The ocean carbon pool: a vital component of the global carbon cycle

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Summary

The global carbon cycle is an integral part of the Earth System. Of the land, atmosphere, and ocean components of the global carbon cycle that exchange carbon on the timescales of decades to centuries, the ocean contains more than 90% of carbon. The ocean carbon pool represents a critical component of the Earth's carbon cycle, playing a pivotal role in regulating atmospheric carbon dioxide (CO_2) levels and influencing climate dynamics. The exponential increase of total anthropogenic CO_2 emissions in the industrial era implies the ocean's uptake has increased exponentially, reaching 2.5 ± 0.6 Pg C yr^{-1} for 2009-2018. Without the ocean and land sinks, atmospheric CO_2 levels would be close to 600 ppm. The ocean carbon pool comprises dissolved inorganic carbon (DIC), organic carbon, and particulate organic matter, collectively responsible for the sequestration and release of carbon into the atmosphere. Phytoplankton, the microscopic marine plants, play a fundamental role in the oceanic carbon cycle by photosynthesizing and fixing atmospheric CO_2 into organic matter. This organic matter can be transferred to the deep ocean through the biological pump, further contributing to the storage of carbon in the form of sinking particles. The bulk of the global ocean margin represents a carbon sink of ~0.1-0.2 Pg C. Oceanic processes, such as ocean circulation and upwelling, help redistribute carbon from surface waters to the deep ocean. The solubility pump, which is driven by changes in temperature and salinity, also affects the solubility of CO_2 in seawater. These natural processes work to mitigate the increase in atmospheric CO_2 concentrations and help regulate global temperatures.

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Introduction

The current climate change crisis is threatening economies as it is accelerating losses of marine biodiversity and habitats (Bindoff et al. 2019). Marine ecosystems require far greater attention than received thus far as a means of securing humanity's future health and well-being (Laffoley 2020; Laffoley et al. 2020). Those marine ecosystems that contribute to climate change mitigation by sequestering excess carbon from the atmosphere are known as Blue Carbon ecosystems. These ecosystems have high carbon burial rates on a per unit area basis and accumulate carbon in their soils and sediments.

The concept of ocean carbon was introduced in 2009 in an assessment report to a special collaboration of the United Nations Environmental Programme (UNEP), Food and Agriculture Organization of the United Nations (FAO) and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC/UNESCO) with the idea that the role of coastal ecosystems such as salt marshes, mangroves and seagrass meadows in absorbing carbon (C) to reduce emissions is of global significance and they should be protected. Marine organisms capture over half (55 %) of all the biological carbon captured around the world. The coastal carbon sequestered and stored by ocean ecosystems is defined as 'Blue carbon' (Nellemann et al. 2009), and has been increasingly used as a concept to justify numerous studies describing C stocks and rates of C sequestration, especially in salt marsh, mangrove and seagrass ecosystems. This is a huge reservoir. Seagrass, mangroves and salt marshes can capture two-thirds of the organic C in oceanic environments signifying them as the most valuable carbon sinks on the earth.

Global Extent and Distribution of Ocean Carbon Ecosystems

Blue carbon ecosystems play an outsized role in the global carbon cycle. They occupy 0.07−0.22% of the Earth's surface and bury 0.08−0.22 Pg C yr^{-1}, which is comparable to 0.2 Pg C yr^{-1} transferred to the seafloor and equivalent to ~10% of the entire net residual land sink of 1−2 Pg C yr^{-1}

