Blue Carbon in Seychelles

Subjects: Green & Sustainable Science & Technology
Contributor: Michael Bennett, Antaya March, Jeremy Raguain, Pierre Failler

Blue carbon has been proposed as a nature-based solution for climate change mitigation through the reduction in greenhouse gases through carbon sequestration. This proposal entails the protection, restoration, and conservation of blue carbon ecosystems such that these systems can optimally provide valuable ecosystem services. Challenges remain in funding the conservation and protection efforts blue carbon systems require to function optimally. The ecosystem services blue carbon systems provide can be capitalised upon through various “payment for ecosystem services” schemes, but these have their own unique challenges to resolve.

Keywords: carbon accounting ; carbon sequestration ; ecosystem services ; nature-based solutions ; climate mitigation and adaptation

1. Introduction

Blue carbon has been proposed as a nature-based solution for climate change mitigation through the reduction in greenhouse gases through carbon sequestration. This proposal entails the protection, restoration, and conservation of blue carbon ecosystems such that these systems can optimally provide valuable ecosystem services. Challenges remain in funding the conservation and protection efforts blue carbon systems require to function optimally. The ecosystem services blue carbon systems provide can be capitalised upon through various “payment for ecosystem services” schemes, but these have their own unique challenges to resolve.

Blue carbon resources can be defined as coastal ecosystems that sequester carbon in their tissues and soils, removing carbon from their surrounding environment . The term denotes marine and aquatic ecosystems specifically as opposed to terrestrial “green” ecosystems such as rainforests [1]. Recognised habitats include mangrove forests, intertidal flats such as saltmarshes, and seagrass meadows, but the recognition of kelp forests and coral reef systems as blue carbon sources is contentious [1][2]. Recognition of blue carbon resources under the UN framework Convention of Climate Change in 2015 (UNFCCC) [3] allows nations to include the carbon sequestered by blue carbon resources under their nationally determined contributions (NDCs) [4] despite blue carbon resources having minimal inclusion in NDCs. A lack of institutional frameworks and insufficient research with which to enable the integration of blue carbon into the national execution of the Paris Agreement have been hypothesised as causes [5]. Nonetheless, several nations have planned development strategies involving blue carbon resources and coastal restoration (China, the United States of America, and countries in the EU) [6][7][8] to assist in the removal of carbon (and legacy carbon) from the atmosphere, contribute to NDCs, and contribute to climate change mitigation and adaptation [9][10]. Moreover, blue carbon resources can serve as loci for conservation, offer entrepreneurship opportunities, deliver ecosystem services, and contribute to the development of the blue economy [11].

The potential capacity of blue carbon resources to sequester carbon is large, with protected resources being able to remove 3% of annual global greenhouse gas emissions despite limited coverage worldwide [12]. The global distribution of blue carbon resources has been estimated between 36 and 185 million ha [12], consisting of mangroves, seagrasses, and tidal flats. Despite the relatively small contribution of blue carbon resources to climate change mitigation through greenhouse gas removal (3%), blue carbon resources are responsible for up to 50% of annual organic carbon storage in coastal environments [13], with the carbon stores of vegetated coastal systems having been estimated at between 10 and 24 Pg [10], making them important components in the marine carbon cycle [14]. Like many other habitats globally, many blue carbon ecosystems are degraded [15][16][17][18], reducing their carbon sink capacities, owing to a lack of environmental protection. However, the conservation of blue carbon resources would avoid emissions of 304 (141–416) Tg carbon dioxide equivalent annually [12], and the restoration of these habitats would amount to sequestering an additional 841 (621–1064) Tg carbon dioxide equivalent by 2030 [12].

Small island developing states (SIDS) are a categorisation of 37 United Nations (UN) member states that share many specific features, particularly their vulnerability to external shocks from environmental and economic factors. Although having common vulnerabilities, SIDS are diverse states with varying sizes of population, land area, exclusive economic zones (EEZ), and archipelagic fragmentation, with some having economies entirely dependent on tourism and fisheries and others on fossil fuel-based exploitation [19]. Nevertheless, many of these SIDS (found in the Pacific, Caribbean, and the Atlantic–Indian–South China Sea region) have the potential to benefit from the development of their blue carbon resources, which can contribute substantially to local livelihoods and well-being [20][21]. Blue carbon development is also beginning to factor into the macroeconomic aims of SIDS, as well as having the potential to contribute significantly to multilateral commitments (such as the Paris Agreement) and address several of the unique challenges that SIDS face. This is facilitated by the numerous ecosystem services that blue carbon habitats provide beyond carbon removal, such as coastal protection, contributing to food security through the stimulation of fisheries through nursery ground provisioning, nutrient filtration, and contributing to aquaculture and ecotourism [11]. For example, mangroves have been invaluable sources of timber for SIDS in particular but have been unsustainably exploited globally with the removal of more than 25% of mangrove cover worldwide [22][23][24][25][26]. The environmental and socio-economic benefits of blue carbon ecosystems, once fully realised, are hypothesised to incentivise their propagation [27], facilitating the development of the blue economy.

SIDS are particularly vulnerable to climate change effects [28] and are also committed to the development of the blue economy (which synergises with blue carbon development), with at least 15 SIDS having policy definitions or visions of a national blue economy [19]. Seychelles is widely known as a model country for blue economy development [29], and, through the Seychelles Marine Spatial Plan, it has designated 32% of its EEZ as protected or for sustainable use, exceeding both Sustainable Development Goal target 14.5 and the UN Convention on Biological Diversity (CBD) 30 × 30 conservation targets. Seychelles also referred to blue carbon in their NDC submissions [30], committing to the protection of 50% of its seagrass and mangrove systems by 2025 and (conditional to external support) 100% by 2030, as well as including the greenhouse gas sink of Seychelles' blue carbon systems within the national greenhouse gas inventory by 2025 [31]. The protection of Seychelles' blue carbon resources is hoped to develop increased resiliency to the effects of climate change, mitigate national emissions, help the country raise climate finance, stimulate the local economy through added benefits from ecosystem services, and conserve endangered and unique biological diversity within these habitats.

There is growing interest in operationalising blue carbon as can be deduced from a growing number of blue carbon projects around the world [32]. However, blue carbon projects suffer from uncertainty on risk–return ratios, implementation pathways, and unclear legislation and policies and have created a situation where the demand for investable blue carbon projects is currently outweighing supply [32]. Much of this is due to key knowledge gaps, with limited research on the operationalisation of blue carbon resources, particularly in a SIDS context, having been conducted. A literature review conducted by [4] identified a major gap in the literature on blue carbon stocks for SIDS countries. The need for blue carbon research, which includes local scientists and practitioners not only in Seychelles but in the context of SIDS as a whole [4][33], is highlighted further by the potential of blue carbon resources to contribute to reducing the vulnerability of SIDS to climate change and external shocks.

2. Mapping Blue Carbon Resources and the Necessity of MPAs

Few studies have valued blue carbon ecosystem services in a SIDS context, and most blue carbon research in the Western Indian Ocean focussed on above-ground seagrasses and mangrove carbon, assessed using remote sensing and previous remote sensing datasets [4]. Using underwater echo-sounding, one study estimated the value of carbon sequestration and storage provided by seagrass meadows in the British Virgin Islands under different scenarios over 50 years [34]. The authors estimated a commercial potential between GBP 49,428 and GBP 664,785 in the baseline year, resulting in values between GBP 4.1 million and GBP 29.8 million over 50 years. Another study performed a scenario analysis informed by stakeholder workshops to assess the economic importance of Grenada's blue carbon resources [35]. Their findings suggest that benefits from carbon sequestration would diminish under expected habitat loss but still outweigh losses from carbon emissions, with welfare gains of USD 0.5–1.9 million over 50 years. However, the study also concluded that should ecosystems remain protected and maintained, benefits could reach USD 10.7 million, with an increase in mangrove cover by 20% (over the next quarter of a century resulting in USD 11.1 million between 2020 and 2070 [35]. Yet another study has estimated the national blue carbon stock for the mangrove habitats in Belize in the Caribbean to be 25.7 Tg C [36]. As has been highlighted for Caribbean SIDS, these studies highlight the extent of opportunity for Seychelles to benefit from the protection and operationalisation of blue carbon resources [37].

