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Review

Blue Carbon as a Nature-Based Mitigation Solution in Temperate Zones

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‡ We dedicate this article in memory of Mine Cinar, a prolific economist dedicated to make the world a better place for future generations.

Abstract: Concern for the future requires local steward-led cooperation between natural and social scientists and decision-makers to develop informed and policy-relevant nature-based mitigation solutions, including blue carbon (BC), which can help secure the future. Salt marshes, kelp forests, and seagrass meadows (and to a lesser extent mangroves) are significant BC ecosystems in temperate areas. We discuss the concept of blue carbon stocks and the scientific approaches to building BC stocks considering the variability in local conditions and the co-benefits of blue carbon ecosystems to improve climate change mitigation and adaptation mechanisms. The study examines (1) methods to assess the potential of BC ecosystems and the impact of disturbances, while (2) building relevant policy based on socio-economic assessments of impacted communities. We highlight economic and social approaches to rebuilding BC using financial tools such as blue bonds, development plans, cost-benefit analyses, cross-ecosystem restoration projects, AI and blockchain, and economic accounts of coastal ecosystems, while emphasizing that cutting carbon emissions is more important than (re)building BC stocks.

Keywords: blue carbon; climate change; nature-based solutions; ocean sustainability



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1. Introduction

Reducing atmospheric carbon dioxide levels and emissions is the most efficient way to mitigate climate change. Ecosystems provide services that contribute to this through carbon dioxide (CO₂) removal (CDR) and carbon sequestration. CDR generally refers to anthropogenic activities that deliberately remove CO₂ from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products. CDR occurs after the emitted carbon has entered the atmosphere, but methods differ in terms of removal process, timescale of carbon storage, technological maturity, mitigation potential, cost, co-benefits, adverse side effects, and governance requirements [1–3]. Carbon sequestration, on the other hand, is characterized by the long-term storage of the removed or captured carbon in environmental reservoirs. Both are tools in our sustainability toolbox that can be used to reduce carbon emissions and mitigate climate change [4,5]. If implemented well, these practices can provide a range of co-benefits, but they can also have unwanted side effects, such as biodiversity loss or food price increases. Innovative integration of

artificial intelligence (AI) and blockchain technology has been recently used in carbon credit trading aiming at achieving sustainable emissions reduction [6]. Another option is chemical and geochemical alkalinity enhancement [3], such as enhanced weathering, a proposed method to increase the natural rate of removal of CO₂ from the atmosphere using silicate and carbonate rocks [3,7]. Still, the most promising methods for CO₂ removal from the atmosphere are nature-based, and most are already widely practiced in terrestrial systems, such as afforestation, reforestation, improved forest management, agroforestry, and soil carbon sequestration [8].

Certain marine ecosystems also naturally sequester and store atmospheric carbon and are called blue carbon (BC) ecosystems. Coastal BC ecosystems are mangrove forests, salt marshes, and seagrass meadows, which provide various co-benefits, such as coastal protection and biodiversity hotspots and fish nursery grounds. In temperate zones, salt marshes and seagrass meadows are the most common BC ecosystems. Some mangrove forests can also be found here, but these BCEs are primarily located in tropical latitudes. BCEs are under anthropogenic pressures, however, as forty percent of the world's human population worldwide currently resides within 60 miles of the coasts, and these numbers have increased drastically over the past few decades (from 1.4 billion in 1970 to 3.1 billion people in 2020). The relevance of the coastal zone methodology for calculation of the percentage of people living in coastal zones (quantitative definition of coastal zone) relates to climate vulnerability and varies according to the country as per the Millennium Ecosystem Assessment that uses 100 kilometers from the coast as the distance threshold plus 50 meters as the elevation threshold, whichever was closer to the sea [9]. The field of BC research thus encompasses interdisciplinary fields involving biophysics, socioeconomics, and management.

Temperate zones and BC are central aspects to be examined as there are various definitions of temperate zones. One is that temperate zones are located between the tropical and the polar latitude regions (23.5 deg N/S and 66.5 deg N/S) and experience a wide range of temperatures with species biogeography with precipitation in four seasons. However, a more precise definition is the global climate zonation by Beck et al. (2018) [10], who used Köppen–Geiger climate classification at high resolution for 1980–2016 and forecasts from 2071 until 2100 using 32 climate model projections with scenario RCP8.5. These allow for variations in temperatures and biodiversity and a reclassification of countries which contain both temperate and tropical zones, such as Vietnam.

