities. Protecting and restoring these ecosystems can significantly contribute to global carbon reduction goals. The carbon cycle in the ocean plays a critical role in regulating Earth's climate by absorbing, storing and redistributing carbon. The deep ocean stores carbon for thousands of years, making it a critical component of the global carbon cycle. Processes like sediment burial and mineral formation contribute to this long-

term storage of carbon. The ocean is a dynamic and integral component of the global carbon cycle, regulating atmospheric CO<sub>2</sub> levels and influencing climate. However, human activities and climate change are disrupting these processes, highlighting the need for conservation and sustainable management of marine ecosystems. In conclusion, blue carbon ecosystems in India provide immense ecological, economic and social benefits. Protecting and restoring these ecosystems is crucial for achieving India's climate goals and ensuring the well-being of the coastal communities.

## Acknowledgements

I would like to express my sincere gratitude to my Chairman, Dr. K. Baranidharan, for his invaluable guidance throughout the course of this work. I am also thankful to the Forest College and Research Institute for providing the necessary facilities and support.

## Authors' contributions

BK assisted in selecting the review topic and preparing its outline. NKR and KM contributed topic-related ideas and drafted the manuscript. MR corrected the sections related to remote sensing. AAR provided support with AI-related work. TT participated in the sequence alignment. BBSA, KM and KMBB assisted with the overall correction of the manuscript. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

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