Applications such as The Nature Conservancy's Blue Carbon Explorer presents a distribution map of blue carbon resources (mangroves, seagrasses, and wetlands) of the Caribbean, Indonesia, and Papua New Guinea [38]. With time and the collection of field data, the mapping of SIDS blue carbon resources may be included for future use. Datasets such as those used by [39][40], as well as those from global initiatives such as Global Mangrove Watch, may contribute to the development of increasingly accurate mapping at finer resolutions. However, some of the previous blue carbon assessments and estimates are associated with large amounts of uncertainty, and consensus is needed on which of the numerous mappings are the most accurate and up-to-date versions, particularly in light of conservation planning and commercialisation of blue carbon resources (see Section 5). An international institution could be recognised as the authority on blue carbon mapping to give credence and quality assurance to policy makers, developers, and investors in blue carbon development projects (as motivated by [12]). A decision tree has recently been produced to aid decision making regarding the choice of remote sensing for blue carbon resources and cost-effective blue carbon accounting [41]. A recent blue carbon assessment of Seychelles mangrove systems [42] as well as a mapping of the seagrass ecosystems (Seychelles Seagrass Mapping and Carbon Assessment Project [43]), in collaboration with Pew Charitable Trust and Seychelles Conservation and Climate Adaptation Trust (SeyCCAT), has been verified with field measurements and could be regarded as authoritative estimates (more accurate than others before) for the operationalising of Seychelles blue carbon resources. It is recommended that a combination of remote sensing assessments and verification of blue carbon estimates through field measurements (ground-truthing) be used for assessing blue carbon resources, as this method provides more accurate estimates of the carbon storage and sequestration capacity of blue carbon resources than either method alone.

Seychelles is developing a Marine Spatial Planning Atlas (MSPA) in support of its Marine Spatial Plan [39]. The atlas contains various maps of ocean floor bathymetry, diversity, protected areas, and industry bounds, as well as ocean currents, commercial activities such as fisheries and tourism, and development planning maps. The MSPA should be modified to include the data and findings of [42] as well as the recent seagrass mapping [43] to facilitate the necessary protection, conservation, and sustainable exploitation of these high-value systems. The Seychelles MSPA could be replicated for use in other SIDS contexts, which would offer enormous value to their own respective coastal and blue economy development.

An estimated 50% of global blue carbon ecosystems have disappeared due to human activities (such as harvesting, dredging, and non-extractive activities such as filling and drainage) as well as climate change phenomena (like severe weather events and sea level rise), resulting in the release of carbon into the environment [4][44]. Long-term carbon sequestration and storage through blue carbon habitats is only effective as long as those ecosystems are protected, as disturbance results in carbon fixed in soils and tissues being released and cycling back into the surrounding atmosphere and environment. It is for this reason that blue carbon conservation is advocated for as well as the establishment of marine protected areas (MPAs). MPA classification of blue carbon ecosystems can ensure that they are not over-exploited (over-harvested) and remain undisturbed, facilitating their growth and production and maintaining (or increasing) their ability to sequester carbon optimally over extended periods. Even a partial protection status that allows for limited harvesting of resources would contribute to the propagation of blue carbon resources, and such policy/legislation may even facilitate the establishment of seaweed (kelp) farms for use as blue resources.

Seychelles has established 16 MPAs covering 26.4% of its EEZ [45] and has designated 36 MPAs to be protected [39]. Seychelles has 78% of its mangroves in protected areas on Aldabra Atoll, indicating that the nation has reached its 2025 target of 50% protection of its seagrasses and mangroves and is on track to achieving its 2030 target of 100% protection [31]. Howard et al. [46] discusses integrating blue carbon into MPA management and design. An even greater number of MPAs may thus be established with the consideration of Seychelles' blue carbon resources (**Table 1**), allowing the Seychelles to exceed its commitment to previously agreed upon sustainability targets and facilitate new blue economy development therewith.

Table 1. Seychelles blue carbon potential (from most recent and relevant estimates).

Blue Carbon Ecosystem	Ground Cover	Estimated Carbon Sequestration Capacity (Annual)	Estimated Carbon Storage Capacity	Source
Mangroves	**2195 ha**	**14,017 tonnes of CO_2 equivalent annually (equivalent to 3858 tonnes organic carbon annually)**	**2.5 million tons of CO_2 equivalent (688,091 tonnes of organic carbon)**	[42]
Seagrasses	**142,065 ha**	**123,596.55 tonnes of organic carbon annually (451,460.45 tonnes CO_2 equivalent annually)**	**16.7 million tonnes of organic carbon (61 million tonnes of CO_2 equivalent)**	[43]
Coral reefs	**169,000 ha, in 2021**	**No data**	**No data**	[47]

3. Mangroves

Global mangrove distribution has been estimated at 13 million ha [4][12]. Mangrove stocks in the Western Indian Ocean (WIO) have been mapped with datasets from 2018 and 2016, although more up-to-date datasets may be necessary to provide a more accurate representation of current stocks. Palacios et al. [4] conducted a literature review pertaining to blue carbon datasets in the WIO. They found one of only four relevant studies, which focused on the mangroves of Barbarons and Anse Boileau (on Mahe), where soil cores were analysed to examine ancient sea level changes [48]. Palacios et al. [4] did not find any studies quantifying soil carbon stocks or accretion rates in Seychelles; however, a number of relevant studies were published thereafter, including [49], which investigated the change in mangrove cover in relation to wave exposure, and [50], which investigated the variation in the mangrove biomass of the Aldabra Atoll.

Mangrove species found in the Seychelles include Avicennia marina, Bruguiera gymnorrhiza, Ceriops tagal, Lumnitzera racemosa, Sonneratia alba, Rhizophora mucronata, Xylocarpus granatum, and Xylocarpus moluccensis [4][39][49][51]. Wartman et al. [42] has recently conducted a blue carbon assessment of Seychelles' mangrove ecosystems. This assessment could likely be regarded as the authoritative source as blue carbon estimates were verified using field measurements (the most recent study to do so in Seychelles). Wartman et al. [42] contains detailed maps of the mangrove distribution among islands in Seychelles. The Seychelles mangrove distribution covers 2195 ha, with 80% of mangroves being located in Aldabra Atoll (**Table 1**, [39][42][49][51]). These ecosystems store a total of 2.5 million tons of CO_2 equivalent (688,091 tonnes of organic carbon). These values are comparable to those from previous global and regional estimates [4][23][52][53]. Mangrove systems in Seychelles store an estimated 313.48 tonnes of carbon per hectare of forest, with 70% of this being stored in their soils and the remaining 30% stored in their plant tissues [42]; however, mangrove biomass stocks are largely influenced by site conditions, species composition, and forest structure [53][54][55]. Aldabra Atoll was estimated to store 67% of the total mangrove-related carbon of Seychelles, followed by the island of Mahe (13%). Aldabra Atoll is a UNESCO World Heritage and Ramsar site, with Seychelles currently protecting 84% of its mangrove distribution [42]. The Seychelles mangrove stock sequesters an additional estimated 14,017 tonnes of CO_2 equivalent annually (equivalent to 3858 tonnes of organic carbon annually), which is equivalent to 3% of Seychelles' annual CO_2 emissions [42].

4. Seagrasses

Species of seagrasses found in the WIO include *Cymnodocea rotunda*, *Cymodocea semulata*, *Enhalus acoroides*, *Halodule* sp. (either uninervis or wrightii), *Halophila ovalis* (minor), *Halophila decipiens*, *Halophila stipulacea*, *Syringodium isoetifolium*, *Thalassia hemprichii*, *Thalassodendron ciliatum*, and *Zostera capensis* [4]. All of the above-mentioned species are found in the Seychelles except *H. stipulacea* and *Zostera capensis* [4]. Seagrasses are habitat engineers with *E. acoroides*, *T. ciliatum*, and *T. hemprichii* often dominating in subtidal areas. Smaller, fast-growing species such as *H. ovalis* and *H. uninervis* are pioneer species, which can be found in the intertidal zones [56]. Seagrasses can also occur as monospecific or mixed stands and can thrive in close proximity to other blue carbon ecosystems such as mangroves and coral reefs [57][58].

