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The potential for mangrove and seagrass blue carbon in Small Island States

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Blue carbon is attracting substantial interest as a natural climate solution. Focus has been on countries with large blue carbon stocks, though the high carbon densities of blue carbon ecosystems make them suitable for Small Island States with small coastal habitats. Small Island States hold 1806–2892 Tg of blue carbon, and mangroves alone offset > 10% of land use emissions for 11-16 Small Island States, highlighting their potential contribution to national climate change mitigation if they are protected and restored. However, < 10% of Small Island States have incorporated blue carbon into their National Greenhouse Gas Inventories or Forest Reference Emissions Levels, only 23% have quantitative and measurable blue carbon targets, and 36% have no mention of blue carbon at all. There is immense scope to implement robust blue carbon targets and actions in many Small Island States, with Nationally Determined Contributions to the Paris Agreement being a key policy lever.

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Introduction

The urgency of the climate crisis requires the use of all interventions that can contribute to climate change mitigation. While decarbonization is the primary mitigation pathway, reducing emissions from the land use sector and sequestering carbon through restoration activities is also expected to play an important role. These options are covered under the umbrella of Natural Climate Solutions (NCS), a set of 20 pathways that reduce emissions of greenhouse gases (GHGs) and increase carbon sequestration through conservation, restoration, and improved management practices in forests, wetlands, and grasslands [1].

Two key NCS pathways are avoided coastal impacts (thus avoiding emissions) and coastal ecosystem restoration [1]. They are expected to be particularly impactful because they involve blue carbon ecosystems (mangroves, seagrasses, and tidal marshes), that are characterised by disproportionately high rates of carbon sequestration [2] and densities of carbon storage [3] compared to many terrestrial ecosystems. Blue carbon is an effective NCS compared to other ecosystems because of its generally negative sustained global warming potential when other GHG emissions (such as methane) are accounted for [4]. Blue carbon conservation and restoration could offset as much as 3% of global fossil fuel emissions [5].

Blue carbon has attracted substantial interest from policymakers [6] and the financial industry [7]. Interest has focused on countries with large blue carbon resources, with Indonesia, Australia, and the USA contributing the most to the world's blue carbon 'wealth' [8]. These countries have established robust frameworks for blue carbon conservation and restoration. For example, Indonesia has recently enacted several new blue carbon policies and has established a new agency responsible for mangrove restoration, with an ambitious mangrove restoration target of 600,000 ha by 2024 [9]. The Australian Government has produced a method for estimating the climate change mitigation benefits of national blue carbon restoration projects [10], and the bipartisan 'Blue Carbon for Our Planet Act' has been discussed by the US Government to provide direct support for blue carbon activities and initiate pilot projects [11].

The disproportionately high carbon densities of blue carbon ecosystems mean it may also be suitable for countries with small and fragmented habitat extent, such as Small Island States. Small Island States are extremely vulnerable to climate change but are responsible for < 1% of global GHG emissions [12], so blue carbon can make a substantial contribution to carbon offsetting for these countries. For example, mangroves and seagrasses in the Republic of Kiribati store 100 times more carbon than the country's annual carbon emissions [13]. A recent study of blue carbon in the Bahamas suggested that current seagrass blue carbon resources were offsetting enough carbon to make the Bahamas carbon neutral [14]. Most Small Island States also rely on blue carbon ecosystems in their broader blue economy, contributing to fishery production, ecotourism, coastal protection, and other ecosystem services [15,16].

This Review discusses the potential for blue carbon as a natural climate solution for Small Island States (defined here as the Membership of the Alliance of Small Island States (AOSIS), established in 1990). We first define blue carbon and describe the rationale for its use in Small Island States, and calculate the potential for blue carbon to contribute to their national climate change mitigation efforts. We then synthesise current management and policy actions in Small Island States that incorporate blue carbon and provide suggestions for increasing blue carbon targets and actions in future climate change mitigation strategies.

Defining blue carbon

Lovelock & Duarte [17] present six multidisciplinary criteria that define a blue carbon ecosystem: (1) whether the ecosystem has a scale of GHG removal or emissions reduction that are significant; (2) there is the potential for long-term storage of fixed carbon; (3) the ecosystem is currently experiencing negative anthropogenic impacts; (4) management is practical to maintain or enhance carbon stocks and reduce greenhouse gas emissions; (5) management interventions will have no environmental or social harm; and (6) their management aligns with other policies for climate change mitigation and adaptation. Currently, mangroves, seagrasses, and tidal marshes satisfy all criteria and have been the focus of most blue carbon research, management, and policy efforts.

