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REVIEW ARTICLE

A review of tropical blue carbon ecosystems for climate change mitigation

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Abstract

Tropical blue carbon ecosystems encompass several components such as mangroves, seaweed, and seagrass, which play a crucial role in delivering a diverse array of services including regulation, provisioning, cultural, and support functions to a significant human population. The preservation and rehabilitation of tropical marine ecosystems hold significant importance for society due to the adverse consequences associated with their degradation, which include the impairment of crucial services such as coastal protection and the provision of seafood resources. Nonetheless, a significant knowledge deficit persists about the comprehensive capabilities of blue carbon ecosystems in terms of mitigating climate change and delivering socio-economic advantages. Hence, the primary objective of this study is to critically examine the economic significance of ecosystem services rendered by blue carbon habitats, along with the associated obstacles, governance mechanisms, and conservation approaches employed to address climate change mitigation through these ecosystems. The integration of blue carbon ecosystems conservation, protection, and restoration should be prioritized within mitigation and carbon stock conservation plans across local, national, and global scales. This article reviews various forms of governance, such as market-based instruments, public investment, partnership initiatives, and community-based management, that have the potential for future implementation. In a broader context, safeguarding tropical marine habitats is an ecological necessity that warrants recognition as a potential avenue for generating more cash and alleviating national debts across various countries. This review paper presents a comprehensive overview of the existing knowledge regarding severely degraded tropical blue carbon ecosystems, with the aim of offering a structured framework that can be utilized by stakeholders to facilitate their efforts in restoring these ecosystems.

Keywords: Blue carbon; Climate change; Ecosystem services; Restoration; Conservation; Governance

Introduction

Blue carbon ecosystems play a significant role in mitigating climate change by sequestering surplus carbon from the atmosphere (Bandh et al., 2023). According to the Intergovernmental Panel on Climate Change (IPCC), blue carbon encompasses all carbon fluxes and storage in marine systems that are biologically driven and may be effectively managed. The primary emphasis has been placed on the examination of terrestrial vegetation within the coastal region, including tidal marshes, mangroves, and seagrasses (Ouyang et al., 2023).

Table 1 and Figure 1 depict the worldwide dispersion of blue carbon ecosystems. The preservation and rehabilitation of coastal blue carbon ecosystems yield significant societal advantages due to their augmentation of ecosystem services, including the maintenance of biodiversity and the availability of seafood (McHenry et al., 2023; Quevedo et al., 2023). Blue carbon sequestration is regarded as a nature-based approach to address the prevailing climate crisis. This is due to the fact that marine vegetated habitats play a crucial role in enabling society to adapt to climate change by safeguarding coastal regions against the escalating frequency of storms, rising sea levels, and coastal erosion. However, it is worth mentioning that the efficacy of restoring blue carbon habitats for the purpose of carbon sequestration remains uncertain (Macreadie et al., 2021). The connection between understanding the advantages of preserving blue carbon ecosystems and the imperative to halt their continued degradation is established through the implementation of economic incentives, multi-regulatory frameworks, and the allocation of financial resources to support the conservation and restoration of these valuable natural resources (Bandh et al., 2023).

Table 1. The worldwide distribution of blue carbon ecosystems (Himes-Cornell et al., 2018)

Region	**Mangrove**		**Seagrass**		**Salt marsh**	
	Hectares	**% of total**	**Hectares**	**% of total**	**Hectares**	**% of total**
Asia	3,276,758	28.6	23,690	10.8	22,008	5.3
Africa	2,631,069	22.9	6,247	1.8	1,565	0.4
Central and South America	2,991,043	26.1	10,368	4.7	5,315	1.5
Australia and South Pacific	1,587,385	13.8	2,622	1.2	16,644	4.7
North America	965,678	8.4	153,266	69.6	143,239	40.8
Europe	0	0	23,614	10.7	162,039	46.2
Middle East	23,995	0.2	351	0.2	174	0
Global total	**11,466,928**		**220,158**		**350,984**	

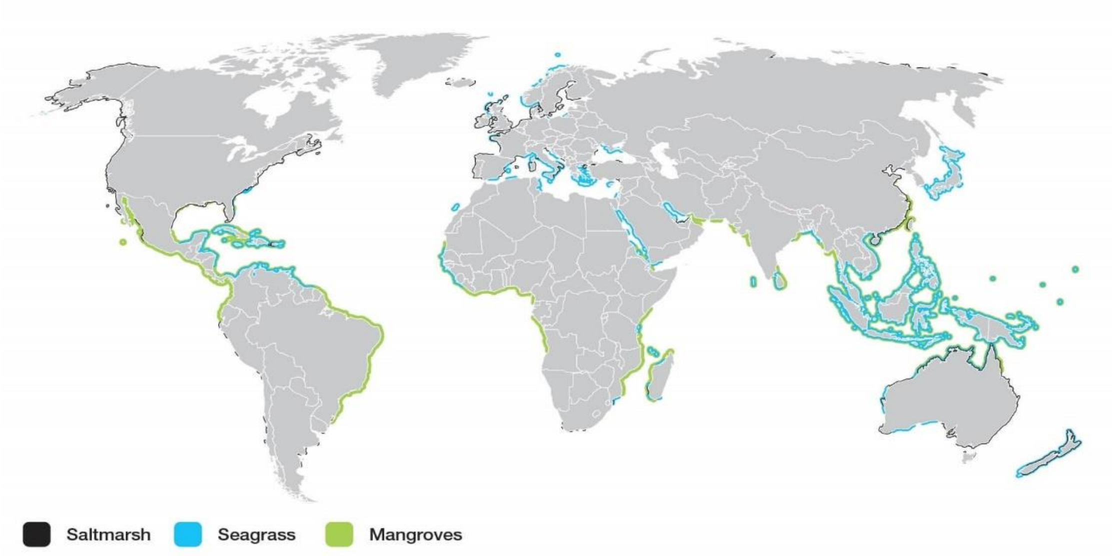


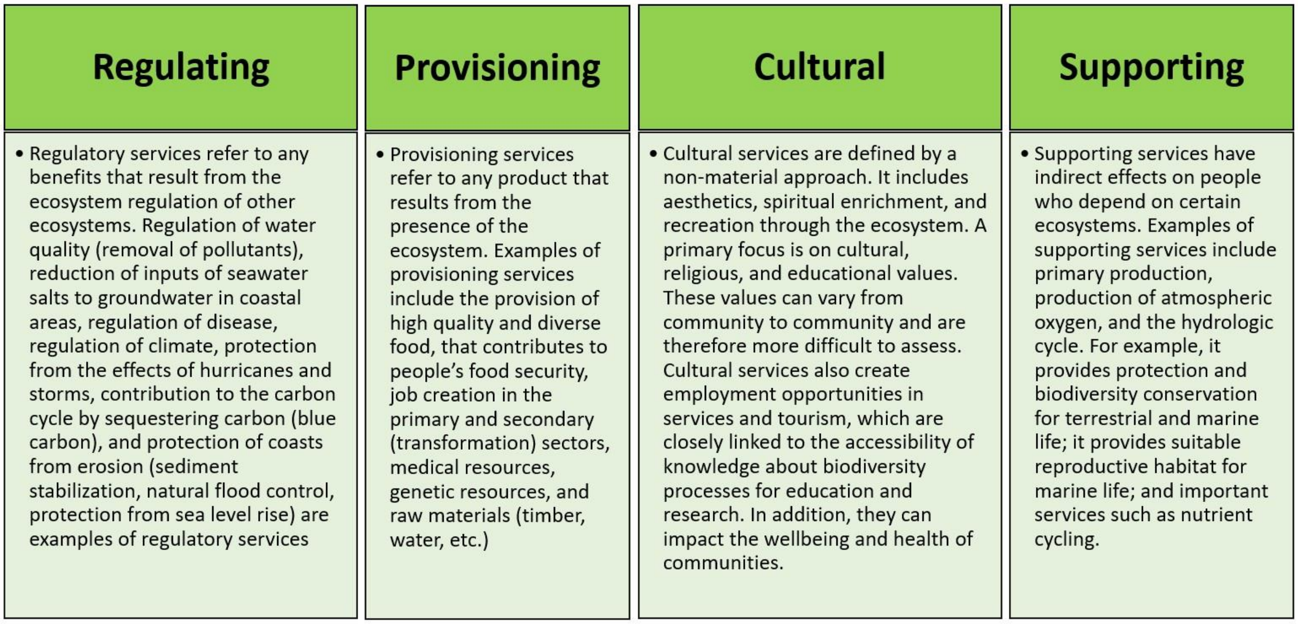
Figure 1. Global map of blue carbon ecosystems