Previously mapped global seagrass distribution and estimates are surrounded by much uncertainty, with global seagrass cover ranging from 16 to 165 million ha [59][60][61]. Although limited studies on seagrasses in the Seychelles have been conducted [4], seagrass meadows in the region are plentiful [56], with seagrass mapping having been previously attempted with data from 2020 [4]. However, these data are incomplete and outdated, requiring more recent surveys for accurate representation of available seagrass stocks in Seychelles. Moreover, the Saya de Malha bank, which may host the world's largest seagrass meadow under Seychelles and Mauritius's Joint Management Area, will be a critical area to survey.

The Seychelles Seagrass Mapping and Carbon Assessment [43] provides the most recent and accurate representation of Seychelles seagrasses, with estimates that have been ground-truthed with field measurements throughout the islands. Seagrass cover in Seychelles currently spans an area of 142,065 ha [43], which is significantly less than what has been estimated before (2 million ha of seagrass cover [39]). This clearly highlights the need for ground-truthing estimates with field measurements. Nonetheless, Seychelles seagrasses are storing 16.7 million tonnes of organic carbon (61 million tonnes of CO_2 equivalent) at a rate of 0.87 tonne organic C $ha^{-1}.y^{-1}$ (**Table 1** [43]). Using these figures above, the Seychelles seagrass stock thus sequesters an estimated additional 123 596.55 tonnes of organic carbon annually (451,460.45 tonnes CO_2 equivalent annually, **Table 1**). However, the stored carbon is not equally spread across all of the Seychelles seagrasses as the species composition of seagrass beds influences their carbon sequestration ability [4], with two-thirds of seagrass carbon being stored in the soil [62] and the remaining third in seagrass tissues.

In a valuation of the Seychelles blue economy using the UNECA's blue economy valuation toolkit (BEVTK), the blue economy contribution of the seagrass ecosystems in the Seychelles contributed 98.21% of USD 48.07 billion (in [63]; see

Figure 4). This valuation considers other ecosystem services that seagrasses may offer beyond merely blue carbon but nonetheless highlights the importance of the seagrass ecosystem to the Seychelles blue economy (98.21%).

5. Coral Reefs

There has been a long-standing debate on whether coral reefs are net carbon sinks [64][65][66], carbon sources [67][68][69], or shifting between the two [70][71][72]. This is accompanied by a significant knowledge gap surrounding the topic. Shi et al. [72] reviews this debate and proposes the inclusion of the microbial carbon pump in the discussion, suggesting that it significantly contributes to the storage potential of coral reef systems as blue carbon resources (see also [73]). The unique combination of physical, chemical, and biological processes in different coral reef locations makes it difficult to achieve consistent calculations of carbon dynamics [65][74]. Furthermore, coral reefs are one of the most vulnerable ecosystems to environmental changes. Phenomena such as coastal acidification, rising sea levels, and regional warming have contributed to the loss of corals on a global scale through coral bleaching [72][75][76], and such stressors not only threaten coral reef survival but also impact the ability to gauge their carbon sink–source attributes [72]. There is a subsequent need to strengthen and support coral reef restoration programmes and to improve their resilience to environmental stress to not only maintain their potential carbon sink function [72] but also the other ecosystem services they offer (e.g., habitat provisioning).

The key point underpinning this debate is that coral systems are mixotrophs, meaning that they can switch between autotrophic (producing energy of their own means, such as through photosynthesis) and heterotrophic (metabolising energy from external inputs, such as filter feeding) modes of energy production. This ability affects whether or not coral reef systems are a net carbon sink or carbon source [77]. When the coral system is governed by autotrophic production, the amount of carbon fixed by photosynthesis is higher than that released by coral respiration, meaning that the reef system is more likely to act as a carbon sink [72]. When the coral system is dominated by heterotrophic production, corals obtain their energy by feeding on zooplankton and suspended matter. The amount of carbon released by respiration exceeds that fixed through photosynthesis, resulting in the coral reef system acting as a carbon source [72]. Corals are likely to shift to heterotrophic production when they are stressed, releasing their photosynthetic algae during bleaching events and subsequently releasing more carbon to the environment. Corals are likely to collapse and disintegrate when dominated by heterotrophic growth [72], emphasising the need for protection and addressing environmental climate change to ensure healthy coral systems. In addition to this, biogenic calcification (i.e., the production of calcium-carbonate, $CaCO_3$) releases CO_2 during its production [74]. The presence of calcifying organisms (including corals, molluscs, crustaceans, and algae) thus influences the carbon sink classification and capacity of an ecosystem, including seagrasses and mangroves, and influences the ecosystem carbon budget [78][79]. Despite the mixotrophic nature of corals and the associated inability to classify them as true blue carbon resources (and carbon sinks), there are specific actions that can be taken to potentially enhance the carbon sequestration capabilities associated with coral reef ecosystems [72]: (1) Strengthening the practice of coral conservation and protection towards the development of healthy reefs as potential carbon sinks. (2) Coordinated holistic land–sea development has the potential to increase the carbon sink potential of coral reef systems. (3) Increasing connectivity within coral reef systems and between other blue carbon systems may facilitate enhanced carbon sequestration [80]. (4) Artificial upwelling has the potential to improve nutrient cycling and carbon sinks in coral reefs [3][72][81][82]. Artificial upwelling is an emerging eco-engineering technology included in the Special Report on the Oceans and Cryosphere in a Changing Climate (SROCCC) of the Intergovernmental Panel on Climate Change (IPCC, see [3]). However, care needs to be taken with blue carbon projects designed around coral restoration and coral outplanting specifically, as the increased amount of biogenic calcification associated with the coral outplanting may influence the carbon budget of the ecosystem such that the ecosystem becomes a net carbon source, thereby invalidating the purpose of the project. Instead, coral reef restoration should be focussed on the conservation of biodiversity and the other ecosystem services coral reefs provide (habitat provisioning, fisheries supplementation, coastal buffering, and cultural value).

Coral cover around the world has been reduced (and continues to reduce) due to the effects of rising sea temperatures and other climate change effects [83][84]. SIDS may be experiencing this reduction at an elevated rate due to their susceptibility and their particular vulnerability to climate change effects [28][85]. This is particularly true for the Seychelles as numerous coral bleaching events have resulted in a 97% reduction in coral cover since 1998 [86]. Coral reef restoration efforts have been underway for some time with successful results: reef restoration efforts at a transplantation site saw a 700% increase in coral cover from 2012 to 2014, with a further documented five-fold increase in species richness and a two-fold increase in coral settlement and recruitment by 2016 [87][88]. However, the third global bleaching event (2014–2017) heavily impacted coral reef systems, including the Aldabra Atoll [89][90]. Aldabra Atoll's benthic community shifted significantly over this period with a significant reduction in coral cover, showing that protected areas are not isolated from climate change pressures [89]. Coral cover in Seychelles was estimated at 1690 km^2 in 2021 (**Table 1**, [47]) but has likely changed since then.

The increasing number of MPAs under the Seychelles Marine Spatial Plan and the associated increase in coral reef cover in the Seychelles facilitates the establishment of sufficient coral systems with potential as blue carbon resources. Despite research on the carbon source–sink nature of coral systems being limited [72], addressing research and data gaps may significantly contribute to the classification of coral reef systems as blue carbon resources. A global study of the mechanisms and processes underpinning the carbon cycle at various levels or organisations has been advocated for to establish the contribution of coral reefs to sea–air CO_2 dynamics [72]. However, recognition as true blue carbon resources may have to be determined on a case-by-case basis (or MPA-by-MPA basis) but may allow countries rich in coral systems such as Seychelles alternative means of contributing to sustainable development goals (SDGs) through nationally determined contributions (NDCs). Revenue generated from coral carbon resources may also be directed towards the continued development of coral reef restoration projects in Seychelles (and neighbouring nations), enhancing the associated benefits from healthy coral reef systems (such as fisheries supplementation, cultural significance, and tourism).

