Coastal mangroves. Credit: hds, Wikimedia Commons.

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International cooperation and carbon peaking and neutrality in Island Countries and Regions: The value of blue carbon

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ABSTRACT

Most scenarios illustrating the pathways to the long-term temperature goals of the Paris Agreement, which aims to avoid dangerous warming of more than 1.5°C to 2.0°C, are based on rapid

and transformative reduction of anthropogenic GHG emissions coupled with increasing large-scale carbon sinks: carbon capture, utilization, and storage. The combined effects of these efforts are expected to achieve the ambitious goals of carbon peaking and neutrality by 2030 and 2060 respectively. Globally, most efforts have focused on reducing GHG emissions, and anchoring carbon in forests, while very little attention is afforded to the most efficient pathway to fix and store carbon—blue carbon. Given their unique terrestrial footprint and vast marine environments, island countries and regions are well positioned to support carbon peaking and neutrality. Therefore, this chapter will explore the salient social and ecological challenges and opportunities of blue carbon in the context of sustainable development and climate change.

INTRODUCTION

The historic United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP21) meeting in Paris in 2015, dubbed the Paris Agreement, aims to limit global warming to below 2°C, and ideally below 1.5°C, by the end of the of this century to avoid irreversible climate change (Masson-Delmotte et al., 2018). Despite significant progress in emissions reduction, climate ambitions around the world remain inadequate to meet the challenge of our climate crises. In fact, nearly a decade after the adoption of the historic Paris Agreement, the most recent ensemble of Nationally Determined Contributions (NDCs) show that globally greenhouse gas (GHG) emissions continue to rise, putting the planet on a trajectory of roughly 3°C above preindustrial levels by the end of the 21st century (see Figure 1) (Kikstra et al., 2022; UNEP, 2022). This represents emissions gaps of 20.3–23.9 $GtCO_2eq$ (UNEP, 2022). Emissions gaps are the differences between emission levels reported by the collective NDCs and the mean emission levels of modelled mitigation pathways consistent with limiting warming to 1.5°C to 2.0°C. It is important to note that the main drivers are rising affluence, which is evident in emissions coupled to international trade, and population growth (Kikstra et al., 2022). Under this future, there would be wholescale devastation of ecosystems and the crucial services they provide, to include unquantifiable and irreparable loss of biodiversity. Additionally, mass population migration (particularly in the global south) the resulting climate refugee crisis, and associated injustice and inequity of staggering proportions can be expected (Podesta, 2019).

The 26th UNFCCC Conference of the Parties meeting (COP26), held in Glasgow (The Glasgow Climate Pact), reemphasizes current progress and future efforts needed to limit dangerous climate change (Wadsworth, 2021). The global ambition of attaining net-zero emissions — where the total anthropogenic GHG emissions is equal to that of the total amount of GHGs removed from the atmosphere, is paramount to attaining the long-term temperature goals of the Paris Agreement (Lebling et al.,

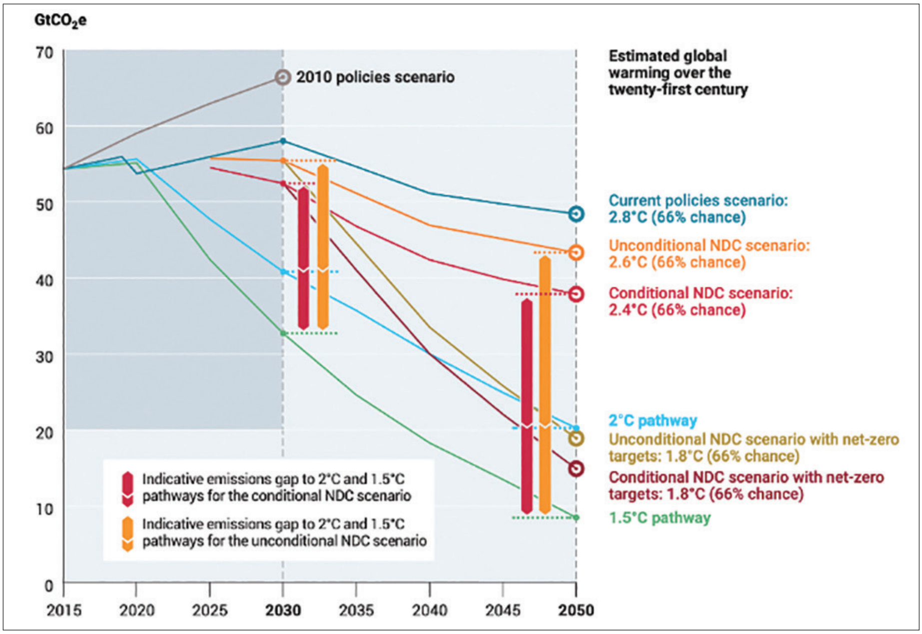

Figure 1: Warming and GHG emissions projections to 2050 ($GtCO_2eq$). Source: UNEP, 2022.

