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Research Paper

Mangroves and Climate Change: Carbon Sequestration Implications. A Review

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Abstract
Mangrove ecosystems are among the most effective natural carbon sinks, playing a crucial role in mitigating climate change by sequestering significant amounts of carbon. However, they are increasingly threatened by the changing climate, which introduces multiple stressors, including sea level rise, increased storm frequency, shifts in precipitation patterns, rising temperatures, and ocean acidification. While these changes can negatively impact mangrove survival and carbon sequestration capacity, some aspects of climate change, such as increased rainfall and sediment deposition, may facilitate mangrove expansion in certain regions.
This review evaluates the effects of climate change on mangrove ecosystems, focusing on their ability to store carbon and their vulnerability to environmental shifts. Projections suggest that while mangrove carbon stocks may increase in some areas under moderate climate scenarios, rising sea levels and habitat loss due to coastal squeeze could significantly reduce mangrove coverage and carbon sequestration potential. The uncertainty surrounding future carbon fluxes raises concerns about whether mangroves will remain net carbon sinks or transition into carbon sources by the end of the century. Understanding these dynamics is critical for developing conservation strategies that enhance mangrove resilience and maximize their role in climate change mitigation.

Keywords:* *Mangroves; Carbon sequestration; Climate change

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I. Introduction

One of the unique coastal ecosystems, mangrove forests that flourish at the intersection of land and ocean [1] are Ecoton or Eco-sensitive zones [2]. Mangroves are widespread along the coasts and estuaries of 123 tropical and subtropical countries with trees that are specially adapted to living in salt and brackish water [1].

Beyond their exceptional biodiversity, mangroves offer vital ecosystem services that benefit human communities. Notably, they play a crucial role in regulating essential processes, including shoreline protection through wave reduction [3] and they act as natural sinks for organic carbon and have crucial role in offsetting greenhouse gas (GHG) [3-6]. The intertidal zone where mangroves exist is marked by intense physical, chemical, and geological fluctuations, including shifting wave patterns, tidal cycles, temperature, salinity, emissions, oxygen levels, and rainfall [7-9]. They thrive in a highly dynamic and stressful environment, characterized by frequent disturbances and constant changes in environmental conditions. These forces continually shape and reshape mangrove ecosystems over time [3]. Located at the interface between land and sea in tropical regions, mangroves are particularly vulnerable to climate change [9].

While mangroves are likely to persist, climate change will predominantly have detrimental effects on these ecosystems, with ongoing and future impacts expected to outweigh any benefits [10]. This review assesses the carbon sequestration and effect of changing climate on mangrove ecosystems.

Climate Change and Mangrove Carbon Sequestration
Carbon sequestration in mangrove forests

Carbon dioxide (CO2) stored in the world's coastal and marine ecosystems such as mangroves, saltmarshes, and seagrasses are called 'blue carbon' [11]. Mangroves hold a substantial amount of the world's carbon, boasting the highest carbon storage capacity per unit area among all ecosystems, whether on land or in the ocean [1]. On average, mangroves store 738.9 megatons of organic carbon per hectare, totaling 6.17 petagrams globally. Although this accounts for only a small fraction (0.4-7%) of carbon stored in terrestrial ecosystems, it represents a significant 17% of the total carbon stored in tropical marine ecosystems [12]. Donato et al. [4] and Chatting et al. [6] stated that mangroves hold up to five times more organic carbon than tropical forests located on land.

The unique combination of mangroves' high growth rates and slow soil decay processes enables them to effectively trap and store organic carbon, especially in their soil [13]. Mangroves' intricate root systems and waterlogged soils trap organic matter, forming thick, carbon-rich peat layers up to 10 meters deep [14,6]. This peat, composed mainly of dead roots, can account for up to 90% of mangroves' organic carbon stores[15,6]. Consequently, mangroves have garnered significant scientific attention for their potential to naturally offset greenhouse gas emissions [4-6].

Alongi [12] mentioned that sequestration involves three key components; Firstly, there's the annual carbon capture rate, which refers to the amount of organic carbon transferred to soils and sediments each year, where it's safely stored , secondly, carbon is also stored in biomass, including both above-ground elements like trees and plants, and below-ground components like roots and lastly, there's the total ecosystem carbon storage, which represents the accumulated carbon stored in soils and sediments over time, effectively capturing the ecosystem's lifetime carbon sequestration.