Much of the balance between BC ecosystems' blue carbon potential and the biogeochemical processes occurring within them are still unclear. For example, certain microbial processes in nutrient and carbon cycling result in the emissions of greenhouse gases (GHGs, e.g., CO₂, methane (CH₄), and nitrous oxide (N₂O)) in BC ecosystems. The warming effects linked to these GHG emissions may thus (in part) counterbalance the reduced warming effects through the sequestration of organic carbon by BCEs. Methane and nitrous oxide emissions from coastal wetlands thus complicate the climate benefit estimates provided by these ecosystems, particularly, because these fluxes largely depend on local conditions, like agricultural nutrient input [11]. In fact, disturbances of and within the sediment in BCEs may alter the biogeochemical processes and skew the balance towards emissions. Thereby, even decades-old carbon stocks become at risk of being emitted as GHGs, emphasizing the importance of preserving BCEs.

With increasing research on the carbon sequestration potential of coastal BC ecosystems in the past decade (see [12]), we have begun to understand that not all coastal vegetated ecosystems are equally efficient in sequestering carbon. Measuring the carbon sequestration potential of these ecosystems requires monitoring of a range of factors influencing vegetation and soil [13]. The former has been shown to incur variation in carbon stocks across BC ecosystems (BCEs) in different latitudes; however, quantifying spatial variability on a regional scale remains a challenge [14]. A recent study on each country's contribution to global BC wealth (calculated with a social cost of carbon) highlighted that while carbon wealth would be expected to depend on the length of the coastline and

the size of the exclusive economic zones (EEZs), uncertainty persists due to variation in available data across different regions of the world [15]. This wealth approach is based on stocks/storage whereas sequestration/removal is another dimension to the carbon emissions. Jennerjahn [16] emphasizes the differences between carbon stocks and carbon accumulation rates, and Williamson and Gattuso [17] point out that carbon accounting is currently unreliable due to variability in carbon burial rates and to errors of measurement. Based on this premise, it is important to consider that BC habitats may have different carbon sequestration potential, which makes it difficult to estimate and compare the carbon potential between projects. Another significant challenge is ensuring emission reductions are permanent [18] and that they will not occur elsewhere in the future.

In addition, while numerous factors can bias evaluations of BC in an area, some ecosystems have been largely overlooked such as macroalgal forests. Most biomass of macroalgae is exported to the open ocean where it may be sequestered in sediments of other (deep) ocean ecosystems. Carbon originating from another ecosystem than where it is sequestered is known as allochthonous carbon, in contrast to autochthonous carbon that is sequestered where it is assimilated into biomass. Such carbon transfers across habitats occur naturally (e.g., macroalgae, or riverine inputs) but can also be caused by disturbances (e.g., sediment resuspension). Yet, the incorporation of this movement in carbon crediting schemes has yet to be achieved [19]. To consider the contribution of allochthonous BC, assessments would require predictive tools to identify how disturbance might impact the movement of carbon to and from relevant ecosystems. The potential of allochthonous BC and the varying effectiveness in sequestering carbon by various coastal BC ecosystems are thus still poorly understood.

There is, however, an urgent need for accurate global BC budgets [7,20], as the current carbon budget is limited. The carbon budget refers to the maximum amount of CO₂ emissions that can be released into the atmosphere by human activities while still limiting global warming to a specific level, and it is the sum of historical emissions from 1850 to 2019 and the remaining carbon budgets from 2020 onwards, which extend until global net-zero CO₂ emissions are reached [8]. The remaining carbon budgets for limiting warming to 1.5 degC, 1.7 degC, and 2.0 degC are 140 PgC (500 GtCO₂), 230 PgC (850 GtCO₂), and 370 PgC (1350 GtCO₂), respectively, based on the 50th percentile of TCRE [3]. At current rates of emissions, it would only take between 8 (2–15) and 25 (18–35) years to emit the equivalent amount of CO₂ for a 67th percentile of 1.5 degC and 2 degC of remaining carbon budget, respectively. Because the current carbon budget is rather limited, and a significant portion of it has already been used, accurate BC stock estimates as well as preserving and increasing BC potential is of utmost importance.