2023). Net-zero emissions are reached when all anthropogenic emissions are in equilibrium with carbon dioxide removal (CDR) (Lebling et al., 2023). To this end, most scenarios illustrating the pathways to the long-term temperature goals of the Paris Agreement require rapid and transformative reduction of anthropogenic GHG emissions coupled with increasing large-scale carbon sinks: carbon capture, utilization, and storage. For instance, it is estimated that transformation of the global energy system across all sectors require widespread (approximately 90%) implementation of renewables for electricity generation by 2050 to achieve carbon neutrality (Minx et al., 2018). However, considering this paradigm shift, it begs the questions, whether and to what extent is this truly net-zero. To be truly net-zero, the emissions generated from the extraction of raw materials, processing, logistics, operation, and associated infrastructure of renewable technologies must be offset by the reduction of GHG emissions achieved by clean power generation, which bypasses the use of conventional fossil fuel combustion (Wadsworth, 2021).

Another issue that remains high on the list of priorities to be resolved is that of the environmental impacts of the large-scale manufacture and implementation of renewables. Similarly, major concerns surrounding social safeguards, including water security and the rights of Indigenous peoples (IPs) and local communities (LCs) have not been adequately addressed (Wadsworth, 2021). Further, GHG emissions are strongly coupled to the development pathways of all countries, regardless of development status. Therefore, all aspects of climate change mitigation including problems definition, solutions determination, interventions design, execution and monitoring must take place within the context of achieving the Sustainable Development Goals (SDGs), the primary instrument that frames the international policy context (Kikstra et al., 2022; Steven et al., 2019). Clearly, the scope of the solutions required to address the magnitude and urgency of the climate problem coupled with numerous emerging concerns, and the limited window of opportunity to deliver GHG emissions reductions and carbon removal compatible with the Paris Agreement must include a mix of technological and nature-based solutions. Undoubtedly, the considerations given to the weighting of this blended approach should be a function of the local and regional contexts.

Currently, much of the emphasis on the global response to the climate crisis has focused on reducing GHG emissions using technological carbon removal and by anchoring carbon in forests (Boehm et al., 2022; Kikstra et al., 2022; UNEP 2022). However, greater ambition in action and support is needed to strengthen the global response to the threats of climate change in the context of sustainable development and the eradication of poverty (UNFCCC, 2023). In this regard, greater attention is needed to mainstream the conservation and restoration of blue carbon ecosystems, which arguably provide the most efficient pathway to climate resilience. Given their unique terrestrial footprint and vast marine environments, Small Island Developing States (SIDS) are well positioned to support global carbon peaking and neutrality by the middle of the century by leveraging their coastal blue carbon assets (Mead, 2021). Despite their diminutive size, collectively, SIDS have been known to shape global significant policies and action. For instance, for more than a decade, SIDS have advocated for the establishment of the 1.5°C as the upper limit for global average temperatures increases due to their increasing vulnerability to the impacts of climate change. Therefore, in addition to a brief assessment of the state of current emissions reduction pathways, the primary objectives of this chapter are to explore the salient feature (opportunities and challenges) of the conservation and restoration of coastal blue carbon ecosystems within SIDS as a pathway consistent with the long-term temperature goals of the Paris Agreement.

TO BE TRULY NET-ZERO, the emissions generated from the extraction of raw materials, processing, logistics, operation, and associated infrastructure of renewable technologies must be offset by the reduction of GHG emissions achieved by clean power generation, which bypasses the use of conventional fossil fuel combustion (Wadsworth, 2021).

TECHNOLOGICAL CARBON REMOVAL

There is high scientific agreement that, in addition to emissions reduction, carbon dioxide removal (CDR) will be needed to limit global warming to 1.5°C (Kikstra et al., 2002). It has further been agreed that to attain this long-term temperature goal will require reaching net-zero emissions by 2050 (Kikstra et al., 2022). Critically, CDR is technologically driven and still largely at an embryonic stage in both development and deployment, which means that the anticipated large-scale benefits remain distal (Minx et al., 2018). At best, our knowledge of technological carbon removal remains diffused and incomplete. This is evident as there is very little guidance on how countries should incorporate CDR technologies in their national climate plans, as well as how these plans can facilitate the scaling up of technological CDR in an equitable and sustainable manner (Lebling et al., 2023). There are also numerous challenges and uncertainties about the scale of CDR needed, who will cover the costs, who will benefit, and the structure of a comparable monitoring, reporting and verification ecosystem (Minx et al., 2018).

Another area of emerging concern associated with CDR is mitigation deterrence — the idea that the current physical and financial emphasis on CDR to provide large-scale mitigation benefits may divert attention and investments away from the need to rapidly reduce emissions (Honegger, 2023; Minx et al., 2018). Similarly, issues related to equity and the development of a suitable measurement, reporting, and verification (MRV) ecosystem remain largely unresolved. Overall, a broader understanding of the roles these technologies and long-term mitigation pathways play in the stabilization of global temperatures is required. At the surface, the benefits, and opportunities of accelerating sectoral transitions (from energy to agriculture) at scales to attain a more sustainable future are significant. However, careful attention should be given to the technological costs, co-benefits and risks, innovation, and diffusion strategies, as well as barriers (including exacerbating existing socio-economic inequalities) to achieving the required emissions reduction within the closing window of opportunity (Minx et al., 2018; Phyland et al., 2022). A common school of thought is that key issues surrounding the economic cost of implementation: alternate livelihoods and reskilling of those affected; social safety nets; and economic diversification must be resolved if we are to achieve just and equitable transitions. Recommendations on possible solutions to these concerns are beyond the scope of this chapter but can be found elsewhere (e.g., Minx et al., 2018; Lebling et al., 2023).