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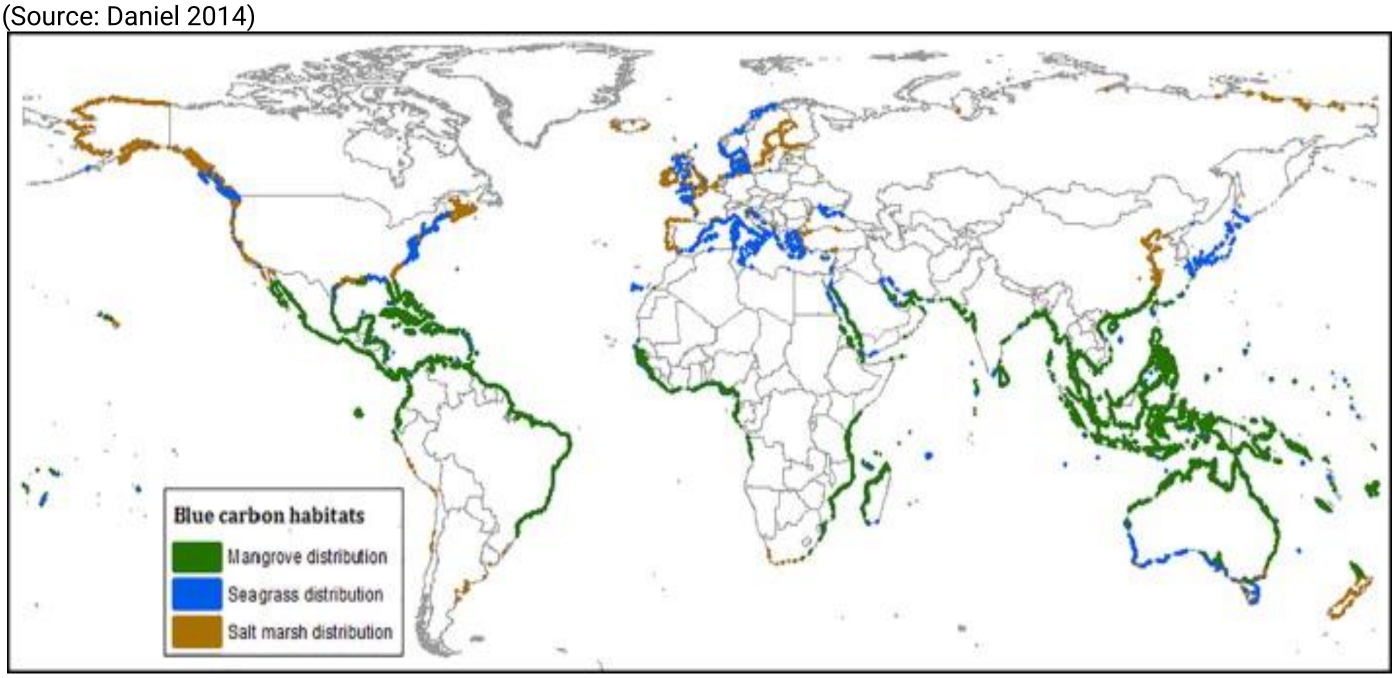
Table 1. Distribution of global ocean carbon ecosystem

Region	Mangroves		Seagrass		Salt marsh	
	Area in (ha)	Percentage of blue carbon ecosystem	Area in (ha)	Percentage of blue carbon ecosystem	Area in (ha)	Percentage of blue carbon ecosystem
Africa	2,631,069	22.9	6247	2.8	1565	0.4
Asia	3,276,758	28.6	23,690	10.8	22,008	6.3
Australia and the South pacific	1,578,385	13.8	2622	1.2	16,644	4.7
Central and South America	2,991,043	26.1	10,368	4.7	5315	1.5
Europe	0	0	23,614	10.7	162,039	46.2
Middle East	23,995	0.2	351	0.2	174	0
North America	9,65,678	8.4	153,266	69.6	143,239	40.8
Global total	11,466,928		220,158		350,984	

(Source: Daniel 2014)



The global coverage of blue carbon ecosystems, including 1,39,170 km^2 of mangroves 3, 19,000 km^2 of seagrasses and roughly 51,000 km^2 of salt marshes. Adding up our estimates of carbon storage globally, those mangroves, salt marshes, and seagrasses together store about 11.25 Pg C (about 41.25 Pg CO2e). Most of the blue carbon pool is in the soils, which contain more than 80% of the overall carbon stock.

