BIOLOGY LETTERS

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Cite this article: Shayka BF, Hesselbarth MHK, Schill SR, Currie WS, Allgeier JE. 2023 The natural capital of seagrass beds in the Caribbean: evaluating their ecosystem services and blue carbon trade potential. *Biol. Lett.* **19**: 20230075.
https://doi.org/10.1098/rsbl.2023.0075

Received: 10 February 2022
Accepted: 7 June 2023

Subject Areas:
ecology, ecosystems

Keywords:
ecosystem valuation, seagrass distribution, climate change, carbon storage, emissions trading schemes, seagrass conservation

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THE ROYAL SOCIETY PUBLISHING

Conservation biology

The natural capital of seagrass beds in the Caribbean: evaluating their ecosystem services and blue carbon trade potential

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Seagrass beds provide tremendous services to society, including the storage of carbon, with important implications for climate change mitigation. Prioritizing conservation of this valuable natural capital is of global significance, and including seagrass beds in global carbon markets through projects that minimize loss, increase area or restore degraded areas represents a mechanism towards this end. Using newly available Caribbean seagrass distribution data, we estimated carbon storage in the region and calculated economic valuations of total ecosystem services and carbon storage. We estimated the 88 170 km^2 of seagrass in the Caribbean stores 1337.8 (360.5–2335.0, minimum and maximum estimates, respectively) Tg carbon. The value of these seagrass ecosystems in terms of total ecosystem services and carbon alone was estimated to be \$255 billion yr^{-1} and \$88.3 billion, respectively, highlighting their potential monetary importance for the region. Our results show that Caribbean seagrass beds are globally substantial pools of carbon, and our findings underscore the importance of such evaluation schemes to promote urgently needed conservation of these highly threatened and globally important ecosystems.

1. Introduction

Climate change is arguably the greatest threat to our global society [1], incentivizing conservation that protects and restores ecosystems that capture and store carbon (C). One proposed method for protecting ecosystems that store C is through the sale of 'blue carbon' offset-credits [2–5], which monetizes the storage of carbon in coastal ecosystems [2]. Many island nations that have historically been more impacted by climate change despite contributing less to greenhouse gas emissions [3,6] have large areas of valuable coastal ecosystems that store carbon [3]. Thus, blue carbon offset-credits or other economic evaluations of C storage via C trade markets [5] could be a mechanism for wealthier countries to compensate for their contribution to climate change that would benefit (i) the economies of impacted countries and (ii) the conservation of coastal ecosystems, which are among the most impaired ecosystem types globally. Recent initiatives demonstrate a global motivation for action [7]. For example, a 2022 United Nations Convention on Biodiversity committed to protect at least 30% of the planet by 2030. Yet, accomplishing these goals first requires quantifying the extent of blue carbon in island nations to identify areas of high-conservation priority and incentivize the protection, restoration and management of these valuable ecosystems [8].

Seagrass beds have among the greatest C burial rates per unit area of any ecosystem in the world [9], making them valuable global blue carbon sinks [2]. This is largely due to high rates of primary production that capture C in biomass and inundated sediments that impede decomposition [10]. In addition to storing C, seagrass beds provide other ecosystem services, including storm protection and the provision of nursery habitat for fish and invertebrates, many of which are valuable fisheries [11,12]. They also filter and store nitrogen and phosphorus, and thus can mitigate anthropogenic pollution from municipal and industrial waste and agricultural run-off [13–15] that causes eutrophication and hypoxia (dead zones) events in coastal waters [16,17]. Despite these important services, seagrass ecosystems are among the most degraded by human stressors, including climate-induced changes, chemical pollution, shipping, recreation and coastal development [18]. Importantly, the degradation of seagrass beds often leads to erosion and sediment resuspension, which can create a positive feedback of increased seagrass loss and the release of C stored in sediments [19–22]. Blue carbon finance thus represents a potential mechanism by which the global community can invest in conserving and protecting these vital ecosystems [5].