Tidal freshwater forested wetlands meet many blue carbon criteria [17], though uncertainty remains on their global extent, which may limit the significance of their GHG removal (*Criteria 1).* Tidal flats have been estimated to store 0.9 Pg C and bury 6.8 Tg C per year globally [18], though their dynamic nature raises concerns around carbon permanence (*Criteria 2*) and whether management can have positive carbon benefits (*Criteria 4*) [17]. Macroalgae has received substantial commercial interest due to their high rates of primary production [19,20], but the proportion that can be stored permanently at timescales relevant to climate change mitigation (*Criteria 2*) is unproven. Indeed, numerous biophysical and ethical issues undermine the viability of macroalgae as an NCS [21]. Other ocean systems have been proposed (e.g. [22]), such as carbon stored in the sea bed, oyster reefs, fisheries management, and marine megafauna. However, several of the criteria proposed by Lovelock & Duarte [17] cannot be proven for these ecosystems, the impact of disturbance is unknown or overestimated [23], or the scale of carbon burial is too small or uncertain (e.g. [24]), to the extent that some may provide 'false hope' and further delay other required climate change mitigation actions [25]. However, such ecosystems could be incorporated into future assessments of blue carbon resources and offsetting potential in Small Island States if their scientific underpinnings become strengthened with new research, and robust and viable carbon accounting mechanisms become available.

The potential for blue carbon in Small Island States

The rationale for including blue carbon in Small Island States

Blue carbon can be an important NCS for Small Island States. Mangroves and seagrasses in particular can represent a substantial proportion of a State's vegetated carbon stock since terrestrial vegetated ecosystems may be limited in extent, particularly in atoll nations. The high carbon densities of these ecosystems mean that a Small Island State does not necessarily need a large extent of blue carbon habitat to be able to have a substantial amount of carbon storage at the landscape scale. Small Island States also often experience rapid loss of their blue carbon ecosystems. For example, four of the top 10 countries experiencing the highest rates of mangrove loss between 2000 and 2012 were Small Island States [26]. As such, there is large scope for blue carbon creation through the conservation of threatened habitats and the restoration of those that have been previously lost, with this additional blue carbon suitable for use in carbon offsetting.

However, the geomorphic setting of some Small Island States may limit the potential of blue carbon in some locations. Many Small Island States are situated on coral atolls, and blue carbon ecosystems in these geomorphic settings can produce substantial greenhouse gas emissions due to the production of CO_2 during calcification, to the extent that calcification-induced CO_2 emissions can exceed rates of blue carbon sequestration [27]. As such, the carbonate geochemistry of karstic systems may reduce the net effectiveness of blue carbon for some Small Island States.

The potential contributions of blue carbon to Small Island States

Blue carbon ecosystems cover 7.1–12.8 million ha across Small Island States (data from [5]). Areal extent estimates are likely to be conservative since small habitat patches are challenging to map with global satellite datasets. Macreadie et al. 2021 calculated national-level blue carbon stocks using a variety of aboveground biomass and soil carbon models (e.g. [28-31]), and these data suggest that Small Island States collectively hold 1806–2892 teragrams of blue carbon, with the majority held in seagrass meadows because of their greater extent across these nations.

To estimate potential climate change mitigation benefits from mangrove carbon sequestration, the approach of Taillardat et al. [2] was adapted. Offsetting potential was estimated for 1) stable mangroves (the carbon sequestration of existing mangrove forests in a country); 2) avoided deforestation (emissions from deforestation and potential sequestration foregone by deforested mangroves only); and 3) the net balance of sequestration and emissions (the carbon sequestration of existing mangrove forests in a country, minus any emissions from deforestation and sequestration potential foregone by deforested mangroves). These were then compared to a nation's emissions from Agriculture, Forestry and Other Land Uses (AFOLU). AFOLU emissions were chosen because this is the United Nations Framework Convention on Climate Change (UNFCCC)'s land use category under which mangrove deforestation emissions would be accounted. This estimation can only be made for mangrove forests due to the availability of globally-consistent data on mangrove area change. The offsetting potential of seagrasses would be expected to be substantially higher (notwithstanding the issues of calcium carbonate geochemistry described above), considering their larger areal extent across Small Island States and often greater rates of loss [32] compared to mangroves.