6. Threats to Blue Carbon Systems and Resources

Similar to other natural ecosystems, blue carbon resources are threatened by human activities, such as overexploitation and unsustainable coastal development. However, blue carbon resources as well as their associated carbon sediment deposits are also influenced by climate change effects over different spatial and temporal scales [14]. Lovelock & Reef [14] reviews the effects of climate change on all types of blue carbon resources (except corals) and focuses on sea level rise due to its fundamental role in altering the distribution and composition of coastal environments. The vulnerability of blue carbon to climate change is a function of exposure, vulnerability, and adaptive capacity [91].

Exposure to climate change varies among ecosystems. All blue carbon is exposed to sea level rise to varying degrees (regionally and temporally [92]). Mangroves are exposed to drought and storms in subtropical regions but less so at the equator [93]. A less considered phenomenon is that saltmarsh blue carbon is vulnerable to mangrove encroachment where the distributions of these habitats overlap [94], in many cases altering and increasing sediment carbon storage [94][95][96]. Exposure of sedimentary carbon deposits to increases in wave energy is likely on more exposed shorelines than on protected estuaries. Temperate seaweeds and seagrasses are vulnerable to marine heat waves at lower latitudes, which can result in their degradation as the environment changes to that characteristic of the tropics [97][98].

The sensitivity of blue carbon resources to climate change also varies [91]. Sedimentary organic carbon density varies globally among different settings [23][62][99], but it is expected that sediments with greater carbon density are more sensitive to processes that may disturb it [50][100]. Furthermore, sedimentary carbon stocks are differentially sensitive to mineralisation. Depending on the specific characteristics of the organic matter as well as the environmental conditions in the area, the process of decomposition and CO_2 release may be accelerated [101][102]. Examples such as nutrient input and pollution [101][102], changes in rainfall and sediment salinity [103][104][105], and wave action intensification [49] may reduce carbon storage capacity and influence the carbon fluxes associated with blue carbon systems such that more CO_2 is released into the atmosphere [14].

The adaptive capacity of blue carbon systems may be thought of as their potential to accrete vertically to adjust to sea level rise (by increasing sediment mass, tissue mass, and thus sequestration capacity), the ability to maintain their carbon density, the ability to maintain their cover by expanding into new areas with associated sea level rise or other changing conditions (this may be complicated for neighbouring blue carbon systems due to similar reasons as for the example of mangrove encroachment of saltmarshes), and the capacity to maintain species biodiversity, which protects and maintains the carbon sequestration function of the ecosystem [14].

7. Threats to Seychelles and Other SIDS Blue Carbon Resources

SIDS are particularly vulnerable to the effects of climate change [28] and, as such, so are their blue carbon resources. Seagrasses dominate the blue carbon ecosystems [4][43] of Seychelles, and threats to seagrasses, such as marine heatwaves, are of importance to conservationists and Seychelles blue carbon stakeholders. However, mangroves are also present among Seychelles islands, and threats to mangrove systems, such as land use change and development, are thus also of concern.

Sea level rise has been established as a threat to the coastal zone [106] and thus to blue carbon systems. The submergence and loss of coastal environments have been observed as their depth range is exceeded and landward migration observed [107][108]. Human development of coastal environments potentially threatens blue carbon systems in what is known as the "coastal squeeze" [109][110]. Coastal squeeze occurs when the upslope migration of blue carbon resources (usually wetlands) is prevented by human-built environments, while the seaward edge is increasingly submerged by rising sea levels. The management of coastal squeeze through managed retreat has the potential to increase the cover of coastal wetlands with sea level rise [109][110].

Wind regimes and the resulting waves influence a broad range of processes that impact carbon cycling and the ecology of coastal systems [111]. These are also affected by climate change and sea level rise [112][113][114]. Ocean islands and atolls are particularly vulnerable to the combined influence of rising sea levels and increased wave height [14]. Changing wind conditions in combination with sea level rise could be responsible for the erosion of 5 of the 20 Solomon Islands in the Pacific Ocean [115]. Elevated wind and wave energy has the potential to cause erosion and the release of particulate carbon, resulting in mineralisation and the release of CO_2 from oxygenated waters [116]. However, in low-energy environments, carbon sediment deposits could remain intact despite vegetation being overwhelmed by the sea level rise, such as the peat bogs in Bermuda, Belize, and Panama [108][117].

Several SIDS are in locations where severe storms like hurricanes and tropical cyclones occur, such as the Caribbean islands in the equatorial Atlantic Ocean and Seychelles in the Western Indian Ocean. These storms have the potential to damage blue carbon ecosystems and disturb their carbon soil sediments, being associated with high wind and wave energy. Such storms are also associated with fresh-water input having the potential to alter the carbon storage capacity of blue carbon resources [14].

Other human activities that threaten blue carbon resources beyond physical disturbance (coastal development and exploitation) include nutrient enrichment from agricultural runoff (applicable to agricultural fertilisers and seaweed-based fertilisers [118]); turbidity changes from runoff, which influence light penetration and limit seagrass productivity [119]; and the construction of dams limiting the ability of coastal environments to accrete sediment necessary for carbon storage [110][120]. However, in some cases, human intervention has the potential to enhance carbon stocks through sediment input from runoff [121][122][123][124]. Biodiversity loss associated with human interventions may reduce blue carbon services, particularly with the loss of ecosystem engineers, species that maintain trophic balance, and species that regulate carbon sequestration and storage services [14].

References

1. Macreadie, P.I.; Anton, A.; Raven, J.A.; Beaumont, N.; Connolly, R.M.; Friess, D.A.; Kelleway, J.J.; Kennedy, H.; Kuwae, T.; Lavery, P.S.; et al. The future of Blue Carbon science. Nat. Commun. 2019, 10, 3998.
2. Lovelock, C.E.; Duarte, C.M. Dimensions of blue carbon and emerging perspectives. Biol. Lett. 2019, 15, 20180781.
3. Bindoff, N.L.; Cheung, W.W.L.; Kairo, J.G.; Aristegui, J.; Guinder, V.A.; Hallberg, R.; Hilmi, N.; Jiao, N.; Karim, M.S.; Levin, L.; et al. IPCC Changing Ocean, Marine Ecosystems, and Dependent Communities. In IPCC Special Report on the Ocean and Cryosphere in a Changing Climate; IPCC: Geneva, Switzerland, 2019; pp. 447–588.
4. Palacios, M.M.; Waryszak, P.; Costa, M.D.P.; Wartman, M.; Ebrahim, A.; Macreadie, P.I. Literature Review: Blue Carbon research in the Tropical Western Indian Ocean WIO; A report submitted to the Seychelles Conservation & Climate Adaptation Trust (SeyCCAT); Deakin University: Geelong, VIC, Australia, 2021; 80p.
5. Wedding, L.M.; Moritsch, M.; Verutes, G.; Arkema, K.; Hartge, E.; Reiblich, J.; Douglass, J.; Taylor, S.; Strong, A.L. Incorporating blue carbon sequestration benefits into sub-national climate policies. Glob. Environ. Chang. 2021, 69, 102206.
6. Wu, J.; Zhang, H.; Pan, Y.; Krause-Jensen, D.; He, Z.; Fan, W.; Xiao, X.; Chung, I.; Marbà, N.; Serrano, O.; et al. Opportunities for blue carbon strategies in China. Ocean. Coast. Manag. 2020, 194, 105241.
7. Bertram, C.; Quaas, M.; Reusch, T.B.; Vafeidis, A.T.; Wolff, C.; Rickels, W. The blue carbon wealth of nations. Nat. Clim. Chang. 2021, 11, 704–709.
8. Frigstad, H.; Gundersen, H.; Andersen, G.S.; Borgersen, G.; Kvile, K.Ø.; Krause-Jensen, D.; Boström, C.; Bekkby, T.; Anglès d'Auriac, M.; Ruus, A.; et al. Blue Carbon—Climate Adaptation, CO2 Uptake and Sequestration of Carbon in Nordic Blue Forests: Results from the Nordic Blue Carbon Project; Nordic Council of Ministers: Copenhagen, Denmark, 2021.