Furthermore, this research paper aims at informing policy recommendations based on the concept of blue carbon stocks and the scientific approaches to building BC stocks considering the variability in local conditions and the co-benefits of blue carbon ecosystems to improve climate change mitigation and adaptation mechanisms. It also addresses methods to assess the potential of BC ecosystems, the impact of disturbances, socio-economic aspects related to impacted communities, financial aspects, development plans, cost-benefit analyses, cross-ecosystem restoration projects, AI and blockchain, and economic accounts of coastal ecosystems, to prove the point that cutting carbon emissions is more important than (re)building BC stocks.

The methodology applied to this paper consisted of desk-top research and specific findings of primary data collection related to natural science, socio-economic aspects, and finance aspects related to the topic.

2. Co-Benefits of Blue Carbon and Their Valorization

The main coastal ecosystems identified for their high carbon sequestration rates are mangrove forests, seagrass meadows, and salt marshes [21] and their additional benefits have been recognized. The BCE consists of biotic (kelp, seagrass, salt marshes, mangroves) and abiotic (water, air, soil) parts that generate many connections and co-benefits for the en-

vironment, for coastal preservation, and human welfare and survival, by sequestering and storing CO₂ from land use activities, since they form carbon sinks with high carbon sequestration. For example, Herr and Landis (2016) [22] estimated that the carbon sequestration by half of the coastal wetlands lost in 2013 would have equaled Spain's carbon emissions that year (0.23 Gt CO₂). The structural complexity created by the foundational vegetation species provides critical habitats for numerous species, and acts as nursery grounds for many species, including those of importance for fisheries. BCEs are thus biodiversity hotspots and essential for sustenance fisheries. Besides, the vegetation and ecosystem structure attenuate wave action and current flow velocity, thereby protecting the coast from erosion and natural disasters [23–25]. Linked to this physical aspect is the deposition of sediment and organic matter within the BCE, contributing to the sequestration of allochthonous carbon, while photosynthesis by the vegetation converts atmospheric CO₂ into biomass, contributing to autochthonous carbon sequestration. The large amounts of biomass and organic carbon produced in BCEs are, however, also integral to marine food webs and ecosystem functioning. BCEs also contribute to ocean health by absorbing excess nutrient and chemical runoff, thereby mitigating eutrophication and pollution [23,24,26,27], and seagrass meadows have been shown to remove (human) pathogens and reduce disease risk in coastal areas [28]. Additionally, they also contribute significantly to various cultural practices (e.g., tourism, education, research) [23,29,30]. It may be clear that BCEs, in addition to climate change mitigation, provide many valuable ecosystem services that also help attain several of the United Nations Sustainable Development Goals (SDGs) such as clean water (SDG6), zero hunger (SDG2), poverty reduction (SDG1), good health and wellbeing (SDG3), and climate action (SDG13). The Sustainable Development Goals adopted in 2015 represent the base for global action for sustainable development and they are composed of building blocks [31] establishing the sustainability parameters for humankind.

Seagrass ecosystems and mangrove ecosystems are critical habitats for marine life. They mitigate destructive effects of ocean acidification on calcifying organisms by a very localized increase in seawater pH (by 0.38 units as reported in [32]), produce large amounts of organic carbon which is integral to marine food webs, eliminate bacterial pathogens improving ecosystem health [28], and retain particles, thereby allowing deposition of pollutants and purification of water around them [23,24].

Salt marshes absorb excess nutrient and chemical runoff, therefore preventing eutrophication [26,27], and protect coastlines by dissipating wave energy and preventing coastal erosion [23]. Natural salt marshes may also grow higher over time, keeping up with rising sea levels and thus protecting communities from this impact of climate change. In addition, they contribute to local fisheries by providing sheltering grounds to smaller juvenile fishes as the oxygen-depleted conditions may prevent larger predators from entering [26].