A current practice in ecosystem science is to quantify the economic value of ecosystems by estimating a dollar value for their ecosystem services, i.e. valuing the natural capital of seagrass [23]. This evaluation can be used to incentivize conservation efforts that seek to: minimize further loss, increase total area or restore degraded areas—all of which can be monetized and sold for C credits [24]. Because seagrass ecosystems are both highly important for C storage and sequestration, and are highly degraded globally, they represent an important bourgeoning market for blue carbon [4,5]. Yet, to date, a fundamental impediment to both evaluating seagrass and promoting it in the blue carbon market has been the lack of thorough seagrass distribution data [25–27]. Here we use newly available seagrass distribution data in the Caribbean to estimate the C storage capacity of seagrass beds throughout the region. We then provide for each country economic valuations of (i) the total services these ecosystems provide and (ii) seagrass C storage. Our study highlights that the seagrass in the Caribbean represents a disproportionately large fraction of total global seagrass coverage and underscores the urgency of its protection to sustain the imperative services it provides society.

2. Methods

Seagrass distribution data at a 4 m cell [28,29] was used to scale C stored in plant tissue and sediments across the Insular Caribbean region (figure 1; countries listed in figure 2*b*) [34]. Seagrass data were derived by Schill *et al.* [28] from a normalized mosaic of PlanetScope Dove Classic three-band (RGB) scenes acquired between 2017 and 2019 [28]. They used an object-based RuleSet technique to classify seagrass ecosystems, in depths up to 30 m, in two habitat types, sparse and dense seagrass, based on field-based training sites and spectral response [28]. They performed extensive corrections based on image interpretation and local knowledge [28]. Cells classified as dense seagrass were assumed to have greater aboveground and belowground biomass than those classified as sparse [31].

C pools were quantified by estimating seagrass biomass and C content, and the amount of organic C in the top 1 m of sediment per 4 m grid cell. Seagrass %C and sediment C_{org} per unit area were compiled from the literature using data for *Thalassia testudinum*, the dominant species in the Caribbean in both sparse and dense habitats [35], and from *Thalassia*-dominated communities in the Caribbean, respectively (table 1). Specifically, for each map cell, aboveground seagrass biomass was calculated by sampling a biomass value from a normal distribution (table 1). For habitats classified as dense and sparse seagrass, values were sampled from the upper half (greater than the mean) and lower half (less than the mean) of the biomass distributions, respectively. These values were multiplied by a %C value that was also sampled from a normal distribution (table 1). To estimate potential error associated with our calculations, we repeated these analyses using (i) the upper 97.5% and (ii) the lower 2.5% of the %C distribution to generate an upper and lower range limit of C stored in seagrass biomass. The same process was repeated for belowground %C. Values were summed to calculate total C in aboveground and belowground biomass, with upper and lower ranges, across the region. Additionally, for each cell, a sediment C_{org} value was sampled (from a normal distribution; table 1), and upper and lower range limits were estimated by sampling values from the upper 97.5% or lower 2.5% of the distribution, respectively. All values were summed to calculate total sediment C_{org} for the region. The entire process was repeated 10 times and averaged to generate our final estimate.

We calculated an economic value for (i) the total ecosystem services provided by seagrass of the Caribbean and (ii) for the C stored in these seagrass beds. The value of seagrass ecosystems reported in the literature ranged from $\$78\ ha^{-1}\ yr^{-1}$ to $\$2.3$ million $ha^{-1}\ yr^{-1}$ depending on valuation method, number of services considered and year of calculation [12]. We chose $\$28\,916\ ha^{-1}\ yr^{-1}$ from Costanza *et al.* [23] because it was a conservative estimate that took into account multiple seagrass ecosystem services, including food production, nursery habitat and recreation. This value was calculated using a statistical value transfer aggregation method that incorporated data from different areas, services and levels of scale [23]. We scaled this amount (per $ha^{-1}\ yr^{-1}$) to the seagrass ecosystems across the Caribbean region.

The market value of C within emissions trading schemes (ETS) globally ranged from \$1.12 to \$49.78 per tonne CO_2e (carbon dioxide equivalent) in 2021 [39]. We used the value of \$18 per tonne CO_2e from the California cap and trade programme—an ETS in which the California Air Resources Board sets a maximum number of allowances for CO_2 emissions in California [39]. This value was an intermediate for ETS globally and one of only two ETS values available for the United States, which we considered more relevant for the Caribbean.