9. Nellemann, C.; Corcoran, E. (Eds.) Blue Carbon: The Role of Healthy Oceans in Binding Carbon: A Rapid Response Assessment; UNEP/Earthprint: Nairobi, Kenya, 2009.
10. Duarte, C.M.; Losada, I.J.; Hendriks, I.E.; Mazarrasa, I.; Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Chang. 2013, 3, 961–968.
11. United Nations Environment Programme (UNEP). Out of the Blue: The Value of Seagrasses to the Environment and to People; UNEP: Nairobi, Kenya, 2020.
12. Macreadie, P.I.; Costa, M.D.P.; Atwood, T.B.; Friess, D.A.; Kelleway, J.J.; Kennedy, H.; Lovelock, C.E.; Serrano, O.; Duarte, C.M. Blue carbon as a natural climate solution. Nat. Rev. Earth Environ. 2021, 2, 826–839.
13. Duarte, C.M.; Middelburg, J.J.; Caraco, N. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2005, 2, 1–8.
14. Lovelock, C.E.; Reef, R. Variable impacts of climate change on blue carbon. One Earth 2020, 3, 195–211.
15. Senger, D.F.; Hortua, D.S.; Engel, S.; Schnurawa, M.; Moosdorf, N.; Gillis, L.G. Impacts of wetland dieback on carbon dynamics: A comparison between intact and degraded mangroves. Sci. Total Environ. 2021, 753, 141817.
16. Sharma, S.; MacKenzie, R.A.; Tieng, T.; Soben, K.; Tulyasuwan, N.; Resanond, A.; Blate, G.; Litton, C.M. The impacts of degradation, deforestation and restoration on mangrove ecosystem carbon stocks across Cambodia. Sci. Total Environ. 2020, 706, 135416.
17. Trevathan-Tackett, S.M.; Wessel, C.; Cebrián, J.; Ralph, P.J.; Masqué, P.; Macreadie, P.I. Effects of small-scale, shading-induced seagrass loss on blue carbon storage: Implications for management of degraded seagrass ecosystems. J. Appl. Ecol. 2018, 55, 1351–1359.
18. Wylie, L.; Sutton-Grier, A.E.; Moore, A. Keys to successful blue carbon projects: Lessons learned from global case studies. Mar. Policy 2016, 65, 76–84.
19. Pouponneau, A. Blue economy: The perspectives of small island developing states. Small States Territ. 2023, 6, 69–82.
20. Barbier, E.B. Natural capital, resource dependency, and poverty in developing countries: The problem of 'dualism within dualism'. In Economic Development & Environmental Sustainability, New Policy Options; Oxford University Press: New York, NY, USA, 2006; pp. 23–59.
21. Patil, P.G.; Virdin, J.; Diez, S.M.; Roberts, J.; Singh, A. Toward a Blue Economy: A Promise for Sustainable Growth in the Caribbean; An Overview; The World Bank: Washington, DC, USA, 2016.
22. Spalding, M. World Atlas of Mangroves; Routledge: London, UK, 2010.
23. Sanderman, J.; Hengl, T.; Fiske, G.; Solvik, K.; Adame, M.F.; Benson, L.; Bukoski, J.J.; Carnell, P.; Cifuentes-Jara, M.; Donato, D.; et al. A global map of mangrove forest soil carbon at 30 m spatial resolution. Environ. Res. Lett. 2018, 13, 55002.
24. Polidoro, B.A.; Carpenter, K.E.; Collins, L.; Duke, N.C.; Ellison, A.M.; Ellison, J.C.; Farnsworth, E.J.; Fernando, E.S.; Kathiresan, K.; Koedam, N.E.; et al. The loss of species: Mangrove extinction risk and geographic areas of global concern. PloS ONE 2010, 5, e10095.
25. Van Bochove, J.; Sullivan, E.; Nakamura, T. The Importance of Mangroves to People: A Call to Action; United Nations Environment Programme, World Conservation Monitoring Centre: Cambridge, UK, 2014.
26. Wilson, R. Impacts of Climate Change on Mangrove Ecosystems in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS). Caribb. Clim. Chang. Rep. Card Sci. Rev. 2017, 2017, 60–82.
27. Bennett, M.; Marsh, A.; Failler, P. Blue Caribbean financing opportunities for the fisheries and aquaculture sectors for Caribbean SIDS. Mar. Policy, 2023; in press.
28. Robinson, S.A. Climate change adaptation in SIDS: A systematic review of the literature pre and post the IPCC Fifth Assessment Report. Wiley Interdiscip. Rev. Clim. Chang. 2020, 11, e653.
29. Benzaken, D.; Voyer, M.; Pouponneau, A.; Hanich, Q. Good governance for sustainable blue economy in small islands: Lessons learned from the Seychelles experience. Front. Political Sci. 2022, 4, 137.
30. Herr, D.; Landis, E. Coastal Blue Carbon Ecosystems. Opportunities for Nationally Determined Contributions. Policy Brief; IUCN: Washington, DC, USA; TNC: Gland, Switzerland, 2016.
31. Republic of Seychelles. Seychelles Updated Nationally Determined Contributions Submission under the Paris Agreement. 2021. Available online: https://unfccc.int/sites/default/files/NDC/2022-06/Seychelles%20-%20NDC_Jul30th%202021%20_Final.pdf (accessed on 30 July 2023).
32. Macreadie, P.I.; Robertson, A.I.; Spinks, B.; Adams, M.P.; Atchison, J.M.; Bell-James, J.; Bryan, B.A.; Chu, L.; Filbee-Dexter, K.; Drake, L.; et al. Operationalizing marketable blue carbon. One Earth 2022, 5, 485–492.

33. Senaratne, M. Hiding in Plain Sight: Exploring Seychelles' blue carbon market opportunities within seagrass meadows. Seychelles Res. J. 2021, 3, 100–111. Available online: https://seychellesresearchjournalcom.files.wordpress.com/2021/01/hiding_in_plain_sight-exploring_seychelles_blue_carbon_market_opportunities_within_seagrass_meadows-malshini_senaratne-srj-3-1.pdf (accessed on 18 July 2023).

34. Tyllianakis, E.; Callaway, A.; Vanstaen, K.; Luisetti, T. The value of information: Realising the economic benefits of mapping seagrass meadows in the British Virgin Islands. Sci. Total Environ. 2019, 650, 2107–2116.

35. McHarg, E.; Mengo, E.; Benson, L.; Daniel, J.; Joseph-Witzig, A.; Posen, P.; Luisetti, T. Valuing the contribution of blue carbon to small island developing states' climate change commitments and Covid-19 recovery. Environ. Sci. Policy 2022, 132, 13–23.

36. Morrissette, H.K.; Baez, S.K.; Beers, L.; Bood, N.; Martinez, N.D.; Novelo, K.; Andrews, G.; Balan, L.; Beers, C.S.; Betancourt, S.A.; et al. Belize Blue Carbon: Establishing a national carbon stock estimate for mangrove ecosystems. Sci. Total Environ. 2023, 870, 161829.

37. Rustomjee, C. Developing the Blue Economy in Caribbean and Other Small States; Policy Brief No. 75; Centre for International Governance Innovation: Waterloo, ON, Canada, 2016.

38. TNC Blue Carbon Explorer. The Nature Conservancy. 2023. Available online: https://sites.google.com/view/blue-carbon-explorer (accessed on 5 May 2023).

