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Review

Blueprint for Blue Carbon: Lessons from Seychelles for Small Island States

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Abstract: Blue carbon has been proposed as a nature-based solution for climate change mitigation; however, a limited number of published works and data and knowledge gaps hinder the development of small island developing states' (SIDS) national blue carbon resources globally. This paper reviews the blue carbon ecosystems of Seychelles as a case study in the context of SIDS, comparing estimations by the Blue Carbon Lab and recent blue carbon (mangrove and seagrass) evaluations submitted to the Seychelles national government. Mangroves (2195 ha, 80% in Aldabra Atoll) and seagrasses (142,065 ha) dominate in Seychelles, with coral reefs having the potential for carbon sequestration (169,000 ha). Seychelles is on track to protecting its blue carbon, but these systems are threatened by rising sea levels, coastal squeeze, erosion, severe storms, and human activities. The importance of carbon inventories, accounting institutions, and continuous monitoring of blue carbon systems is discussed. Blue accounting is necessary for accurate accounting of carbon sequestration and carbon storage, generating carbon credits, and representing impactful reductions in greenhouse gases for NDCs. Challenges and opportunities include policy legislation regarding ownership rights, accreditation and certification for carbon credits, sustainable financing mechanisms like natural asset companies and blue tokens, local engagement for long-term success, and carbon market dynamics following COP27. The restoration and regulation of blue carbon resources for optimal ecosystem services delivery, carbon inventories, and blue carbon policy are recommended development priorities. Blue carbon ecosystems have the potential to contribute to NDCs of SIDS while simultaneously offering sustainable development pathways for local communities through the multiple ecosystem services they provide.

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

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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 [1]. The term denotes marine and aquatic ecosystems specifically as opposed to terrestrial "green" ecosystems such as rainforests [1,2]. 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 [2,3]. Recognition of blue carbon resources under the UN framework Convention of Climate Change in 2015 (UNFCCC) [4] allows nations to include the carbon sequestered by blue carbon resources under their nationally determined contributions (NDCs) [5] 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 [6]. 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) [7–9] to assist in the removal of carbon (and legacy carbon) from the atmosphere, contribute to NDCs, and contribute to climate change mitigation and adaptation [10,11]. 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 [12].

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 [13]. The global distribution of blue carbon resources has been estimated between 36 and 185 million ha [13], 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 [14], with the carbon stores of vegetated coastal systems having been estimated at between 10 and 24 Pg [11], making them important components in the marine carbon cycle [15]. Like many other habitats globally, many blue carbon ecosystems are degraded [16–19], 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 [13], and the restoration of these habitats would amount to sequestering an additional 841 (621–1064) Tg carbon dioxide equivalent by 2030 [13].

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 [20]. 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 [21,22]. 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 [1,12]. 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 [23–27]. The environmental and socio-economic benefits of blue carbon ecosystems, once fully realised, are hypothesised to incentivise their propagation [28], facilitating the development of the blue economy.

SIDS are particularly vulnerable to climate change effects [29] 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 [20]. Seychelles is widely known as a model country for blue economy development [30], 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 [31], 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 [32]. 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 [33]. 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 [33]. 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 [5] 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 [5,34], is highlighted further by the potential of blue carbon resources to contribute to reducing the vulnerability of SIDS to climate change and external shocks.

This paper reviews blue carbon ecosystems in Seychelles in the context of SIDS, incorporating the most recent blue carbon evaluations, blue accounting, and the challenges and opportunities in operationalising and monetising blue carbon for long-term sustainable growth. The aim of this paper is to collate available information on operationalising blue carbon resources in one document, using Seychelles as a case study country as an example for other SIDS to emulate. The paper aims to suggest actionable steps to be considered by policy makers and conservation biologists in the operationalising of blue carbon as well as propose novel yet important areas of consideration, identifying gaps where future research and work are required for the successful use of SIDS blue carbon resources in contributing to NDCs as well as commercialising blue carbon resources for national development. The rest of this review paper is structured as follows: a brief methodology on the literature reviewed (Section 2); a review of current and potential blue carbon in Seychelles (Section 3), blue accounting and valuing of blue carbon resources (Section 4), and opportunities and challenges in operationalising blue carbon resources (Section 5); and a conclusion (Section 6) with possible steps forward in operationalising blue carbon for Seychelles.

2. Methods

With a synoptic approach, this review consisted of a desktop study literature review. The literature review comprised a Boolean search of relevant academic articles and studies, publications for development organisations (such as the World Bank and the Blue Carbon Lab), public news articles, and national documents. Science Direct, Google, and Google Scholar were the databases used to gather relevant sources on the study topic online. Keywords in the literature search included search strings such as "blue carbon", "operationalising blue resources", "blue economy", "ecosystem services", "blue accounting", "blue carbon accounting", "carbon trading", "SIDS", and "Seychelles". Sources that dealt with blue carbon outside of the context of island countries and SIDS were excluded from the review. However, sources that discussed threats to blue carbon ecosystems, as well as sources discussing the contentious status of potential blue carbon ecosystems (such as kelps and coral reefs), were not excluded from the review, as these topics are directly applicable to operationalising blue carbon in a SIDS context. The paper incorporates findings from the literature review as well as knowledge from the authors' experience and professional network of scientists and researchers in the realm of Seychelles blue carbon and Seychelles blue economy development (including inputs from SeyCCAT and the Seychelles Seagrass Mapping and Carbon Assessment).