3. Results

A total seagrass area of $88\,170\ km^2$ was mapped in the Insular Caribbean (figure 1*a*), which amounts to 2–2.8 times the Mediterranean seagrass area [30] and 33–55% of an estimated global seagrass area of $160\,387–266\,562\ km^2$ [40]—although global seagrass area estimates vary greatly due to lack of distribution data [31]. We estimated that seagrass in the Caribbean stores 1337.8 (360.5–2335.0, minimum and maximum estimates, respectively) Tg C (teragrams carbon). Most of this C is stored in the top 1 m of the sediment, and seagrass biomass (above- and belowground) accounts for only 0.4% of the total C (figure 1*b*).

C stored in seagrass beds in the Caribbean is substantial relative to other important global stores of C. Seagrass beds in the Mediterranean contain approximately 1200–1700 Tg

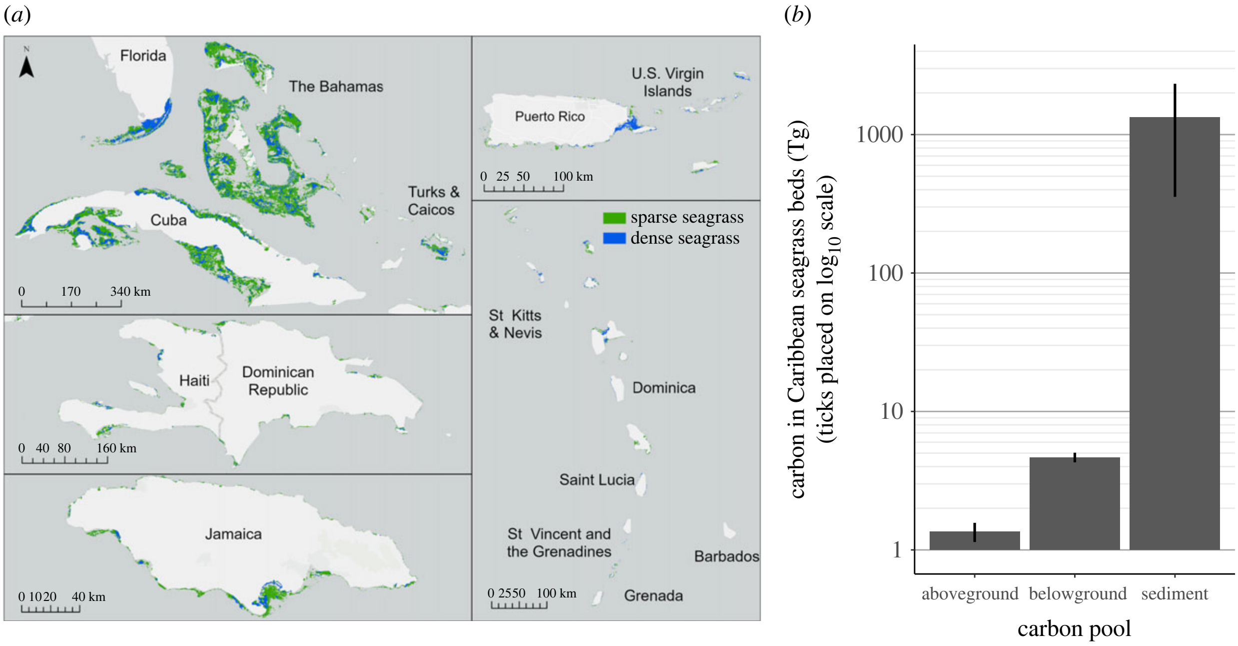

Figure 1. (*a*) Map of seagrass distribution in the Caribbean. (*b*) Total amount of carbon in seagrass beds of the Caribbean. Bars show amount in teragrams (Tg), with range limits. *Y*-axis is on a $\log_{10}$ scale.