Table 2. Carbon stocks and burial rates within top 1 m soil of tidal marsh, mangrove, seagrass ecosystems and macroalgae in the ocean

Ecosystem	Global Extension (km^2)	Global C Burial Rate (Tg C year^{-1})	Global C Stock in Soil (Pg C)
Tidal marshes	22,000-400,000 (Mcowen et al. 2017)	4.8- 87.3 (Mcleod et al. 2011)	0.4-6.5 (Cai ,2010)
Mangroves	137,760-152,3615 (Mcleod et al. 2011)	22.5-24.9 (Breithaupt et al. 2012)	5- 10.4 (Jardine & Siikamaki 2014)
Seagrasses	177,000-600,000 (Mcleod et al. 2011)	48-112 (Mcleod et al. 2011)	4.2-8.4
Macroalgae	1,400,000-5,700,000 (Krause-Jensen & Duarte 2016)	61-268 (Krause-Jensen & Duarte 2016)	n/a

Ecology of blue carbon ecosystem

Carbon storage in the soils of marine angiosperm (higher plant) habitats can be up to 1,000 t C ha^{-1}, much higher than in most terrestrial ecosystems (IPCC 2019). Rising atmospheric CO_2 levels are causing ocean acidification, but the increased amount of CO_2 in seawater can stimulate photosynthesis helping to remove carbon from the seawater (Wada et al. 2021). Increasing population densities and urbanization of coastal areas have damaged vegetated coastal habitats worldwide due to the impacts of fisheries, aquaculture, pollution and sedimentation (Gullstrom et al. 2021). Around 62% of mangroves worldwide were destroyed between 2000 and 2016 (Goldberg et al. 2020), there has been about a 90%

loss of salt marsh ecosystems (Gedan & Silliman 2009) and seagrass carbon stocks are declining in various regions of the world (Waycott et al. 2009). Since the 1950s, there has been a global decline in the extent of macroalgal kelp forests of 0.018 year^{-1}, attributed to harvesting, pollution, invasive species, and/or temperature (Byrnes et al. 2016). When these blue carbon stocks are damaged, they may switch from sinks to sources of CO2 and methane (CH_4) in the atmosphere, a much more potent greenhouse gas (Vanderklift et al. 2019). Ocean warming affects the ability of marine systems to remove CO_2 from the atmosphere because warmer waters absorb less CO_2 and because it is a stressor for cool water-vegetated marine habitats. For example, kelp forests in the warmest part of their NE Atlantic distribution store around 70% less carbon and release 50% less carbon than populations in the cooler parts of their distribution (Pessarrodona et al. 2018).

Marine forests of kelp and fucoid seaweeds are being lost globally at their low latitude boundaries due to marine heat waves and the gradual warming of surface seawater temperatures combined with human-induced stressors (Bernal-Ibanez et al. 2021). Beyond Blue Carbon hotspot habitats, carbon is also stored in marine animals, so fish taken out of the sea contribute to Blue Carbon release (Mariani et al. 2020). Bottom trawled fishing gear damages ancient Blue Carbon stores such as rhodolith/ maerl beds in seafloor sediments and is estimated to release a gigaton of CO_2 from seabed sediments each year, equivalent to the entire aviation industry's annual emissions to the atmosphere (Sala et al. 2021). In sandy sediments, bottom fishing kills organisms that regulate carbon cycling on the seafloor (Hale et al. 2017), whereas in mud habitats it also releases carbon stored in the sediment itself (Sciberras et al. 2016). Bottom trawling also decreases the flux of organic carbon from shallow coastal waters to the deep sea by over 60% in North Western Mediterranean waters (Pusceddu et al. 2014; Laffoley 2020).

Carbon cycling in blue carbon ecosystems

Tidal marshes, mangroves, seagrass meadows, and macroalgal communities are net autotrophic ecosystems (*i.e.*, fix CO_2 as organic matter photosynthetically more than the CO_2 respired back by biota (Duarte & Cebrian 1996). They constitute hot spots of C cycling, ranking among the most intense C sinks in the biosphere, often with rates of production comparable to the most productive crops. There are several reasons why BC ecosystems are hot spots for C sequestration. First, they are highly productive ecosystems converting CO_2 into plant biomass. Second, they are mainly found in (and/or export C to) depositional environments, which accumulate both autochthonous and allochthonous particulate C (Kennedy et al. 2010). Third, soils within BC ecosystems have high accretion rates resulting in the rapid burial of organic matter in anoxic conditions that slow down microbial decomposition thereby contributing to the formation of organic-rich soils that can exceed 10 m in depth. In addition, their vegetation canopies and/or aerial root networks are complex three-dimensional structures that slow water flow and facilitate the trapping and settling of particles, including C, while protecting the soil C deposits from erosion.