Given the high value of ecosystem services and co-benefits of BCEs, there is a need for standardized environmental accounting units. Boyd and Banzhaf (2006) [33] argue that consistently defined units are important to measure nature's impact on human welfare. Ecosystem services should thus be defined as public goods and services in an economic context, and the quality of public goods for an ecosystem service market needs to be defined by the respective governance authority. Vallecillo et al. (2019A) [34] discuss the accounting of ecosystem services as still highly experimental and implementation of accounting tables for different ecosystem services are necessary to evaluate the trade-offs among services with a consistent use of accounting methodology throughout the European Union. A way to find a consistent way of accounting for ecosystem services worldwide is the United Nations-supported System of Environmental-Economic Accounting (SEEA) framework's Experimental Ecosystem Accounting that specifically targets the role of ecosystem services. Within this framework, the supply and use of ecosystem services can be measured and transferred in a monetary context. This process might help to reach UN's SDG14 goals about life below water and more specifically targets the Blue Carbon Initiative, starting in the European Union [35].

3. Scientific Approaches to Building BC Stocks

Despite their value for climate action and the many co-benefits, BCEs are in serious jeopardy due to coastal development projects, heatwaves, and pollution. Preventing further damage to these ecosystems is thus highly important as the loss of coastal wetlands reduces blue carbon capture capacity and the carbon stored in the sediment/soil will also be released back into the atmosphere as greenhouse gas emissions. Active restoration efforts realize the success of these projects but costs are variable. Decision support tools and a code of conduct have been developed to optimally design and plan restoration projects [36–39].

Seagrass meadow restoration is costly, and therefore it is crucial to select appropriate sites and ensure that causes of seagrass meadow decline are addressed. The successful injection of seeds directly in the sediment as in the Dutch Wadden Sea [40] is a rather labor-intensive method but is especially useful for restoring or planting seagrasses in areas exposed to relatively strong tidal currents [41,42]. Several plant-based methods also exist, including the use of nurseries to grow seagrass meadows and transplant them to restoration sites, as well as the transplantation of seagrass shoots by anchoring them [43]. Artificial biodegradable structures have recently also become an interesting option, as they can be designed to mimic a given environment, such as the dense root mats of seagrass meadows including the shoots, roots, and rhizomes [44]. As such, it can be ensured that the self-facilitating positive feedback mechanisms [45] in seagrass meadows are present from the beginning, thereby promoting the establishment of meadows. A positive link has been found between the number of seeds or plants used in the initial restoration phase and the survival/growth rates of these plants; in addition, there are indications that there is a density threshold above which restoration success is significantly more likely [46,47]. This contrasts with earlier restoration projects which used low-density seeding/planting based on the assumption that competitive effects among plants had to be avoided and space for growth needs to be provided [48]. Instead, positive self-facilitating interactions among seagrasses need to be considered. Incorporating other interactions in restoration planning may also boost success rates. Bivalve reefs positively influence seagrass meadow development, whereas seagrasses may protect bivalves from pollution with bacterial pathogens [49]. Cross-ecosystem restoration projects may thus provide additional benefits [42]. Besides, the lucinid bivalves living in seagrass meadow sediments harbor microbes that neutralize the toxic sulfides in the sediment, thereby facilitating seagrass survival and allowing meadow expansion. It has thus also been suggested with caution that sediment microbiome manipulation may increase restoration success [42]. Other ecological factors that need to be considered are connectivity between populations that would boost further natural recovery, and the genetic diversity and provenance of plants and seeds used for restoration. These factors are important for improving the resilience of seagrass meadows, particularly in the light of the adverse impacts that climate change may have on seagrasses. Currently, seeds and plants are mostly collected from natural populations nearby. However, mariculture of seagrass [50] may be an alternative source of seeds. Combined with assisted evolution approaches, the stress tolerance of seagrass used for restoration may be experimentally boosted. Once seagrass meadows are restored successfully, the area can quickly expand and rapid recovery of ecosystem services has been observed [51], including improved water quality, sequestration of nitrogen and carbon in sediments, and increased biodiversity and animal biomass.

Salt marshes are estuarine ecosystems primarily found in temperate and subtropical regions and dominated by halophytic and halotolerant plants. They develop particularly well in areas with large tidal ranges but low wave action, and in turbid waters containing fine-grain sediments that settle under the relatively sheltered salt marsh conditions, contributing to the expansion and elevation of these coastal wetlands. These requirements and their development over long periods make restoring salt marshes a long-term project [52,53]. The objective of the restoration projects is important for planning and management, such as restoration scale, vegetation species to be used, and initial restoration works. Non-native plants that prevent salt marsh vegetation establishment may need to be