Existing forests are able to be incorporated into National Greenhouse Gas Inventories (e.g. Forest Land Remaining Forest Land; [33]). When calculating offsetting potential using the existing mangrove resource, mangrove sequestration in sixteen countries was able to offset > 10% of AFOLU emissions in 2020. These included countries that reported low AFOLU emissions (such as the Federated States of Micronesia, Seychelles, and Singapore), and countries with higher AFOLU emissions but also relatively large mangrove areas (such as Belize, Cuba, and Papua New Guinea). Twelve countries had mangroves that could sequester sufficient carbon to offset 1–10% of the nation's AFOLU emissions, and the remaining six countries had mangroves that were making a negligible (< 1%) contribution. These latter countries included Barbados (0.1%), Comoros (0.3%), Cook Islands (0.3%), and Dominica (0.0%), which all have mangrove extents < 1km^2, so the contributions of existing mangroves would be expected to be limited.

Avoided deforestation strategies are common in carbon accounting as a method of estimating the emissions that could have been saved by conservation. Eleven countries would have been able to offset > 10% of their AFOLU emissions in 2020 if they had deployed mangrove avoided deforestation strategies, with a further four countries potentially able to offset 1–10% of emissions. The countries with the greatest offset potential reported high rates of mangrove deforestation between 2019 and 2020. For example, Guinea Bissau lost 18.76 km^2 and Papua New Guinea lost 10.88 km^2 of mangroves between 2019 and 2020 [34]. Some countries lost a smaller area of mangrove in absolute terms, but the rates of loss were high relative to the nation's AFOLU emissions (e.g. Antigua and Barbuda, and the Federated States of Micronesia). Eleven countries (such as Cook Islands, Kiribati, Maldives, Singapore and Tuvalu) had negligible offset potentials (0–1%) with avoided deforestation because they are experiencing little to no mangrove deforestation as recorded by global-scale remote sensing. Interestingly, eight Small Island States (Bahamas, Barbados, the Dominican Republic, Jamaica, Mauritius, Saint Kitts and Nevis, Saint Vincent and the Grenadines, and Samoa) had a negative offsetting potential for avoided deforestation. This means that avoided deforestation strategies could not be deployed because these countries reported an expansion in the mangrove area between 2019 and 2020, rather than a net loss.

When considering the net balance of sequestration by existing mangroves and emissions and foregone sequestration due to deforestation, mangroves were able to offset > 10% of AFOLU emissions for eleven Small Island States. This includes Cuba (11.4% of AFOLU emissions offset), the Federated States of Micronesia (67.4%), Fiji (55.3%), and the Maldives (172.0%). A further eleven countries had existing mangrove carbon balances that could offset between 1% and 10% of their national AFOLU emissions, while three countries had a negligible offsetting potential between 0% and 1%. Importantly, nine countries (Antigua and Barbuda, Comoros, Guinea Bissau, Guyana, Papua New Guinea, Saint Lucia, Suriname, Trinidad and Tobago, and Vanuatu) had a negative offsetting potential; this means that mangroves in these nations contributed more emissions than they sequestered in 2020. However, these countries represent an important climate change mitigation opportunity; if deforestation can be stopped or slowed then sufficient mangroves still remain that could be able to make a contribution to offsetting AFOLU emissions.

There may also be a substantial opportunity to offset AFOLU emissions through habitat restoration. Models suggest that as much as 62,319 ha of former mangrove areas have the potential to be restored across Small Island States, and if successful would eventually create biomass and soil carbon stocks of 38,502,315 Mg C in volume (data from [35]). However, it should be noted that this potential refers to areas that are biophysically suitable for restoration and does not include the myriad socioeconomic and governance factors that will substantially reduce the area that is ultimately feasible for restoration [36]. Achieving these

Table 1

Offsetting potential for (a) carbon sequestration for existing mangroves; (b) potential avoided deforestation offsetting; and (c) net balance of mangroves against AFOLU.

