Conserving Mangrove Wetlands with Coastal Blue Carbon in the Caribbean

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ABSTRACT

The growing conservation finance gap presents a critical challenge to wetlands protection. However, the growing interest in nature-based solutions may help close this gap. In this paper, we review the various factors that might impact the viability of blue carbon as a market mechanism for supporting implementation of wetland protection programs, such as the Ramsar Convention, financially in the Caribbean. We conduct a literature review to ascertain the compatibility of the existing program mechanisms with different valuation methods, including an overview of requirements for accessing markets, a summary of market values that might be considered, and a broad overview of the potential value of mangrove carbon stocks in the Caribbean. We find that the existing coastal wetland carbon stocks of the Caribbean hold enormous monetizable potential, as the region boasts large expanses of some of the most productive carbon sequestering ecosystems, especially mangroves. However, there are still substantial gaps in our understanding of these stocks, including the exact extent of different ecosystem types and estimates of their carbon stocks under different geological, hydrological, and environmental conditions. Blue carbon financing could be a viable funding source to promote the wise use of coastal wetlands by supporting ongoing as well as future restoration efforts.

RESUMEN

La creciente brecha financiera para la conservación presenta un desafío crítico para la protección de los humedales. Sin embargo, el creciente interés en las soluciones basadas en la naturaleza puede ayudar a cerrar esta brecha. En este artículo, revisamos los diversos factores que podrían afectar la viabilidad del carbono azul como mecanismo de mercado para apoyar la implementación de programas de protección de humedales, como la Convención Ramsar, en el Caribe. Llevamos a cabo una revisión de la literatura para determinar la compatibilidad de los mecanismos del programa existente con diferentes métodos de valoración, incluyendo una descripción general de los requisitos para acceder a los mercados, un resumen de los valores de mercado que podrían considerarse y una descripción amplia del valor potencial de las reservas de carbono de los manglares en el Caribe. Encontramos que las reservas de carbono existentes en los humedales costeros del Caribe tienen un enorme potencial financiero, ya que la región cuenta con grandes extensiones de algunos de los ecosistemas secuestradores de carbono más productivos, especialmente los manglares. Sin embargo, todavía existen déficits en nuestra comprensión de estas reservas, incluida la extensión exacta de los diferentes tipos de ecosistemas y las estimaciones de sus reservas de carbono en diferentes condiciones geológicas, hidrológicas y ambientales. El carbono azul podría ser una fuente de financiación viable para promover el uso racional de los humedales costeros apoyando los esfuerzos de restauración actuales y futuros.

INTRODUCTION

There have been many local, national and international initiatives to protect wetlands against human as well as natural pressures. Adequacy of funding as well as adequate infrastructure and law enforcement consistently correlate with overall management effectiveness (though not necessarily with improved resource outcomes; Cook and Heinen 2005; Heinen et al. 2017; Leverington et al. 2010), and sustainability of funding is assumed to ensure protected area longevity (Ervin 2003). Unfortunately, sustainable financing mechanisms have persistently posed a challenge to biodiversity conservation, especially in least economically developed nations (Emerton et al. 2006). The lack of funding has affected a wide range of conservation activities (Bruner et al. 2004), including protected area expansion (though to a lesser extent) (Hockings et al. 2006), operations and enforcement (Diaz-Campos and Vilés-Lopez 2020; Munguía and Heinen 2021; Munguía et al. 2023), and conservation education programs (Shah 2021).

In addition to the need for funding, ecosystem valuation can help nations and site managers better place into context the value of their natural resources and evaluate the opportunity costs of protection (Sinclair et al. 2021). Wetlands represent a disproportionate amount of the monetary value of global ecosystem services provided by natural biomes (Costanza et al. 2014; Davidson et al. 2019). Some of these values are more easily monetized, such as the flood protection, carbon sequestration, subsistence, and recreational values of coastal wetland systems. The Ramsar Convention has promoted the analysis and determination by contracting parties of various economic values of wetlands since at least its 1997 report, Economic Valuation of Wetlands (Barbier et al. 1997). It has subsequently employed its Scientific and Technical Review Panel (STRP) and other

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partners to produce further guidance on wetland valuation (de Groot et al. 2006). Recently, the Ramsar secretariat has expressed interest in broadening the convention's otherwise biodiversity-centric objectives to include provisioning of other ecosystem services (Convention on Wetlands 2018), namely, coastal blue carbon (Beers et al. 2020).