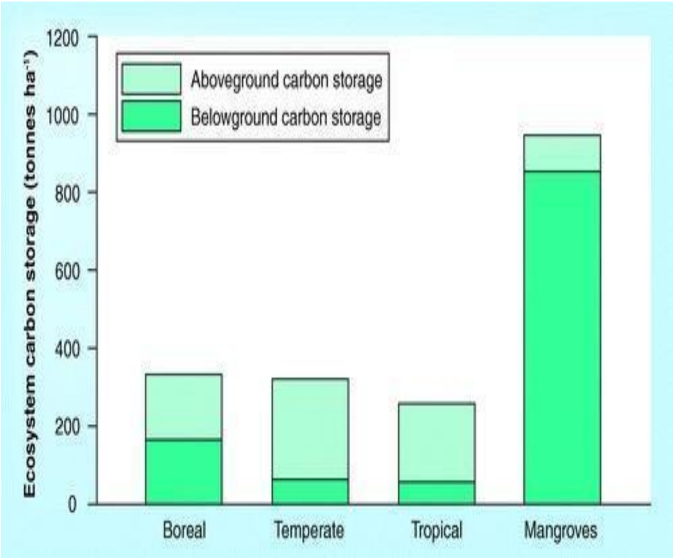

Figure 1: Differences in whole-ecosystem carbon stocks among boreal, temperate and tropical terrestrial forests, and subtropical and tropical mangrove forests.

Source : Nature Geoscience [16]

Threats to mangrove ecosystems

Mangrove forests are among the most endangered ecosystems in the tropics [17,18], primarily due to human activities such as land conversion for farming and aquaculture, urban expansion, and pollution [18,19]. Additionally, mangroves are highly susceptible to climate change impacts like rising sea levels [18,20] and droughts [18,21], which can exceed the tolerance limits of mangrove species, further threatening their survival [18,22].

According to Alongi [23] and Chatting et al. [6], widespread mangrove deforestation since the 1950s has led to significant greenhouse gas emissions, with estimates suggesting that up to half of the world's mangroves have been lost, mainly due to conversion for other land uses.

Effect of changing climate on mangrove ecosystems

Agarwal et al. [24] stated that climate change is a pressing concern in this century, largely driven by the surge in carbon dioxide emissions. Over the past 60 years, the increased use of fossil fuels has led to a significant rise in CO2 levels, from 280 ppm pre-industrial levels to 407.25 ppm as of July 2017. To stabilize this trend and slow the accelerating growth of CO2, it's crucial to capture and store this gas in natural carbon sinks, such as vegetation.

Mangroves are impacted by a range of climate change components. These include rising sea levels, increased frequency of extreme water events, enhanced storm activity, changes in precipitation patterns, rising temperatures, and elevated atmospheric CO2 levels. Additionally, shifts in ocean circulation, degradation of adjacent ecosystems, and human adaptations to climate change also affect mangrove ecosystems [25].

Table 1: Direct and indirect effects of climate change [26]

Direct effects of climate change	Indirect effects of climate change
● Sea level rise ● Warming of surface waters ● Warming of atmosphere ● Changing atmospheric moisture ● transport and precipitation ● Changing atmospheric gas composition (higher CO2)	● Changing surface ocean circulation affecting tidal exchange and geospatial dispersal of mangrove propagules ● Changing salinity gradients affecting tidal exchange ● Surface water acidification ● Changing freshwater inflow ● Changing allochthonous sediment input ● Changes in extreme weather events ● Increased frequency of extreme high water events ● Changes in seasonality ● Degradation of ecosystems that are functionally linked to mangroves

Relative sea-level rise poses a significant threat to mangroves and tidal wetlands, potentially surpassing the impact of human activities like aquaculture and land reclamation [25,27,28]. Although human actions have been the primary driver of mangrove loss to date [17,23,25,29-31], rising sea levels are expected to cause substantial declines in mangrove area and health, both now and in the future [25,29,32-39].

Rising sea levels pose a significant threat to mangrove ecosystems, potentially altering inundation patterns and increasing tree mortality [6,40]. Projections suggest that up to 96% of Middle Eastern coastal wetlands, including mangroves, may be lost by 2100 [6,41]. Additionally, coastal "squeeze" – where mangroves are trapped between rising seas and expanding human settlements [6,10, 42] could lead to lost carbon sequestration of up to 3.4 Pg by 2100 [6,42]. Friess [3] claimed that sea level rise is a stealthy but potent threat to mangroves, with far-reaching implications for their long-term survival.

Alongi [10] predicted that mangroves along arid coastlines are particularly vulnerable to climate change, facing increased salinity, reduced freshwater supply, and rising temperatures. Additionally, mangrove die-offs can occur due to freezing temperatures, especially in temperate-tropical transition zones [18,43], although the long-term impact of such freeze events is unclear [18]. According to recent research, increased temperatures are likely to have a negligible effect on organic carbon stores [6,44].

Climate change is expected to have a dual impact on mangrove ecosystems, posing significant threats while also creating opportunities for expansion . Mangroves can adapt to rising sea levels by migrating to new areas, increasing their elevation, or tolerating increased flooding [18,45]. Furthermore, climate-driven changes are enabling mangroves to spread beyond their traditional tropical and subtropical ranges, invading new areas at higher latitudes [18,43]. Climate change is projected to increase rainfall and flooding, leading to large sediment deposits in coastal areas, which in turn can facilitate the rapid seaward expansion of mangroves [18,46], while the temperature- driven displacement of saltmarsh plants by mangroves is likely to enhance carbon sequestration in coastal wetlands [18,47].