Countries	E_{AFOLU} in 2019 (TgC yr^{-1})[a]	(a) Existing mangrove contribution			(b) Avoided deforestation contribution					(c) Net balance contribution	
		Surface area in 2019 (km^2)[b]	$S_{mangrove}$ in 2019 (TgC yr^{-1})[c]	Potential of stable mangroves to offset AFOLU emissions (%)	Mangrove change 2019–2020 (km^2 yr^{-1})[b]	$E_{mangrove}$ 2019–2020 (TgC yr^{-1})[d]	$S_{mangrove\_foregone}$ (TgC yr^{-1})[c]	$E_{mangrove}$ + $S_{mangrove\_foregone}$ (TgC yr^{-1})	Potential of avoided deforestation to offset AFOLU emissions (%)	$S_{mangrove}$ - ($E_{mangrove}$ + $S_{mangrove\_foregone}$) (TgC yr^{-1})	Mangrove potential to offset AFOLU emissions (%)
Antigua and Barbuda	0.006	8.77	0.001	24.0	-0.08	0.005	< 0.001	0.005	85.9	-0.004	-61.7
Bahamas*	0.004	1517.49	0.255	5897.2	23.72	-1.861	n/a	-1.861	-43048.1	2.116	48945.3
Barbados	0.013	0.1	< 0.001	0.1	0.01	-0.001	n/a	-0.001	-7.0	0.001	7.1
Belize	0.096	530.43	0.089	93.2	-1.74	0.085	< 0.001	0.085	88.8	0.004	4.4
Comoros	0.055	0.98	< 0.001	0.3	-0.01	< 0.001	< 0.001	0.001	1.7	-0.001	-1.4
Cook Islands	0.002	0.03	< 0.001	0.3	0.00	0.000	0.000	0.000	0.0	< 0.001	0.3
Cuba	3.532	3599.72	0.605	17.1	-2.78	0.203	< 0.001	0.203	5.7	0.402	11.4
Dominica	0.010	0.01	< 0.001	0.0	0.00	0.000	0.000	0.000	0.0	< 0.001	0.0
Dominican Republic	2.762	191.47	0.032	1.2	0.37	-0.022	n/a	-0.022	-0.8	0.054	2.0
Federated States of Micronesia	0.012	88.18	0.015	120.8	-0.24	0.006	< 0.001	0.007	53.1	0.008	67.8
Fiji	0.104	488.71	0.082	79.3	-0.57	0.025	< 0.001	0.025	24.0	0.057	55.4
Grenada	0.004	1.93	< 0.001	7.9	0.00	0.000	0.000	0.000	0.0	< 0.001	7.9
Guinea Bissau	0.493	2707.08	0.455	92.2	-18.76	0.985	0.003	0.988	200.4	-0.533	-108.1
Guyana	0.763	290.42	0.049	6.4	-1.83	0.114	< 0.001	0.114	15.0	-0.066	-8.6
Haiti	1.180	154.17	0.026	2.2	-0.16	0.011	< 0.001	0.011	0.9	0.015	1.3
Jamaica	0.146	99.42	0.017	11.4	0.03	-0.002	n/a	-0.002	-1.3	0.019	12.7
Kiribati	0.002	1.46	< 0.001	12.2	0.00	0.000	0.000	0.000	0.0	< 0.001	12.2
Maldives	< 0.001	0.97	< 0.001	172.0	0.00	0.000	0.000	0.000	0.0	< 0.001	172.0
Mauritius	0.031	4.27	< 0.001	2.3	0.05	0.000	n/a	0.000	-1.0	0.001	3.4
Papua New Guinea	0.199	4535.62	0.762	382.8	-10.88	0.830	0.002	0.832	418.1	-0.070	-35.3
Saint Kitts and Nevis	0.002	0.34	< 0.001	2.3	0.01	-0.001	n/a	-0.001	-40.4	0.001	42.7
Saint Lucia	0.011	1.63	< 0.001	2.6	-0.01	0.001	< 0.001	0.001	6.8	< 0.001	-4.2
Saint Vincent and the Grenadines	0.004	0.32	< 0.001	1.2	0.01	0.000	n/a	0.000	-11.0	0.001	12.2
Samoa	0.051	2.31	< 0.001	0.8	0.01	0.000	n/a	0.000	-0.3	0.001	1.0

Table 1 (*continued*)