Blue carbon ecosystems that are reviewed include mangroves and seagrasses. Estimates of blue carbon stocks in Seychelles were investigated, and the most recent assessments are reported as they have been validated with field measurements [35,36]. The potential of coral reef systems as blue carbon habitats is also discussed. Considering that Seychelles does not have any tidal saltmarshes [37–39] and is not rich in kelp forests, a review of the stock assessments of these habitats has thus been omitted. The islands do experience influxes of floating *Sargassum* seaweed (as do other SIDS elsewhere), but these allochthonous influxes of *Sargassum* are not suitable for use as national blue carbon resources because the seaweed moves through multiple national boundaries (complicating carbon accounting) and, when it breaks down, releases carbon stored in its tissues [11,40]. The study is limited in that it does not discuss allochthonous inputs of blue carbon (such as migrating Sargassum seaweed), as developing a carbon accounting framework for such allochthonous blue carbon presents numerous challenges involved in the carbon flux accounting of kelp blue carbon resources, the primary being that there is no consensus of allowing migrating blue carbon (and associated carbon fluxes) to count towards national NDCs. Carbon accounting of kelp ecosystems is highly complex and has been discussed elsewhere [41–43]. This paper also does not discuss the blue carbon potential of seaweed (kelp) farming in the context of Seychelles; however, this topic has been covered elsewhere [44,45].

Research ethics approval was not applicable nor required for this review article.

3. Blue Carbon Resources for SIDS

3.1. 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 [5]. 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 [46]. 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 [47]. 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 [47]. 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 [48]. 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 [49].

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 [50]. 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 [51,52], 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 [13]). 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 [53]. A recent blue carbon assessment of Seychelles mangrove systems [35] as well as a mapping of the seagrass ecosystems (Seychelles Seagrass Mapping and Carbon Assessment Project [36]), 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 [51]. 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 [35] as well as the recent seagrass mapping [36] 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 [1,5,54]. 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 [55] and has designated 36 MPAs to be protected [51]. 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 [32]. Howard et al. [56] 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)	[35]
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)	[36]
Coral reefs	169,000 ha, in 2021	No data	No data	[57]

3.2. Mangroves

Global mangrove distribution has been estimated at 13 million ha [5,13]. 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. [5] 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 [58]. Palacios et al. [5] did not find any studies quantifying soil carbon stocks or accretion rates in Seychelles; however, a number of relevant studies were published thereafter, including [59], which investigated the change in mangrove cover in relation to wave exposure, and [60], 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 [5,51,59,61]. Wartman et al. [35] 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. [35] 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, [35,51,59,61]). 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 [5,24,62,63]. 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 [35]; however, mangrove biomass stocks are largely influenced by site conditions, species composition, and forest structure [63–65]. 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 [35]. 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 [35].

3.3. 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* [5]. All of the above-mentioned species are found in the Seychelles except *H. stipulacea* and *Zostera capensis* [5]. 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 [66]. 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 [38,67].

Previously mapped global seagrass distribution and estimates are surrounded by much uncertainty, with global seagrass cover ranging from 16 to 165 million ha [68–70]. Although limited studies on seagrasses in the Seychelles have been conducted [5], seagrass meadows in the region are plentiful [66], with seagrass mapping having been previously attempted with data from 2020 [5]. 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 [36] 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 [36], which is significantly less than what has been estimated before (2 million ha of seagrass cover [51]). 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 [36]). 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 [5], with two-thirds of seagrass carbon being stored in the soil [71] 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 [72]; 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%).

3.4. Coral Reefs

There has been a long-standing debate on whether coral reefs are net carbon sinks [73–75], carbon sources [76–78], or shifting between the two [79–81]. This is accompanied by a significant knowledge gap surrounding the topic. Shi et al. [81] 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 [82]). The unique combination of physical, chemical, and biological processes in different coral reef locations makes it difficult to achieve consistent calculations of carbon dynamics [74,83]. 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 [81,84,85], and such stressors not only threaten coral reef survival but also impact the ability to gauge their carbon sink–source attributes [81]. 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 [81] 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 [86]. 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 [81]. 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 [81]. 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 [81], 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 [83]. 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 [87,88]. 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 [81]: (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 [89]. (4) Artificial upwelling has the potential to improve nutrient cycling and carbon sinks in coral reefs [4,81,90,91]. 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 [4]). 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 [92,93]. SIDS may be experiencing this reduction at an elevated rate due to their susceptibility and their particular vulnerability to climate change effects [29,94]. This is particularly true for the Seychelles as numerous coral bleaching events have resulted in a 97% reduction in coral cover since 1998 [95]. 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 [96,97]. However, the third global bleaching event (2014–2017) heavily impacted coral reef systems, including the Aldabra Atoll [98,99]. 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 [98]. Coral cover in Seychelles was estimated at 1690 km^2 in 2021 (Table 1, [57]) 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 [81], 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 [81]. 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).

3.5. 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 [15]. Lovelock & Reef [15] 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 [100].

Exposure to climate change varies among ecosystems. All blue carbon is exposed to sea level rise to varying degrees (regionally and temporally [101]). Mangroves are exposed to drought and storms in subtropical regions but less so at the equator [102]. A less considered phenomenon is that saltmarsh blue carbon is vulnerable to mangrove encroachment where the distributions of these habitats overlap [103], in many cases altering and increasing sediment carbon storage [103–105]. 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 [106,107].

The sensitivity of blue carbon resources to climate change also varies [100]. Sedimentary organic carbon density varies globally among different settings [24,71,108], but it is expected that sediments with greater carbon density are more sensitive to processes that may disturb it [60,109]. 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 [110,111]. Examples such as nutrient input and pollution [110,111], changes in rainfall and sediment salinity [112–114], and wave action intensification [59] 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 [15].

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 [15].

3.6. Threats to Seychelles and Other SIDS Blue Carbon Resources

SIDS are particularly vulnerable to the effects of climate change [29] and, as such, so are their blue carbon resources. Seagrasses dominate the blue carbon ecosystems [5,36] 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 [115] 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 [116,117]. Human development of coastal environments potentially threatens blue carbon systems in what is known as the "coastal squeeze" [118,119]. 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 [118,119].

Wind regimes and the resulting waves influence a broad range of processes that impact carbon cycling and the ecology of coastal systems [120]. These are also affected by climate change and sea level rise [121–123]. Ocean islands and atolls are particularly vulnerable to the combined influence of rising sea levels and increased wave height [15]. 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 [124]. 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 [125]. 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 [117,126].

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 [15].

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 [127]); turbidity changes from runoff, which influence light penetration and limit seagrass productivity [128]; and the construction of dams limiting the ability of coastal environments to accrete sediment necessary for carbon storage [119,129]. However, in some cases, human intervention has the potential to enhance carbon stocks through sediment input from runoff [130–133]. 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 [15].