removed but, most importantly, the hydrological conditions need to be restored/created. Salt marshes are topologically complex ecosystems with creeks and pans. To accelerate salt marsh development and restore hydrology, artificial creeks are constructed yet design and construction of these creeks have often been suboptimal, with limited success [54]. More studies into the characteristics of salt marsh creek development and how these can be replicated are thus needed. Natural recovery of salt marsh vegetation is related to the concept of Windows of Opportunity (WoO), which is defined as “disturbance-free periods of a critical minimal duration directly following potential diaspore dispersal, which allow seedling establishment and can induce a sudden shift to a new persistent vegetation cover” [55]. Sufficiently long WoO are relatively rare, explaining why natural re-establishment of vegetation across the ecosystem may take decades. However, WoO can be created by adjusting the sediment micro-topography as the slightly elevated surfaces provide a more sheltered hydrodynamic environment [56]. This subsequently results in higher recruitment and growth of pioneering plant species [56,57], and the higher density of plants also allows for self-facilitation, further boosting salt marsh development. Self-facilitating conditions can also be generated in restoration practices by mimicking emergent traits, thereby further enhancing re-establishment of vegetation [58]. For example, planting salt marsh grasses in artificial structures that resemble the properties of dense stem and root aggregations (e.g., alter hydrodynamics and allow sediment settlement) improves their survival and growth, thereby improving restoration success rates. Once restoration projects have been completed, monitoring remains of high importance to ensure the salt marshes evolve and disturbances remain limited. However, monitoring programs need to be long-term, as salt marsh development takes decades. In the UK, for example, it has been estimated that it takes roughly 100 years following restoration until restored salt marshes contain equivalent amounts of carbon as natural salt marshes [59]. The potential to harvest or cultivate salt-tolerant crops (such as *Salicornia europaea*) on salt marshes may also provide incentives to boost salt marsh restoration efforts.

Mangrove forests are mainly located in (sub)tropical regions [60], but temperate mangrove ecosystems are present in some locations in New Zealand, southern Australia, South Africa, Japan, Brazil, Bermuda, and Louisiana in the USA [61]. Temperate mangroves have expanded over the last few decades, particularly in New Zealand and Australia, and increasing global temperatures will likely contribute to poleward range expansion and thus BC stock of temperate mangroves. In other regions, temperate mangrove forests have declined, and restoration projects may provide important benefits for building additional BC stocks. Insights obtained from restoration projects in the tropics, where mangroves have declined over decades, but where recent trends look more favorable [62,63], may prove useful. Based on success stories and failures, best practice guidelines for mangrove restoration have been set up [63–65]. One of the main criteria is that the hydrological conditions in the restoration zone should not have been altered or need to be restored prior to restoration and rehabilitation efforts. Many restoration projects have failed due to low survival rates of the transplanted seedlings at restoration sites, which has generally resulted from improper selection of restoration sites where the conditions are unsuitable for mangroves. Restoration policies should be evidence-based [66] and only aim to restore these ecosystems in suitable areas with restoration potential [65,67].

Macroalgae have been largely overlooked as BC stocks despite their potentially large role in carbon sequestration in the marine environment [68]. The reason is, in contrast to the other coastal BC ecosystems, the biomass of macroalgae is generally not sequestered within its native ecosystem, but transported to other angiosperm-dominated coastal BC ecosystems or into the open ocean where it may be sequestered in deep-sea sediments [69]. Seaweed is thus an allochthonous source of BC in other BC sinks. However, their value for BC is now increasingly recognized [69,70], and mass cultivation of seaweeds followed by sinking the macroalgae into the deep ocean for sequestration has turned into a BC business model with multiple companies developing methods and offering services. While promising, this approach still has many uncertainties [71,72]. For example, it needs to

be clarified how quickly this macroalgal biomass is metabolized and thus how much is sequestered versus remineralized again, as well as to what extent seaweed farming may disturb the nutrient cycling and availability in nearby ecosystems impacting natural processes and ecosystem functioning. Still, there are also ethical concerns [72], as seaweed is a high-quality product whose compounds can be used for human consumption, animal feed, fertilizer, and biofuels [71]. Recent cost estimates suggest that sinking 1 Gt of CO₂ costs \$560/tCO₂, whereas using seaweed for products that avoid 1Gt of CO₂-equivalent greenhouse gas emissions might make a profit of \$30/tCO₂ [73]. Overall, this raises questions about feasibility and desirability of sinking macroalgal biomass into the deep ocean for building BC stocks.