Countries	E_{AFOLU} in 2019 (TgC yr^{-1})[a]	(a) Existing mangrove contribution			(b) Avoided deforestation contribution					(c) Net balance contribution	
		Surface area in 2019 (km^2)[b]	$S_{mangrove}$ in 2019 (TgC yr^{-1})[c]	Potential of stable mangroves to offset AFOLU emissions (%)	Mangrove change 2019–2020 (km^2 yr^{-1})[b]	$E_{mangrove}$ 2019–2020 (TgC yr^{-1})[d]	$S_{mangrove\_foregone}$ (TgC yr^{-1})[c]	$E_{mangrove}$ + $S_{mangrove\_foregone}$ (TgC yr^{-1})	Potential of avoided deforestation to offset AFOLU emissions (%)	$S_{mangrove}$ - ($E_{mangrove}$ + $S_{mangrove\_foregone}$) (TgC yr^{-1})	Mangrove potential to offset AFOLU emissions (%)
Sao Tome and Principe	0.004	0.48	< 0.001	1.8	0.00	0.000	0.000	0.000	0.0	< 0.001	1.8
Seychelles	0.001	3.83	0.001	74.3	0.00	0.000	0.000	0.000	0.0	0.001	74.3
Singapore	0.005	7.3	0.001	24.3	0.00	0.000	0.000	0.000	0.0	0.001	24.3
Solomon Islands	0.020	527.5	0.089	433.5	-0.99	0.087	< 0.001	0.088	428.1	0.001	5.4
Suriname	0.168	808.3	0.136	80.8	-7.86	0.404	0.001	0.405	241.1	-0.269	-160.3
Timor Leste	0.266	10.52	0.002	0.7	-0.02	0.002	< 0.001	0.002	0.6	< 0.001	0.1
Tonga	0.0213	10.58	0.002	8.3	-0.15	0.001	< 0.001	0.001	6.5	< 0.001	1.8
Trinidad and Tobago	0.062	83.45	0.014	22.6	-1.22	0.066	< 0.001	0.066	106.2	-0.052	-83.6
Tuvalu	0.001	0.09	< 0.001	1.9	0.00	0.000	0.000	0.000	0.0	< 0.001	1.9
Vanuatu	0.127	16.35	0.003	2.1	-0.51	0.045	< 0.001	0.045	35.5	-0.042	-33.4

The net carbon balance of mangroves is estimated for stable mangroves by calculating the carbon sequestration of existing mangroves ($S_{mangrove}$) versus emissions from mangrove loss ($E_{mangrove}$) and foregone carbon sequestration opportunity ($S_{mangrove\_foregone}$).

[a] Minx et al. [41].

[b] Bunting et al. [34].

[c] Using an average sequestration value estimated by Taillardart et al. [2];

[d] Based on estimates of national carbon stocks provided by Macreadie et. al [5]; Note that Cabo Verde, Nauru, Niue, Palau and the Republic of the Marshall Islands are not included in this analysis due to no presence of mangroves, or insufficient data on mangrove extent or AFOLU emissions.

[*] Values for the Bahamas are high due to low reported E_{AFOLU} and a large reported increase in mangrove extent.

Table 2

A non-exhaustive summary of current plans and actions around blue carbon for climate change mitigation in Small Island States, based on the publicly available information (See Table S1 for full information and references).