There is a prevailing consensus among scholars and experts that a prolonged recovery from the global COVID-19 crisis is imperative (Raihan et al., 2022a; Raihan & Himu, 2023). However, regrettably, these demands have not been heeded. According to Badruddin (2023), there was a notable 6% rise in global carbon dioxide (CO_2) emissions resulting from the combustion of fossil fuels during the year 2020-2021. This increase led to a record-breaking annual amount of 36.3 gigatons (Gt). In order to mitigate the most severe consequences of climate change, it is imperative for the global community to expeditiously curtail emissions (Raihan et al., 2022b; Raihan et al., 2023a). Nevertheless, it is worth mentioning that there exists a potential avenue for mitigating atmospheric CO_2 levels through the implementation of nature-based climate solutions (NbCs). The blue carbon method, as assessed by Raw et al. (2023), is projected to have a limited capacity to mitigate climate change, amounting to less than 1% of current emissions. However, it is important to note that the advantages of adapting to climate change are substantial and should not be overlooked (Raihan et al., 2022c; Raihan et al., 2023b). According to Macreadie et al. (2021), blue carbon ecosystems in both terrestrial and marine environments within the NbC category possess the capacity to sequester a substantial amount of carbon, exceeding 30,000 teragrams (TgC). This carbon storage potential translates into a significant mitigation effect, estimated to prevent the release of approximately 300 carbon dioxide equivalents (CO_2e) on an annual basis. The potential expansion and restoration efforts have the capacity to sequester an estimated 841 Tg CO_2e annually by the year 2030, which would account for almost 3% of global emissions. According to Bandh et al. (2023), blue carbon ecosystems possess the capacity to store carbon at a rate that is ten times greater than that of terrestrial ecosystems over long periods of time. This carbon sequestration occurs through processes such as natural carbon assimilation during photosynthesis, as well as the sequestration of sediments and organic matter inside their intricate root systems (Raihan & Said, 2022; Raihan et al., 2023c). Moreover, these ecosystems play a crucial role as significant hubs for economic endeavors owing to their abundant resources including aquaculture, agriculture, fisheries, ports, tourism, and other related sectors (Datta & Roy, 2023). Numerous services play a crucial role in facilitating adaptation to climate change in coastal regions (Raihan et al., 2022d; Roy et al., 2023). The benefits encompassed by this phenomenon consist of safeguarding against erosion and sea level escalation, offering a habitat for both vertebrate and invertebrate species, and ensuring food security for numerous global communities (Raihan et al., 2022e; Lincoln et al., 2023). Nevertheless, it is worth mentioning that tropical regions have a higher population density compared to other geographical locations (Raihan et al., 2022f; Raihan et al., 2023d). According to Ratnatunga et al. (2022), it is estimated that around 40% of the global population currently resides in tropical regions. Projections suggest that this proportion is anticipated to rise to 50% by the conclusion of the year 2030. The escalating process of urbanization and pollution poses a significant threat to the preservation of mangroves, salt marshes, and seagrasses (Raihan et al., 2022g). Consequently, these ecosystems are experiencing habitat loss at a comparable or even more severe rate than tropical forests (Naidoo, 2023). According to Hatje et al. (2023), global losses of mangroves, seagrasses, and intertidal salt marshes have been calculated at approximately 67%, 29%, and 35% respectively. According to Arina et al. (2023), these ecosystems have the potential to transition from carbon sinks to carbon sources. Consequently, safeguarding and rehabilitating these ecosystems to mitigate emissions emerges as a crucial objective in endeavors to address climate change (Raihan et al., 2022h; Raihan et al., 2023e). Activities aimed at restoring and safeguarding blue carbon habitats not only contribute to the preservation of biodiversity but also present opportunities for the establishment of market-driven mechanisms that leverage current carbon offset frameworks (Vanderklift et al., 2022). Financial incentives for blue carbon have the potential to serve as a means of safeguarding and capitalizing on the additional ecological services offered by these habitats, including fisheries (Arkema et al., 2023).

This study provides a concise overview of the various services offered by tropical coastal ecosystems, with a particular focus on carbon storage and sequestration. Furthermore, this study examines various compensating strategies, including green aquaculture, marine protected areas, and wetland restoration, which have the potential to augment carbon sequestration. This article examines various governance approaches that can be employed in the future to facilitate the successful restoration and protection of blue carbon ecosystems. These approaches encompass market-based instruments, public investment, partnership initiatives, and community-based management, all of which are crucial for ensuring the effectiveness of such endeavors.

Blue carbon ecosystem services

Mangroves, seagrass beds, and seaweeds are well recognized as pivotal carbon sinks within tropical marine ecosystems, commonly referred to as "blue carbon" habitats. Mangroves exhibit taxonomic diversity, with approximately 50-75 species of woody vegetation (Asante et al., 2023). These ecosystems span a total area of 135,000 to 150,000 km^2, distributed throughout 118 nations in Southeast Asia, South America, Africa, and the Caribbean (Adame et al., 2021). Seagrasses, which consist of submerged flowering plants, are predominantly found in Southeast Asia, covering an area of approximately 320,000 km^2 (Nguyen et al., 2022). The assessment of seaweed coverage presents challenges due to its dependence on the agriculture industry. Blue carbon ecosystems offer a diverse array of functions that can be categorized into four distinct groups: regulatory, provisioning, cultural, and supportive. The services offered by tropical blue carbon ecosystems are depicted in Figure 2.