C in biomass and sediment to 1 m deep [30,31], roughly the same amount stored in the Caribbean (figure 2*a*). The seagrass biomass in the Caribbean (0.0060 Pg C; petagrams carbon) represents 0.5% of the C in all marine autotrophs (1.3 Pg C) [41]. By comparison, Caribbean seagrass stores 1.09% of the C contained in above- and belowground woody biomass in the Amazon [33]—one of the largest global pools of C (figure 2*a*). Caribbean seagrass also stores 1.12% of the C contained in the biomass and sediment (to 1 m deep) of global temperate forests (figure 2*a*) [32]. C stored in Caribbean seagrass beds is also comparable to other pools of C on a global scale. For example, the C stored in Caribbean seagrass and sediment is almost twice the C stored in all fish biomass on Earth (≈0.7 Pg C) [41], 13 times larger than the amount of C in all livestock biomass on Earth (≈0.1 Pg C) and 22 times larger than the amount of C in the biomass of humans on Earth (≈0.06 Pg C) [41].

The total estimated economic value of the ecosystem services provided by seagrass in the Caribbean using the value from Costanza *et al*. [23] is \$255 billion yr^{-1}. Using other literature values [12], the economic value of Caribbean seagrass could be \$0.69–20 279 billion yr^{-1}. The value of C in seagrass in the Caribbean, using the market value of C in the California ETS, is \$88.3 billion. The Bahamas represents the largest proportion of seagrass among all nations in the Caribbean (61%) and alone values at \$156 billion yr^{-1} for all ecosystem services and \$54.0 billion for C storage (figure 2*b*). Cuba contains the second highest areal cover of seagrass (33% of the total Caribbean) valuing at \$84.6 billion yr^{-1} for all services and \$29.3 billion for C storage (figure 2*b*).

4. Discussion

Our study provides evidence that Caribbean seagrass beds are globally substantial reservoirs of C. Seagrass in the Caribbean could account for up to half of global seagrass area and a third of the estimated C stored in all seagrass beds on Earth, with uncertainty stemming from the lack of accurate global seagrass distribution data [26,27,31,40]. This highlights the potential importance of these ecosystems in the growing C trade market that is being promoted as a mechanism to mitigate net C emissions that contribute to climate change. Importantly, incorporating Caribbean seagrass ecosystems into global C markets will supplement current sustainable development goals to promote the conservation of this natural capital and may have vast implications for local communities and economies of the region [5,8,26,42].

The value of seagrass based on the total services they provide society and on their storage of C alone is tantamount to substantial proportions of the economies of many Caribbean countries. For example, in The Bahamas, the country with the largest area of seagrass in the Caribbean, we estimated the value of ecosystem services provided by seagrass beds to be \$156 billion yr^{-1} and the value of C alone in seagrass to be \$54.0 billion. Despite being conservative estimates of ecosystem service evaluations, these numbers still represent more than 15 and five times the country's 2020 gross domestic product (GDP) (\$9.91 billion), respectively [43]. In other countries, despite having substantially smaller areas of seagrass, the value of C is still equivalent to a substantial proportion of their economy. For example, the value of C in the seagrass around Cuba, which represents 33% of the total seagrass in the Caribbean, is equivalent to 27% of the country's 2020 GDP (\$107 billion) [43]. Irrespective of the exact value of the services seagrass provide, our estimates in conjunction with the rapidly growing awareness of their importance on both local and global scales (see perspective by Unsworth *et al*. [27]), provide a very clear message: *seagrass ecosystems need to be at the forefront of the global conservation agenda*.

Monetizing the value of seagrass ecosystems is challenging because most of the value of these ecosystems comes indirectly from the services they provide [12]. This contrasts with other ecosystems in which resources represent a direct resource, such as timber. Seagrass monetary evaluation