Tidal marshes, mangroves, and seagrass meadows store C in two main pools: (1) an aboveground pool in the form of standing biomass (leaves, stems, branches, and trunks), in situ dead biomass such as trees and plant litter, and epiphytes that grow on the surface of these materials and (2) a belowground pool comprising living and dead belowground biomass (roots and rhizomes) and C within the soils. Typically, the majority of the C stocks are found in the soils, with 90% of total C stocks found in the soils of tidal marshes and seagrasses and 75% in the soils of mangroves. A proportion of both the autochthonous and allochthonous C is buried in their soils where it can be preserved for thousands of years, thereby constituting a relevant C sink for climate change mitigation. In contrast, most macroalgal communities grow on rocky shores and, therefore, do not accumulate sediments. Consequently, within macroalgal habitats, such as kelp forests, the C stock is in the form of standing biomass. However, as with the other BC ecosystems, a large portion of the organic matter and C produced within macroalgal ecosystems is exported as dissolved or particulate organic C to adjacent ecosystems, including sandy shores and the open ocean, where it can also accumulate over time scales relevant for climate change mitigation.

At a global scale, BC ecosystems combined (tidal marsh, mangrove, seagrass, and macroalgae) sequester 130- 490 Tg year^{-1} of C (equivalent to 500 - 1800 Tg of CO_2 per year), whereas current fossil fuel emissions total some 9900 Tg C year^{-1} (36,200 Tg CO_2 per year; O'Connor 2020). Their annual C sequestration, therefore, is equivalent to 1%- 5% of current CO_2 emissions from fossil fuel combustion, making them important and efficient (sequestration rate/area) C sinks. Indeed, over the last millennia and owing to their capacity to raise the seafloor, tidal marsh, mangrove, and seagrass ecosystems accumulated 10- 25 Pg C in 1-m thick soils, equivalent to 2.4%- 6.3% of global fossil fuel CO_2 emissions between 1751 and 2014 (O'Connor 2020). However, this is likely an underestimate because the long-term preservation and continuous accretion of C in tidal marsh, mangrove, and seagrass soils results in the formation of organic-rich deposits several meters in thickness.

Carbon storage in blue carbon environments

The majority of carbon in coastal ecosystems is trapped in the soils. Mangroves are remarkably rich in carbon, containing three to four times the volume of carbon typically found in boreal, temperate, or upland tropical forests. According to our estimates, one hectare of mangroves comprises about 467.5 t C per hectare (1714 t CO_2e ha^{-1}), which is equivalent to the annual emissions from more than 330 passenger vehicles in the United States, on average (5.1 t CO_2 per vehicle, on average, 12,000 miles driven at the fuel consumption of 21 miles per gallon). Globally, mangroves contain about 6.5 Pg C (almost 26.8 Pg CO_2*e*), including carbon in above- and belowground biomass and in the first 1 m of soils. Salt marshes have slightly less carbon per hectare than mangroves, about 393 tons per hectare, or equivalent to annual emissions from 77 passenger vehicles, on average, in the United States. The global coverage of salt marshes (51,000 km^2) therefore results in a global total carbon stock of about 2 Pg C. Seagrasses have the least amount of carbon per hectare, approximately 72 tons (equivalent to annual emissions from 14 passenger vehicles, on average, in the United States), but their large global coverage (319,000 km^2) results in a substantial estimate of total carbon stock, 2.3 Pg C.