LAND-BASED CARBON REMOVAL

Globally, an increasing number of policies and national plans have focused on land-based carbon removal as a more cost-effective option of climate change mitigation (relative to the decarbonization of the energy and transport sectors) *en route* to achieving the long-term temperature goals of the Paris Agreement. In fact, it is widely propagated that well managed land provides the only feasible option to enhance removals of carbon dioxide at scales that can lead to carbon neutrality (Arneth et al., 2019; Kikstra et al., 2022). Moreover, these natural capitals also provide a range of co-benefits (e.g., soil and biodiversity conservation, and water cycling) that intersect with national, and sustainable development goals. Critically, it is important to emphasize that, beyond the social and environmental benefits of land-based carbon removal, it should not be viewed as a simple solution to achieving global emissions reduction targets, and therefore should not overshadow other pathways that are likely to provide even more significant benefits. Furthermore, the current proposals for land-based carbon removal do not adequately address numerous social and environmental safeguards (Dooley et al., 2022).

THE LAND GAP

While the benefits of land in climate change mitigation are many, it should not be seen as the panacea of our current and future climate challenges. When carefully dissected, several critical challenges surrounding land-based mitigation are exposed. Here, some of these challenges and potential implications are briefly discussed. Extended discussions around these issues can be found elsewhere (Kikstra et al., 2022). One of the primary barriers surrounding land-based mitigation is that, at the global scale, the extent of land needed to meet the proposed biological removal of carbon in national pledges is approximately 1.2 billion hectares — close to the extent of current global crop land. This highlights an unrealistic overreliance on land-based carbon removal with potential consequences for livelihoods, land tenure security, food systems and ecosystem functioning (Kikstra et al., 2022).

Of the almost 1.2 billion hectares of land prioritized for mitigation, approximately 551 million hectares will be the subject of various conservation and restoration activities with co-benefits for climate change, biodiversity conservation, and sustainable development (Kikstra et al., 2002). However, the extent of these benefits largely depends on proper carbon accounting, land rights and livelihoods of IPs and LCs, and transformation of our current food systems (Dooley et al., 2022). On the issue of carbon accounting, current assumptions tend to ignore the variability associated with carbon stock losses as a function of ecosystem health. Secondly, IPs and LCs with land tenure security have been shown to outperform both governments and private landholders in many aspects of climate change, biodiversity, and sustainability (Dooley et al., 2022). Despite this, Indigenous and local civil groups remain largely unrecognized for their roles at the local, regional, and international scales (Dooley et al., 2022). Our current global food system is responsible for approximately one-third of all global emissions, making it one of the largest sectoral contributors. At a disaggregated level, the unsustainable use of synthetic nitrogen fertilizers in crop production is the primary sources of land-based nitrous oxide (N_2O) emissions. Similarly, livestock and rice production are responsible for nearly 36% of global methane emissions (CH_4). Despite the recent progress made with land-based mitigation measures, it is equally evident that these approaches remain manifestly inadequate as net anthropogenic CO_2 emissions from land use change and forestry was an estimated 11% or approximately 7 $GtCO_2eq$ of global emissions in 2019 (Blunden et al., 2022; Kikstra et al., 2022). Further, agricultural land use remains the primary driver of biodiversity loss and land degradation globally (Kikstra et al., 2002).

BLUE CARBON AS A MITIGATION LEVER

Revised estimates from scenarios illustrating pathways to limit global warming to 1.5°C are based on negative emissions with a cumulative value of 400–1000 Gt CO_2eq for the remainder of the century (Kikstra et al., 2022; Masson-Delmotte et al., 2018; Minx et al. 2018). The speed and scale of the mitigation efforts required to avert a climate catastrophe, coupled with, for example, multiple feasibility and sustainability limitations for land-based (and other) climate change mitigation pathways, have led to an increase in the popularity of coastal vegetation and their management as a mitigation lever (Masson-Delmotte et al., 2018). Globally, coastal vegetation covers less than 2% of the total area of the ocean, but they can capture atmospheric CO_2 up to 55 times the rate of tropical rain forest. More importantly, this carbon can remain buried in sediments for centuries, relative to that stored in tropical forests, which is on a decadal time scale (IUCN, 2017; Lebrasse, 2022; Ouyang & Lee, 2020). A synthesis of the state of climate action suggests that on average, land-based pathways could provide mitigation potential of 5.8 $GtCO_2eq$ per year at a cost of up to \$100/tCO_2eq from 2020 to 2050 (Blunden et al., 2023; Kikstra et al., 2022). However, the consensus is that this remains insufficient, with anthropogenic CO_2 emissions from land use, land-use change and forestry reaching almost 6.6 $GtCO_2eq$ in 2019, or approximately 11% of global greenhouse gas emissions (Boehm et al., 2022; Kikstra et al., 2022). When considered together, investments in the conservation and restoration of blue carbon ecosystems as a mitigation lever is favoured (KPMG, 2022).