Regulating	Provisioning	Cultural	Supporting
• Regulatory services refer to any benefits that result from the ecosystem regulation of other ecosystems. Regulation of water quality (removal of pollutants), reduction of inputs of seawater salts to groundwater in coastal areas, regulation of disease, regulation of climate, protection from the effects of hurricanes and storms, contribution to the carbon cycle by sequestering carbon (blue carbon), and protection of coasts from erosion (sediment stabilization, natural flood control, protection from sea level rise) are examples of regulatory services	• Provisioning services refer to any product that results from the presence of the ecosystem. Examples of provisioning services include the provision of high quality and diverse food, that contributes to people's food security, job creation in the primary and secondary (transformation) sectors, medical resources, genetic resources, and raw materials (timber, water, etc.)	• Cultural services are defined by a non-material approach. It includes aesthetics, spiritual enrichment, and recreation through the ecosystem. A primary focus is on cultural, religious, and educational values. These values can vary from community to community and are therefore more difficult to assess. Cultural services also create employment opportunities in services and tourism, which are closely linked to the accessibility of knowledge about biodiversity processes for education and research. In addition, they can impact the wellbeing and health of communities.	• Supporting services have indirect effects on people who depend on certain ecosystems. Examples of supporting services include primary production, production of atmospheric oxygen, and the hydrologic cycle. For example, it provides protection and biodiversity conservation for terrestrial and marine life; it provides suitable reproductive habitat for marine life; and important services such as nutrient cycling.

Figure 2. Services of blue carbon ecosystems

According to Veettil et al. (2019), mangroves offer various benefits to local populations, including the provision of lumber, fuel, and charcoal. Additionally, they serve as a natural defense mechanism against the impacts of sea level rise and heightened storm activity, providing coastal protection (Raihan et al., 2018; Raihan et al., 2022i). The recognition of the significance of mangroves in coastal defense has grown subsequent to the occurrence of the 2004 Indian Ocean tsunami, which caused extensive damage to the coastal environment. It has been acknowledged that the preservation and proper management of mangroves could have alleviated a substantial portion of the severe consequences resulting from the tsunami (Marois & Mitsch, 2015). Furthermore, it should be noted that mangrove ecosystems play a crucial role in serving as significant feeding and spawning grounds, while also mitigating the risk of predation for numerous fish species (Carrasquilla-Henao et al., 2019). According to Cotas et al. (2023), seaweed and seagrass beds play a crucial role in ecosystem regulation through their ability to stabilize sediments, mitigate shoreline erosion, and contribute to water purification. Theuerkauf et al. (2022) emphasize the significance of these habitats as crucial ecosystems that offer refuge to numerous fish species, as well as lobsters and crabs. Seagrasses offer a diverse array of services, including the provision of sustenance and the supply of pharmacological resources for medicinal purposes (Lakshmi, 2021). Seaweed cultivation, in turn, has proven to be a readily achievable practice, leading to the emergence of aquaculture as a prominent sector that offers substantial employment opportunities and sustains the lifestyles of several families residing in remote coastal towns (Rimmer et al., 2021). Furthermore, ongoing investigations are being carried out on the utilization of seagrass as a source of biofuel and its potential as an alternative to plastic packaging (Balestri et al., 2019; Yong et al., 2022). Seaweed agriculture has experienced significant growth throughout Asia, Africa, and the western Indian Ocean, principally driven by its utilization in food production (Eggertsen & Halling, 2021; Msuya et al., 2022). According to data from the Food and Agriculture Organization (FAO) in 2020, there has been a significant growth in worldwide seaweed cultivation throughout the period from 1950 to 2020. Specifically, the cultivation of seaweed has experienced a remarkable increase of 1,000 times, rising from 34.7 thousand tons to 34.7 million tons. It is noteworthy that aquaculture has played a dominant role in this expansion, accounting for almost 97% of the present production. Nevertheless, the potential adverse effects of seaweed farms can be attributed to habitat destruction (Theuerkauf et al., 2022).

According to Osland et al. (2022), carbon sequestration emerges as the primary ecosystem benefit offered by tropical coastal ecosystems. Figure 3 illustrates the role of blue carbon ecosystems in mitigating climate change through the sequestration of atmospheric carbon. Mangroves have a significant role in the sequestration of organic carbon stocks (Corg) both above-ground (leaves, branches) and below-ground (sediment, roots) within the soil (Raihan et al., 2019). This carbon storage occurs at varying depths, spanning from 30 cm to depths exceeding 3 m, hence offering a mechanism for long-term carbon retention (Suello et al., 2022). The current assessment of carbon accumulation in mangroves is based on radiometric analyses, as reported by Lamont et al. (2020). These analyses indicate that the range of carbon accumulation in mangroves is between 0.17 and 4.3 Mg C per hectare per year. The values fall within the estimated range obtained from soil carbon measurements, which vary from 1.74 to 2.5 Mg C per hectare per year (Suprayogi et al., 2022). Nevertheless, the rates of carbon acquisition through root systems, which vary from 5.06 to 6.63 Mg C per hectare per year, surpass the estimates of carbon accumulation derived from radiometric analyses or soil mass carbon determination (Lamont et al., 2020). The aforementioned measurements do not take into account the presence of roots, which account for the observed variances. Recent studies have indicated that the estimates of carbon sequestration through mangrove litterfall are greater compared to the estimations obtained through radiometric and mass analysis. According to Chen et al. (2021), the predicted rate of carbon sequestration by mangrove litter ranges from 3 to 5 Mg C per hectare per year. When considering the carbon stored in the higher layers of sediments, the combination of these numbers results in a total forest stock of 693 Mg C per hectare and a soil forest stock of 516 Mg C per hectare (Alongi, 2022). The carbon stored in soils has the potential to expand by up to 2,792 Mg C per hectare when accounting for deeper layers. Based on the median value of 627.8 MgC per hectare and widely accepted estimates of worldwide mangrove areas ranging from 83,495 to 137,760 km^2, Alongi (2022) conducted an estimation, revealing that the global carbon store for mangroves is within the range of 5.23 to 8.63 Pg C. According to Alongi (2022), the aforementioned values lead to an annual burial of carbon in mangrove forests ranging from 9.6 to 15.8 Tg C per year, which is notably 4 to 5 times greater than the carbon burial seen in boreal, temperate, and tropical highland forests. The comparison of carbon stored in the soils and biomass of various ecosystems is depicted in Figure 4.

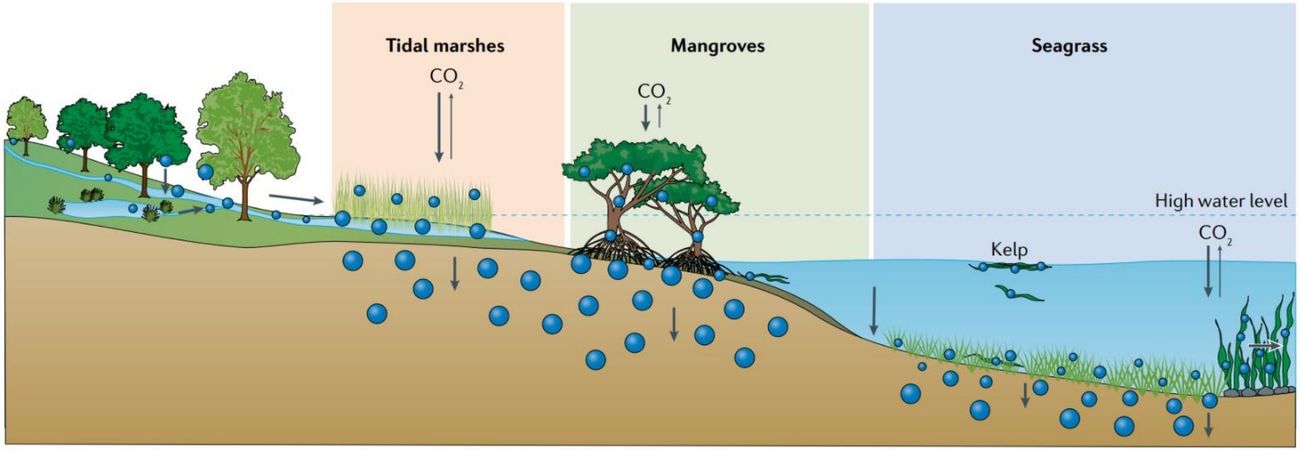


Figure 3. Blue carbon ecosystem for combating climate change by storing atmospheric carbon (Macreadie et al., 2021).