The International Partnership for Blue Carbon is a global network of governments, organizations, and research institutions that collaborate to accelerate the adoption and implementation of blue carbon activities (Blue Carbon Partnership 2023). Although the term "blue carbon" was initially coined to refer generally to carbon sequestered by the marine biome, "coastal blue carbon" refers to carbon that is sequestered in three ecosystem types: mangroves, seagrasses, and intertidal marshes (International Partnership for Blue Carbon 2017). Recent research has indicated that coastal vegetated systems may represent the most significant carbon sink per unit area (Barbier et al. 2011; Moomaw et al. 2018), especially mangrove systems. The increasing attention on these coastal wetlands has highlighted the need for expanded research in inventorying carbon stores in these systems and understanding their sociopolitical and economic contexts to improve management (Thomas 2014).

The Ramsar Convention joined the International Partnership for Blue Carbon in 2017 (The Ramsar Convention Secretariat 2017). This partnership aims to improve information sharing among representatives of government, non-governmental, and research organizations. It may also provide a viable avenue for financing wetland conservation and enhancing Ramsar implementation, provided that certain scientific, policy, and economic requirements are met. However, the Convention itself has not historically provided guidance for gaining access to carbon markets, instead leaving that work to the UN Framework Convention on Climate Change (UNFCCC) (Herr et al. 2015). UNFCC guidance thus far has focused on helping contracting parties incorporate blue carbon in their nationally determined contributions.

Blue carbon pilot projects are currently underway across the globe, like Mikoko Pamoja (a community-led, voluntary market reforestation project) in Kenya and the Sundarbans (a restoration project funded as an offset mechanism for a company) in India (Wylie et al. 2016), but there are few coordinated efforts in the Caribbean. According to Neumann and colleagues (Neumann et al. 2015), this region is under significant threat of climate change, particularly due to sea level rise in the insular nations, and needs decisive action to promote carbon mitigation on the global stage. The coastal zone is also under intense pressure for development to meet the needs of the growing resident population and to support a burgeoning tourism industry (Gable 1997). The Caribbean has widespread participation in the Ramsar Convention, with nearly 70 coastal Ramsar sites in the 19 nations that are party to the Convention. Unfortunately, a 2020 citizen science survey reported significantly greater deterioration and wetland loss in this region compared to other areas worldwide (McInnes et al. 2020).

Given the multitude of risks that the Caribbean faces, and the strong presence of coastal wetlands of international importance, it presents a unique opportunity for a region-wide, integrated effort at understanding the role blue carbon might play in financing wetland conservation. In this paper, we review the various factors that might impact the viability of blue carbon as a market mechanism for supporting implementation of the Ramsar Convention financially. The logical first step in determining market viability is to identify appropriate benchmarks for valuation depending on the institutional and socio-economic contexts of Ramsar sites. We conduct a literature review to ascertain the compatibility of the Convention with different valuation methods, including an overview of requirements for accessing markets, a summary of market values that might be considered, and a broad overview of the potential value of mangrove carbon stocks in Ramsar sites in the Caribbean. This paper is intended to provide a starting point for decision-makers in the basin to explore the potential value of blue carbon within their territories, and specifically in their Ramsar sites.