4. Blue Accounting

Accurate accounting of carbon sequestration and carbon storage is essential for generating carbon credits and representing an impactful reduction in greenhouse gases (CO_2). Blue accounting is thus necessary for the full operationalisation of blue carbon resources. Blue accounting covers accounting throughout the blue economy (including industries such as mining and tourism) and other ecosystem services of blue carbon ecosystems, whereas blue carbon accounting deals mainly with natural capital accounting (distribution) and ecosystem services accounting (such as carbon sequestration and storage). Failler et al. [72] reviewed various approaches to blue accounting in an African context. They explored approaches such as environmental satellite accounts (or "Integrated Economic and Environmental Accounts"), green accounting, natural capital accounting, ecosystem services accounting, blue economy (BE) economic accounting, BE social accounting, BE environmental accounting, and the application of BE accounting tools, namely the UNECA blue economy valuation toolkit (BEVTK), which had been applied in Seychelles [72]. Many of these approaches are based on the United Nations' (UN) System for Environmental Economic Accounting (SEEA) Central Framework, which is "an international statistical standard for environmental measurement and its impact on the economy" [134]. In a recent study, the SEEA framework was used as a base to develop an integrated blue accounting system for China's coastal blue carbon [135]. The system was designed as an integrated method that combines the ecological state of the blue carbon stocks, blue carbon accounting, investment payback period (that which was used for restoration costs), and carbon market prices to provide a comprehensive decision-making tool for operationalising national blue carbon resources [135]. McHarg et al. [47] followed a different approach, having conducted a scenario analysis to evaluate SIDS' (Grenada) blue carbon climate mitigation services. However, it is recommended that the approach used by Liu et al. [135] be adapted and considered for implementation in SIDS elsewhere.

There is a growing need for high-quality carbon, particularly in the voluntary carbon market, where demand is driven by the private sector's voluntary commitments to reduce carbon emissions. Blue carbon accounting is necessary in order to trade high-quality carbon credits on voluntary carbon markets as well as regulated international compliance markets (between national governments), in accordance with Article 6 of the Paris Agreement [136]. Article 6 of the Paris Agreement allows countries the opportunity to voluntarily cooperate with each other to achieve emission reduction targets as set out in their NDCs [136]. Article 6 specifies that emission reductions that have been authorised for transfer to another country (selling carbon emission offset credits), may only count towards one country's NDC [136]. This is critical such that double counting does not overestimate global emissions reductions. Agreement on Article 6 has established an accounting mechanism known as "corresponding adjustment" to ensure that double counting does not occur [136]. This means that the carbon mitigation outcome (carbon offset according to the number of carbon credits) must be "un-counted" from the party that agreed to transfer (sell) it [137]. While this appears simple to enact, questions surrounding when a corresponding adjustment should be applied remain contentious. Greiner et al. [137] discuss background information on such issues as well as others pertaining to the operationalisation of Article 6 of the Paris Agreement. Furthermore, the application of blockchain technology is being investigated by the World Bank as a method to reduce the potential for the same carbon credit to be counted twice, which may provide a solution to the questions and issues surrounding corresponding adjustments in the future [136]. Blockchain technology works by tracking all transactions in a secure and transparent digital ledger. If carbon credits for emissions reductions that are traded between two different parties (such as two national governments or a government and private parties) are catalogued on the blockchain, the potential for the same carbon credit to be counted twice for contributing to NDCs is reduced, and the associated "corresponding adjustment" can be applied correctly [136].

The core carbon principles (CCPs) have been established as a global benchmark in the development of high-quality carbon for the voluntary carbon market. The CCPs set rigorous thresholds on disclosure and sustainable development, providing a credible means of identifying high-integrity carbon credits, which create a verifiable climate impact [138] (iC 2023). The CCPs contribute to reducing "greenwashing", where organisations claim to facilitate a beneficial environmental impact when it does not exist. The ten CCPs are divided according to three areas of impact: emissions impact, governance, and sustainable development, and mandate "no double-counting". While the CCPs are intended for the voluntary carbon market (for the private sector), it is assumed that carbon traded on the international compliance market has been verified (according to the CCPs) by national government (approved) institutions or at least that such carbon credits attempt to adhere to the CCPs.

4.1. Valuing Blue Carbon Stocks

The sea–air CO_2 partial pressure difference has long been a deciding factor in whether an area of the sea is a carbon source or sink [139]; however, various blue carbon pools have been defined (such as soil organic carbon and plant carbon), and they need to be evaluated and considered in the valuation of a blue carbon system. The construction of a carbon inventory is essential for the valuation and operationalisation of blue carbon resources [140]. A carbon inventory can be thought of as the balance sheet of carbon-related ecosystem services at various levels (site-specific, national, regional, or even global scales). Quantifying the total greenhouse gas emissions from land use changes and estimating avoided carbon emissions from a climate change-related conservation project are examples where a carbon inventory is necessary. Creating a carbon inventory for a given area requires understanding (1) the past and present distribution of coastal vegetated ecosystems linked to the human uses of the area, (2) the current carbon stock within the project area and rate of carbon accrual, and (3) the potential carbon emissions that will result from expected or potential changes to the landscape [140].

There are various approaches to the valuation of the ecosystem services blue carbon resources provide. These include (from [141]) a market price approach (where commodities such as food, raw materials, and ecosystem services are measured according to the current market value); a benefits transfer approach (which relies on secondary data such as previous studies used to estimate non-market economic values of ecosystem services by transferring information from these previously completed works); an avoided cost and replacement cost approach (calculates the economic value of benefits that an ecosystem provides that would otherwise be an added cost to society if the ecosystem service did not exist); and a production functions approach (measuring the economic value of ecosystem services that lead to production in other areas such as the nursery function that mangroves supply in supplementing the fisheries industry).