Country	Summary of blue carbon plans and actions	Quantitative targets?	Integrated into National GHG Inventory?
Antigua and Barbuda	Mangrove and seagrass conservation	✓	X
Bahamas	Mangrove conservation and restoration, considering blue carbon credits	X	X
Barbados	No identifiable blue carbon actions can be found	X	X
Belize	Mangrove conservation and restoration, including calculation of blue carbon benefits, considering blue carbon credits	✓	**Commitment for next NDC**
Cabo Verde	Seagrass conservation	X	X
Comoros	No identifiable blue carbon actions can be found	X	X
Cook Islands	No identifiable blue carbon actions can be found	X	X
Cuba	No identifiable blue carbon actions can be found	X	X
Dominica	No identifiable blue carbon actions can be found	X	X
Dominican Republic	Mangrove conservation and restoration	X	X
Federated States of Micronesia	No identifiable blue carbon actions can be found	X	X
Fiji	Mangrove and seagrass conservation and restoration	X	X
Grenada	Mangrove and seagrass conservation	X	X
Guinea Bissau	Mangroves in National Greenhouse Gas Inventory	X	✓
Guyana	Mangrove conservation and restoration	X	X
Haiti	Mangrove conservation and restoration	✓	X
Jamaica	Mangrove restoration project established	X	X
Kiribati	Mangrove and seagrass conservation and restoration	✓	✓
Maldives	No identifiable blue carbon actions can be found	X	X
Mauritius	Mangrove and seagrass restoration	X	X
Nauru	No identifiable blue carbon actions can be found	X	X
Niue	No identifiable blue carbon actions can be found	X	X
Palau	Offsetting emissions using blue carbon	X	X
Papua New Guinea	Committed to incorporating blue carbon into the National Greenhouse Gas Inventory	X	**Commitment** for **next NDC**
Republic of the Marshall Islands	No identifiable blue carbon actions can be found	X	X
Saint Kitts and Nevis	No identifiable blue carbon actions can be found	X	X
Saint Lucia	Conducting a blue carbon stock assessment	X	X
Saint Vincent and the Grenadines	No identifiable blue carbon actions can be found	X	X
Samoa	Mangrove restoration	✓	X
Sao Tome and Principe	No identifiable blue carbon actions can be found	X	X
Seychelles	Mangrove and seagrass conservation	✓	X
Singapore	Mangroves incorporated into the National Greenhouse Gas Inventory	X	✓
Solomon Islands	Mangrove conservation	X	X
Suriname	Mangroves in Forest Reference Emissions Level	✓	✓
Timor Leste	Mangrove restoration	X	X
Tonga	Mangroves may have been incorporated into the National Greenhouse Gas Inventory	X	X
Trinidad and Tobago	Mangroves incorporated into the National Greenhouse Gas Inventory	✓	✓
Tuvalu	No identifiable blue carbon actions can be found	X	X
Vanuatu	Mangrove conservation	X	X

carbon stock values will also take substantial time, as some mangrove forests can take as long as 40 years to reach maturity [37], with soil carbon stocks expected to take much longer [38]. An analysis similar to Table 1 cannot currently be conducted for restoration, because of insufficient data on carbon sequestration in mangrove restoration projects through time, which is essential because sequestration and soil carbon accumulation in mangroves show non-linear responses with age [39,40]. Similarly, global estimates of restoration potential and expected sequestration rates do not currently exist for seagrasses or tidal marshes.

Current blue carbon actions in Small Island States

An analysis of publicly available information on blue carbon actions for climate change mitigation (Table 2, Table S1) shows a mixed picture for Small Island States.

These actions are primarily described through a country's Nationally Determined Contribution (NDC) to the Paris Agreement, and associated Nationally Appropriate Mitigation Actions [42] and National Greenhouse Gas Inventories. Only 23% of Small Island States have quantitative and measurable blue carbon targets in their NDCs, and only four countries (Guinea-Bissau, Kiribati, Suriname, Trinidad and Tobago) have explicitly incorporated blue carbon into their National Greenhouse Gas Inventories or Forest Reference Emissions Levels. Forty-one per cent of Small Island States mention blue carbon or describe ambitions without quantitative targets. While this shows an appreciation of the role of blue carbon ecosystems in climate change mitigation, quantitative targets are required to show the measurable impact of blue carbon management and provide incentives for incorporating blue carbon into national policies. Thirty-six per cent of Small Island States had no identifiable blue carbon plans or actions. However, many of these countries did mention these ecosystems in their NDCs in the context of climate change adaptation; this suggests that governments are aware of the importance of these ecosystems and have policies that may cover them, and climate change mitigation could be added to these efforts.

It is encouraging to see that some Small Island States have begun to estimate their blue carbon resources and incorporate them concretely into policy processes. The NDC for Belize outlines a range of quantitative targets for blue carbon management [43,44]. The Belize government has pledged to (i) halt and reverse net mangrove loss by 2025; (ii) protect > 6000 ha of mangroves by 2025 and an additional 6000 ha by 2030; (iii) restore > 2000 ha of mangroves by 2025 and an additional 2000 ha by 2030; and (iv) through these actions remove a cumulative total of 381,000 Mg CO_2e between 2021 and 2030. These targets are quantitative and measurable so their success can be assessed across successive NDC submissions. Belize is also one of the few countries to move beyond targets for area conservation and expansion, and towards quantifying what the climate change mitigation outcomes of those interventions might be. These ambitious targets have spurred several studies on blue carbon in Belize, including a recent assessment of the national climate change mitigation potential of blue carbon, associated ecosystem service co-benefits, and spatial prioritization of locations for protection and restoration [45].