METHODS

Literature Review

We first conducted a literature review to gain more comprehensive insight into primary valuation methods for carbon, the state of knowledge of blue carbon sequestration and storage potential in Caribbean mangroves, and the relevant structures of the Ramsar Convention for financing wetland conservation. We summarized the general requirements for valuing mangrove blue carbon and primary valuation techniques based on previous work (Jerath et al. 2016) to provide a practical overview for decision-makers. We also searched for papers that discussed requirements or estimates for blue carbon projects at Ramsar sites or sites already under some management and protection regime. To locate estimates of blue carbon stocks in Caribbean mangrove systems, we used Web of Science using the search terms "carbon" and "mangrove*" and the names of each member country or overseas territory in the Caribbean basin in the title or abstract as a search parameter, yielding 145 publications across the 19 contracting parties to the Ramsar Convention in the Caribbean. In addition, we searched for global or regional analyses by using the search terms "carbon" and "mangrove*" and "Caribbean" or "region**" or "global," which produced an additional 51, 563, and 459 papers, respectively. Given the high overlap of papers across searches, we then removed duplicates as well as papers that were not specifically pertinent to the basin or its nations (including removing papers reporting results from sites from non-Caribbean regions of Caribbean countries, like the Gulf of Mexico or the Pacific coasts) and any papers that were not reporting estimates of carbon stocks across one of the three primary carbon sinks (aboveground biomass (AGB), belowground biomass (BGB), or soil (SOC)) to produce a final literature set of 158 articles. We supplemented these findings with soil core data from the Coastal Carbon Network's Coastal Carbon Atlas (Holmquist et al. 2023), which includes soil carbon cores collected by practitioners that may not have been published in peer-reviewed literature. Finally, we searched the Ramsar Convention's documents, technical reports, and Conference proceedings to locate information on financing and the Convention's current engagement with blue carbon efforts. We also supplemented these findings with academic articles about the Convention, located using a Google Scholar search of "Ramsar Convention" and "structure" or "financ*" and "blue carbon". This provided an overview of financing within the Convention, and the current level of engagement in blue carbon projects by Ramsar parties and the secretariat.

Valuation

Next, we isolated various estimates for carbon stocks for the Caribbean basin. From this table, we calculated the lowest and highest possible carbon sequestration potential per unit area. We used estimates of mangrove coverage extent for the Caribbean and multiplied that area by the minimum, maximum and average carbon sequestration potential per unit area to estimate a range of total carbon stocks in Caribbean mangroves.

We then used the valuation information gathered to calculate estimated values of the total carbon stock based on different valuation techniques. More information on different valuation techniques is provided in our summary of carbon valuation methods in the next section. Here, we provide the value per unit of carbon based on three valuation techniques: voluntary markets, compliance markets, and the social cost of carbon (SCC). We used the average 2021 price for carbon offsets in the Ecosystem Marketplace ($3.13/tCO2), a voluntary marketplace for forest carbon credits (Donofrio et al. 2021), and inflated it to 2023 USD values ($3.32/tCO2) by applying an annual inflation rate of 3%. We then calculated the current market value per unit of carbon ($12.19/tC) (conversion factor: 1tC = 3.67 tCO2). For the compliance markets, we used the United Nation's Clean Development Mechanism's average 2022 price ($77.07/tC) (certified emissions reductions sold for between $7.34 and $146.8/tC) (UNFCCC 2022), and again adjusted this to 2023 prices per metric tonne of C ($79.38/tC). For comparison, we also used the average price per carbon credit from the European Union's Emissions Trading Scheme for 2022 (EUR 294.99/tC) (European Energy Exchange (EEX) 2022b; European Energy Exchange (EEX) 2022a; European Energy Exchange (EEX) 2022c; European Energy Exchange (EEX) 2022d), converted to 2023 USD/tC ($337.27/tC) (conversion factor: 1 EUR = 1.11 USD). For the SCC, we used an estimate from recent studies (Rennert et al. 2022b; Barrage and Nordhaus 2023) based on a 2% discount rate of approximately $620.23/tC (2019$) and adjusted this price to a 2023 price per unit of C ($698.07/tC). We multiplied these values by the total stocks to provide a range of estimates for the total potential values of carbon stocks in the region.