Considering all of the different approaches to ecosystem service valuation, there is a need for a standardised and widely accepted/recognised method for blue carbon accounting [47], as many blue carbon valuation estimates are associated with a degree of scientific and economic uncertainty [47]. Such estimates are unlikely to convince investors and stakeholders of the financial attractiveness of a blue carbon project, further highlighting the need for quality-assured and trusted estimates. The parameterisation of the benefits that arise from ecosystem protection and rehabilitation, as well as their variation in space and time and with climate change effects (such as sea level rise), will contribute to more accurate estimates in blue carbon accounting [2,33,142]. Macreadie et al. [33] suggest that the use of technical advancements such as remote sensing and analytical tools would improve the quantification of blue carbon sequestration as well as the tracking of changes over time. The discovery of new blue carbon sequestration pathways as well as the investigation of lesser-known pathways (although not included in IPCC estimates of greenhouse gas emissions) could be incorporated into future national carbon inventories when future research provides the necessary evidence ([33]; for examples, see [102,143,144]). DNA tracing of carbon fluxes is an example of new developing research in the field [145].

The International Blue Carbon Initiative has prepared a "Blue Carbon Manual" for blue carbon accounting, providing step-by-step processes and identifying stages where expert advice or additional technical data may be required in the accounting process. The manual is consistent with international standards, the International Government Panel of Climate Change (IPCC) guidelines, and other relevant sources. Wartman et al. [35] have referenced this blue carbon manual in their evaluation of Seychelles mangrove systems, ground-truthing estimates through soil-core analyses as recommended. The blue carbon manual could be used to inform a national blue carbon accounting framework for the valuation of all of the blue carbon resources a (SIDS) country possesses, ensuring consistency across various carbon flux assessments related to different resources. Such a framework could be incorporated as part of a broader national blue economy accounting framework.

4.2. National (Centralised) Accounting Institution or Organisation

A first-pass assessment of Seychelles' blue carbon stocks has been estimated to be 250 million tonnes of organic carbon by the Blue Carbon Lab [146]. However, a more thorough assessment has been conducted, with the national blue carbon stock being estimated at 17 million tonnes of carbon [147]. These values from Seychelles' government-recognised and -endorsed organisation conflict with one another, as well as with other estimates in the available literature (Sections 3.2 and 3.3). Local valuations of blue carbon resources are associated with a degree of both scientific and socio-economic uncertainty [47]. Standardised assessment of blue carbon resources is necessary, but where this is found lacking, an internationally recognised institution could lend credence to estimates they produce through their reputation and scientifically sound methodologies (as has been carried out with prior estimates). Such an institution can provide critical quality assurance to stakeholders and is essential in the operationalisation of blue carbon projects. However, it should be stressed that ground-truthing of estimates with field measurements is the most accurate and reliable verification of blue carbon estimates (as in Wartman et al. [35]).

Furthermore, one centralised organisation that uses standardised accounting methodologies for a nation's blue carbon assessments facilitates consistency and ease across the valuations of different blue carbon systems a nation might have. Such consistency is essential when calculating a nation's carbon inventory for contributing towards NDCs and carbon offsets (with the potential of decarbonising other industries like shipping). Standardised units, unit conversions, and timescales are necessary to ensure consistency and coherence to judge how resources may have changed and how the valuation is then adjusted accordingly. Currently, one carbon credit indicates a once-off removal of one ton of CO_2 or greenhouse gas equivalent from the atmosphere. The price of a carbon credit fluctuates depending on which market they are traded on and associated market fluctuations. As with fiat currencies, standardised units are required for the exchange of value (in this case, carbon sequestration services) and further emphasises the need for thorough consistent accounting methodologies through a centralised organisation (e.g., a bank).

Seychelles Conservation and Climate Adaptation Trust (SeyCCAT) appears to be a logical choice as a centralised institution for blue carbon accounting for Seychelles. SeyCCAT has already contributed to the development of blue carbon through its Coastal Wetlands and Climate Change Project, which includes the mapping of blue carbon habitats and blue carbon stores for inclusion in the national greenhouse gas inventory.

4.3. Continuous Monitoring of Blue Carbon Systems

Continuously updated values for carbon ecosystem services are necessary for leveraging blue carbon resources over the long term for commercial value (i.e., on the carbon market) and attracting funding for transitioning to a more sustainable blue economy through the ability to track advancements in economic and environmental developments [72]. As such, continuous monitoring of the distribution of blue carbon ecosystems is necessary as well as long-term monitoring of the associated carbon fluxes. Monitoring needs to be reliable and trusted to inform decisions concerning carbon offsets and NDC contributions. Internationally recognised blue carbon accreditation presents a solution (Section 5.5) in providing quality assurance to investors and blue carbon stakeholders alike.

Accurate mapping of blue carbon stocks above and below ground in soils is essential to be able to account for the carbon sequestered by any one system as well as for being able to incorporate blue carbon into NDCs [5]. A major geographical gap in blue carbon datasets has been identified in Seychelles [5], but recent research efforts are working to address this [35,36]. Where remote sensing methodologies can be used for mapping the distribution of blue carbon resources (Malerba et al. [53] discuss the use of remote sensing for the estimation of carbon stocks and flux), on-site field measurements can provide ground-truthing [140].

Given that the majority of Seychelles' blue carbon stocks are situated within the outer islands of the archipelago, government and international actors facilitating accessibility to these islands (such as financing transport and permit approval) would ease research efforts and address important data gaps [5]. The continuous monitoring of soil carbon and mapping of mangroves and seagrass to provide accurate representations of the extent of Seychelles' blue carbon resources are recommended for their future sustainable exploitation [5], as is recommended for other SIDS as well.