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The carbon sequestered by tidal vegetated wetlands (mangroves and salt marshes) and seagrass beds is referred to as coastal blue carbon. However, unlike terrestrial ecosystems, which are likely to become saturated with carbon on a decadal or centennial time scale, blue carbon ecosystems continuously accrete carbon and are not constrained by such phenomenon. Traditionally, blue carbon is stored primarily through

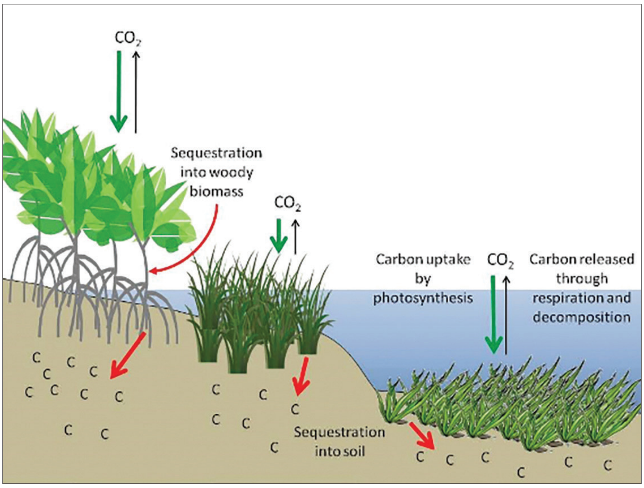

Figure 2: Blue carbon ecosystem (from left to right: mangroves, tidal marshes, and seagrasses), highlighting a simplified mechanism of carbon sequestration through carbon uptake by photosynthesis (green arrows) and long-term storage into woody biomass and soil (red arrows) or respired (black arrows). Source: Howard et al., 2017.

a combination of physical carbon solubility pump (dissolution of atmospheric CO_2 in seawater), biological pump (photosynthetic uptake of CO_2 by plants and subsequent deposition to the seafloor), and the marine carbonate pump (uptake, conversion, and release by marine organisms) over time (see Figure 2) (Simon et al., 2020; Wang et al., 2021). Although current estimates of carbon sequestration are not satisfactorily constrained, on average, the annual carbon burial per square kilometre of coastal wetland is believed to be approximately 0.22 Gg of carbon or 3.36×10^5 L of CO_2 emitted from gasoline combustion (Wang et al., 2021), rendering blue carbon ecosystems ideally suited for nature-based solutions and climate governance (Delgado et al., 2020). Approximately half of the carbon stored by living marine organisms is in the coastal blue carbon ecosystems (Bertman et al., 2021; Hilmi et al., 2021). Blue carbon ecosystems provide nature-based climate solutions in two ways: the first of which is through conservation leading to a reduction in GHG emissions arising from the degradation and loss of these ecosystems; and secondly through restoration, which increases CO_2 drawdown and its long-term storage (Williamson & Gattuso, 2022).

RETHINKING MITIGATION IN THE CONTEXT OF COVID-19 AND OTHER CRISES

The onset of the acute public health crisis triggered by the COVID-19 pandemic has undoubtably resulted in strong macro-economic headwinds with adverse implications for climate financing. On the other hand, government policies during the pandemic have significantly altered the demand for energy resulting in daily global CO_2 emissions reduction of approximately 20% (Figure 3). Although the exact impact of the COVID-19 pandemic on the development strategies of SIDS (including emission reduction targets) remains to be quantified, what is certain is that mitigation efforts must now be addressed not only in the context of the SDGs, but also that of the post-COVID-19 era. It is unlikely that the COVID-19 induced restrictions would have resolved our climate issues, but almost certainly will exacerbate common social and economic vulnerabilities that were already evident in climate matters.

To make a bad situation worse, the geopolitical upheaval caused by the Russia–Ukraine conflict has caused a reversal of key global alliances, with disproportionate indirect effects for food and energy security as well as climate action toward net-zero emissions. As a good illustration, the disruption of gas supply from Russia to other parts of the world has prompted a significant reversal to coal-fired power plants in many countries/regions with potentially significant long-term environmental consequences (Kuzemko et al., 2022). Against this background, any attempt to achieve the long-term temperature goals of the Paris Agreement requires deep transformation that deliver GHG reductions and carbon removals (at speeds and scales) across all sectors within this decade (Minx et al., 2018; UNFCCC, 2023).

Therefore, any approach by SIDS (and the rest of the world) towards achieving the 2030 development agenda, national development plans, and the long-term temperature goals of the Paris Agreement, must be part of an integrated framework that considers energy transformation, economic diversity, and blue carbon. One of the remarkable attributes of SIDS is their ability to collectively influence global outcomes to address climate-related challenges. An exemplar outcome is the role of SIDS in lobbying for the need to keep global temperature rise to below 1.5°C and culminating in the IPCC special report on the impacts of global warming of 1.5°C (Mead, 2021).