According to Alongi (2022), the carbon stock of mangroves exceeds the estimated carbon stock of seagrass meadows. Seagrass carbon stores in the uppermost 1 meter of sediment exhibit a range of 12 to 120 Megagrams of carbon per hectare, with a median value of 69.3 Megagrams of carbon per hectare, as reported by Miyajima et al. (2022). The sequestration rates of carbon in seagrass habitats vary from 94 to 161 kilograms of carbon per hectare per year, according to the same study. In a recent study conducted by Van Dam et al. (2021), it was discovered that numerous estimations fail to consider other processes such as denitrification, sulfur cycling, and inorganic carbon cycling. These processes constitute a significant contributor of CO_2 emissions to the atmosphere, surpassing the capacity of organic carbon sequestration (Raihan & Tuspekova, 2022a). In contrast to mangroves and seagrasses, seaweed does not exhibit the capacity to accumulate coastal sediment that is rich in carbon. However, the majority of the organic carbon is found within the living biomass (Raihan & Tuspekova, 2022b). Furthermore, a portion of the carbon assimilated by seaweed is deposited in the continental shelf and deep ocean, thus establishing a worldwide carbon reservoir (Hurd et al., 2022). A study conducted in Singapore has demonstrated that macroalgae possess the capacity to store a substantial amount of biomass, reaching up to 650 Mg C. This value exceeds the aboveground carbon content observed in seagrass meadows, although falls short of the carbon levels found in mangrove forests. The annual sequestration rate of carbon in mangrove forests is estimated to be approximately 450 Mg C per year, equivalent to 0.77 Mg C per hectare per year (Kwan et al., 2022). Furthermore, it should be noted that the significance of offshore sediments as carbon sinks surpasses that of other carbon sinks due to their expansive coverage (Legge et al., 2020; Raihan & Tuspekova, 2022c). Tidal marshes, which exhibit carbon sequestration properties, are predominantly found in temperate and high latitudes, with an area over 51,000 km^2 (Miyajima & Hamaguchi, 2019).

The provided figures regarding carbon sequestration should be regarded as approximate estimations due to the escalating challenges faced by mangroves and seagrass beds. These challenges include deteriorating water quality and the encroachment of coastal development activities such as aquaculture and timber production (Raihan & Tuspekova, 2022d). Consequently, these ecosystems are experiencing habitat degradation and a swift decline in their surface area and ecological functions. According to the findings of Dunic et al. (2021), there has been a significant decrease in the overall assessed seagrass area, amounting to a reduction of 19% since the year 1880. Notably, the tropical Atlantic and tropical Indo-Pacific regions have experienced substantial losses in seagrass coverage within the tropical areas. According to Bolívar-Anillo et al. (2020), the pace of mangrove depletion is currently reaching up to 3% annually, which raises concerns about their potential functional disappearance within a century. Mangroves experience significant oscillations, encompassing both natural regeneration and destruction processes (Song et al., 2023). The depletion of mangroves due to excessive harvesting and their substitution with nypa palms have been recognized as significant contributors to deforestation in certain regions of West Africa and South Asia (Nwobi & Williams, 2021; Ng et al., 2022).

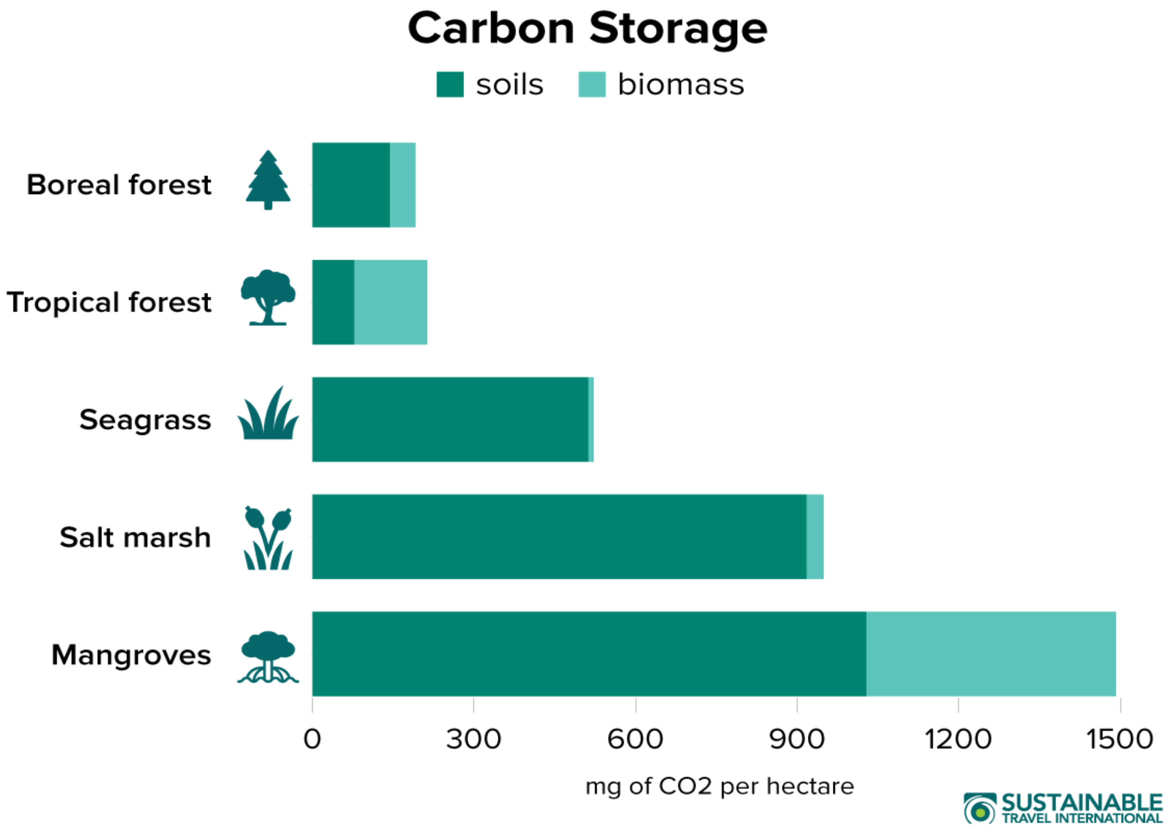


Figure 4. Comparison of carbon stored in the soils and biomass of different ecosystems
Data sources: Pendleton et al. (2012) and Pan et al. (2011)

In recent decades, there has been a dramatic reduction in the size of mangrove ecosystems (Murillo-Sandoval et al., 2022; Raihan & Tuspekova, 2022e). The study conducted by Wu et al. (2020) reveals that mangrove forests in Southeast Asia experienced a mean yearly decline of 0.18%. Furthermore, the research indicates that a total area of over 100,100 hectares of mangroves was cleared between the years 2000 and 2012 in this region.