A comprehensive Blue Carbon Road Map has been produced for the Seychelles [46]. Mangroves stored 810,858 Mg C and estimates of seagrass carbon stocks ranged from 16.9 to 249.8 million Mg C, primarily due to differing estimates of national seagrass extent. In total, this report estimated that Seychelles' blue carbon ecosystems draw down 200,000 Mg C per year, offsetting 60% of national CO_2 emissions. The road map advocates for blue carbon data repositories, the establishment of a blue carbon expert working group, and the evaluation of national policies for entry points for blue carbon, amongst other actions [46]. The NDC for Seychelles has committed (with external support and funding) to protecting 50% of its seagrasses and mangroves by 2025, rising to 100% by 2030, in order to contribute to the country's net zero ambitions [47].

In Grenada, blue carbon ecosystems fall under the National Adaptation Plan, designed to support the country's NDC. Scenario analyses suggest that current rates of habitat loss will lead to the emissions of 212,860 Mg CO_2 by 2050, valued at US$7.63 million, though more pessimistic scenarios suggest that the carbon cost to society could exceed US$25 million [48].

In Singapore, Friess et al. [49] estimated that 12.6 million Mg of CO_2e were released through the destruction of blue carbon ecosystems in Singapore since 1953, and ~580,000 Mg C of blue carbon remains stored along its coastline today. Friess et al. [49] also describe various management and policy actions that have been implemented in Singapore to conserve and restore blue carbon ecosystems, including various coastal restoration projects, the incorporation of blue carbon into national planning strategies, and the establishment of Singapore as a regional financial hub for carbon credit trading.

Challenges remain for blue carbon implementation in Small Island States

While successful case studies of blue carbon management and target setting exist in Small Island States, there is a substantial gap between blue carbon potential and implementation for many nations. Blue carbon strategies face numerous biophysical, socioeconomic and governance barriers such as financing, land availability and tenure, and community inclusion [50,7,51-53], which have limited their application globally. In addition to these generic constraints, Small Island States are likely to experience barriers specific to their unique environmental, socioeconomic and political settings.

- *Lack of baseline information*. Few previous blue carbon studies have been conducted in Small Island States [48], as seen in Table 1, and noted more broadly in the Indian Ocean region [54], which is home to a proportion of Small Island States. Baseline information is essential in order to quantify blue carbon contributions and integrate them into National Greenhouse Gas Inventories. Some academic studies have produced data on national blue carbon stocks for countries such as Belize [45] and the Bahamas [14]. The NDCs of Bahamas, Belize and Cabo Verde proposed to initiate blue carbon assessments (Table S1), and assessments are underway in Guyana, Saint

Lucia, and Suriname. However, the focus is primarily on carbon stocks, rather than key additional information required for carbon accounting, such as carbon sequestration and other fluxes.

Lack of information should not necessarily be seen as a reason not to include blue carbon in NDCs and national GHG inventories, as these mechanisms are designed to incorporate varying data availability and uncertainty through a tiering system. Tier 1 has the most basic data requirements and relies on global or Intergovernmental Panel on Climate Change (IPCC) default values; Tier 2 incorporates country-specific data; and Tier 3 is the most data-intensive approach which includes the collection of local data and the creation of landscape-specific models that incorporate more process pathways than previous tiers. Thus, it is possible to incorporate some blue carbon information into national GHG inventories even prior to a national blue carbon assessment.