RESULTS

State of the Science

Carbon sequestration in Caribbean mangroves remains comparatively underreported in the academic literature. In our review, we initially located 145 publications across 19 countries, as well as 51 from our search for Caribbean-wide reports. After deduplication and removal of reports that did not report stocks or sequestration rates from the Caribbean for the country-level search, only 30 reports remained across 10 countries. The greatest number of publications were from Colombia (11) and Mexico (8). Only one of the publications from the Caribbean search was actually a Caribbean-wide analysis, and it covered parts of the Americas not included in the Caribbean. The relatively limited knowledge of carbon stocks in the region was additionally supported by the low number of cores included in the Coastal Carbon Atlas. Of 6,723 cores, only 219 (3.26%) were from the Caribbean. This is disproportionate to the areal extent of mangroves in the Caribbean compared to the global extent, which is closer to at least 10% (Bunting et al. 2022). Within the Ramsar system of sites, nearly one-third of all mangroves are in Latin America and the Caribbean (Beers et al. 2020).

Given the wide range of mangrove-dominated ecosystems in the Caribbean, including species composition (four species), canopy height (dwarf mangroves vs tall stands), sediment depth (shallow sediment karstic environments to deep peat environments), and extent of tidal influence (riverine vs. coastal fringing), carbon stocks vary widely. Carbon sequestration is also measured using a variety of methodologies (Howard et al. 2014), constantly evolving as new data points are acquired to improve modeling and as new remote sensing technology is deployed (Bukoski et al. 2020; Ouyang and Lee 2020; Zhu and Yan 2022; Malerba et al. 2023). In addition, as there is no singular definition for the Caribbean region, with some studies only including the islands and others lumping the Caribbean in to Central and South America, we did not find an analysis that reported mangrove stocks for the insular and continental Caribbean coastline. Instead, we present multiple estimates in Table 1 from different studies to provide context for the range of carbon stocks across different pools in the region. Across these studies, aboveground biomass represents a smaller carbon pool than either sediment or belowground. Belowground biomass is comparatively understudied, in part due to challenges in its estimation. Furthermore, where regional and global estimates are provided, Caribbean man-

Table 1. Summary of various global and regional estimates of mangrove area and the carbon stocks held in above and belowground biomass, sediments, and total ecosystem from published literature and IPCC recommendations (Hiraishi et al. 2014).

	Total Mangrove Area (ha)		Aboveground Biomass (MgC/ha)		
Global Estimate	16,661,402	13,065,675	115.23 + 48.89	114.9	83
Regional Estimate	2,686,555	571,493.75	115.1	98.45	--
Source	(Sanderman et al. 2018)	(Hu et al. 2020)	(Hu et al. 2020)	(Kauffman et al. 2020)	(Hiraishi et al. 2014)
Notes	Range: 1 (Aruba) to 922,812 (Mexico) based on global LandSat imagery (Giri et al. 2011)	Defined Caribbean as strictly insular. Additional mangrove extent classified under either Central (1,388,962.5) or South (2,062,231.25) America. Based on multisource remote sensing data combined with previously reported estimates (Spalding et al. 2010)	Defined Caribbean as strictly insular. Number reported here is an average of their Caribbean, Central, and South American estimates. Note: Caribbean stocks were larger than C. or S. American	No separate Caribbean estimate. Number reported here is an average of their Central and South American estimates	IPCC Default Value for Tier 1 Estimation

	Belowground Biomass (MgC/ha)	Sediments (MgC/ha)		Total Ecosystem Carbon Stock (MgC/ha)		
Global Estimate	407.5	360.5 + 136	333.7 + 11.2	856.1 + 32.1	511	858.98
Regional Estimate	333.5	388.1	556.8	710.8	--	912.75
Source	(Kauffman et al. 2020)	(Sanderman et al. 2018)	(Kauffman et al. 2020)	(Kauffman et al. 2020)	(Hiraishi et al. 2014)	--
Notes	No separate Caribbean estimate. Number reported here is an average of their Central and South American estimates. Their BGB also included soil up to 1 m depth; we've subtracted their SOC estimate to produce BGB estimates	Country-by-country estimates provided for up to 2m depth from predictive models. Restricted list to included nations and provided averages. Range: 243.4 (Mexico) to 589.4 (Cayman Islands)	No separate Caribbean estimate. Number reported here is an average of their Central and South American estimates for soil C up to 1 m depth	No separate Caribbean estimate. Number reported here is an average of their Central and South American estimates	IPCC Default Value for Tier 1 Estimation	Sum of means of reported stocks across each carbon pool in this table

groves tend to be on par with or above global carbon stock averages, with the exception of aboveground biomass.