39. Smith, J.L.; Tingey, R.; Sims, H.E. Seychelles Marine Spatial Plan Atlas; Developed by The Nature Conservancy for the Seychelles MSP Initiative; Seychelles Marine Spatial Plan (SMSP), 2020; Developed by The Nature Conservancy for the Seychelles MSP Initiative; Unpublished maps accessed at www.seymsp.com; Available online: https://seymsp.com/outputs/atlas/ (accessed on 28 June 2023).

40. Bunting, P.; Rosenqvist, A.; Lucas, R.M.; Rebelo, L.-M.; Hilarides, L.; Thomas, N.; Hardy, A.; Itoh, T.; Shimada, M.; Finlayson, C.M. The global mangrove watch—A new 2010 global baseline of mangrove extent. Remote Sens. 2018, 10, 1669.

41. Malerba, M.E.; de Paula Costa, M.D.; Friess, D.A.; Schuster, L.; Young, M.A.; Lagomasino, D.; Serrano, O.; Hickey, S.M.; York, P.H.; Rasheed, M.; et al. Remote sensing for cost-effective blue carbon accounting. Earth-Sci. Rev. 2023, 238, 104337.

42. Wartman, M.; Costa, M.D.P.; Palacios, M.M.; Nourice, B.; Macreadie, P.I. Blue Carbon Assessment for Mangrove Systems in Seychelles; A report submitted to Seychelles' Ministry of Agriculture, Climate Change and Environment; Deakin University: Geelong, VIC, Australia, 2022; 84p.

43. Rowlands, G.P.; Antat, S.; Baez, S.K.; Cupidon, A.; Faure, A.; Harlay, J.; Lee, C.B.; Martin, L.E.C.; Masque, P.; Morgan, M.; et al. The Seychelles Seagrass Mapping and Carbon Assessment. A report to be submitted to the Government of Seychelles, Ministry of Agriculture, Climate Change and Environment (MACCE). 2024.

44. Pendleton, L.; Donato, D.C.; Murray, B.C.; Crooks, S.; Jenkins, W.A.; Sifleet, S.; Craft, C.; Fourqurean, J.W.; Kauffman, J.B.; Marbà, N.; et al. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS ONE 2012, 7, e43542.

45. WIOMSA. WIO MPA Outlook Report: Marine Protected Areas and the Seychelles. Western Indian Ocean Marine Science Association, 2021. Available online: https://www.wiomsa.org/news/wio-mpa-outlook-report-marine-protected-areas-and-the-seychelles/ (accessed on 15 July 2023).

46. Howard, J.; Mcleod, E.; Thomas, S.; Eastwood, E.; Fox, M.; Wenzel, L.; Pidgeon, E. The potential to integrate blue carbon into MPA design and management. Aquat. Conserv. Mar. Freshw. Ecosyst. 2017, 27, 100–115.

47. Varaden, S.; Ramsurn, R.; Aumeeruddy, A. Coral Reefs and Their Importance for the Island Economies. United Nations Development Programme (UNDP), 23 September 2021. Available online: https://www.undp.org/mauritius-seychelles/blog/coral-reefs-and-their-importance-island-economies# (accessed on 17 July 2023).

48. Woodroffe, S.A.; Long, A.J.; Milne, G.A.; Bryant, C.L.; Thomas, A.L. New constraints on late Holocene eustatic sea-level changes from Mahé, Seychelles. Quat. Sci. Rev. 2015, 115, 1–16.

49. Constance, A.; Haverkamp, P.J.; Bunbury, N.; Schaepman-Strub, G. Extent change of protected mangrove forest and its relation to wave power exposure on Aldabra Atoll. Glob. Ecol. Conserv. 2021, 27, e01564.

50. Constance, A.; Oehri, J.; Bunbury, N.; Wiesenberg, G.L.; Pennekamp, F.; A'Bear, L.; Fleischer-Dogley, F.; Schaepman-Strub, G. Soil nutrient content and water level variation drive mangrove forest aboveground biomass in the lagoonal ecosystem of Aldabra Atoll. Ecol. Indic. 2022, 143, 109292.

51. Walton, R.; Baxter, R.; Bunbury, N.; Hansen, D.; Fleischer-Dogley, F.; Greenwood, S.; Schaepman-Strub, G. In the land of giants: Habitat use and selection of the Aldabra giant tortoise on Aldabra Atoll. Biodivers. Conserv. 2019, 28, 3183–

3198.

52. Atwood, T.B.; Connolly, R.M.; Almahasheer, H.; Carnell, P.E.; Duarte, C.M.; Lewis, C.J.E.; Irigoien, X.; Kelleway, J.J.; Lavery, P.S.; Macreadie, P.I.; et al. Global patterns in mangrove soil carbon stocks and losses. Nat. Clim. Chang. 2017, 7, 523–528.

53. Simard, M.; Fatoyinbo, L.; Smetanka, C.; Rivera-Monroy, V.H.; Castañeda-Moya, E.; Thomas, N.; Van der Stocken, T. Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. Nat. Geosci. 2018, 12, 40–45.

54. Jones, T.G.; Ratsimba, H.R.; Ravaoarinorotsihoarana, L.; Glass, L.; Benson, L.; Teoh, M.; Carro, A.; Cripps, G.; Giri, C.; Gandhi, S.; et al. The Dynamics, Ecological Variability and Estimated Carbon Stocks of Mangroves in Mahajamba Bay, Madagascar. J. Mar. Sci. Eng. 2015, 3, 793–820.

55. Kamau, J.N.; Ngila, J.C.; Kirui, B.; Mwangi, S.; Kosore, C.M.; Wanjeri, V.; Okumu, S. Spatial variability of the rate of organic carbon mineralization in a sewage impacted mangrove forest, Mikindani, Kenya. J. Soils Sediments 2015, 15, 2466–2475.

56. Obura, D.O.; Bandeira, S.O.; Bodin, N.; Burgener, V.; Braulik, G.; Chassot, E.; Gullström, M.; Kochzius, M.; Nicoll, M.; Osuka, K.; et al. The Northern Mozambique Channel. In World Seas: An Environmental Evaluation, 2nd ed.; Sheppard, C., Ed.; Academic Press: Cambridge, MA, USA, 2019; pp. 75–99.

57. Lugendo, B. Mangroves, salt marshes and seagrass beds. In Regional State of the Coast Report; United Nations: New York, NY, USA, 2016; pp. 52–68.

58. Gullström, M.; Castro, M.D.L.T.; Bandeira, S.O.; Björk, M.; Dahlberg, M.; Kautsky, N.; Rönnbäck, P.; Öhman, M.C. Seagrass Ecosystems in the Western Indian Ocean. AMBIO A J. Hum. Environ. 2002, 31, 588–596.

59. Jayathilake, D.R.M.; Costello, M.J. A modelled global distribution of the seagrass biome. Biol. Conserv. 2018, 226, 120–126.

60. McKenzie, L.J.; Nordlund, L.M.; Jones, B.L.; Cullen-Unsworth, L.C.; Roelfsema, C.; Unsworth, R.K.F. The global distribution of seagrass meadows. Environ. Res. Lett. 2020, 15, 74041.

61. UNEP-WCMC; F Short. Global Distribution of Seagrasses (Version 7.0); Seventh Update to the Data Layer Used in Green and Short (2003); UN Environment World Conservation Monitoring Centre: Cambridge, UK, 2020.

62. Fourqurean, J.W.; Duarte, C.M.; Kennedy, H.; Marbà, N.; Holmer, M.; Mateo, M.A.; Serrano, O. Seagrass ecosystems as a globally significant carbon stock. Nat. Geosci. 2012, 5, 505–512.

63. Failler, P.; Liu, J.; Lallemand, P.; March, A. Blue Accounting Approaches in the Emerging African Blue Economy Context. J. Sustain. Res. 2023, 5, e230002.

64. Kayanne, H.; Suzuki, A.; Saito, H. Diurnal changes in the partial pressure of carbon dioxide in coral reef water. Science 1995, 269, 214–216.