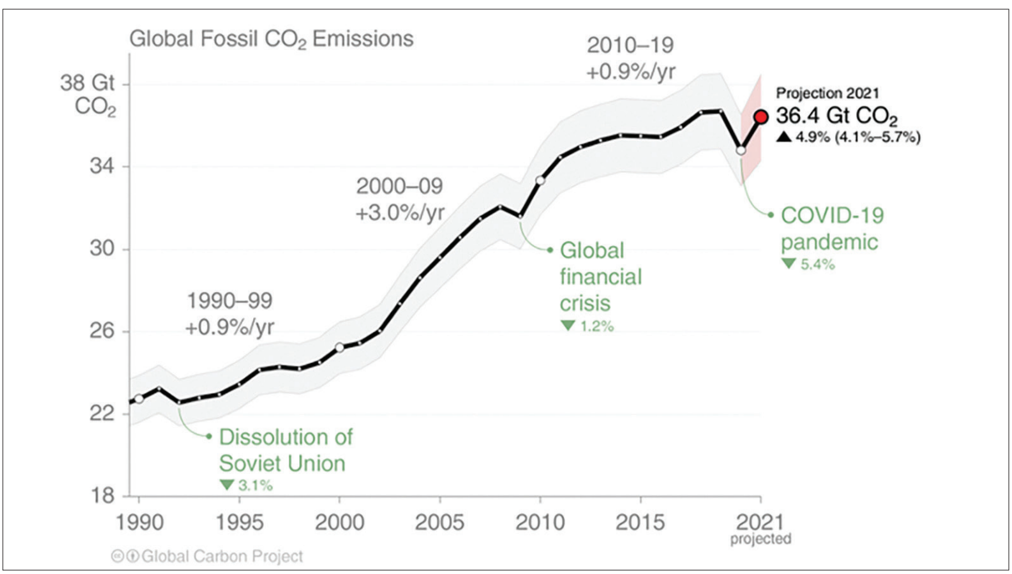

Figure 3: Multi-year trends in global fossil CO_2 emissions. Source: Friedlingstein et al., 2022.

SMALL ISLAND DEVELOPING STATES (SIDS)

Small Island Developing States (SIDS) represent a collection of 58 small islands and low-lying coastal developing countries and territories within the equatorial regions of the Caribbean, Atlantic, Indian, and Pacific Oceans and are home to approximately 65 million inhabitants and sustain roughly 20% of global biodiversity. Some SIDS, such as Haiti, Comoros, and Tuvalu, are classified as least developed countries (LDCs) (Delgado et al., 2020). SIDS and LDCs are generally characterized by similar developmental challenges, including resource constraints, vulnerability to natural disasters and external shocks, and high dependence on international trade and aid (FAO, 2014; McHarg et al., 2022). Despite a combined contribution of less than 1% of global carbon emissions, SIDS, by virtue of their size, geographic location, and economies of scale, remain among the most vulnerable to the cascading and compounding impacts of climate change, which often result in economic and environmental devastation, and the loss of life (Mead, 2021). Moreover, the heavy reliance of SIDS on food and energy imports, as well as revenues from tourism products, has increased their vulnerability to external shocks from multiple and simultaneous crises. In fact, there is strong agreement and high confidence that climate shocks have significantly eroded many developmental gains in some of the most resource constrained parts of the world (Birkmann et al., 2022). For instance, in some jurisdictions, abnormally warm weather coupled with severe drought act a drivers of food crises and other social discontentment. Elsewhere, massive flooding and landslides caused by unusually heavy rainfall have been reported to be the source of major devastation in SIDS (Meira & Philips, 2019). Although these phenomena have become more global in nature, SIDS remain disproportionately impacted due to their inherent vulnerability (FAO, 2014).

THE VALUE OF BLUE CARBON IN SIDS

Although SIDS are generally characterized by limited landmass, an increasing number of states are now self-identifying as “large ocean states” in reference to the vast oceans and resources within their domains — exclusive economic zones (EEZs) (Mead, 2021). It is estimated that through these EEZs, SIDS account for roughly 30% of all oceans and seas. This translates to 666,110 km^2 in EEZs relative to a combined landmass of 24,111 km^2 (UNDP, 2017). As a function of their geography and environment, SIDS are generally well known for their diverse blue carbon ecosystems, namely mangrove, seagrasses, and saltmarshes. In general, blue carbon ecosystems store significant quantities of carbon. For instance, mangroves have been shown to store significantly more carbon per unit area than that stored in terrestrial ecosystems (Figure 4). Similarly, seagrasses and saltmarshes also exhibit significant carbon sequestration potential. More importantly, having a thorough understanding of the carbon dynamics (carbon stocks and sequestration rates) of these ecosystems is essential for quantifying their

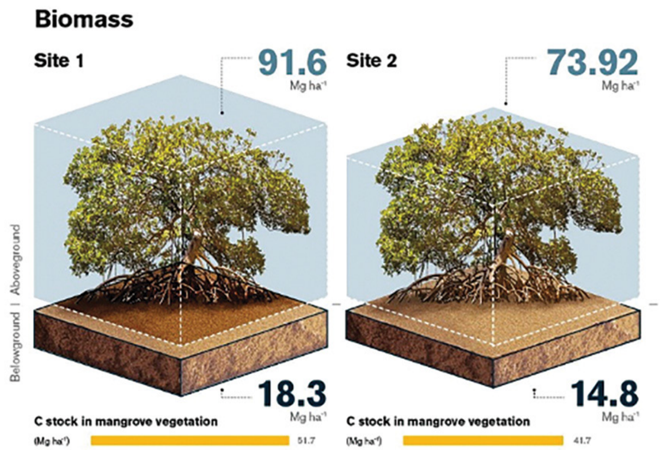

Figure 4: Illustration of carbon sequestered in mangrove forests. Source: Beck et al., 2019.

climate change mitigation potential (McHarg et al., 2022).