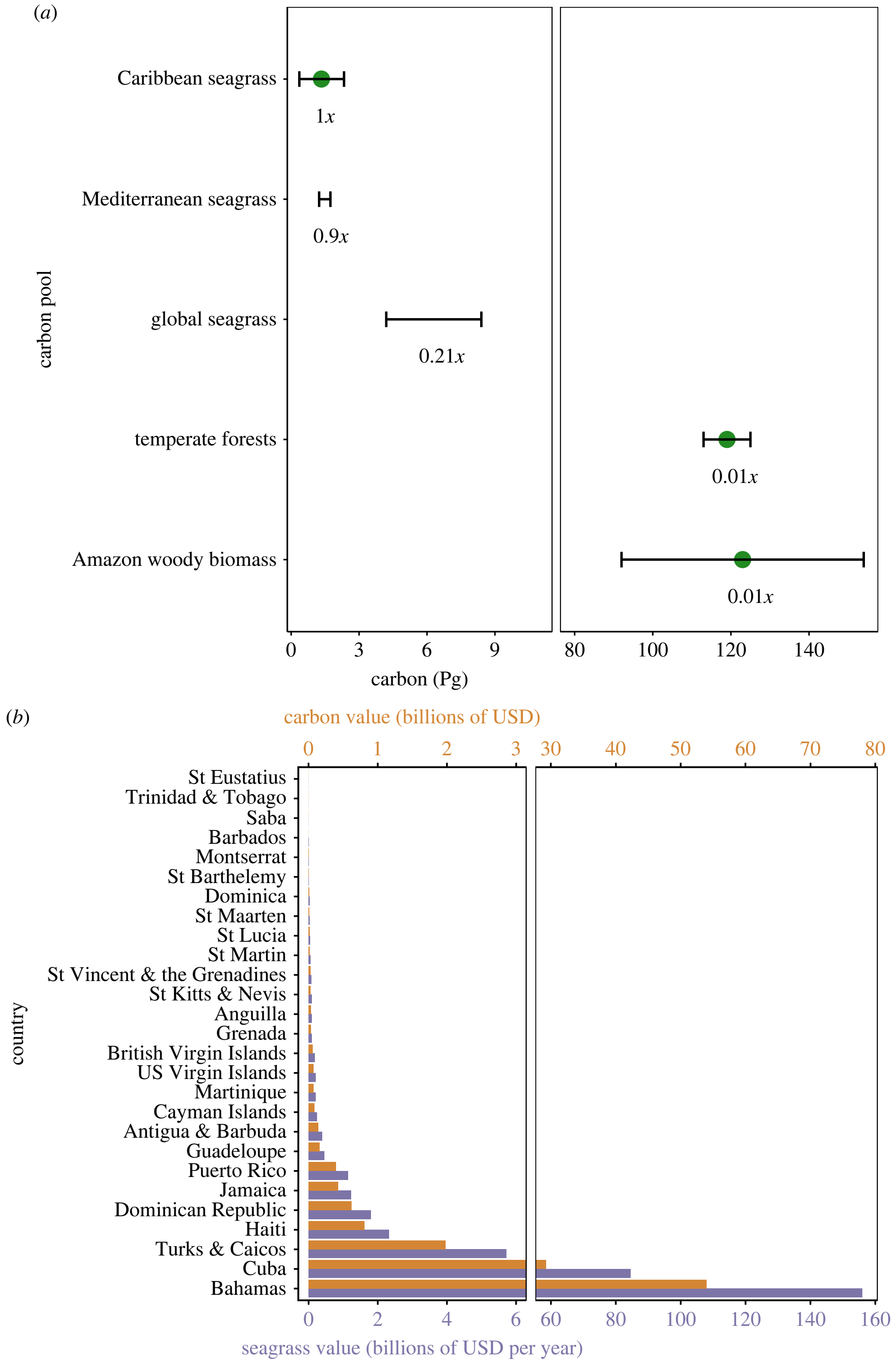

Figure 2. (*a*) Carbon storage in various global pools for comparison with Caribbean seagrass beds. Error bars represent: range limits for Caribbean seagrass beds, range for Mediterranean seagrass beds [30] and global seagrass beds [31], 95% confidence interval for temperate forests [32], and 25% uncertainty for Amazon woody biomass [33]. If present, dots represent mean value. Pg = petagrams. Text values below bars indicate amount of C in Caribbean seagrass relative to each global pool. (*b*) Monetary value of seagrass bed ecosystem services and C in the Caribbean by country. Purple bars represent value of all seagrass bed ecosystem services per year. Orange bars represent value of carbon stored in seagrass beds calculated based on market value of carbon in California (USA) cap and trade programme.

typically focuses on one or a few services and many use different evaluation methods, making comparisons among estimates difficult [12]. Further, the science around seagrass ecosystem services is constantly evolving, creating challenges for their evaluation [23]. For example, our study provides evidence that seagrass beds contain massive C stocks—a fact that has been long recognized [31]. But research on their role in sequestration of C is evolving rapidly, with evidence that some seagrass beds may be net emitters of CO_2 [44]. Additionally, because of the role of seagrass in trapping sediment, C can move between local stocks, and much of the C stored in seagrass beds may be allochthonous [8]. Regardless