Summary of Techniques for Valuing Carbon

There are well-documented and specific conditions that facilitate a payment for ecosystem scheme. Fundamentally, these are voluntary transactions wherein a single buyer pays a single provider for an ecosystem service, contingent upon the provision of the service (Kemkes et al. 2010). These conditions are not always met, in some cases because services are poorly defined or provided at low levels (Kosoy and Corbera 2010). For a payment for ecosystem services arrangement to be successful, both financially and ecologically, transaction costs must be minimized, the selling price should ideally be sufficient to offset the opportunity cost of provisioning, and the exact type of good must be clearly defined (e.g., public good, market good, common pool resource, etc.) as not all types are amenable to payment for environmental services (Kemkes et al. 2010).

Carbon sequestration is an ecosystem service with clearly defined parameters and a relatively well-established market under global frameworks (Thomas 2014; Wylie et al. 2016). There are currently two major markets: a compliance market, in which nations purchase emissions credits to meet emissions reductions standards, and a voluntary market, in which companies or organizations may purchase offsets for corporate sustainability or philanthropic purposes (Yee 2010). Thus far, the compliance market accepts certified emissions reductions from forested systems only, so the only blue carbon offsets that could be sold through it would be from mangroves (International Partnership for Blue Carbon 2017). As these are the more important carbon sinks, this is a good start, but there are several barriers to entry that can be prohibitive due to the high certification standards that must be met (Wylie et al. 2016). The voluntary market is more accessible, but emissions credits are typically sold at a lower price point to compensate for the reduced verifiability of offsets (Yee 2010).

In either market, there are four factors that determine whether a carbon offset can be sold (Canning et al. 2021; Vanderklift et al. 2022). A project should demonstrate additionality, meaning that the offsets gained would not have been feasible without the payment (Pittock 2010). Projects must also minimize the risk of leakage , so that avoided damage is not simply displaced to a different area (Ullman et al. 2013). The carbon stock should have relative permanence, such that the avoided emissions do not occur after the sale has been concluded. Finally, carbon gains must be verifiable. Many potential projects struggle to establish baseline carbon stocks and demonstrate they meet these four expectations. Forest carbon markets have been heavily criticized in recent years for weaknesses in demonstrating additionality, concerns about the permanence of forest sinks, and the apparent disconnect between project cost and value (Boyd et al. 2023). Despite the challenges to selling blue carbon emissions offsets, there are several examples of existing blue carbon projects that are successfully participating in both markets (Wylie et al. 2016).

However, markets are only one way of valuing carbon. Another common valuation technique is the social cost of carbon (SCC), which is intended to reflect society's willingness to pay to avoid the worst impacts of increasing carbon emissions (Jerath et al. 2016). To calculate the SCC, analysts predict future emissions based on a variety of factors, model the resultant climate response, and assess the economic impact of those climate changes to major industry sectors like agriculture, health, and more (Auffhammer 2018). Finally, these future damages are converted into their present day value using a discount rate that reflects the level of relative significance of present costs/benefits vs. future costs/benefits. As a reflection of sociocultural norms and prioritization, as well as the complex, unequally distributed impacts of carbon emissions, the SCC can be highly context-dependent. Scholars have recommended a variety of solutions, including adopting an equity-weighted global social cost of carbon that takes into account a range of priorities and detrimental effects of climate change and other carbon pollution impacts (Errickson et al. 2021; Rennert et al. 2022b). Given the variety of factors that can inform a social cost of carbon, there is no single rate that has been globally accepted (Wang et al. 2019; Rennert et al. 2022a), and many have called to instead adopt a target-based approach (Stern and Stiglitz 2021; Wagner 2021) or use a country-level SCC (Ricke et al. 2018; Tol 2019).