Beyond their climate change mitigation potential, these carbon-rich ecosystems provide a raft of critical co-benefits, including habitats for marine species, enhanced coastal resilience (Figure 5) through protection from erosion and storm damage, enhanced fisheries productivity, water quality regulation, cultural and religious significance, while offering copious livelihood opportunities for scores of local communities. Given their scale and function, protecting existing ecosystems and restoring degraded ones provides mitigation potential with synergies for adaptation, the 2030 developmental goals, and bolstering biodiversity conservation. Such restoration has been described as a 'no regrets' mitigation option (Arneth et al., 2019; Bindoff et al., 2019). Reducing conversion of blue carbon ecosystems avoids emissions from above and below ground biomass and soil carbon through avoided degradation. Critically, broader societal recognition roles and potential is crucial for building broader support for blue carbon initiatives and fostering integrated coastal zone management in SIDS.

BLUE CARBON PEAKING AND NEUTRALITY TARGETS IN SIDS

Blue carbon's role in achieving carbon peaking and carbon neutrality

The term carbon peaking refers to attaining maximum carbon emissions before initiating a decline. On the other hand, carbon neutrality aims to balance the emissions of GHGs with their removal from the atmosphere (He et al., 2022; Wang, 2021). While several low carbon initiatives have been proposed and/or are in varying stages of implementation, the proliferation of nature-based approaches as part of the portfolio of carbon peaking and carbon neutrality has not kept pace with the convention (Yi et al., 2021). Given their carbon sequestration potential, blue carbon ecosystems can be

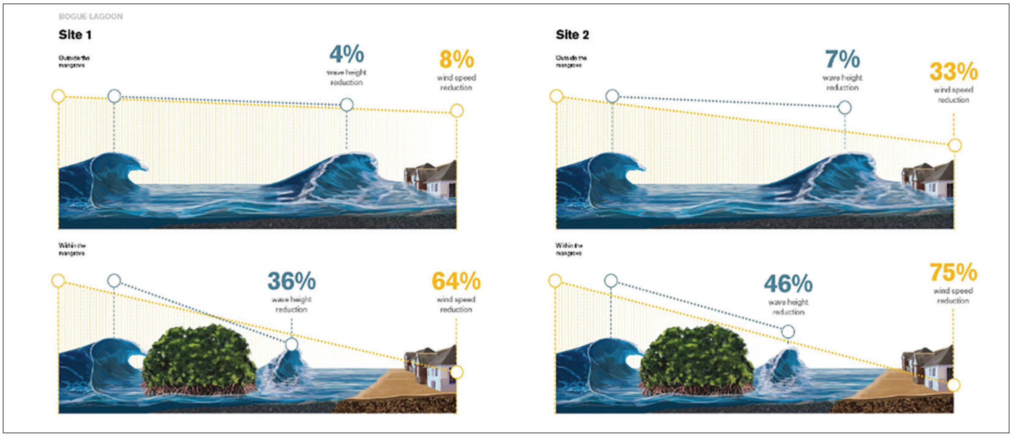

Figure 5: Model of coastal protection by mangrove forests. Source: Beck et al., 2019.

leveraged by SIDS as part of their carbon peaking and carbon neutrality framework by sequestering and storing substantial amounts of carbon in a stable form. These living carbon sinks can also help to offset emissions from various sources. Therefore, integrating blue carbon conservation and restoration into climate change mitigation options can substantially assist SIDS to achieve their carbon peaking and carbon neutrality goals in a sustainable and environmentally sound manner. To achieve this, robust policies and institutional frameworks must have cornerstone foundations in any effort to integrate blue carbon into national climate strategies. It is also imperative for SIDS to work on developing comprehensive legal and regulatory frameworks that give recognition to and incentivize the conservation and restoration of blue carbon ecosystems. These efforts would also benefit from strengthening collaboration among the public and private sectors, NGOs, local communities (including Indigenous groups), and international organizations.

FINANCIAL MECHANISM FOR BLUE CARBON CONSERVATION AND RESTORATION IN SIDS

International protocols such as the Paris Agreement of the UNFCCC, the United Nations Sustainable Development Goals (SDGs), and the Biodiversity Conservation provide the framework for promoting cooperation on ending hunger and the triple helix of climate change (mitigation, including blue carbon; and adaptation), biodiversity loss, and environmental degradation. These agreements can be leveraged by SIDS (individually or collectively) to access appropriate funding, technical assistance, and capacity support to undertake blue carbon initiatives. Access to financing is imperative for the implementation of blue carbon initiatives in SIDS. To this end, major international funding mechanisms such the Green Climate Fund (GCF) and the Global Environmental Facility (GEF) are available to provide support for blue carbon conservation and restoration projects. Other funding mechanisms include, but are not limited to, the World Bank, The Inter-American Development Bank (IDB) and GIZ (The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH). Additionally, public-private partnerships and carbon markets are also keyways of supporting blue carbon initiatives. Similarly, technical assistance and capacity building are an indispensable component of any international cooperation on blue carbon. Some of the benefits of technical assistance and capacity building include cross fertilization of experiences, best practices, and scientific advancements in blue carbon conservation and restoration. Furthermore, exchanges among scientists, policymakers, and practitioners can facilitate highly successful implementation of blue carbon projects through innovative approaches.