Table 1. Values used in model calculations of carbon (C) storage. All values are means ± s.d. AG = aboveground, BG = belowground, DW = dry weight.

variable	value	source
AG biomass	47.8 ± 29.0 gDW m^{-2}	Fourqurean *et al.* [31]
AG %C	36.9 ± 2.5%	Fourqurean *et al.* [36]
BG biomass	191 ± 136 gDW m^{-2}	Fourqurean *et al.* [31]
BG %C	30.9 ± 1.06%	Layman *et al.* [37]
sediment C	15 090 ± 4840 gC m^{-2}	Howard *et al.* [38]

of these complexities, ensuring that the long-term sediment C pools are not released through anthropogenic impacts is essential in the global fight against anthropogenic climate change. These stores are precarious, and seagrass ecosystems, when disturbed, can rapidly release massive amounts of C and nutrients from sediment back into the environment. Importantly, this can occur as a result of even small-scale perturbations that initiate positive feedbacks that rapidly destabilize and erode large expanses of seagrass bed sediment [22,45]. Our study, by estimating the extent of C stored in Caribbean seagrass ecosystems and their value, provides the needed first step toward integrating these important ecosystems into the bourgeoning C trade market.

Given the highly threatened status of seagrass ecosystems globally [11] and the urgent need for climate change mitigation, incorporating seagrass ecosystems into C markets represents an important opportunity that could prove beneficial at local and global scales [5,8]. For example, the largest seagrass restoration project to date, which offsets 0.42 tCO_2e ha^{-1} yr^{-1} in the Virginia Coast Reserve, is currently under verification for inclusion in C markets [4,46]. Additionally, as has been shown with mangroves in the Caribbean, prioritizing the conservation of coastal ecosystems for C storage guarantees the preservation of other ecosystem services [47]. Further, incorporating seagrass ecosystems into C markets is particularly important for island nations because (i) it could provide a means by which larger, wealthier countries that have disproportionately contributed to causing climate change can provide needed economic support to island nations that are disproportionately affected by climate change-associated phenomena such as sea-level rise and hurricane intensity, and (ii) it can provide needed economic incentives for local efforts to protect seagrass ecosystems from further anthropogenic disturbances (i.e. chemical pollution, dredging and coastal development [18,42]).

Our study highlights the importance of integrating seagrass beds into global C markets to preserve the benefits of these ecosystems at local and global scales. If valued appropriately and incorporated into C markets, conservation efforts focusing on seagrass beds in the Caribbean could contribute greatly to the economies of Caribbean nations. Improved processes for valuing the ecosystem services provided by seagrass ecosystems are critical for these ecosystems to be integrated into the blue economy. Although our understanding of the net value and role of seagrass beds in global C markets is still evolving, the relatively conservative estimates we provide here for Caribbean seagrass beds can be immediately used by governments and managers to motivate conservation efforts in seagrass ecosystems and promote their integration in global C markets.

Data accessibility. The seagrass distribution data used in this manuscript are publicly available through The Nature Conservancy. Data can be accessed at this link: https://sites.google.com/view/caribbean-marinemaps [29].

The code used in this manuscript is available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.z612jm6h4 [34].

Authors' contributions. B.F.S.: conceptualization, data curation, formal analysis, methodology, visualization, writing—original draft and writing—review and editing; M.H.K.H.: formal analysis, methodology and writing—review and editing; S.R.S.: data curation, resources, visualization and writing—review and editing; W.S.C.: methodology and writing—review and editing; J.E.A.: conceptualization, funding acquisition, methodology, resources, supervision, visualization, writing—original draft and writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

Funding. Support for this study was provided by the Lucille and David Packard Fellowship and National Science Foundation OCE (grant no. 1948622) to J.E.A.

Acknowledgements. We thank Scott Settelmyer, Denise Perez and Ryan Moyer for useful comments on the manuscript and The Nature Conservancy for seagrass distribution data (https://sites.google.com/view/caribbean-marine-maps).

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