The Worth of Caribbean Mangroves

Based on the data compiled in Table 1, we estimate that mangroves cover between 571,493.75 and 2,686,555 ha in the Caribbean region. As we were not able to locate previously published estimates of mangrove extent in the islands plus strictly along the Caribbean coastlines of Central and South American nations in the basin, we will use both areal extents to represent an extreme underestimation (only island mangroves), overestimation (including Pacific slopes of continental countries in the basin), and the average of the two (1,629,024 ha) for mid-range calculations. It should be noted that this does not reflect uncertainty in the amount of mangrove cover, but rather uncertainty in the delineation of Caribbean itself. For example, some define it strictly as the insular Caribbean, while others included both the Pacific and Caribbean slopes of Central American countries but not necessarily northern South American countries. We provide both of these ends of the spectrum so users of either definition may gain some insight into the carbon stocks of "their" Caribbean. For a more robust treatment of the limitations and caveats of the estimates provided in this section, refer to the Discussion. Based on the estimates provided in table 1, we found that total ecosystem carbon stock (TECS) in the Caribbean ranged from 406.22 TgC to 2,452.15 TgC (Table 2). Note that the IPCC estimate of 832.43 TgC falls in the lower end of the above range of estimate.

Based on the TECS estimates (Table 2), we calculated a range of monetary values for the carbon stocks in the Caribbean based on SCC. On the low end of the spectrum, the total carbon pool in Caribbean mangroves is contributing approximately $283.6 billion in climate mitigation value, whereas the high-end estimate nears $2 trillion ($1,711,772,350,500). Based on the IPCC's default value for TECS, Caribbean mangroves store $581.0 billion worth of carbon. These estimates are based on a relatively low discount rate (2%) and calculations for a future climate with less than 2oC of warming. The above estimated values are stock values or value of carbon in perpetuity, or the "stock" value over a hypothetically infinite period of time (Mercer et al. 2017). The value in perpetuity can also be converted to annualized values. The annualized value, as the name suggests, is the value of the same ecosystem service in one year, reflecting the "flow" value. The annualized or flow value is determined by multiplying the value in perpetuity or stock value by an accepted rate of annual return on stock. We apply an annual rate of return equivalent to the same 2% discount rate used above. The above estimates of stock value of the Caribbean carbon of $283.6 billion - $2.0 trillion will result at most conservative annualized (flow) value of $5.7 billion - $40 billion.

Table 2: Range of estimates of total carbon stored in aboveground biomass (AGB), belowground biomass (BGB), soil organic carbon (SOC) and total ecosystem carbon stock (TECS).

	Carbon Pool (in TgC)			
Estimate	**AGB**	**BGB**	**SOC**	**TECS**
low	56.26	190.59	221.80	406.22
Mid	173.94	543.28	769.63	1322.40
High	*309.22*	895.97	1495.87	2452.15
IPCC	135.21	--	--	832.43

Market values are dependent upon additional carbon sequestered based on an implemented project. Therefore, rather than using the region-wide TECS we calculated to estimate market value, we use the difference between regional TECS and the total carbon held in all Ramsar sites across Latin America and the Caribbean, which is estimated at 620.7 TgC (Beers et al. 2020). Thus, it represents the potential of expanding protection by designating new Ramsar sites to protect additional mangrove area. As this estimate includes both the islands and the continent, we did not use the low estimate of TECS, as that only incorporated mangroves from the insular Caribbean. We find that there is as much as 1,831.45 million metric tonnes of additional carbon to be protected. On the voluntary market, projects to expand these protections could be worth upwards of $22 billion in stock value. Based on average 2023 compliance prices under the Clean Development Mechanism (low end) and the European Union's Emissions Trading Scheme (high end), this carbon stock might be worth between $145.4 - 617.7 billion.

DISCUSSION

There are several caveats to the estimates we provide here that should be considered when evaluating the potential of blue carbon as a financing mechanism for Ramsar sites in the Caribbean. Funding is frequently cited as a major driver of the gap between intention and execution, in the literature (Leverington et al. 2010; Heinen et al. 2017) and in contracting parties' triennial reports. However, there is no one way to implement the Convention. For example, while some contracting parties have passed national legislation that makes all Ramsar sites protected areas (e.g., Panama), for others, Ramsar sites are not under any sort of protection just by merit of their status under the Convention unless explicitly designated as a protected area (e.g., Jamaica). Thus, while blue carbon may be a financing mechanism for Ramsar sites, designation is certainly insufficient to ensure carbon is sequestered and sufficiently protected to meet the standards of market participation.