5. Opportunities and Challenges in Operationalising Blue Carbon

Macreadie et al. [33] discuss the numerous challenges and uncertainty involved in operationalising blue carbon, including social, governmental, financial, and technical and scientific aspects. Macreadie et al. [33] suggest a few important actions that can be taken to advance the operationalisation of blue carbon: (i) establishing (or adopting) principles and practices for equitable sharing of benefits; (ii) establishing legislation to enshrine carbon trading systems; (iii) developing technologies and protocols to monitor the change in blue carbon systems, as well as co-benefits; and (iv) the development of stakeholder partnerships to develop assurance requirements for financial markets [33]. The integration of these actions (as well as actions described in Section 4) into a transdisciplinary research, development, and extension program will facilitate an operational market for blue carbon, attracting investment opportunities at an appropriate scale [33]. Agreement on principles and practices for equitable benefits provides the overall value proposition and the future vision for stakeholders of blue carbon programs [148]. The creation of legislation that encompasses carbon-trading systems and the development of technologies and protocols monitoring the co-benefits of blue carbon systems will ensure the quality and assurance needed to develop attractive financial agreements for a range of investors [33].

In operationalising blue carbon in Seychelles, the Blue Carbon Lab conducted a blue carbon stakeholder questionnaire in Seychelles [149]. A report was synthesised from the results of 103 stakeholders from 56 organisations and identified key points about local attitudes, knowledge, and frameworks surrounding Seychellois coastal ecosystems. In partnership with the James Michel Foundation, the Blue Carbon Lab has developed the Seychelles Blue Carbon Roadmap, detailing development pathways for operationalising blue carbon resources [150]. The Seychelles Blue Carbon Roadmap lays out a long-term development plan to establish nation-wide, evidence-based programs with the aim of protecting and restoring blue carbon resources to leverage them for climate change mitigation and adaptation. In supplementing the Seychelles Blue Carbon Roadmap, the following key challenges and opportunities remain to be addressed for operationalising blue carbon.

5.1. Ownership and National Policy

Coastal vegetated systems occupy intertidal and subtidal zones along coastlines, creating complications from a legal perspective [33]. The boundary between privately owned and state-owned land is often covered with mangrove cover, and seagrasses and seaweeds can exist beyond exclusive economic zones (EEZs, such as the Joint Marine Area between Seychelles and Mauritius and the Saya de Malha bank) or within countries but where state laws conflict [33]. Confusion can thus arise as to land tenure and how this intersects with the commercialisation of blue carbon assets [151]. Who owns the blue carbon and who has the right to transact carbon credits for a given blue carbon project: the landholder, project developer, indigenous groups, or national/subnational government? For example, in Indonesia, the rights to carbon credits from REDD+ projects have been contested because land ownership does not automatically give rights to carbon sequestration services [152]. Governments have different laws for determining the boundary between private and public land, and in cases where human modification to the coastal zone has occurred (such as floodgates, levees, and dykes), the tidal boundaries have been altered, further complicating the matter [144]. Furthermore, climate change effects such as sea level rise and the subsequent landward retreat of coastal ecosystems (such as wetlands) create difficulties in development planning and managing land tenure, with novel legal issues arising [153,154].

Land tenure issues can be resolved through contractual agreements whereby both parties can agree on where carbon ownership lies irrespective of underlying property rights [155]. The investigation and development of solutions for land tenure complications are necessary where climate change effects alter the distribution of blue carbon resources [33]. This is particularly important for countries with complex land tenure structures and where blue carbon projects have been designed to achieve multiple benefits that must be shared among several stakeholders (such as stacking environmental credit markets from one area of land, i.e., nitrogen and carbon credits) [33]. The financial viability of a blue carbon project is often greater with increased size; however, this necessitates working with multiple land and carbon owners, thus increasing transaction costs associated with project establishment and requiring the development and use of novel solutions such as common asset trusts [156].

Shifting boundaries increase the uncertainty of blue carbon accounting in cases such as mangrove encroachment (onto saltmarshes) or vice versa [105,157,158]. The use of "rolling covenants", which balances short-term use of land with inland blue carbon migration, may be a solution [159]. An alternative solution may be the temporary privatisation of blue carbon resources such as that being carried out with the kelp concessions in South Africa. Blue carbon resources could be divided up into concession areas and then auctioned to the highest bidder for a predetermined period (for example, 1–2 years). The highest bidder obtains ownership rights to the asset for this period to leverage the ecosystem services as they please. Once the lease period expires, the boundaries of concession areas can be re-determined or adjusted and auctioned again. Such a system facilitates a changing suite of stakeholders, ensuring that new stakeholders can enter a future blue carbon industry. An important aspect of this system is the enforcement of strict rules as to the use and alterations of the concession area, such as imposing permanent interdicts of coastal infrastructure development but allowing environmental development and restoration to occur, setting a limit as to the number of concession areas that may be owned by one party, and regulating the sub-letting of concession areas and sustainable harvesting.

The Seychelles' updated NDC [32] in accordance with the Paris Agreement, as well as the currently ongoing initiative to update the Seychelles climate strategy (published in 2009), demonstrates the commitment of Seychelles to align its development trajectories with the objectives of the Paris Agreement and sustainable development goals. The updated NDC specifies the protection of 50% of its seagrass and mangrove systems by 2025 (100% protection by 2030), the establishment of long-term monitoring programs for blue carbon systems and carbon sinks, the inclusion of blue carbon into the national greenhouse gas inventory, and committing to the Seychelles Marine Spatial Plan for the effective management of its EEZ [32]. However, it does not deal with the issue of land ownership, land tenure, community rights, and similar related issues pertaining to operationalising blue carbon. *In lieu* of this, it is advisable that the benefits of state-owned blue carbon resources (such as those within MPAs) be delivered at the local level for associated benefits beyond those of NDCs (such as the sale of sovereign credits from state blue carbon once NDCs have been fulfilled). Seychelles' civil code (1976) and Environmental Protection Act (1995) suggest that marine resources such as seabeds, rivers, foreshores, and intertidal zones (up to the highwater mark) belong to the public domain and are thus owned by the Seychelles government [160]. However, this is not always the case, as in the example of the offshore Saya de Malha Bank, which is jointly governed by Seychelles and Mauritius. In 2012, Seychelles and Mauritius extended their continental shelf to include the Mascarene Plateau, resulting in the shared governance of 400,000 km^2 of seabed (while the rest of the water column remains on the high seas [160]). Both Mauritius and Seychelles thus need to develop legal frameworks for the conservation and use (particularly what pertains to the rights to blue carbon) of biodiversity areas beyond national jurisdiction (BBNJ); the UN is currently developing an international legally binding instrument to address this issue (BBNJ Agreement). Notwithstanding, the rights to carbon credits (as well as other developing credits such as biodiversity and resilience credits) need to be understood and defined in the framework of the Seychelle legal system [160].