Table 3. Summary of carbon stock and burial estimates for blue carbon ecosystems

BCE	Storage per ha (t C ha $^{-1}$)	Storage per ha (t CO2 ha^{-1})	Global annual Storage (pg C)	Global annual emissions (million tons C)
Mangroves				
Biomass	148	541	2.1	7.5
Soil	320	1173	4.5	16.3
Total stock	468	1714	6.5	23.9
Burial rate	1.15	4.2	0.016	0.06
Salt marshes				
Biomass	3.315	12.2	0.017	0.1
Soil	390	1430.0	1.989	8.5
Total stock	393.3	1442.2	2.01	2.0
Burial rate	2.1	7.7	0.011	10.6
Seagrass				
Biomass	1.54	5.6	0.040	0.3
Soil	70	256.7	2.233	9.6
Total stock	71.5	262.3	2.3	3.1
Burial rate	0.535	2.0	0.017	9.8

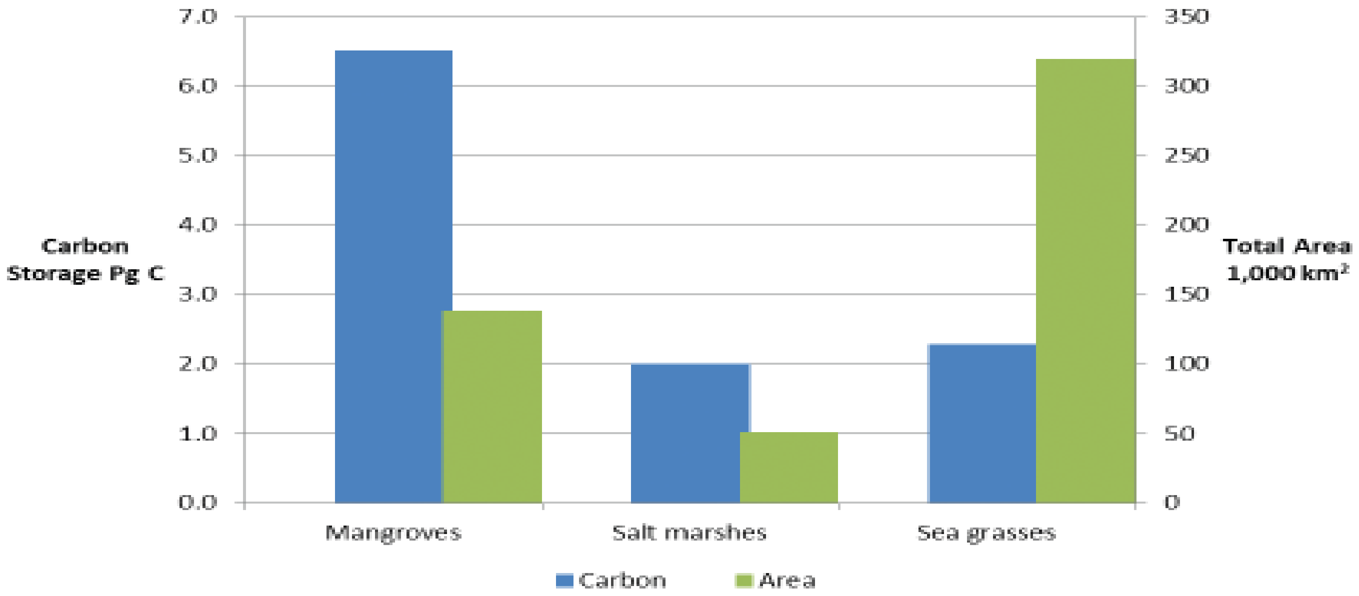


Figure 1. Global carbon storage (Pg C) and habitat area (1,000 km^2) of mangroves, salt marshes and seagrasses

Conclusions

However, human activities, such as the burning of fossil fuels and deforestation, have led to a dramatic increase in CO2 emissions, resulting in ocean acidification and warming. These changes are negatively impacting marine ecosystems, disrupting the delicate balance of the ocean carbon pool. The consequences of these disruptions extend beyond marine life and can have severe implications for climate stability, as a perturbed ocean carbon pool may no longer act as an effective buffer against rising atmospheric CO2 levels. In conclusion, the ocean carbon pool is an integral part of the Earth's carbon cycle, with the capacity to mitigate the effects of increased atmospheric CO2 concentrations. Understanding the dynamics of this complex system is essential for comprehending climate change and designing effective strategies for carbon management. To preserve the stability of the ocean carbon pool, it is crucial to reduce anthropogenic carbon emissions and promote sustainable practices to safeguard the health of our oceans and, by extension, the planet

Declaration of Interests

The authors have no conflict of interest to declare.

Data Sharing

All relevant data are within the manuscript.

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