Contracting parties will need to invest in baseline and ongoing measurements to ensure mangroves continue to be managed to sequester additional carbon in longer-term carbon pools. Ensuring additionality goes beyond designating new protected areas, as studies have shown that only protected areas that enforce relatively strict ecosystem-scale protections are successful in stemming mangrove loss (Miteva et al. 2015). In some cases, such protections may conflict with the Ramsar principle of wise use, though a case could be made for re-framing wise use to emphasize the "wise" element. Additionality will only become more challenging as the compounding threats of climate change impact the Caribbean and mangroves worldwide (Alongi 2022; Chatting et al. 2022; Singh et al. 2022; Rull 2023). This could be an argument for acting more immediately to stave off these worst impacts. Given the increasing risk of intense hurricane events in the Caribbean (Vosper et al. 2020), there are additional concerns about the permanence of carbon stocks stored in mangroves. Much of the carbon in Caribbean mangroves is stored in sediments which are significantly more resilient to hurricanes, even following catastrophic losses of aboveground biomass (Krauss et al. 2020). Effective management can intervene to facilitate restoration (e.g., planting genetically diverse propagules, clearing debris, and restoring hydrological regimes), which can attempt to address both permanence and additionality concerns and is in alignment with the Ramsar Convention's restoration priorities (Gardner 2003). In the broader context of the impacts of climate change on coastal mangroves, some research has indicated that the carbon sequestration potential of coastal ecosystems may actually be enhanced by landward and poleward migration (Lovelock and Reef 2020). Facilitating this migration may be another avenue for identifying additional carbon sequestration.

The estimates we provide for carbon stocks are also based on simplification of the variety of factors that influence carbon sequestration in mangroves. Allocation of biomass across various carbon pools is dependent on nutrient effectiveness (Pan et al. 2023), tidal amplitude and duration (Rovai et al. 2018), precipitation and cyclone frequency (Simard et al. 2019), among others. Belowground biomass and soil organic carbon is driven by characteristics like soil depth and texture (Kauffman et al. 2020). Carbon stock and sequestration are also sensitive to physiographic types, species composition, salinity, and hydroperiod (Estrada and Soares 2017; Dai et al. 2018; Rovai et al. 2021). Given the relatively few data points in the basin, and the varying ways that scholars have delineated the Caribbean's boundaries for assessing carbon stocks, we also had to make assumptions about mangrove extent and the relative homogeneity of carbon stocks across a variety of different conditions. More studies are needed to quantify mangrove biomass across a variety of different ecosystem types and conditions in the basin.

With respect to price estimates, as expected, market values were substantially lower than the social cost of carbon value. This reflects the difference between willingness to pay for averted losses and the expected cost of those losses (Jerath et al. 2016). However, the SCC calculation requires a number of assumptions and normative preferences be made, and there are a variety of different estimates for that social cost of carbon that we did not choose (Ricke et al. 2018; Tol 2019). We chose the cost we did because it reflected a 2o C warming scenario – which is an increasingly optimistic outcome given delays in meeting Paris Accord emissions reduction targets – and a relatively low discount rate of 2%. These are value judgements to prioritize the immediacy of action needed given the Caribbean's sensitivity to climate change (Vosper et al. 2020), while still producing relatively achievable estimates. As the carbon market matures, one might be able to add more quality-based nuances to market designs and pricing.

These assumptions are critically important to understand, and for countries to test and adapt prior to market entry, because they will fundamentally shift the calculus of whether or not it is economically viable to sell carbon credits. If a low carbon price is set, or a low social cost of carbon adopted, in a context where sequestration is low and transaction costs are high, selling emissions credits is not financially comparable to conversion of the mangrove forest to alternate uses. From a policy perspective, countries may need to establish a work group to determine and regularly update a national social cost of carbon, as the United States has done (Stern and Stiglitz 2021), or adopt previously modeled values (Ricke et al. 2018; Tol 2019). However, we recognize that making a case for designing a payment for blue carbon through internal or external funding based on SCC may seem financially prohibitive. A more affordable basis for underwriting such programs would be abatement costs or compliance market prices.