5.2. Payment for Ecosystem Services

There are different forms of payment or compensation for ecosystem services, which are reviewed by Bennett et al. [28]; however, Vanderklift et al. [161] provide a published review of the constraints and opportunities of market-based finance for blue carbon restoration and protection. Payment or compensation for ecosystem services includes biodiversity offsetting, nutrient trading credits and markets, and natural capital as publicly traded equities (Section 5.3). However, the development of blue carbon resources and assets is mainly commercialised through nutrient trading markets, specifically carbon credit markets. For example, Macreadie et al. [13] proposed that 20% of the world's mangrove forests may qualify for carbon credit schemes, with 10% being profitable, having the potential to generate USD 1.2 billion per year in carbon benefits [162].

A major issue with any form of carbon mitigation project is that it is highly reliant on carbon accounting methodologies [163], regardless of whether these are used for national development contributions (NDCs), voluntary markets, or compliance markets. This implies that investments may end up being directed to projects where the scope of carbon capture and sequestration impact can most easily be accounted for at the lowest costs instead of carbon sequestration projects that lead to optimal carbon outcomes [28]. Data limitations contribute to the limited attention and funding such projects are able to collect [28].

The Verified Carbon Standard Program (VCS, the most widely used voluntary program for greenhouse gas emission reduction) has previously updated its methodologies to include blue carbon-related emissions reduction into the REDD+ methodology framework, which has enabled coastal blue carbon projects to sell carbon credits in voluntary or regulated markets [164]. Any blue carbon project is likely to be either part of NDCs or the voluntary carbon market. High demand in compliance markets has limited the uptake of carbon credits and carbon offsets. Market conditions for carbon credit prices have been continuously changing; however, carbon prices on the EU ETS have been rising since the end of November 2020. There was a price of around EUR 22 per carbon credit at the end of November 2020 [165]. The latter half of 2021 saw rising prices on voluntary offsetting markets, which several market participants expected to continue in 2022 [166]. Prices peaked around EUR 96 in February 2022 but fell as Russia invaded Ukraine. A stable carbon price (as is the case for other nutrient trading markets) would facilitate more accurate estimates as to the financial attractiveness of blue carbon projects, which in turn may increase investor confidence (through more accurate risk assessments) and accelerate the operationalisation of blue carbon globally [28].

Major companies and countries are increasing their voluntary commitments to mitigating climate change by making net zero pledges (Seychelles among them). One challenge is that voluntary offsetting is inherently external to the operations of the companies buying the offsetting, which limits their incentive to invest. If faced with an immediate economic downturn (or the risk of one), there is a risk that companies will have to discontinue voluntary offsetting or switch to cheaper credits [28]. This may also indirectly incentivise participation in regulated markets more so than voluntary ones. Furthermore, given the expected rise in demand, a concern has been the lack of quality, reliable projects [28]. Declaring an ecosystem that provides these benefits as an MPA may increase the perceived reliability with which the offsetting can be expected to be available year on year. Further, it facilitates buyer confidence that the service will be improved upon and that credits may in the future become relatively cheaper. The declaration of where proceeds are invested may further encourage buy-in from potential offset buyers, as it would contribute to other NDCs like fisheries and aquaculture development, which may be of benefit to the buyers if they operate in those industries (added benefits to carbon offset investing if the environment also provides fisheries stimulation, i.e., capitalising on co-benefits).

While carbon market prices change, other nutrient credit markets may not be as volatile. This may present a unique opportunity where other elements (nitrogen) may be charged and capitalised similarly, increasing the value of any one ecosystem, especially considering the bioremediation capabilities that ecosystems like mangroves and seaweeds may have in reducing the negative effects associated with pollutants or fertiliser runoff. The multiple co-benefits (ecosystem services) of blue carbon systems (such as coastal protection, tourism and recreation, and biodiversity and fisheries enhancement) can be capitalised upon through the conceptualisation of "resilience credits" [33]. Resilience credits comprise the stacking of multiple ecosystem services credits, where buyers pay for both carbon and coastal protection, for example. The market for biodiversity and nature credits is now beginning to emerge [33], with a leading verification standards body promoting a climate, community, and biodiversity standard (CCBS) that transparently assesses the contribution of a carbon credit project to a variety of biodiversity and community livelihood criteria [33]. Almost 200 projects have been assessed against these criteria up to now [167], and project developers are beginning to promote the quantification of biodiversity as a marketable credit option [168].

5.3. Natural Asset Companies

The Intrinsic Exchange Group (IEG) in collaboration with the New York Stock Exchange is pioneering the creation of a new asset class: natural asset companies (NACs). The purpose of such companies is to maximise the performance of the natural asset they are associated with, whether this be through ecosystem services provisioning, restorative/regenerative agricultural use, or hybrid cases integrating both. These companies are evaluated by the IEG and listed for trading on world platforms, enabling the conversion of natural assets into financial capital. The same approach could be applied to blue carbon assets as a way of monetising not only the carbon sequestration benefits of the resource but all of the co-benefits that are associated with such systems. Examples of co-benefits include other ecosystem services, such as nursery services supplementing fisheries and aquaculture, coastal protection, food and job security, and socio-cultural heritage and supporting endemic biodiversity.

The valuation and metrics performance measures used to assess the natural assets need to be standardised and agreed upon. This presents a challenge as non-neighbouring natural assets (in different countries for example) face different ecological, climate, social, and political stressors, which dictate their functioning and performance. The establishment of an optimal functioning baseline of performance becomes inherently difficult and is facilitated by the historical data available for each region, as well as human bias or mistakes during the evaluation [28].

Nonetheless, natural capital can now be used for revenue generation through NACs, similar to the companies of other industries whose equity can be traded on international stock markets. The sustainable management of the blue carbon resource that underpins the ecosystem services such that the maximum benefits are realised is thus incentivised by potentially global markets [28].