65. Chisholm, J.R.; Barnes, D.J. Anomalies in coral reef community metabolism and their potential importance in the reef CO2 source-sink debate. Proc. Natl. Acad. Sci. USA 1998, 95, 6566–6569.

66. Yan, H.; Yu, K.; Shi, Q.; Lin, Z.; Zhao, M.; Tao, S.; Liu, G.; Zhang, H. Air-sea CO2 fluxes and spatial distribution of seawater pCO2 in Yongle Atoll, northern-central South China Sea. Cont. Shelf Res. 2018, 165, 71–77.

67. Gattuso, J.P.; Allemand, D.; Frankignoulle, M. Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: A review on interactions and control by carbonate chemistry. Am. Zool. 1999, 39, 160–183.

68. Lønborg, C.; Calleja, M.L.; Fabricius, K.E.; Smith, J.N.; Achterberg, E.P. The Great Barrier Reef: A source of CO2 to the atmosphere. Mar. Chem. 2019, 210, 24–33.

69. Cotovicz, L.C., Jr.; Chielle, R.; Marins, R.V. Air-sea CO2 flux in an equatorial continental shelf dominated by coral reefs (Southwestern Atlantic Ocean). Cont. Shelf Res. 2020, 204, 104175.

70. De Goeij, J.M.; Van Duyl, F.C. Coral cavities are sinks of dissolved organic carbon (DOC). Limnol. Oceanogr. 2007, 52, 2608–2617.

71. Wimart-Rousseau, C.; Lajaunie-Salla, K.; Marrec, P.; Wagener, T.; Raimbault, P.; Lagadec, V.; Lafont, M.; Garcia, N.; Diaz, F.; Pinazo, C.; et al. Temporal variability of the carbonate system and air-sea CO2 exchanges in a Mediterranean human-impacted coastal site. Estuar. Coast. Shelf Sci. 2020, 236, 106641.

72. Shi, T.; Zheng, X.; Zhang, H.; Wang, Q.; Zhong, X. Coral reefs: Potential blue carbon sinks for climate change mitigation. Bull. Chin. Acad. Sci. 2021, 36, 270–278. (In Chinese)

73. Jiao, N.; Herndl, G.J.; Hansell, D.A.; Benner, R.; Kattner, G.; Wilhelm, S.W.; Kirchman, D.L.; Weinbauer, M.G.; Luo, T.; Chen, F.; et al. Microbial production of recalcitrant dissolved organic matter: Long-term carbon storage in the global ocean. Nat. Rev. Microbiol. 2010, 8, 593–599.

74. Ware, J.R.; Smith, S.V.; Reaka-Kudla, M.L. Coral reefs: Sources or sinks of atmospheric CO2? Coral Reefs 1992, 11, 127–130.

75. Pratchett, M.S.; Hoey, A.S.; Wilson, S.K.; Messmer, V.; Graham, N.A. Changes in Biodiversity and Functioning of Reef Fish Assemblages following Coral Bleaching and Coral Loss. Diversity 2011, 3, 424–452.

76. Pratchett, M.S.; Thompson, C.A.; Hoey, A.S.; Cowman, P.F.; Wilson, S.K. Effects of coral bleaching and coral loss on the structure and function of reef fish assemblages. In Coral Bleaching; Springer: Cham, Switzerland, 2018; pp. 265–293.

77. Conti-Jerpe, I.E.; Thompson, P.D.; Wong, C.W.M.; Oliveira, N.L.; Duprey, N.N.; Moynihan, M.A.; Baker, D.M. Trophic strategy and bleaching resistance in reef-building corals. Sci. Adv. 2020, 6, eaaz5443.

78. Saderne, V.; Geraldi, N.R.; Macreadie, P.I.; Maher, D.T.; Middelburg, J.J.; Serrano, O.; Almahasheer, H.; Arias-Ortiz, A.; Cusack, M.; Eyre, B.D.; et al. Role of carbonate burial in Blue Carbon budgets. Nat. Commun. 2019, 10, 1106.

79. Macreadie, P.I.; Serrano, O.; Maher, D.T.; Duarte, C.M.; Beardall, J. Addressing calcium carbonate cycling in blue carbon accounting. Limnol. Oceanogr. Lett. 2017, 2, 195–201.

80. Guerra-Vargas, L.A.; Gillis, L.G.; Mancera-Pineda, J.E. Stronger together: Do coral reefs enhance seagrass meadows “blue carbon” potential? Front. Mar. Sci. 2020, 7, 628.

81. Liu, C.C.; Jin, Q. Artificial upwelling in regular and random waves. Ocean. Eng. 1995, 22, 337–350.

82. Radice, V.Z.; Hoegh-Guldberg, O.; Fry, B.; Fox, M.D.; Dove, S.G. Upwelling as the major source of nitrogen for shallow and deep reef-building corals across an oceanic atoll system. Funct. Ecol. 2019, 33, 1120–1134.

83. Pandolfi, J.M.; Bradbury, R.H.; Sala, E.; Hughes, T.P.; Bjorndal, K.A.; Cooke, R.G.; McArdle, D.; McClenachan, L.; Newman, M.J.; Paredes, G.; et al. Global trajectories of the long-term decline of coral reef ecosystems. Science 2003, 301, 955–958.

84. Heron, S.F.; Maynard, J.A.; Van Hooidonk, R.; Eakin, C.M. Warming trends and bleaching stress of the world’s coral reefs 1985–2012. Sci. Rep. 2016, 6, 38402.

85. Kelman, I. Islandness within climate change narratives of small island developing states (SIDS). Isl. Stud. J. 2018, 13, 149–166.

86. Reef Resilience Network. Coral Gardening as an MPA Management Tool. Seychelles—Coral Restoration. 2022. Available online: https://reefresilience.org/case-studies/seychelles-coral-restoration/ (accessed on 7 June 2023).

87. Reef Rescuers Project. Nature Seychelles. 2023. Available online: http://natureseychelles.org/what-we-do/coral-reef-restoration (accessed on 7 June 2023).

88. Graham, N.A.J.; Jennings, S.; MacNeil, M.A.; Mouillot, D.; Wilson, S.K. Predicting climate-driven regime shifts versus rebound potential in coral reefs. Nature 2015, 518, 94–97.

89. Cerutti, J.M.; Burt, A.J.; Haupt, P.; Bunbury, N.; Mumby, P.J.; Schaepman-Strub, G. Impacts of the 2014–2017 global bleaching event on a protected remote atoll in the Western Indian Ocean. Coral Reefs 2020, 39, 15–26.

90. Eakin, C.M.; Devotta, D.; Heron, S.F.; Connolly, S.; Liu, G.; Geiger, E.; Cour, J.D.L.; Gomez, A.; Skirving, W.; Baird, A.H.; et al. The 2014–17 Global Coral Bleaching Event: The Most Severe and Widespread Coral Reef Destruction; Research Square: Durham, NC, USA, 2022.

91. Portner, H.O.; Roberts, D.; Masson-Delmotte, V.; Zhai, P.; Tignor, M.; Poloczanska, E.; Mintenbeck, K.; Nicolai, M.; Okem, A.; Petzold, J. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate; IPCC Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2019.

92. Dangendorf, S.; Marcos, M.; Wöppelmann, G.; Conrad, C.P.; Frederikse, T.; Riva, R. Reassessment of 20th century global mean sea level rise. Proc. Natl. Acad. Sci. USA 2017, 114, 5946–5951.

93. Sippo, J.Z.; Lovelock, C.E.; Santos, I.R.; Sanders, C.J.; Maher, D.T. Mangrove mortality in a changing climate: An overview. Estuar. Coast. Shelf Sci. 2018, 215, 241–249.

94. Saintilan, N.; Wilson, N.C.; Rogers, K.; Rajkaran, A.; Krauss, K.W. Mangrove expansion and salt marsh decline at mangrove poleward limits. Glob. Chang. Biol. 2014, 20, 147–157.