According to Ferreira et al. (2023), the removal of mangroves and subsequent dredging of land for economic purposes results in the release of sediments into the atmosphere or water column. This process also leads to the restoration of carbon, which is subsequently released back into the atmosphere and ocean (Raihan & Tuspekova, 2022f). According to Siikamaki et al. (2013), the annual carbon emissions resulting from the loss of mangroves are projected to be approximately 35 million tons. According to Atwood et al. (2017), the estimation of worldwide potential CO_2 emissions resulting from mangrove loss is around 7 teragrams (Tg) per year, when measured in terms of CO_2e. Indonesia and Malaysia are identified as the nation's having the greatest potential for CO_2 emissions originating from soil, with estimated annual emissions of 3,410 Gg CO_2 and 1,288 Gg CO_2, respectively. In spite of notable declines in mangrove ecosystems, there has been a notable implementation of comprehensive conservation and restoration initiatives in recent times (Sasmito et al., 2023). Community-based restoration, reforestation, integrated coastal ecosystem restoration, and economic approaches have been implemented as strategies to address global warming and the trade of mangroves (Raihan & Tuspekova, 2022g; Lhosupasirirat et al., 2023). According to the study conducted by Begum et al. (2023), it was determined that the primary drivers for local stakeholders' engagement in mangrove restoration and management are livelihood and economic advantages. Hence, the implementation of mangrove restoration initiatives is anticipated to mitigate the shortcomings observed in community-based restoration programs (Lhosupasirirat et al., 2023).

Economic estimations of blue carbon ecosystem services

In light of the growing attention towards the significance of vegetated coastal habitats on a global, national, and local level, it is imperative to accurately assess the economic worth of their capacity to absorb and store carbon (Raihan et al., 2021a; Hurd et al., 2022; Raihan & Tuspekova, 2022h). This valuation would contribute to increasing awareness among the community and among policy makers (Raihan & Tuspekova, 2022i). Additionally, it would facilitate investment in suitable coastal protection and ecological restoration measures, which could otherwise lead to significant economic consequences (i.e., the cost of not taking action).

According to Barbier (2016), the estimated value of mangroves for the purpose of coastal protection and stabilization over a span of 20 years is $12,263 per hectare. Additionally, the cost incurred due to the loss of 1 square kilometer of mangroves in Thailand is around $1,879 per hectare. According to a study conducted by Anneboina and Kumar (2017), the monetary contribution to local fisheries resulting from the presence of one hectare of mangroves can vary significantly, ranging from $42 to $37,500. This variation is influenced by factors such as the geographical location and the value attributed to different species. Furthermore, it should be noted that the yearly economic value added per hectare for penaeid shrimp, which is considered the most commercially viable fishery connected with mangroves, exhibits a range of US$91 to US$5,292, as reported by Anneboina and Kumar in 2017. In addition, mangroves also generate additional value in the sectors of tourism, education, and cultural activities (Vargas-del-Río & Brenner, 2023). As an illustration, the economic benefits of mangroves have been quantified in several regions. In Malaysia, it has been estimated that mangroves provide approximately $1 million to tourism income annually (Spalding & Parrett, 2019). Similarly, in Iran, the yearly economic impact of mangroves on tourism revenue is projected to be around $7 million (Spalding & Parrett, 2019). In the Sundarban Reserves located in India and Bangladesh, the annual economic value of mangroves in terms of tourism revenue is estimated to be approximately $42,000 (Uddin et al., 2013). According to Barbier (2016), the global valuation of mangroves, encompassing all services provided, amounts to US$69.9 billion. The utilization of voluntary carbon markets has facilitated the generation of revenue for local communities by leveraging mangrove habitats to sell carbon credits that correspond to carbon sequestration (Raihan et al., 2021b; Raihan & Tuspekova, 2022j; Raihan et al., 2023f). This practice has been recognized as a promising approach for implementing payment for ecosystem services (PES) initiatives, as highlighted by Nguyen et al. (2023). These mechanisms facilitate the financing of conservation efforts. Nevertheless, the generation of carbon credits through blue carbon projects is limited due to the necessity of incorporating supplementary climate market mechanisms (Vanderklift et al., 2022). The depletion of seagrass can lead to significant economic ramifications due to its role as an indirect provider of sustenance and pharmacological resources. Nevertheless, the assessment of such expenses has been limited. Furthermore, seagrasses serve as a significant attraction for tourists, as exemplified in Indonesia, where the presence of seagrass ecosystems contributes to tourism revenues ranging from $2,287 per hectare per year to $80,226 per hectare per year (Dewsbury et al., 2016). According to Cullen-Unsworth and Unsworth (2013), the economic impact of carbon dioxide emissions resulting from the deterioration of seagrass is predicted to range from $1.9 billion to $13.7 billion annually on a global scale.