To support this concept Chatting et al. [6] used modeling to investigate the impact of climate change on future carbon stocks and soil carbon sequestration rates under two scenarios: a "business-as-usual" moderate-emissions scenario (SSP245) and a high-emissions scenario (SSP585).

Table 2: Mean ± 2 standard errors of the net effects of climate change and mangrove deforestation on total global mangrove carbon stocks and sequestration rates.

	Global total stocks (Tg C)					
	Current day		Forecasted		Losses from deforestation	Net change
	Tree C stocks	Soil C stocks	Tree C stocks	Soil C stocks		
SSP245	1246.9 ± 427.1	3296.1 ± 114.8	1382.0 ± 450.6	3481.4 ± 121.3	196.7 ± 32.3	123.7 ± 1146.1
SSP585			1439.8 ± 502.5	3457.0 ± 125.6		157.1 ± 1202.3

	Global Sequestration Rates (Tg C yr^{-1})		
	Current day	Forecasted	Net change
SSP245	18.3 ± 0.9	17.8 ± 0.9	−0.5 ± 1.8
SSP585		17.1 ± 0.9	−1.2 ± 1.8

Forecasted stocks and sequestration rates represent global estimates for the year 2095. Soil C stocks are estimated to 1 m soil depth. Net change is forecasted stocks/sequestration rates minus current day stocks/sequestration rates minus losses from deforestation.

Source: Chatting et al. [6]

Chatting et al. [6] predicts a global increase in mangrove carbon stocks under two climate scenarios. While some regions like Southeast Asia and southern Brazil may experience declines, others like the Caribbean, Australia, and parts of Africa are expected to gain. Countries with significant mangrove cover, such as Indonesia, Malaysia, and Nigeria, may see carbon stock increases of over 10% under a "business-as-usual" scenario, highlighting the potential of mangroves as a tool for offsetting emissions. Mangrove deforestation between 1996 and 2020 resulted in carbon emissions equivalent to roughly four times the global CO2 emissions from fossil fuel combustion and cement production in 2018 [1]. The projections of Chatting et al. [6] showed that, globally, increases in total C stocks (biomass + soil) induced by climate change would exceed emissions from mangrove deforestation between 2012 and 2095.

Conversely, according to Jennerjahn et al., [26] climate change is projected to cause a 10–15% loss of mangroves by 2100, resulting in the annual release of 4.7–35.3 teragrams (Tg) of carbon per year, totaling 400–3000 Tg. A complete loss, although unlikely, would release 47–235 Tg C year−1. While this is a relatively small fraction (2.5%) of annual human-caused carbon emissions, it is still significant. Due to uncertainty in carbon fluxes, it is unclear whether mangroves will remain carbon sinks or become sources by 2100. However, these projections suggest that climate change alone could transform mangroves from carbon sinks to sources by the end of the century [26].

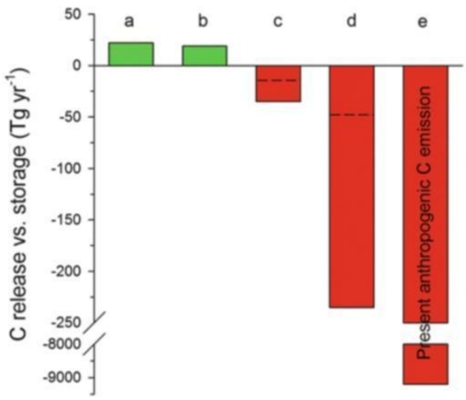

Figure 2: Annual mangrove carbon storage (green) and release (red) today (a) and under 10–15% loss (b and c) and total loss scenarios (d) until the year 2100 compared to the present-day (i.e., 2012) anthropogenic carbon emissions (e). Dashed lines denote the lower limit of carbon release from mangroves as reported in the text (Data sources: 4,6,48.Note the break in the Y-axis)

II. Conclusion

Mangroves play a crucial role in storing organic carbon, making them a valuable tool in mitigating greenhouse gas emissions. However, climate change and deforestation could undermine their carbon storage potential, highlighting the need for global projections of future changes to inform conservation efforts [6].

Gilman et al., [25] examines the current understanding of the impacts of projected climate change on mangrove ecosystems, including the assessment of mangroves' ability to resist and recover from sea-level rise. Resistance refers to the mangrove's capacity to maintain its functions, processes, and structure despite rising sea levels [49,50], whereas resilience refers to its ability to adapt and reorganize through landward migration, thereby preserving its ecosystem integrity[51,52].Under this changing climate scenario, mangroves, natural sinks of carbon, may be affected both positively and negatively in terms of their carbon sequestration due to various reasons.

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