5.4. Other Sustainable Financing Mechanisms

Bennett et al. [28] reviewed various finance and financing solutions for application in the fisheries and aquaculture sectors of SIDS; however, these can easily be applied to blue carbon resources as well. Seychelles is a global frontrunner in the use of debt-for-nature swaps (Seychelles debt swap of 2015) as well as blue bond financing (Seychelles blue bond, [169]); however, other solutions such as blue tokens and blue levies may be useful for funding blue carbon restoration and conservation.

Blue tokens may be particularly beneficial as they could democratise investment into blue carbon resources, giving anybody a chance to be a stakeholder in national blue carbon development. Blue tokens operate on the proposition where blockchain and financial technology are used to garner finance for development projects [170]. An issuer could set an amount they would like to raise, for example, USD 10 million with an initial fixed repayment coupon. The initial price of each token could be predetermined at USD 10, with one million tokens being issued on a secure blue token market or platform. Any investor who has been approved through rigorous identity checks, like know your client (KYC) and anti-money laundering (AML) checks, can then buy tokens and either hold them to maturity or trade them among other investors on the blue token platform [170].

Other opportunities exist in applying for funding from international organisations or programmes, such as the UN Warsaw framework for REDD$^+$ programme. The REDD$^+$ framework (which was recognised in the Paris Agreement) details methodological and financing guidance for REDD$^+$ activities [171]. These activities were mainly nestled in the forest sector, concerning the reduction in emissions from deforestation and forest degradation [171]. Through *Mangroves for the Future* (a partnership-based international initiative), the United Nations Development Programme (UNDP) and the International Union for the Conservation of Nature (IUCN) have spearheaded the inclusion of mangrove forests into REDD$^+$ strategies and frameworks [164]. The mangrove forests of Seychelles may qualify for REDD$^+$ support [164]. Different organisations, initiatives, and donors that supply funding for REDD+ activities can be found on the REDD+ Web platform.

5.5. Blue Carbon Accreditations

Blue carbon resource accreditations are necessary for operationalising blue carbon systems, specifically in the form of official recognition/certification of verified carbon sinks. Such accreditation would be particularly useful and important for "non-traditional" blue carbon resources such as kelp forests and coral reefs, where site-specific assessment is necessary to confirm the ecosystem's net carbon sink functioning (as not all systems of the same type are carbon sinks). Some international accreditations or certifications of blue carbon projects include Verified Carbon Standard (VCS), Plan Vivo, Verra Climate Community and Biodiversity Standards (CCBS), Social Carbon, and Gold Standard [164]. These certifications are necessary in generating quality carbon credits and increasing confidence in specific blue carbon systems, as well recognising conservation and restoration progress that has taken place (avoiding greenwashing). Furthermore, the opportunity for the establishment of a reference system using recognised accreditations may provide an easier and on-hand indication as to the capacity of the blue carbon resource to sequester carbon. For example, a "level 1" blue carbon resource would indicate that a system sequesters only 20 Mg C.ha^{-1}.year^{-1}, whereas a "level 5" system sequesters carbon at a scale of millions of Mg C.ha^{-1}.year^{-1}. Such a system may be beneficial to inform investor, stakeholder, conservation, and development decision making.

5.6. Local Engagement

Local engagement should be incorporated into the operationalisation of blue carbon resources as part of transformative change and the development of social equity solutions and opportunities [33]. Previous injustices have occurred with the development of the blue economy [172], and the incorporation of knowledge from local indigenous communities in operationalising blue carbon resources may be the first step to transformative change. However, the approach, methodologies, and process of how to perform this have been identified as a key knowledge gap [173,174]. There are opportunities to align blue carbon credit incentives with other benefits such as sustainable tourism ventures and enhance ecosystem delivery such that local communities may benefit from blue carbon development, either as part-beneficiaries or through the prior agreed commitment to developing the livelihoods of the local communities (through education development, job creation, or infrastructure creation).

Key lessons can be learnt from coastal and marine protected area management in terms of what encompasses local and long-term support [174]. Previous research on carbon projects shows that the involvement of the local community facilitates the success of carbon projects more so than without [175]. This includes not only free, prior, and informed consent but also necessitates broad community support such that local communities are invested in the success of the blue carbon project [28]. For example, projects that aim to preserve seagrasses may collaborate with fishers where fishing operations intersect with seagrasses. Instead of starting operations with the sole purpose of monitoring sea grasses, collaboration with fishers could be cost effective (by having them participate in monitoring efforts) and provide further income for fishers [28].

The establishment of locally managed marine areas (LMMAs) can be an effective platform for achieving social and environmental development goals [160]. In 2020, Seychelles established its first LMMA as part of a regional project by Nature Seychelles and the IUCN. The Locally Empowered Area Protection project seeks to engage local communities in the management of Port Launay and Baie Ternay Marine National Parks, while the communities benefit from the sustainable use of these systems [160]. The project will build infrastructure, undertake conservation and restoration actions, provide training and equipment, and support sustainable tourism and fisheries [160]. The goal of the project is to improve local governance such that it can support equity in the design, decision making, and benefit sharing of developing ecosystem frameworks through evidence-based policy review [160].

5.7. United Nations Climate Change Conference (COP27)

The recent 2022 United Nations Climate Change Conference (COP27) furthered the development of carbon markets and non-market-based carbon offsetting, as well as other elements of Article 6 of the Paris Agreement. Of the notable decisions made at COP27 was the decision to allow companies the opportunity to purchase sovereign carbon credits [176], credits intended for international compliance markets and contributing towards NDCs. This allowance should be made on the condition that signatory countries have fulfilled their NDCs and are able to generate surplus credits afterwards; otherwise, countries may be fiscally incentivised to sell these credits prior to fulfilling their NDCs, rendering their use null. Sufficient frameworks for such allowances need to be established either in national legislation or in the regulated compliance market for it to be used responsibly and effectively.