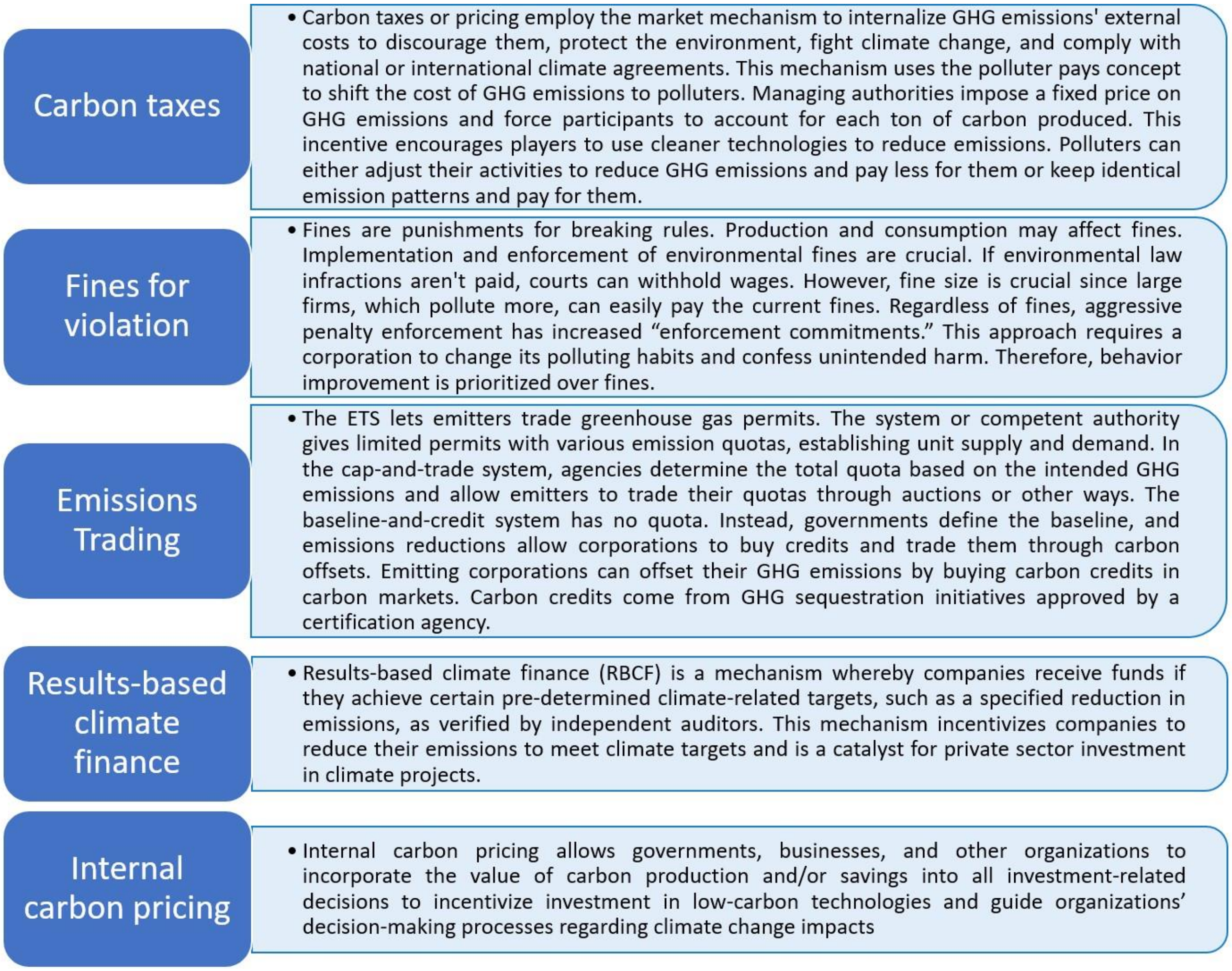
In addition, it should be noted that seaweed aquaculture exhibits potential for climate change mitigation and serves as a significant economic resource in tropical nations (Ross et al., 2023). According to Jagtap and Meena (2022), an approximate quantity of 500 million tons of seaweed output is projected to sequester around 135 million tons of carbon. Furthermore, the practice of cultivating seaweed not only serves to mitigate communal poverty but also enhances the economic well-being of coastal populations. China, Indonesia, the Philippines, Korea, Japan, Malaysia, and Tanzania are recognized as the leading nations in terms of seaweed production. Seaweed aquaculture in Malaysia was initiated during the 1980s, and over the years, production has witnessed a significant growth, reaching a total of 269,431 tons by the year 2013. According to Hussin and Khoso (2021), Malaysia's contribution to global seaweed output during that period amounted to 1%, positioning it as the eighth largest producer worldwide. According to Hussin and Khoso (2021), the Malaysian government set a target to increase seaweed production to 900,000 tons by the year 2020. This increase in production is estimated to have a monetary value of around USD 344.76 million. The primary utilization of seaweed in Southeast Asia is for the purpose of carrageenan extraction (Rupert et al., 2022). Carrageenan, a hydrocolloid derived from red seaweed, is widely utilized in various food and pharmaceutical applications. According to Farghali et al. (2023), the worldwide production of grown seaweed for multiple biorefineries reached a total of 34.7 Gt in 2019, with an estimated value of USD 14.7 billion.

Protection measures of tropical blue carbon ecosystems

There exist multiple potential approaches for the successful implementation of restoration and preservation measures in a thorough and efficient manner (Raihan & Tuspekova, 2023a). These encompass many strategies such as market-based instruments (e.g., taxes and fines), public investments, community-based management, government incentives, and other similar approaches (Raihan et al., 2022j). This section provides a comprehensive summary of the current state of affairs regarding the various alternatives that have been addressed, as well as an examination of their potential implementation strategies.

Market-based solutions

Altering market outcomes through pricing policies is one form of economic intervention that can improve both efficiency and equity (Raihan & Tuspekova, 2023b). All natural and artificial resources used in manufacturing should be reflected in the price of goods and services (Raihan et al., 2023g). Blue carbon depletion from production and consumption must be reflected in the market price of the product by giving each activity that compromises ecosystem integrity a value corresponding to the carbon created or displaced. Socially advantageous behaviors are encouraged, while socially costly ones are discouraged, through the use of market-based solutions (Raihan & Voumik, 2022a). In order to account for the social as well as private costs and benefits of an action, they implement price interventions. All costs, including those for the ecosystem services that mangroves provide, will be borne by the activity (industrial development project or fishery) that causes their destruction. Damage fees for harming blue ecosystems, carbon prices, tax credits, and financial backing for blue carbon protection are all examples of interventions. Policy instruments can be used interchangeably or in combination. To achieve the same distributional goals as standards or subsidies, taxes can be used instead (Raihan & Voumik, 2022b).



Carbon taxes

- Carbon taxes or pricing employ the market mechanism to internalize GHG emissions' external costs to discourage them, protect the environment, fight climate change, and comply with national or international climate agreements. This mechanism uses the polluter pays concept to shift the cost of GHG emissions to polluters. Managing authorities impose a fixed price on GHG emissions and force participants to account for each ton of carbon produced. This incentive encourages players to use cleaner technologies to reduce emissions. Polluters can either adjust their activities to reduce GHG emissions and pay less for them or keep identical emission patterns and pay for them.

Fines for violation

- Fines are punishments for breaking rules. Production and consumption may affect fines. Implementation and enforcement of environmental fines are crucial. If environmental law infractions aren't paid, courts can withhold wages. However, fine size is crucial since large firms, which pollute more, can easily pay the current fines. Regardless of fines, aggressive penalty enforcement has increased “enforcement commitments.” This approach requires a corporation to change its polluting habits and confess unintended harm. Therefore, behavior improvement is prioritized over fines.

Emissions Trading

- The ETS lets emitters trade greenhouse gas permits. The system or competent authority gives limited permits with various emission quotas, establishing unit supply and demand. In the cap-and-trade system, agencies determine the total quota based on the intended GHG emissions and allow emitters to trade their quotas through auctions or other ways. The baseline-and-credit system has no quota. Instead, governments define the baseline, and emissions reductions allow corporations to buy credits and trade them through carbon offsets. Emitting corporations can offset their GHG emissions by buying carbon credits in carbon markets. Carbon credits come from GHG sequestration initiatives approved by a certification agency.

Results-based climate finance

- Results-based climate finance (RBCF) is a mechanism whereby companies receive funds if they achieve certain pre-determined climate-related targets, such as a specified reduction in emissions, as verified by independent auditors. This mechanism incentivizes companies to reduce their emissions to meet climate targets and is a catalyst for private sector investment in climate projects.

Internal carbon pricing

- Internal carbon pricing allows governments, businesses, and other organizations to incorporate the value of carbon production and/or savings into all investment-related decisions to incentivize investment in low-carbon technologies and guide organizations’ decision-making processes regarding climate change impacts

Figure 5. Possible economic interventions for the protection of tropical blue carbon ecosystems.