A recent study found that only about 20% of global mangrove forests are investible for carbon finance projects due to their imminent conversion pressure (additionality), of which only 40.6% would be financially viable based on current market rates when factoring in costs of project establishment, management, and a gradually increasing carbon price (Zeng et al. 2021; Boyd et al. 2023). By their calculation, no countries in the Americas are in the top 10 for net present value of mangrove blue carbon. In addition, a more holistic calculation of global blue carbon wealth might also take into account the carbon benefits to other countries of avoided emissions to determine which nations contribute the greatest blue carbon wealth (Bertram et al. 2021). Regardless of the financial arguments for mangrove conservation, halting deforestation is absolutely critical for protecting biodiversity as well as increasing carbon stocks, perhaps by as much as 10% in the next century (Sanders et al. 2016).

Halting this trend in mangroves and across wetlands writ-large is one of the goals of the Ramsar Convention. As with many multilateral environmental agreements, the Ramsar Convention has struggled to maintain sufficient contributions to match the scale of its vision, and it has a significantly lower operating budget than other global conventions (Pittock 2010). Unfortunately, international funding mechanisms which have historically supported biodiversity conservation efforts (Emerton et al. 2006), and contributions to the Convention (Ramsar Standing Committee 2018), are increasingly being outpaced by the expanding need for significant investment to face escalating global and local development challenges. For Ramsar sites to participate in carbon markets to close this financing gap, standards for the aforementioned four requirements (additionality, permanence, leakage, and verifiability) are set and influenced by both markets and national policies (Thamo and Pannell 2016; Regan et al. 2020). Thus, to capitalize on the blue carbon opportunity in Ramsar sites across the Caribbean (Beers et al. 2020), national policies must be evaluated to ensure that conditions, like land tenure, transaction costs, and social license to operate are favorable for a payments for ecosystem services scheme (Kemkes et al. 2010).

CONCLUSION

The existing coastal wetland carbon stocks of the Caribbean hold enormous monetizable potential, as the region boasts large expanses of some of the most productive carbon sequestering ecosystems, especially mangroves. However, there are still substantial gaps in our understanding of these stocks, including the exact extent of different ecosystem types and estimates of their carbon stocks under different geological, hydrological, and environmental conditions, including a consideration of how these stocks may be impacted by climate change. Using the site-based framework of Ramsar, pilot projects can be established to better estimate ecosystem carbon stocks and potential for designing carbon markets. For instance, there are numerous multinational companies that are seeking carbon sequestration opportunities. The carbon investment fund, Livelihoods, which represents companies like Hermès, Michelin, and Danone, has invested in blue carbon credits from projects in Ghana (Bird 2016) and the previously mentioned project in the Sundarbans (Wylie et al. 2016). Apple funded Conservation International's efforts in Colombia to develop the first comprehensive mangrove carbon credit that remedied the undervaluation that was occurring due to using terrestrial forest methods, and the corporation claimed some of the credits for its own offsets but primarily participated philanthropically to advance the development of mangrove carbon markets (Klein 2021). National governments might seek such opportunities to partner with nongovernmental organizations and corporations to finance the development of carbon credit generating mangrove projects.

By providing small grants and training to strategically selected coastal Ramsar sites throughout the Caribbean, the Convention could contribute significantly to a more complete knowledge base of ecosystem blue carbon stocks. This paper provides a variety of benchmarks for carbon stock as well as flow values. Once carbon stocks are quantified, nations can determine where restoration projects and the establishment of new protected areas and Ramsar sites might be politically and economically viable, given access to carbon financing. Though full scientific certainty may not exist currently, the coastal Caribbean region cannot afford to postpone intervention. Blue carbon financing could be a viable funding source to promote the wise use of coastal wetlands, both by supporting restoration efforts within Ramsar sites and by adding more sites to the Ramsar network.

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