95. Yando, E.S.; Osland, M.J.; Willis, J.M.; Day, R.H.; Krauss, K.W.; Hester, M.W. Salt marsh-mangrove ecotones: Using structural gradients to investigate the effects of woody plant encroachment on plant–soil interactions and ecosystem carbon pools. J. Ecol. 2016, 104, 1020–1031.

96. Kelleway, J.J.; Saintilan, N.; Macreadie, P.I.; Skilbeck, C.G.; Zawadzki, A.; Ralph, P.J. Seventy years of continuous encroachment substantially increases ‘blue carbon’ capacity as mangroves replace intertidal salt marshes. Glob. Chang. Biol. 2016, 22, 1097–1109.

97. Arias-Ortiz, A.; Serrano, O.; Masqué, P.; Lavery, P.S.; Mueller, U.; Kendrick, G.A.; Mateo, M.A. A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. Nat. Clim. Chang. 2018, 8, 338.

98. Wernberg, T.; Krumhansl, K.; Filbee-Dexter, K.; Pedersen, M.F. Status and trends for the world's kelp forests. In World Seas: An Environmental Evaluation; Sheppard, C., Ed.; Academic Press: Cambridge, MA, USA, 2019; pp. 57–78.

99. Rovai, A.S.; Twilley, R.R.; Castañeda-Moya, E.; Riul, P.; Cifuentes-Jara, M.; Manrow-Villalobos, M.; Pagliosa, P.R. Global controls on carbon storage in mangrove soils. Nat. Clim. Chang. 2018, 8, 534–542.

100. Lovelock, C.E.; Atwood, T.; Baldock, J.; Duarte, C.M.; Hickey, S.; Lavery, P.S.; Steven, A. Assessing the risk of CO2 emissions from blue carbon ecosystems. Front. Ecol. Environ. 2017, 15, 257–265.

101. Spivak, A.C.; Sanderman, J.; Bowen, J.L.; Canuel, E.A.; Hopkinson, C.S. Global-change controls on soil-carbon accumulation and loss in coastal vegetated ecosystems. Nat. Geosci. 2019, 12, 685–692.

102. Bianchi, T.S. The role of terrestrially derived organic carbon in the coastal ocean: A changing paradigm and the priming effect. Proc. Natl. Acad. Sci. USA 2011, 108, 19473–19481.

103. Dunton, K.H.; Hardegree, B.; Whitledge, T.E. Response of estuarine marsh vegetation to interannual variations in precipitation. Estuaries 2001, 24, 851–861.

104. Hutchison, J.; Manica, A.; Swetnam, R.; Balmford, A.; Spalding, M. Predicting global patterns in mangrove forest biomass. Conserv. Lett. 2014, 7, 233–240.

105. Osland, M.J.; Feher, L.C.; Griffith, K.T.; Cavanaugh, K.C.; Enwright, N.M.; Day, R.H.; Rogers, K. Climatic controls on the global distribution, abundance, and species richness of mangrove forests. Ecol. Monogr. 2017, 87, 341–359.

106. Nicholls, R.J.; Cazenave, A. Sea-level rise and its impact on coastal zones. Science 2010, 328, 1517–1520.

107. Spencer, T.; Schuerch, M.; Nicholls, R.J.; Hinkel, J.; Lincke, D.; Vafeidis, A.T.; Reef, R.; McFadden, L.; Brown, S. Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. Glob. Planet. Chang. 2016, 139, 15–30.

108. Ellison, J.C. Mangrove retreat with rising sea-level, Bermuda. Estuar. Coast. Shelf Sci. 1993, 37, 75–87.

109. Mills, M.; Leon, J.X.; Saunders, M.I.; Bell, J.; Liu, Y.; O'Mara, J.; Lovelock, C.E.; Mumby, P.J.; Phinn, S.; Possingham, H.P.; et al. Reconciling development and conservation under coastal squeeze from rising sea level. Conserv. Lett. 2016, 9, 361–368.

110. Schuerch, M.; Spencer, T.; Temmerman, S.; Kirwan, M.L.; Wolff, C.; Lincke, D.; McOwen, C.J.; Pickering, M.D.; Reef, R.; Vafeidis, A.T.; et al. Future response of global coastal wetlands to sea-level rise. Nature 2018, 561, 231–234.

111. Worthington, T.; Spalding, M. Mangrove Restoration Potential: A Global Map Highlighting a Critical Opportunity; University of Cambridge: Cambridge, UK, 2018.

112. Möller, I.; Kudella, M.; Rupprecht, F.; Spencer, T.; Paul, M.; Van Wesenbeeck, B.K.; Wolters, G.; Jensen, K.; Bouma, T.J.; Miranda-Lange, M.; et al. Wave attenuation over coastal salt marshes under storm surge conditions. Nat. Geosci. 2014, 7, 727–731.

113. Koch, E.W.; Barbier, E.B.; Silliman, B.R.; Reed, D.J.; Perillo, G.M.; Hacker, S.D.; Granek, E.F.; Primavera, J.H.; Muthiga, N.; Polasky, S.; et al. Non-linearity in ecosystem services: Temporal and spatial variability in coastal protection. Front. Ecol. Environ. 2009, 7, 29–37.

114. Morim, J.; Hemer, M.; Wang, X.L.; Cartwright, N.; Trenham, C.; Semedo, A.; Erikson, L. Robustness and uncertainties in global multivariate wind-wave climate projections. Nat. Clim. Chang. 2019, 9, 711–718.

115. Albert, S.; Saunders, M.I.; Roelfsema, C.M.; Leon, J.X.; Johnstone, E.; Mackenzie, J.R.; Hoegh-Guldberg, O.; Grinham, A.R.; Phinn, S.R.; Duke, N.C.; et al. Winners and losers as mangrove, coral and seagrass ecosystems respond to sea-level rise in Solomon Islands. Environ. Res. Lett. 2017, 12, 094009.

116. Blair, N.E.; Aller, R.C. The fate of terrestrial organic carbon in the marine environment. Annu. Rev. Mar. Sci. 2012, 4, 401–423.

117. Toscano, M.A.; Gonzalez, J.L.; Whelan, K.R. Calibrated density profiles of Caribbean mangrove peat sequences from computed tomography for assessment of peat preservation, compaction, and impacts on sea-level reconstructions. Quatern. Res. 2018, 89, 201–222.

118. Deegan, L.A.; Johnson, D.S.; Warren, R.S.; Peterson, B.J.; Fleeger, J.W.; Fagherazzi, S.; Wollheim, W.M. Coastal eutrophication as a driver of salt marsh loss. Nature 2012, 490, 388–392.

119. Waycott, M.; Duarte, C.M.; Carruthers, T.J.; Orth, R.J.; Dennison, W.C.; Olyarnik, S.; Kendrick, G.A. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc. Natl. Acad. Sci. USA 2009, 106, 12377–12381.

120. Saintilan, N.; Khan, N.S.; Ashe, E.; Kelleway, J.J.; Rogers, K.; Woodroffe, C.D.; Horton, B.P. Thresholds of mangrove survival under rapid sea level rise. Science 2020, 368, 1118–1121.

121. Kirwan, M.L.; Murray, A.B.; Donnelly, J.P.; Corbett, D.R. Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. Geology 2011, 39, 507–510.

122. Swales, A.; Bentley Sr, S.J.; Lovelock, C.E. Mangrove-forest evolution in a sediment-rich estuarine system: Opportunists or agents of geomorphic change? Earth Surf. Proc. Landforms 2015, 40, 1672–1687.

123. Fennessy, M.S.; Ibanez, C.; Calvo-Cubero, J.; Sharpe, P.; Rovira, A.; Callaway, J.; Caiola, N. Environmental controls on carbon sequestration, sediment accretion, and elevation change in the Ebro River Delta: Implications for wetland restoration. Estuar. Coast. Shelf Sci. 2019, 222, 32–42.

124. FitzGerald, D.M.; Hughes, Z. Marsh processes and their response to climate change and sea-level rise. Annu. Rev. Earth Planet. Sci. 2019, 47, 481–517.