Greener development, as well as the extension and discovery of low-carbon technologies, can stimulate economic growth if the appropriate steps are taken in a number of different ways (Ghosh et al., 2023Li & Wen, 2023; Sultana et al., 2023). Possible financial steps to safeguard tropical blue carbon ecosystems are depicted in Figure 5. In many cases, tax benefits motivate the very behaviors that generate them. Project costs will factor in the benefits of initiatives that generate blue carbon as a byproduct, which will be of interest to developers and corporations eligible for environmental tax credits (Voumik et al., 2022). Fines and other forms of administrative punishment are less complicated to impose than criminal penalties. The most effective responses to environmental violations are administrative fines and criminal prosecution. In cases of moderate severity, monetary penalties are crucial. Since it utilizes preexisting tax infrastructure, carbon dioxide taxes are simpler to implement than alternative carbon pricing systems (Begum et al., 2020; Voumik et al., 2023a). They are easy to implement and promote the development and use of low-carbon technologies by all entities responsible for producing emissions (Isfat & Raihan, 2022; Voumik et al., 2023b). In conclusion, tax reuse has the potential to improve morale and output. However, carbon pricing may increase the cost of related items, which may reduce the competitive advantage of energy-intensive businesses and slow economic growth (Ali et al., 2022; Raihan, 2023a). Polluters may pass on the costs to consumers, which may increase tax revenue for the government without increasing emissions. The public's backing for carbon fees could weaken if collected funds are not reused. Furthermore, carbon taxes in developed nations may cause a transfer of emissions to less developed nations where fewer safeguards exist for the environment (Raihan, 2023b).

Financing for the maintenance and preservation of blue carbon

A significant problem is the insufficient funding for blue carbon ecosystem maintenance and restoration. Funding is contingent on a project having both a history of success and a low risk profile. The Clean Development Mechanism (CDM) allocates 80% of its revenues to sustainable energy projects and only 1% to forestry projects. According to Vanderklift et al. (2019), the majority of social responsibility offsets come through the voluntary market. As predicted by Favasuli and Sebastian (2021), this industry might be worth $50 billion by 2030. Vanderklift et al. (2019) argue that publicly sponsored blue carbon initiatives could lower risk and increase return. As a means of reducing price swings, they advocate for blue carbon credits to be priced at a guaranteed minimum. It is not entirely clear what legal and policy grounding blue carbon projects have. This has resulted in a reduction in public funds for blue carbon ecosystem conservation (Vanderklift et al., 2019), which has a negative impact on the financial stability of many projects.

In 2011, Gordon et al. analyzed 14 different funding mechanisms for blue carbon projects. The majority of the funds are invested in REDD+ research and development. UNFCCC REDD+ projects help cut down on harmful gases released as a result of cutting down trees (Jaafar et al., 2020; Raihan, 2023c). Funding options for blue carbon are included. The Hatoyama Initiative ($158 million), the Amazon Fund ($133.3 million), and the Global Environment Facility Trust Fund ($105 million) all contribute to REDD+ initiatives. Private sector blue carbon funding is extremely dependent on philanthropic funds, according to Earth Security (2020). The MacArthur Foundation funded Blue Ventures' almost $1 million expansion to Tahiry, Madagascar. Research for 1,300 metric tons of blue carbon credits has been sponsored through this initiative. Charity funding is also an important source of innovation (Raihan, 2023d). They frequently investigate and apply commercial strategies that indirectly protect blue carbon. Non-profit organizations and other sources of funding can entice and reassure private investors (Raihan, 2023e). Major private investors such as JPMorgan Chase and Encourage Capital were attracted to the project thanks to a partial debt guarantee and $6 million investment from the Global Environment Facility and the U.S. International Development Finance Corporation.

Blue carbon protection, and particularly mangrove protection, is a common use for municipal bonds. Similar to other types of bonds, municipal bonds can be used to fund local government operations on a state or local level (Raihan, 2023f). Typically, money is used to build things like schools and roads. Bonds totaling $400 million were issued by a group of cities on the U.S. coast; of that amount, $192 million will go toward mangrove restoration. Green bonds are issued to finance environmental initiatives like those that aim to reduce pollution, promote sustainable agriculture, and save ecosystems (Raihan, 2023g). Tax breaks are one way to entice potential backers. In order to finance environmental initiatives, the World Bank employs this method. Debt-for-nature swaps can be used to finance blue carbon reserves by reducing or providing favorable terms on national or local debt (Raihan, 2023h). By the year 2020, national debts will have exploded. Post-World War II general government debt is reported by the International Monetary Fund (2020). Developing nations on islands are particularly at risk (Raihan, 2023i). Because of this, debt-for-nature/climate swaps are proposed by Thomas and Theokritoff (2021). When a debtor nation's debt is forgiven by a creditor nation, the debt is purchased at a steep discount by an intermediary for use in environmentally responsible investment projects.

Regulatory mechanisms for blue carbon restoration and conservation

It is challenging to legally preserve mangrove habitats and to restore any that have been destroyed (Raihan, 2023j). Mangroves are governed by a complex web of hard and soft rules and policies at the international, regional, and national levels. Legal instruments include guidelines (such as the polluter-pays principle), theories, regulatory decision-making tools (such as environmental impact assessments), treaties, declarations, objectives, and goals. Many countries have adopted these pieces of legislation, which serve to protect and preserve mangroves (Raihan, 2023k). Lack of enforcement, human and financial constraints, and unclear government directives are just some of the problems plaguing "traditional environmental law," which affects all of these tools. The use of incentives and financial mechanisms alongside international tools (both hard law and soft law) is commonplace. These sector-spanning instruments address the aforementioned threats by enacting laws in multiple sectors that overlap and are intrinsically linked to one another.

The Ramsar Convention on Wetlands, the World Heritage Convention, and the Convention on Biological Diversity are all examples of biodiversity frameworks that address coastal blue carbon (Raihan, 2023l). Mangroves fall under the latter category because Parties are obligated to include biodiversity into sectoral policy and provide incentives for protection. Detailed objectives are laid out in the Aichi Biodiversity Targets. The CDM is a flexible mechanism that encourages carbon sequestration and is part of several climate change frameworks including the UNFCCC, the Paris Agreement, and REDD+ (Raihan, 2023m). The CDM allows for the payment of results from forest conservation and management in a country (Raihan, 2023n). The United Nations Convention on the Law of the Sea (UNCLOS) and the Convention on International Trade in Endangered Species (CITES) both address mangrove concerns. CITES is a template for international pacts involving jurisdictions that have wildlife that is constantly on the move. Environmental impact assessments, as well as the World Bank's and the Center for Tropical Ecosystem Research's rules of conduct, are being adopted as "soft law" mechanisms. Most mangroves thrive in brackish water; thus they tend to grow at the mouths of rivers that empty into the sea (Raihan, 2023o). The United Nations Water Convention and the United Nations Convention on the Right of Non-Navigational Uses of International Watercourses are two examples of international water regimes that apply to mangroves.

A significant challenge in coastal policymaking is coordinating between marine and freshwater legal and administrative systems on the mainland. The mangroves are an example of this holistic worry. The Water Framework Directive (WFD) serves as a model for regional and European water management by establishing good status targets for continental, coastal, and transitional waters. Good status in these areas depends on land-based and maritime influences for the physiochemical, biological, and hydro-morphological components (Raihan, 2023p). Integrated water management calls for the coordination and use of coastal and river basin mechanisms (such as monitoring, basin planning, governance, and funding). "Overseas territories" (OVTs) with special regulatory status, such as tropical areas, are included in this framework as well. Foreign countries and territories that are reliant on an EU member state but are not EU members are not required by law to implement the WFD. Mangrove management in French Guiana needs community input to meet European Union marine and freshwater regulations. Downstream coastal knowledge is being expanded using WFD monitoring and planning funds in particular watersheds. The Somone Coastal Basin Conservation Area is a joint effort by the Senegalese Ministry of Environment (in charge of coastal zone management) and the Ministry of Water and Sanitation (in charge of river basin planning). One notable mangrove in the watershed's downstream provides a wide range of biological benefits to the surrounding environment (Raihan, 2023q). Due to excessive water consumption in the upstream basin (with expanding demography, industry, and agricultural exports), freshwater runoff to the reserve is reduced, sedimentation and salinity are rising, and mangrove lands and biodiversity are lost immediately (Raihan, 2023r). In order to better conserve and restore mangrove forests, a new concertation mechanism is being developed.