The recent developments under Article 6 may also hold challenges for the voluntary carbon market. Governments may now have an incentive to push private companies to use Article 6 credits instead of voluntary offsets, as these credits could be used in counting towards NDC emissions reductions whereas offsets on the voluntary market cannot [177]. This may have financial implications as prices for carbon offsets may differ between voluntary and international compliance markets. Companies may also opt for Article 6 credits out of economic interest as they may hold tax implications in the future [177]. Article 6 credits may reduce a company's tax bill (making it uneconomical to use voluntary carbon offsets), functioning similarly to the EU's Carbon Border Adjustment Mechanism, where foreign firms pay a tariff on exports into the EU unless a carbon tax has been paid elsewhere [177]. Furthermore, once Article 6 credits become available to the private sector, voluntary carbon credits carry reputational risk, potentially disincentivising their use, particularly in light of greenwashing and fear of public backlash [177].

5.8. IUCN National Blue Carbon Policy Assessment Framework

The International Union for the Conservation of Nature (IUCN) has developed a National Blue Carbon Policy Assessment Framework with the goal of helping countries assess policy development options and priority blue carbon development pathways for the operationalisation of national blue carbon ecosystems [178]. The five-step framework facilitates a first-order analysis of blue carbon resources and blue carbon policy, identifying the potential for improved coastal ecosystem management at the national policy level [178]. The approach of the framework allows the user to analyse the application of existing legal and financial incentive schemes (such as payment for ecosystem services schemes) to national blue carbon resources [178]. This framework is thus recommended for use by SIDS hoping to fully operationalise their national blue carbon resources through the continuous development of a blue carbon policy.

While Seychelles is often regarded as a model country for sustainable blue development, including blue carbon development, there are no past or present blue carbon development projects that have followed the IUCN National Blue Carbon Policy Framework in its entirety (to the best of the authors' knowledge). However, the Seychelles Conservation and Climate Adaptation Trust's (SeyCCAT) "Coastal Wetlands and Climate Change Project", having started in 2015, is likely the most developed blue carbon project in terms of restoration and conservation, already contributing to NDCs, which has been provisioned for in national policy. The National Blue Carbon Policy Assessment Framework [178] can thus be used as a tool for reviewing the development outcomes of this project as well as monitoring policy development priorities as relates to blue carbon utilisation and conservation. The associated framework assessment tool is also recommended to be used for the establishment of new Seychelles blue carbon projects in the future (such as on Aldabra Atoll or Saya de Malha Bank in partnership with Mauritius).

6. Conclusions

The blue carbon stocks in Seychelles have the potential to contribute to NDCs as well as to be operationalised and monetised for use on the carbon market. Seychelles is rich in blue carbon seagrass resources as well as mangroves and thus has significant potential in blue carbon coral systems. Seychelles is also well known for its coral reef systems, which hold blue carbon potential but are dependent on the results of site-specific blue carbon accounts. Continuous mapping and monitoring of carbon fluxes (above and below ground) are necessary and are currently being addressed through the SeyCCAT Coastal Wetlands and Climate Change Project. Updated datasets of the blue carbon distribution and storage capacity are instrumental for investor decision making, and future research should be directed to fill knowledge gaps concerning SIDS blue carbon.

Regulated blue accounting programmes and recognised institutions are necessary for quality assurance in leveraging blue carbon resources for commercialisation. Institutions such as international banks or certification organisations may serve as globally recognised authorities in valuing blue carbon resources. Accurate mapping and regular assessment of blue carbon resources over time are necessary, particularly in the light of changing environments in the context of climate change, to ensure correctly valued *quid pro quo* exchanges for ecosystem services produced from blue carbon resources. Currently, this responsibility falls to whomever is wanting to operationalise the resource. However, a national centralised blue carbon accounting institution or organisation that covers the valuation of Seychellois blue carbon systems is recommended to ensure consistency and quality assurance across the various valuations. The use of internationally recognised standardised methods and approaches to blue carbon valuation and the conception of a national blue accounting framework would be beneficial in this regard. The blue accounting framework could be incorporated into existing blue carbon development initiatives such as the Seychelles Blue Carbon Roadmap. Official recognition and accreditations of specific blue carbon resources are necessary to leverage high-quality carbon credits on international and voluntary markets to add credence to emerging blue carbon resources and ecosystem services on market platforms, particularly for carbon sink coral reef systems and marine kelp forests and aquaculture operations. In summary, the process for generating carbon credits from a blue carbon system is as follows: (i) the monitoring of ecosystem services to establish baselines, (ii) establishing operations that facilitate carbon credit generation, (iii) the certification of carbon credit generation, (iv) the trading of carbon credits, and (v) the equitable sharing of benefits.

While several opportunities and challenges for operationalising blue carbon resources in Seychelles exist, the development of a blue carbon policy concerning ownership (and the distinction or lack thereof between land ownership and carbon ownership) is necessary to inform a developing but nascent industry. The legitimacy of blue carbon projects is a significant factor in attracting investors and garnering funding. Local stakeholder engagement and community development alongside blue carbon development may incentivise project funding, and the use of digital technology such as blue tokens and the blockchain may encourage individual and community-level buy-in (particularly pertaining to corresponding adjustments on carbon markets), necessary for the long-term success of blue carbon projects.

There is an opportunity for the operationalisation of blue carbon resources in Seychelles and in SIDS elsewhere. Ecosystem services that blue carbon ecosystems provide can be commercialised through capitalising on nutrient markets (other than just the carbon market), registration as natural asset companies, and capitalising on the many co-benefits that blue carbon resources provide. The priorities for operationalising blue carbon systems in SIDS elsewhere should be the restoration and regulation of blue carbon resources to facilitate optimal carbon sequestration capabilities, the development of carbon inventories for national resources and continuous monitoring programmes, and the development of payment for ecosystem services and a blue carbon policy. Despite the limited impact blue carbon systems have in the global reduction in greenhouse gases, these systems should be leveraged as potentially impactful nature-based solutions for sustainable community and coastal development among SIDS through the multiple ecosystem services they provide with the benefit of carbon sequestration. Blue carbon ecosystems have the potential to contribute to NDCs of SIDS while concurrently offering sustainable development pathways for local SIDS communities.

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