CHALLENGES AND OPPORTUNITIES IN SIDS BLUE CARBON ARCHITECTURE

Efforts to tap into the massive mitigation potential of blue carbon ecosystems as an option to limit global warming to 1.5°C must be supported by immediate action to protect, restore, and sustainably manage these natural assets (Figure 6). At the very extreme end of the spectrum, some of these efforts are significantly off track, while others are even heading in the wrong direction and therefore require a change of course (Boehm et al., 2022).

Technical and methodological challenges

Some of the primary issues affecting the reliability and climate cost-effectiveness of blue carbon ecosystems include: high variability in carbon burial rates; errors in the determination of carbon burial rates; lateral carbon transport; fluxes in CH_4 and N_2O; carbonate formation and dissolution; variability in future climate change and vulnerability to non-climate factors (Williamson & Gattuso, 2022). In relation to the variability of carbon burial rates in blue carbon ecosystems, numerous biological, physical, and chemical factors interplay to impact primary productivity, sedimentation, decomposition, and stabilization, resulting in highly variable site-specific estimates. Carbon burial inventories have also been known to suffer from errors due to poorly constrained bioturbation and microbial decomposition rates (Williamson & Gattuso, 2022). Overall, the high yet variable carbon stocks result in a range of estimates of the global mitigation potential of these ecosystems (Bindoff et al., 2019). Therefore, as a climate change mitigation option, it is important to decipher the source of the carbon buried in the sediment, followed by the exclusion of carbon from terrestrial or atmospheric sources (allochthonous), or other marine ecosystems (autochthonous). This is because the long-term storge of allochthonous carbon is likely to have occurred regardless (Rofner et al., 2017).

The anaerobic conditions of blue carbon ecosystems created by tidal inundation is not only responsible for their long-term carbon storage ability, but also supports

Figure 6: Sections of a 3500 hectare of degraded mangrove forest, which is slated for restoration under the South Clarendon (Jamaica) Blue Carbon Restoration Project funded by the IDB (photo credit: Adrian Spence, 2021).

the production and release of CH_4 and N_2O, two of the fastest rising GHGs with higher global warming potential (GWP) than CO_2 (Kikstra et al., 2002), and the potential to erase the climate gains of carbon burial within these ecosystems depending on salinity (Kroeger et al., 2017; Williamson & Gattuso 2022). However, given an atmospheric lifespan of roughly 12.5 years, the higher GWP of CH_4 is more important in medium-term climate governance such as the 2030 and 2050 climate goals, rather than global radiative flux budget in 2100. Other risks associated with the mitigation potential of blue carbon ecosystems include uncertainties under future climate scenarios, with emphasis on coastal squeeze – where coastal wetlands may be lost if upland area is not available for migration due to rising sea levels, warmer sea surface temperatures and ocean acidification (Bindoff et al., 2019). One thing for certain, is that our understanding of the implications of variability in future climate remains at a comparatively early stage (Rogers et al., 2019).

Even under the most optimistic future — where the long-term temperature goals of the Paris Climate Agreement are met — the issue of the vulnerability of blue carbon ecosystems to non-climatic factors remains nuanced. For instance, conflicts with other land use in coastal zones for agriculture, and fisheries, recreation, industry, and settlements are likely to impact conservation and restoration endeavors, and the opportunity costs associated with such activities (Susman et al., 2021). This is of special significance in the context of SIDS that already exhibit an overreliance on coastal ecosystems for their economy, capital assets, and livelihoods (Lebrasse, 2022). Lastly, the cost-effectiveness of restoring blue carbon ecosystems for both climatic and non-climatic benefits remain uncertain. These uncertainties are not just limited to the discussions above, but also due to the extraordinary variation in costs associated with restoration efforts (Bayraktarov et al., 2016). Some of the issues raised can be offset by strong economic incentives with the aim to prioritize the preservation of blue carbon ecosystems over more profitable short-term land use gains.

Among SIDS, there are numerous technical and methodological challenges associated with the monitoring, reporting, and verification (MRV) of blue carbon. These challenges are due in part to the geographic location of some SIDS coupled with resource limitations. For instance, many SIDS are geographically remote, and are often constrained by poor and/or dated infrastructure. This gives rise to many logistical complexities and high data collection costs. Moreover, the geographic diversity and environmental variability of SIDS as well as the spatial heterogeneity of blue carbon ecosystems (structure and characteristics) requires context-specific sampling strategies for sediments, living and dead biomass and considerations, e.g., tides, currents, salinity, and temperature, for accurate determination of carbon stocks, carbon losses and sequestration rates, carbon dynamics and water quality variables. These features take on even greater significance as sea-level rise and other climate induced impacts have been shown to alter the structure and functioning of blue carbon ecosystems across various SIDS (Bertram et al., 2021). These challenges are further compounded by a systemic lack of historical data for blue carbon ecosystems across SIDS making it difficult to track changes in MRV efforts (Figure 7) (Mengo et al., 2022). Simultaneously, the lack of funding, technical expertise (e.g., ecologists, carbon biogeochemists and statisticians), and physical resources to execute comprehensive blue carbon assessment campaigns all have adverse implications for an efficient long-term MRV program. Long-term monitoring is of special significance as it provides the means to track changes in carbon stocks due to natural and anthropogenic activities. Overall, an effective MRV program must have foundations in clear policies, institutional support, and strong stakeholder collaboration. However, establishing such frameworks may be difficult for SIDS due to the often-complex nature of multilateral agreements and partnerships (Hasan et al., 2022).