In conclusion, conservation and natural recolonization are lower-cost but effective strategies to maintain and build BC stocks. Studies into the restoration potential of locations and local cost-benefit analyses will thus be urgently required to assess where BC stocks can be built most efficiently. Efforts to build BC stocks will also provide many co-benefits, including improved coastal defense, biodiversity values, and food security. These are relevant aspects of the socioeconomic benefits of BC to sustainable development in order to preserve fundamental substratum and vital resources for the present and future generations [74]. However, restoration and conservation efforts on BCEs also require, in addition to financial tools and incentives, the support of local communities, and raising awareness on the importance of coastal wetlands is of utmost importance—this can be done via traditional educational programs but also in more ludic fun ways, such as the Mangrove Restoration Project in the popular game Minecraft [75] to show the effects of forest restoration on biodiversity and carbon capture.

4. Identifying Financial and Technological Tools to Enhance the Role of Blue Carbon

Transitioning to a net-zero carbon economy and attaining the international climate goals require coordinated and articulated action involving the reorientation of fiscal, financial, and monetary policies as well as expenditure decision-making [76,77]. Identifying BC finance depends on the specific environmental mapping and categorization of BCEs. In addition, exposure to climate change impacts BCEs and their C stocks and requires considering the frequency and intensity of stressors, ecosystem resilience, sensitivity, geography, and the magnitude of change [20]. There is a growing understanding of the variety of barriers to financial scaling and obstacles to private sector financing of nature-based solutions. These comprise the high-risk profile of blue carbon projects, small project scale and long-time frames, the magnitude of impacts, institutional complexities, lack of capacity, and the level of engagement with coastal communities [78]. These issues warrant a critical assessment of the suitability of the role of financial tools in enhancing BCEs.

In general, there are four main components of carbon capture and storage implementation measures: capture, transport, storage, and monitoring (including measuring and verification) [79]. The particularity of BC capture and storage is that the first three of these steps take place within the same ecosystem; therefore, sustainable coastal firms and farms only must deal with the last measure of monitoring, and verification processes. We note that the majority of buried carbon in seagrass meadows, salt marshes, and mangrove forests tends to be imported (allochthonous) and there is no/little natural long-term carbon storage in macroalgae forests. Local participation and monitoring are essential. Wylie et al. (2016) [80] compared the carbon financing schemes of Kenya, Vietnam, India, and Madagascar and drew similar conclusions: even if international and national agencies fund the projects, they need to involve local people and their livelihoods, and benefit local communities from their initial stages. In other words, securing funding for the preservation of BC will only be sufficient if local incentives are made clear to all interest groups. The vast carbon storage potential has led to increased interest in coastal restoration projects financed using carbon credits. Carbon crediting schemes are voluntary actions by firms that choose not to decrease their emissions and therefore need to offset them by purchasing vouchers in voluntary carbon markets [81]. An example of it is the Blue Carbon Accelerator Fund

(BCAF) that has connected projects in developing countries with private finance to ensure that global blue carbon ecosystems are protected, sustainably managed, or restored. Carbon crediting schemes have been demonstrated to suffer from systematic over-crediting [82–84]. The need to remove carbon long-term from the atmosphere, the natural emissions of ecosystems, and the accounting of additionality are noted as central issues in other carbon credit schemes [85] and also apply to BCEs.

Along with pricing carbon sequestration benefits, calculating related opportunity (foregone) costs can provide guidance where BC stock building is beneficial. For example, the opportunity costs of coastal BC forestation (e.g., mangrove, seagrass, or salt marsh restoration) or the development of BC macroalgal farms are foregone costs for shoreline development, tourism, and housing. Thompson et al. (2014) [86] calculated the price of the opportunity cost of carbon and examined the cost and benefit of BC farming for losses from the milkfish aquaculture in the Philippines.

BC has large public good benefits and where costs are local, the benefits are both global and local. Thus, these local opportunity costs must be calculated per region—they cannot be calculated globally. Hence, as a policy measure, the protection and development of blue carbon must be incentivized more than the local alternative investments/activities. Locally, the opportunity costs of keeping and expanding seagrass meadows, mangroves, and coastal wetlands will vary by region, country, and development level of the economy and must be assessed per region.