- *Lack of scientific and policy capacity.* Numerous NDCs stated that proposed actions were conditional on external support and expertise. Blue carbon is an emerging research field so local expertise may be lacking in some contexts. Interviews with stakeholders suggest that those without relevant expertise can be overwhelmed by the strict accounting requirements of blue carbon strategies [55]. Small Island States such as the Dominican Republic, Fiji, Guyana, Papua New Guinea, Suriname and Vanuatu are signatories to the Reducing Emissions from Deforestation and Degradation (REDD)+ Readiness Fund [56]. This fund is designed to support countries to build capacity to prepare frameworks for forest carbon activities, that could include mangroves. This Fund focuses particularly on creating policy expertise and assisting with national strategy design, carbon accounting and inventories [57].
- *Challenges in incorporating non-forested ecosystems.* Existing blue carbon knowledge is particularly focused on mangrove forests [58], and only ~21% of Small Island States mentioned seagrasses in their blue carbon plans and actions (Table S1). This is despite seagrasses accounting for ~86.9–87.8% of the blue carbon habitat extent across Small Island States, and 53.8–79.6% of blue carbon stocks (calculated from [5]). The disproportionate attention on mangroves is in part because of underlying biases in scientific and media attention [59]. There may also be a perception that it is challenging to incorporate non-forested ecosystems such as seagrasses and tidal marshes into national GHG inventories because mangroves can be considered within the Forests category, as is done in the NDCs of Small Island States such as Singapore and Suriname (Table S1). However, seagrasses are included in three of nine CO_2 emissions and removal activities in the IPCC's Wetlands Supplement [60], so can be included in GHG inventories. The Blue Carbon Initiative [61] provide comprehensive guidance to countries for incorporating blue carbon into NDCs, including readiness assessments and setting baseline emissions from blue carbon loss.
- *Limited understanding of calcium carbonate geochemistry.* We now know that geochemical processes inherent to karstic systems produce carbon emissions that can in some cases exceed rates of blue carbon sequestration [27]. Calcifying algae found in some seagrass systems may also add to these emissions [62]. Current methods of blue carbon accounting largely ignore the inorganic carbon cycle [63], and the net effect of organic and inorganic carbon cycling is a key area for future research both globally [64] and for Small Island States on karstic geologies. Measurements of carbon fluxes associated with calcification would give a more accurate picture of the true potential of karstic mangrove and seagrass systems to act as a climate change mitigation strategy.
- *Lack of funding.* Many NDCs stated that proposed blue carbon actions were conditional on external funding support, and a range of funding sources will need to be accessed. This is particularly an issue because blue carbon projects (particularly those restoration) can be substantially more expensive than equivalent projects in terrestrial ecosystems [65]. Some blue carbon projects in Small Island States have been funded by development loans, such as a 1600 ha mangrove restoration project in Jamaica supported by the Inter-American Development Bank [66]. Small Island States would also qualify for intergovernmental funding such as the UNFCCC's Green Climate Fund. A host of private sector funding sources are also suitable for blue carbon projects, with carbon credit purchases for offsetting purposes gaining huge attention from the corporate sector [7]. Blue carbon is now traded on international carbon credit exchanges, with 250,000 credits sold in 2022 through a Singapore-based exchange for at least US$6.95 million, at a minimum reserve price of US$27.80 per tonne [67]. Financial instruments such as Blue Bonds have been launched or proposed for several Small Island States, though have faced criticism for unclear metrics of impact and poor transparency [68]. Thus, multiple funding sources exist, and Small Island States may ultimately require a blended finance approach incorporating multiple public, private and philanthropic funding streams [7].

All barriers will benefit from greater knowledge sharing amongst the Small Island States. Groups exist to provide guidance on blue carbon implementation, some of which include some Small Island States in their membership. For example, the governments of Fiji, Papua New Guinea, and Seychelles are members of the International Partnership for Blue Carbon, alongside intergovernmental organizations such as the Pacific Island Development Forum and the Pacific Islands Forum

Secretariat. Other Fora include a larger number of Small Island States and may provide a more inclusive platform for knowledge sharing, including AOSIS and the United Nations Office of the Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States (UN-OHRLLS).

Conclusions

The disproportionate carbon densities of blue carbon ecosystems mean they can play a meaningful contribution to the national climate change mitigation targets of Small Island States, even when their ecosystem extents are small. They can offset a substantial proportion of carbon emissions, particularly for nations with low fossil fuel or land use emissions. Some nations such as Belize, Kiribati and Singapore have already begun quantifying their blue carbon assets and incorporating quantitative blue carbon targets into their NDCs. However, there is a large potential to expand this across other Small Island States. Blue carbon is still a new management and policy tool, though evidence, guidance and standardized procedures for blue carbon accounting and policy now exist. However, the implementation of seagrasses into national blue carbon efforts is lagging compared to mangroves. This is a missed opportunity, as seagrasses account for the majority of ecosystem extent and blue carbon stock across Small Island States. Information sharing is needed between Small Island States on creating blue carbon inventories and implementing blue carbon solutions in these unique environmental and policy settings. A number of structures such as AOSIS already exist to facilitate knowledge exchange; doing so may help better conserve and restore imperilled coastal ecosystems in island nations.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cosust.2023.101324.

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