As has been demonstrated above, there is no universally binding legal framework for protecting mangroves; rather, there is a patchwork of international instruments, methods, and standards that might be used. As part of the forest, marine and coastal law, water and wetland, aquaculture, and climate change ecosystems, mangroves may be subject to varying national regulations. Consequently, "tagging-based instruments" can protect mangroves, which are essential to ecological systems (Raihan, 2023s). The national level of regulation must execute global environmental treaties because it must consider the principles, concepts, and standards in international treaties (Raihan, 2023t). Executive decrees, rules, legal judgments, levies, and strategic tools can safeguard mangroves at the national level. Governance, land tenure, and rights are issues at the national level. Although "specific mangrove laws" do not exist, countries do have laws that govern the extraction industry, fishing industry, and farming. Planning and permitting regulations—private or public—are important and may consider good governance principles including access to information, public engagement, and justice. Villages and towns are involved in social forestry, land use, and other planning initiatives. MPAs, MSPs, IZMs, and EMBs are other national legal tools.

Challenges in governance, incentives, and enforcement

Mangrove habitats are extremely important to both nature and humanity due to the many benefits they bring. Mangroves can be protected through the use of sustainable monetization strategies, such as payments for ecosystem services, product certification, carbon offsets, REDD +, and fiscal incentives and disincentives. Companies interested in profiting from carbon sequestered in mangroves have looked into REDD + and the selling of voluntary carbon offsets. Mangrove area and ecosystem service ownership, carbon property rights, and carbon value norms are examples of legal circumstances necessary to realize these possibilities but are lacking in many countries. Carbon offsetting schemes in mangrove forests face legal challenges. The application of UNFCCC flexible mechanisms is complicated by the fact that the definition of "forest" varies from nation to country. Conservation and long-term sustainability can benefit from both tax incentives and disincentives. Mangroves have challenges from a lack of land-based and marine-based techniques, as well as from a lack of institutional coordination, governance concerns, lack of community participation, and land tenure issues. Transparency, accountability, and adherence to the rule of law in governance are essential for citizen engagement. The major problems with implementation are a lack of institutional ability and financial support. Corruption, capacity building, and inefficient national bureaucratic systems are the primary obstacles to effective enforcement. New legal instruments and measures should be developed to foresee implementation, enforcement, and compliance issues and to produce proactive rather than reactive law in order to meet future climate change challenges and reach global and regional accords and goals. Ownership is critical to the success of law enforcement. Appropriation is the main threat to coastal management strategies and the conservation, protection, and restoration of ecosystems. The gap between the two can be bridged by integrated planning and the inclusion of the community in the prioritization of pressures and actions. Diagnosing, protecting, conserving, and restoring these ecosystems is made easier through local governance and participatory management involving stakeholders (communities and citizens, local authorities, regional and national governments and their local representatives, economic sectors, non-governmental organizations, science, and universities). This means that more money could be raised for these ecosystems, which would increase people's willingness to pay for them. The combined effort to build holistic coastal ecosystem management is not to be lamented from a regulatory and institutional standpoint, since it is applicable in spite of climate change and contributes to territorial growth.

Conclusions and policy implications

The conservation of tropical blue carbon habitats holds significant significance, not alone for the sequestration of carbon, but also for the safeguarding of various other ecosystem services linked to these ecosystems. Provisioning and regulating services exert a significant influence on society, manifesting in both economic value and the well-being of ecosystems. The preservation of tropical blue carbon ecosystems presents a potential avenue for generating additional money and alleviating debt burdens by use of inventive financial arrangements. This is closely linked to the United Nations Sustainable Development Goals that are being pursued. Incentives for the attainment of these objectives can be derived from various sources such as governance structures, regulatory frameworks, market-oriented approaches, and alternative finance mechanisms. Preserving the ecology and its vitality necessitates international governmental cooperation. The aspect of timing is crucial in guaranteeing the long-term viability of protective measures. Blue carbon habitats are inherently intricate, necessitating a concerted effort to enhance our understanding of their biological aspects. This is crucial in order to mitigate uncertainty surrounding their capacity to sequester carbon. Nevertheless, it is possible that seaweed ecosystems may not effectively control CO_2 emissions and could potentially contribute to CO_2 emissions themselves. In this particular scenario, there exists a tangible possibility of expenditures made in natural climate solutions that may ultimately provide minimal climate benefits.

Furthermore, it should be noted that coastal vegetation systems possess the inherent ability to retain and accumulate significant quantities of plastic and microplastic materials. Moreover, these systems exhibit the potential to serve as valuable feedstock for the production of bioenergy. Diverse ocean ecosystems have the potential to facilitate climate mitigation efforts and conserve carbon stocks. Additionally, they can contribute to the circular economy by utilizing blue carbon for bioenergy production, as well as aid in mitigating plastic and microplastic pollution. For the successful implementation of conservation efforts, it is imperative to involve local inhabitants in the decision-making process. Participation in these ventures yields immediate advantages, including engaging tasks and a steady stream of earnings. In order to effectively merge social protection efforts with actions addressing climate change and economic recovery, it is imperative to establish global coalitions that can facilitate the implementation of prompt initiatives. The implementation of this approach is crucial for the reconstruction and reformation of economies from an ecological perspective. In light of the diverse array of studies undertaken on coastal ecosystems, forthcoming endeavors may prioritize exploring the prospective viability of biofuel generation derived from the biomass yielded by those ecosystems. This measure will contribute to mitigating the escalating concentrations of greenhouse gases and addressing the phenomenon of climate change on a worldwide scale.

Moreover, it is imperative to emphasize the necessity of international collaborative endeavors across many economies in order to ensure the preservation and safeguarding of coastal habitats, hence enabling the continued extraction of numerous advantages from these ecosystems. There exists a pressing demand for actors within the realms of policy, advocacy, and particularly the scientific community to establish linkages between intersecting frameworks. It is imperative that these actors prioritize biodiversity protection based on its intrinsic value, rather than just valuing it for its capacity to sequester carbon. Scientists can assume a prominent position in fostering these discussions by enhancing their engagement in policy debates and effectively communicating their findings in a manner that is accessible to others without specialized expertise. Significantly, scientists have the ability to establish standardized methodologies for assessing, tracking, and documenting carbon accounting across various ecosystems. These methodologies aim to produce transparent and reliable data, employing comparable metrics to evaluate the potential for carbon sequestration, similar to those used for describing greenhouse gas emissions and emission reductions. This enables appropriate comparisons and provides a comprehensive understanding of the concept of additionality. Ocean-based solutions to climate change must possess a high level of resilience and credibility, while also offering various advantages at different levels. Furthermore, these solutions should exhibit the concept of additionality. Hence, the allocation of resources towards substantial and expandable initiatives aimed at preserving, conserving, and restoring blue carbon holds significant significance in effectively tackling the climate issue.

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