According to the World Economic Forum, “restoring coastal ecosystems could result in a return of \$11.8 billion in carbon finance by 2040” [87], but it is necessary to have a holistic perspective and envisage the broader spectrum of opportunities presented by the transition to a sustainable blue economy and the multiple investment modalities and streams that can add up to blue carbon finance in the long run. The financing sources can be structured into different ways to transform economic sector activities and minimize impacts on coastal habitats, generate blue infrastructure by transforming local infrastructure systems, and develop coastal blue supply chains by minimizing the carbon footprint. The integration of coastal conservation and restoration into banking operations can be by issuance of blue bonds (inspired by the experience of green bonds for biodiversity and sustainable land use) which will contribute to coastal wetland conservation, restoration activities, and the evaluation of metrics of blended finance structures. Apart from these financial tools, the alignment of corporate goals with science-based targets is another crucial role of businesses in mitigating and adapting to climate change [88]. Moreover, different sectors also benefit from the recent advancements in artificial intelligence and blockchain, which makes it possible to predict that the integration of solutions to future environmental sustainability tools will be positively enhanced based on the integration of new operational systems and the decentralization of carbon trading platforms. The use of artificial intelligence and blockchain technology can contribute to enhanced security, efficiency, and transparency of carbon market trading operations as well as scale up sustainability into several industries.

All stakeholders (communities, policymakers, governments, private sector) are important in designing strategies, capabilities, and financial streams toward scaling the blue carbon economy as governments can use blue carbon to achieve their mitigation and adaptation goals under the Paris Agreement. Yet, another point is that although there are many carbon trading systems operating around the globe, they still generally operate independently from each other, involve both high costs and high risks, and are still mainly operated by high-income countries. Low-income regions and countries are thus left at a disadvantage [89].

It is necessary to align policies, regulations, and practices (guided by international agreements and based on common parameters of harmonization) to engage all stakeholders, with their respective institutions, and their legal and economic systems, in actions of local blue carbon co-management [90,91]. Advancing nature finance expertise as well as integrating blue carbon activities into infrastructure projects and coastal planning can create diverse revenue streams. Climate change funds are important mechanisms of resource

mobilization and support to provide long-term financial inflows to address a long-term threat. Transforming the world economy from the current levels of carbon footprint to a net-zero emission economy requires government, industry, and civil society to act in convergence through clear local and global parameters. For this to happen, it is important to promote clear understanding of the specific trade-offs between economic growth and socio-environmental impacts.

5. Social and Governance Approaches to Conserving and Rebuilding BCEs

Blue carbon projects usually affect coastal communities which makes community engagement a crucial component for governance approaches to conserving and rebuilding BCEs. Co-management of blue carbon ecosystems [90] can enhance food security, livelihoods, resilience, and contribute to delivering Nationally Determined Contributions (NDCs) through carbon sequestration and adaptation. Coastal communities should play an active role in project design, implementation, expertise (local knowledge) in assessing existing management practices, and in building scientific capacity. When local communities act as users and stewards to ensure the success and sustainability of blue carbon management, the results tend to be more significant in terms of protection (coastal and marine) and socio-environmental outcomes [92–94]. By incorporating livelihood considerations [80] into conservation and restoration projects for blue carbon, local communities can pursue community-focused goals. The current trend shows a new appreciation of nature-based solutions to climate change; the need for high-quality carbon credits and the momentum created by the new UN global biodiversity framework agreed at the UN's COP15 biodiversity talks in Montreal saw countries agree to protect at least 30% of coastal and marine areas by 2030 ("30 by 30").

In the past decades, the continuous loss of many BCEs indicates that local economic benefits were considered greater for the alternative land use and that there is a need for shifting social and governance approaches, often termed 'transformative governance' [95–97]. These studies indicate the need for governance that can achieve transformative change based on the recognition that human connection to nature is fundamental for biodiversity protection [98,99] and that justice and conservation are intertwined [100,101]. Community-based management [88] proved to be effective for blue carbon projects in mangroves of Mekong Delta, Vietnam. This project conserves and restores the mangrove ecosystem at the same time it supports organic shrimp farmers to obtain the organic certification and higher profits from the produce as well as funds from carbon financing. At the same time, the coastal ecosystem services contribute to nursery, feeding, and spawning ground for fish juveniles and improve the fish stock in the adjacent sea [80].