EVEN UNDER THE MOST optimistic future – where the long-term temperature goals of the Paris Climate Agreement are met – the issue of the vulnerability of blue carbon ecosystems to non-climatic factors remains nuanced.

Governance, policy challenges and community engagement

While blue carbon holds many roles and potential for SIDS, its integration into national developmental and climate plans may be onerous, as coastal ecosystems, blue carbon intersects both marine and terrestrial environments with implications at the community level, as well as for the fisheries, forestry (and other land use), tourism and environmental sectors, each with its own organizational structure and peculiarities. Therefore, all integration efforts must be harmonized with the existing governance frameworks of the various sectors, sub-sectors, local communities, and Indigenous groups to avoid conflicting objectives. As a good example, policies promoting coastal infrastructure development may be diametrically opposed to blue carbon conserva-

Figure 7: MRV research activities being conducted in blue carbon ecosystems in Jamaica to assess their carbon sequestration potential (photo credit: Taneisha Edwards, Patrice Francis, & Camilo Trench, 2019).

tion and restoration endeavours. This requires an all-inclusive stakeholder engagement and a nuanced understanding of Indigenous and local knowledge (ILK), cultural values, local needs, economic growth and job creation, land tenure security, food security, adaptive management, capacity building, along with climate change mitigation and adaptation.

A successful integration of blue carbon ecosystems into a low-carbon future, is one in which all aspects of problem definitions, solutions determination, intervention designs, execution, and MRV have cornerstone foundations in community engagement, leading to co-ownership of the problems and the solutions. The interface of ILK and scientific knowledge is a precursor for community-owned solutions. Therefore, strategies to empower local communities and promote the equitable distribution of benefits from blue carbon conservation and restoration to enhance their adaptive capacity require several attributes, including ILK. Indigenous and local knowledge is context-specific, flexible, and holistic since Indigenous people are keen on finding solutions to build resilience against climate change and other external shocks (Arneth et al., 2019).

International cooperation

Although not trivial, the challenges of a SIDS blue carbon architecture are not insurmountable. To address these challenges a multi-dimensional approach based on strong interdisciplinary collaboration among local and international scientists, governments, multilateral organizations, and other non-state actors is required. At the centre of this approach should be context-specific methodologies, best practices, capacity building to include the use of drones for high-resolution mapping, and manipulation of remote sensing data to provide a time-series of information on land cover changes, as well as the integration of blue carbon considerations into national development and climate plans. Additionally, data-sharing platforms incorporating artificial intelligence options and machine learning can be established as cost-optimized tools for the purposes of circumventing some of the common challenges associated with data collection, transparency, validation, harmonization, and long-term monitoring particularly in difficult to reach areas. It is also important that these protocols are stringently aligned with international guidelines and best practices for carbon accounting (IPCC, 2006; Arneth et al., 2019), and are buttressed by built-in management flexibility to account for changes induced by natural or anthropogenic factors.

CONCLUSION AND RECOMMENDATIONS

GHG emissions are closely linked to national development pathways, and rich countries and individuals have traditionally been the biggest emitters. At the other end of the spectrum, poorer countries (such as SIDS) and individuals remain the most vulnerable to the compounding and cascading impacts of climate change. However, what is universal is that regardless of status, accelerating climate action and support in this crucial decade is of paramount importance. Despite the urgency and narrowing of the window within which to act, efforts in this area have not kept pace with the current global and regional realities and/or future challenges of what may be described as an unfamiliar climate regime. Therefore, national commitments to achieve carbon peaking and neutrality and avert the sixth mass extinction should have a strong focus on the conservation and restoration of blue carbon ecosystems, and SIDS are well positioned to play a leading role. It is also important to note that the timing of achieving net-zero emissions will vary by country.

An important prerequisite for carbon peaking and neutrality in SIDS using nature-based solutions is to carry out a thorough and transparent assessment of the status of their blue carbon assets. Furthermore, leveraging blue carbon ecosystems as a strategy by SIDS to meet their long-term low carbon and net-zero climate ambitions also requires an enabling environment that facilitates the standardization and refinement of methodologies for blue carbon inventories. Other important deficiencies that must be addressed include assessment of existing data sources, gaps in knowledge and research, accessibility, quality, and format, and harmonizing solutions and pathways beyond the middle of the 21st century. Critically, access to adequate climate finance and strengthening monitoring, evaluation, and capacity building are crucial elements needed to harness the mitigation of blue carbon ecosystems in SIDS. It is also imperative that the design of the future direction of blue carbon initiatives within SIDS not only focuses on the immediate and long-term climate benefits, but also their roles in helping island countries to implement and achieve the Sustainable Development Goals and biodiversity conservation. All conservation and restoration projects should be built around a decadal lifespan and the position of governments of island countries and regions on climate action and support must be clearly articulated in their national development plans.

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