Biodiversity conservation and protection of BCEs interacts in complex ways with ecosystem use. Conservation creates trade-offs for different societal actors [102], limiting feasible pathways for just and equitable protection of BCEs. Biodiversity conservation can create new injustices or exacerbate existing ones, for example, when access prohibitions disproportionately affect the poorest populations [103]. Thus, where protection strongly affects local communities, they can be the strongest partners or fiercest opponents of ecosystem conservation. Inversely, structural injustice can facilitate biodiversity loss, such as when conservation colludes with politics in ocean grabbing [104]. In practice, the past poor management and monitoring of BC initiatives [105] call for approaches in partnership with and led by local communities [106]. Approaches built on the principles of blue justice, i.e., environmental justice related to the ocean, can support identifying opportunities for just and equitable protection of BC ecosystems.

Success of restoration depends on site suitability (biophysical factors) as well as local stewardship where the latter can lead to transformative governance of BCEs. Positive outcomes for well-being and conservation are reported when local stewards, including local communities and Indigenous people, have a leading role in marine conservation. Inversely, external control is associated with negative social outcomes and relatively ineffective conservation [107]. Best practices for identifying policy-relevant mitigation solutions

are led by local stewards and are informed by natural and social scientists, interest groups, and decision-makers. Therefore, transformative governance is based on the principles of inclusion of diverse voices and recognition of different knowledge systems [101]. First, diverse voices can be included through co-production and other transdisciplinary methods, including citizen science, action research, dialogue, and focus group discussions [108]. At the same time, inclusive BC conservation practice and ocean science can increase the connection of local communities and, in particular, youth to nature [109]. Second, recognizing different knowledge systems requires acknowledging that BCEs are assessed, and values are assigned differently by local stewards than scientists [110]. In conclusion, steward-led BC conservation challenges the existing paradigms of the superiority of scientific knowledge and is more likely than non-inclusive approaches to provide informed and policy-relevant BC conservation strategies.

6. Policy Proposals, Conclusions, and Recommendations

While BCEs absorb and provide long-term storage of carbon from the atmosphere, biophysical processes and disturbances may cause the release of significant amounts of carbon stored in BCEs, thus making future emissions a real and looming possibility. Coastal systems may thus switch from being a carbon sink to a carbon source, emitting GHGs, such as CO₂ and methane. Cutting down emissions will have a direct and permanent impact on the concentration of atmospheric carbon and cannot be replaced by protecting and rebuilding BCE stocks [111]. It is, however, important to highlight recent findings on the asymmetry of the climate-carbon cycle: the removal of CO₂ from the atmosphere needs to be greater than an equivalent emission to reach similar atmospheric carbon concentrations [112]. In other words, given the uncertainty of measurements and related costs, cutting down emissions is more impactful than relying solely on carbon sequestration.

Another major issue concerns the choice of pathways to develop better BC practices. Academic and scientific research can guide policies by pointing to places (1) where the required costs for mitigation remain relatively small, (2) where the successful outcomes last long, (3) where policies are undertaken with knowledge of all local costs/benefits, (4) where mitigation can balance equity concerns and reduce poverty, and (5) which are led by local stewards.

Similarly, in economic and financial terms, the risks of manipulated information to benefit one party, speculations by major players, asymmetric information between parties, and erroneous conclusions can skew the debate away from climate change mitigation. Successful blue carbon projects will depend on actual action and clear timelines consisting of practical implementation of sustainable community-based management, the combination and sharing of knowledge systems, a high-quality carbon credits system, and scaling up finance of blue carbon activities and their integration into infrastructure projects and coastal planning. It is also important to minimize monitoring, reporting, and verification costs, and to develop more advanced biogeochemical models combined with remote sensing methods to predict, monitor, and verify greenhouse gas emissions, sequestration, and stock changes. In order to scale up solutions, stakeholders should work with artificial intelligence and blockchain experts to incorporate technological advancements into creating new pathways for carbon reduction and market efficiency. Finally, these are measures that will reflect transformative governance since they are aligned to the goals of the UN global biodiversity framework.

Most of the world population lives in temperate zones where anthropogenic climate change and habitat destruction are greater than other less-populated areas. BC in temperate areas, especially their destruction from their present-day status, is an important issue for the global community. Restoration of BCEs is essential but more essential is the measured carbon emissions reduction.

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